Engineering Energy Systems of the Future as Cyber-Physical Ecosystems

Marija Ilic, Carnegie Mellon University

milic@andrew.cmu.edu

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Talk outline

- Examples of existing and evolving energy industry architectures as particular cases of cyber- physical systems; likely end state--cyber-physical ecosystems [1,2]
- Complexity of the evolving energy industry architectures
- The key role of liquid transparent information exchange and processing for arriving at desired solutions (Dynamic Energy Control Protocols –DECPs) [2-6]
- Major R&D questions

  - The challenge of posing the real-world physical system problems as Cyber-Physical Ecosystems

  -Preventing blackouts: From Complexity to Order [7]

  -Evolution from today's paradigms to the end state (dynamically evolving itself)

  -Design of industry policy paradigms in support of valuing IT (in addition to large capital investments) [8]

Some basic difficult questions

- How does it work today?
- What needs fixing?
- What are some possible performance metrics which provide us with quantifiable ways of showing improvements?
- Are methods under consideration capable of meeting the pre-decided upon performance criteria?
- What are systematic ways of deploying new technologies into the existing system without making the overall operations even more complex?
- How to integrate new in ways transparent and useful to those operating the system?
- How to provide policy and financial incentives for deploying the most effective technologies as measured in terms of pre-agreed upon metrics?

Some predictions of (long-term) energy network architectures

- Interstate EHV DC delivery system connecting large nuclear power plants (backbone network)
- Closer to the end users a mix of

  -highly distributed micro-grids with their own back-up small power plants and/or connections to the backbone

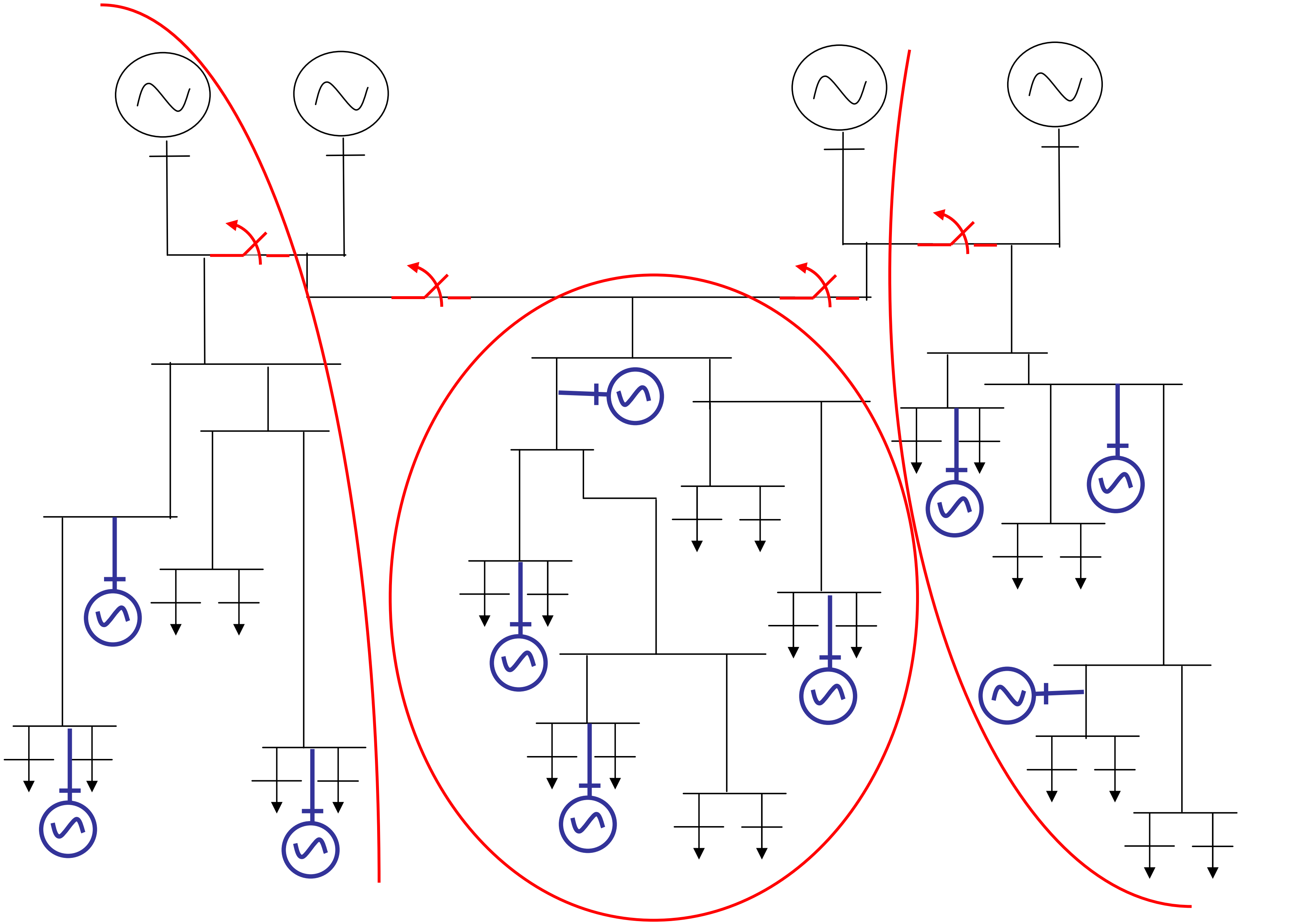
  -medium-sized fossil fuel/gas power plants

  -distributed renewable resources (DGs)
- Significant penetration of IT:

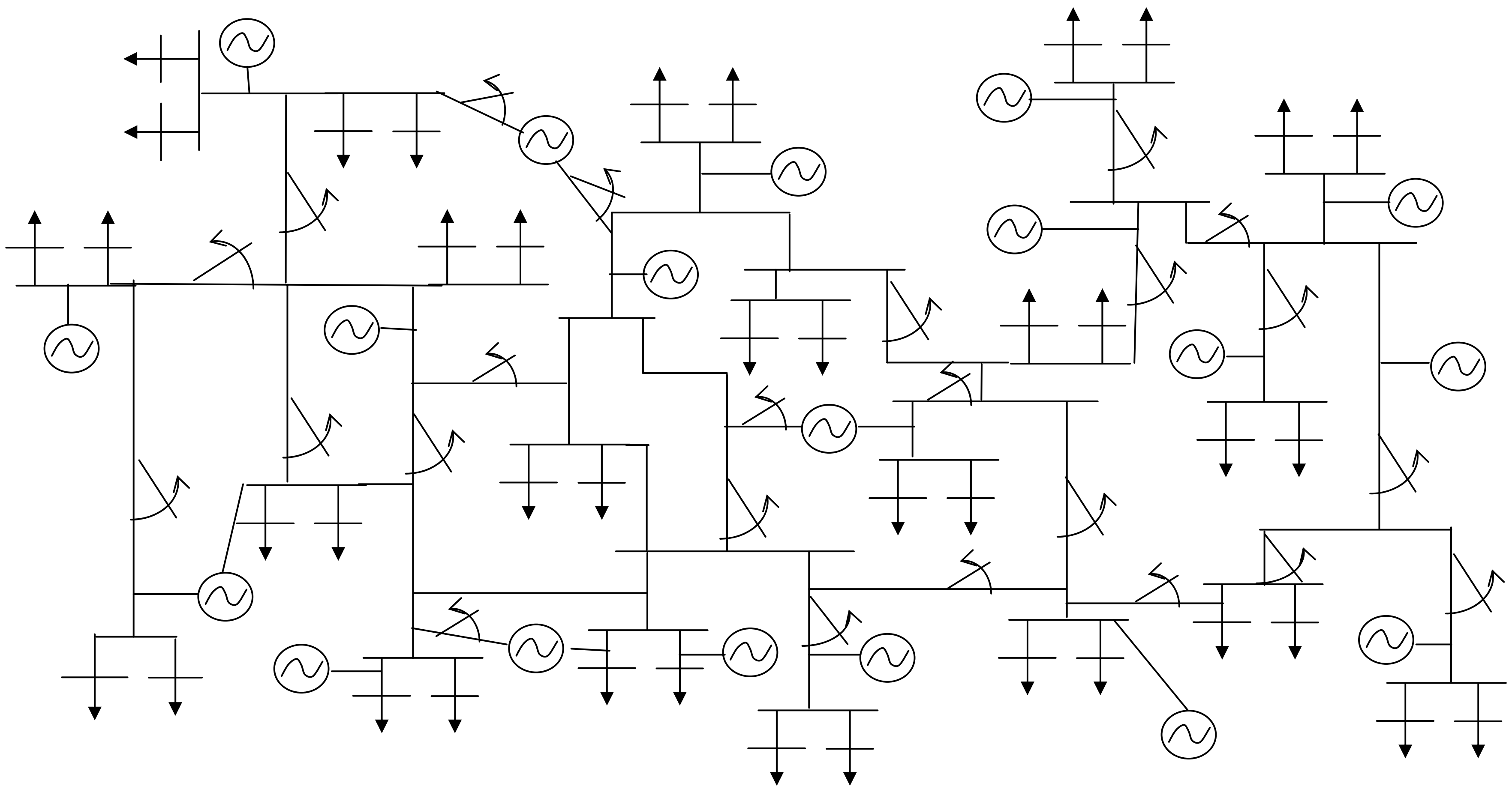
  -Making micro-grids highly flexible (BOTH reliable/secure and efficient!) with the end user actively participating;

  -Facilitating on-line coordination of the backbone network and the micro-grids for reliability.

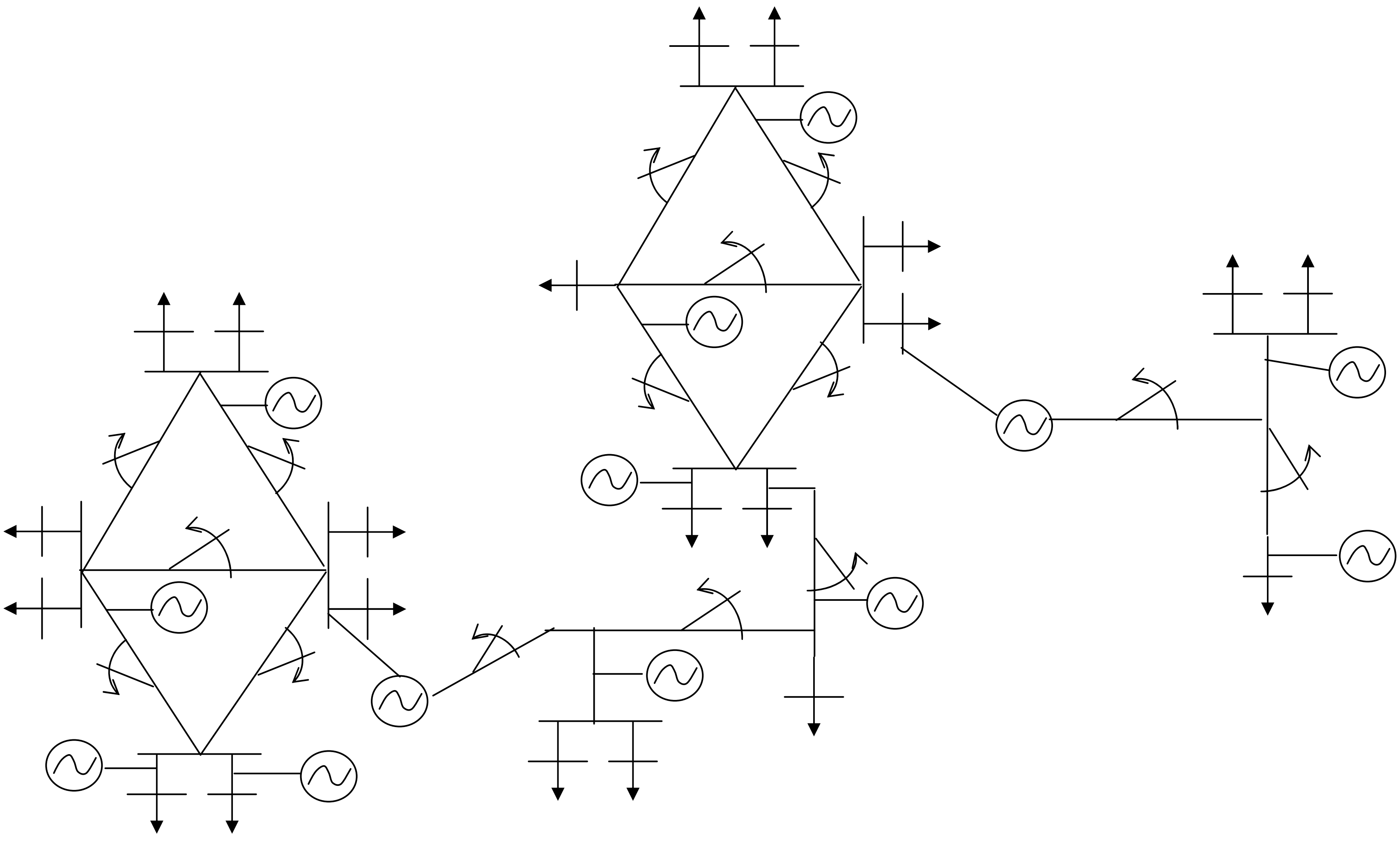
Integrated and hybrid paradigm



Decentralized Paradigm



Re-aggregation



The likely end state

- Conceived by late Prof. Schweppe (1978-- homeostatic control) paradigm;
- BASIC VISION OF CYBER-PHYSICAL ECO-ENERGY SYSTEMS
- Becoming commercially feasible (cost-effective supporting technologies; distributed IT infrastructure in place; low additional cost for implementing customer choice)

Complexity of the Evolving Industry Architectures

- The industry challenge is much more complex than ever before as a result of variety of reasons:

  - the needs for more energy are growing, but it is no longer possible to build according to the existing planning and operating criteria (there is simply not enough resources to provide the same energy density per capita as at present; right of ways hard to obtain; greenhouse effects major concern);

  -it has become inevitable that we must make the “most” out of what is available (even at the expense of violating once sacred principles of unconditional service provision to the customers);

  -the “most” not a single criterion subject to constraints (instead, the notion of the “most” has become multi-dimensional and must be viewed as a result of reconciling major tradeoffs)

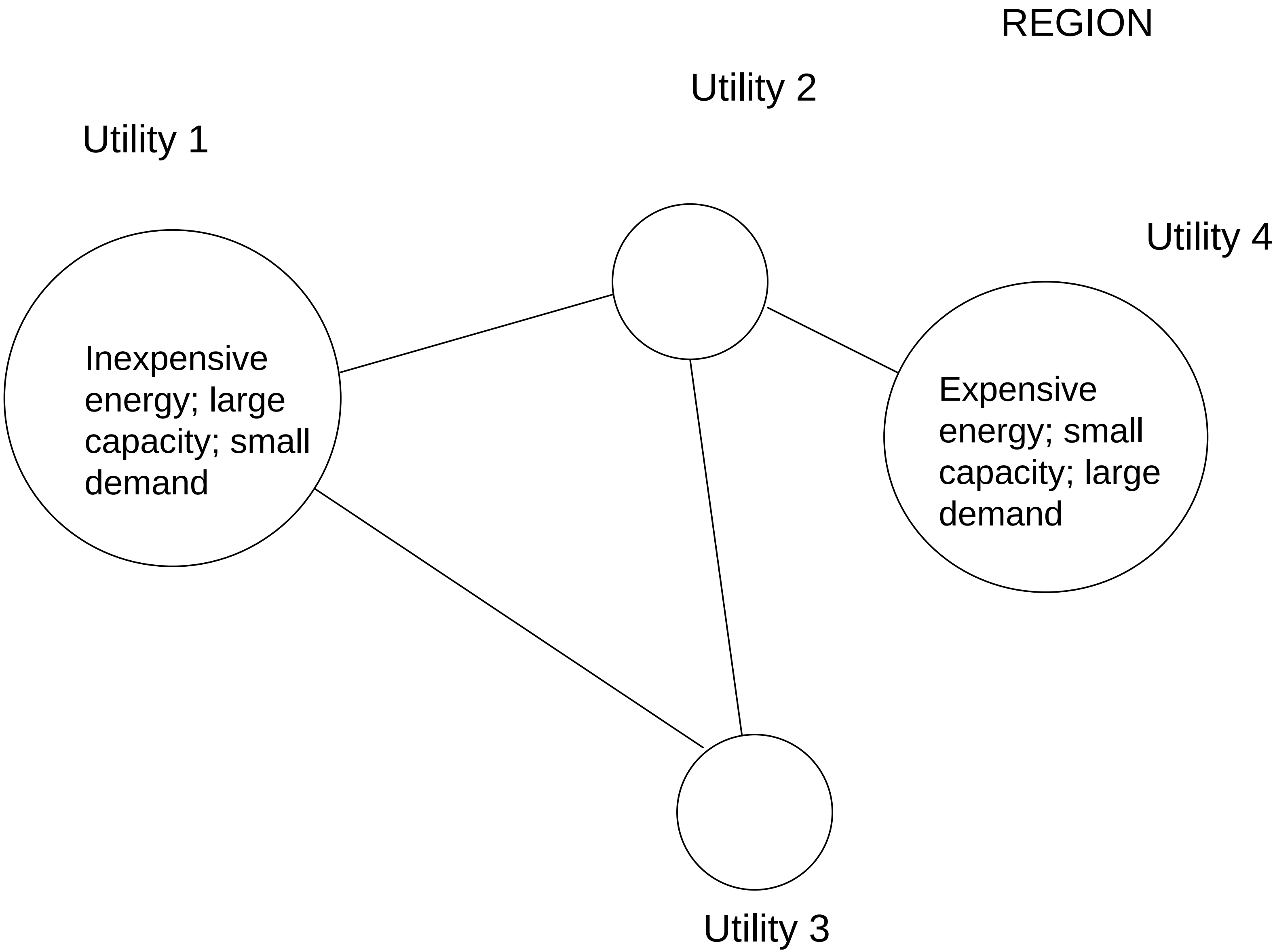
Single optimization subject to constraints vs. Reconciling multi-dimensional tradeoffs

Single optimization subject to constraints	Reconciling tradeoffs
Schedule supply to meet given demand	Schedule supply to meet demand (both supply and demand have costs assigned)
Provide electricity at a predefined tariff	Provide electricity at QoS determined by the customers willingness to pay
Produce energy subject to a predefined CO_2 constraint	Produce amount of energy determined by the willingness to pay for CO_2 effects
Schedule supply and demand subject to transmission congestion	Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned)
Build storage to balance supply and demand	Build storage according to customers willingness to pay for being connected to a stable grid
Build specific type of primary energy source to meet long-term customer needs	Build specific type of energy source for well-defined long-term customer needs, including their willingness to pay for long-term service, and its attributes
Build new transmission lines for forecast demand	Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service

Vastly different performance of candidate architectures

- Architecture 0 - sub-optimal utilization of regional resources.
- Architecture 1 – suboptimal utilization of regional resources; utility (State) 1 subsidizing owners of their divested power plants;
- Architecture 2 -- Very interesting $$ flow.

- Only some candidate architectures become real-world solutions depending on regulatory rules/constraints. Very different performance.
- Major problems: Biased solutions, without systematic reconciliation of tradeoffs. Often one time solution w/o ability to evolve into better performance.


REGION
Utility 2
Utility 1
Utility 4
Inexpensive energy; large capacity; small demand
Expensive energy; small capacity; large demand
Utility 3

An example of effects of engineering/regulatory and financial constraints

- Initial Architecture 0 (Utility 1 in State 1 has excess inexpensive capacity; Utilities 2 and 3 have just about enough to supply their own customers; utility 4 in State 4 has high demand, and expensive energy.)

- Possible future architectures (at a regional 4-utility level):

Architecture 1 – Generation divests and Utility 4 loses its large nuclear energy source to its new owners in State 1 (regulatory change only, no new physical investments). No spot markets in individual States (utilities)

Architecture 2– The same as Architecture 1, except State (utility) 4 establishes spot market and FERC demands open access competition across all four States (no new physical investments).

An example of effects of engineering/regulatory and financial constraints (continued)

Architecture 3 —The same as architecture 0, except many new small gas power plants added

Architecture 4 —The same as architecture 1, except many new small gas power plants added

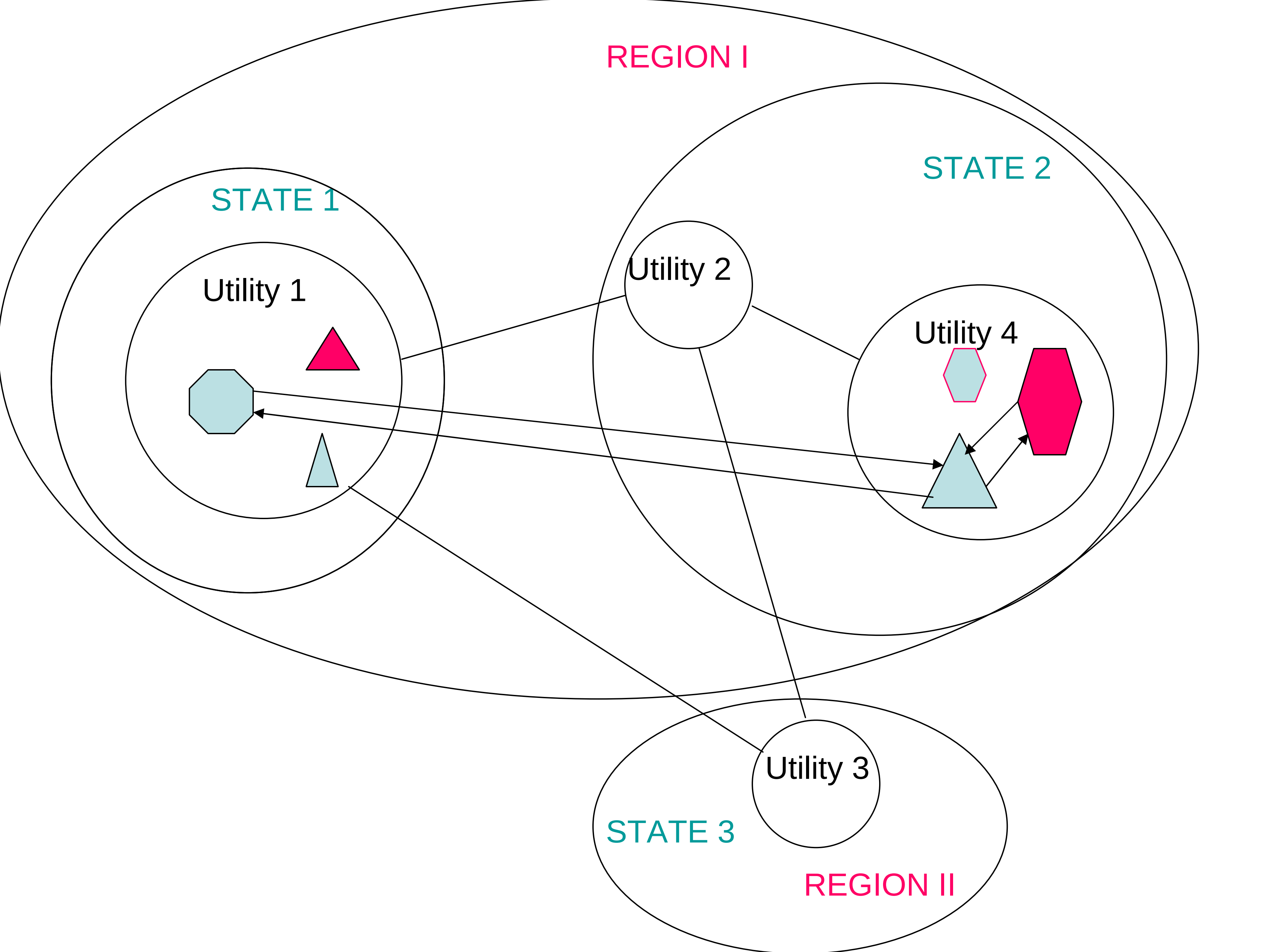
Architecture 5 —The same as Architecture 0, but transmission interface constraint

Architecture 6 -The same as Architecture 5, but new transmission added

Architecture 7 - The same as Architecture 0, except mandatory 10% new renewable resources in all four states (including many novel technologies, such as low-cost solar, wind, etc)

Possible ways forward: DECPs

- Dynamic Energy Control Protocols (DECPs) as a means of reconciling tradeoffs
- For example, in order to implement supply-demand balancing, S and D need to iteratively communicate over time.
- Or, to build a specific type of energy resource, iterative sharing of future uncertainties through transparent and liquid market arrangements becomes essential (need for long-term energy/capacity forward markets).
- Or, to build a specific transmission line, iterative sharing of future uncertainties and associated risks is essential (need for longer-term forward transparent transmission contracts).
- Depending on the temporal and spatial granularity of the DECPs much can be achieved in terms of reconciling tradeoffs through choice and information exchange.


REGION I
STATE 2
STATE 1
Utility 2
Utility 1
Utility 4
Utility 3
STATE 3
REGION II

Industry architectures as a function of DECPs in place

- Architecture 0- Regulated industry (communications top-down at the utility control center level; planning and operations w/o much active info exchange with the customers; communications between utility and State regulators – annual, regulation lags in response to utility performance; no information exchange between States; no choice in response to price of electricity)
- Architecture 1 —Divested generation (new communications between power generation and utilities, purchasing on behalf of their customers ; the rest is the same by and large as in Architecture 1.
- Architecture 2 -- Additional info exchange day ahead between the control center (spot market) and power producers selling into the spot market. Very little information exchange between some (large) customers and the spot market.

Engineering Energy Services of the Future by Careful Design of DECPs

- It can be shown that depending on the type of information exchange in place, the system performance is qualitatively different
- New regulation needed to define type of information exchange required for predictable performance (short-term, and long-term)
- For example, if power delivery is to be equally valued as generation (local expensive generation equivalent to far away cheap generation plus value of transmission), one must have well-understood protocols in place for both building new transmission and providing it according to well-defined contractual arrangements (of particular importance is T-value for short-term reliable service, as well as for longer-term assurance that there will be energy in the areas where no generation is planned)
- Another example, if effects of pollution are to be paid for by those who use energy, there ought to be a protocol for customers providing their willingness to pay for cleaner energy, and the power suppliers providing offers to sell different primary energy. Clean energy should be allowed to be offered at the higher price.

Major R&D Issues

- Something old: **Is all well in today's operations and planning (emerging problems with reliability, missed missed opportunities for enhanced economic utilization; challenges to the existing software)**
- **Performance metrics for assessing value-added by the existing software**
- **Information and software specifications for reliable operations**
- Something new: **Operating and planning in the changing industry**
- **Needs for novel IT and software solutions**
- **Performance metric for assessing value-added by IT and software for the changing industry**
- **Information and software specifications for the changing industry**
- **Technical and economic policy roadblocks to software deployment in the changing industry**

Something old: Is all well in today's operations and planning

- Operators and planners have two basic objectives, namely to serve customers reliably and at acceptable cost.
- Operations and planning inter-dependent (planning assuming operating practices; and, vice versa, operating practices assuming planning principles)
- In the past, operations relatively straightforward based on robust design which enables many simplifying assumptions in operations (localized response to system failures; semi-stationary feedforward for given demand forecast; hierarchical temporal and spatial separation)
- Even during equipment failures sufficient reserves and pre-planned procedures almost always sufficient for acceptable service.
- Economic utilization achieved using very simple ED computations for real power; sufficient support for reactive power through design.
- Utilities run by the human experts w/o critical reliance on on-line software use and extensive automation.

Simplifying assumptions no longer justifiable

- The interactions among utilities and within utilities themselves have become more complex than in the past, and are beyond human's ability to manage;
- Economic factors no longer allow robust operations through design; need for just-in-time (JIT) and just-in-place (JIP) decision-making.
- JIT and JIP services require much on-line sensing, monitoring and software-based decision making
- Unexpected network system response as utilities trade for economic reasons (patterns very different than what was pre-agreed on; load decrease could cause continuing decrease in frequency and voltage, contrary to the operator's intuition; wide-spread backbone effects of equipment failures leading to cascading failures)

Fundamental need for on-line information processing

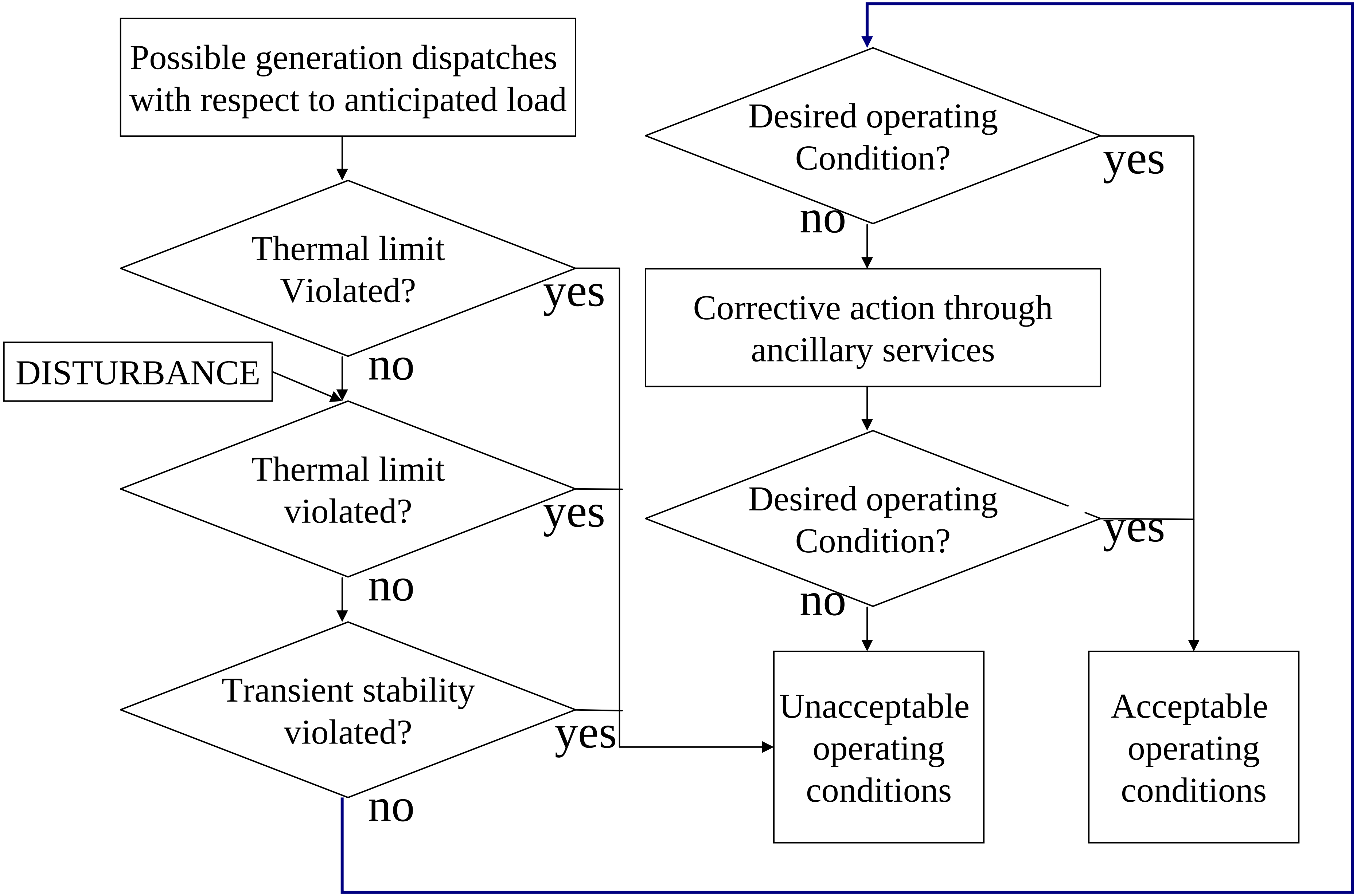
- Implementation of pre-agreed performance metrics over a broad range of conditions (short-term enhanced reliability; enhanced short-term utilization of existing resources; enhanced long-term service to customers)
- The overall problem of operating the system away from "nominal" conditions
- These are not directly interpretable in terms of (N-x) reliability standards (particular amount of reserve does not necessarily guarantee pre-specified LOLE, and, more generally QoS.

Software specifications for facilitating reliable operations

- Relying on software risky unless one has robust and easy-to-use software
- Today's software does not meet these requirements
- Software has evolved by solving particular sub-problems under strong (often hardware-ensured assumptions)
- In order to implement (N-x) reliability standards one needs a dynamic shell (architecture) for integrating the existing modules with well-defined performance criteria and internal logic for relating various software modules (hard, and loaded with open problems)

An illustration of performance metrics

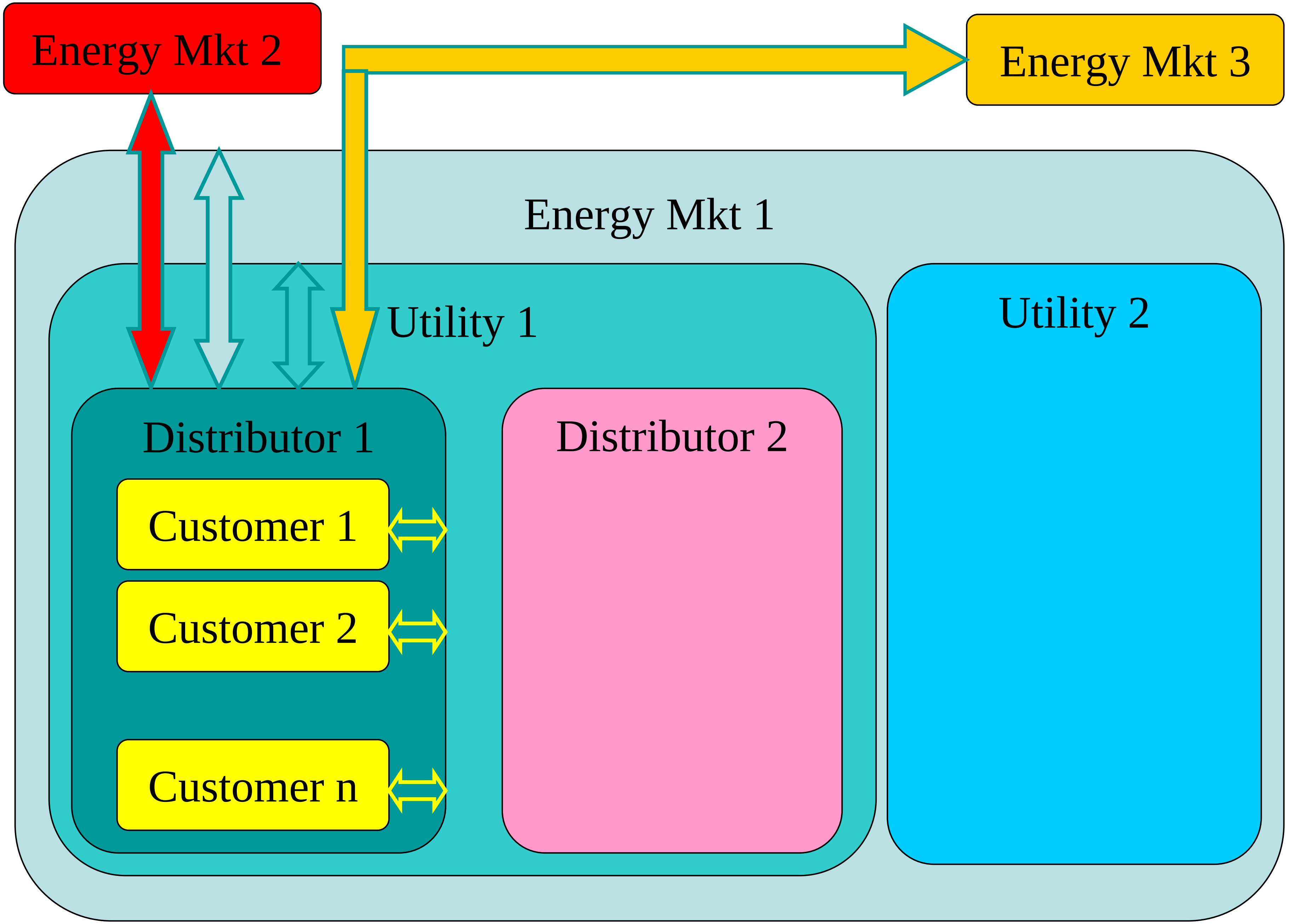
- At the shell (architecture) level: Customers served according to QoS (TOU service, probability of not being served)
- Designing a sufficiently general architecture for minimal coordination (logic) among the internal software modules is one of most difficult tasks
- The second hardest task is processing of huge amount of data into used and usable set of recommendations to operators for ensuring QoS as conditions vary
- A well-functioning shell should be sufficiently flexible to allow for many solutions (technologies, hardware and software) which, jointly, result in comparable performance at the shell level



Possible generation dispatches with respect to anticipated load
Thermal limit Violated?
yes
no
DISTURBANCE
Thermal limit violated?
yes
no
Transient stability violated?
yes
no
Desired operating Condition?
yes
no
Corrective action through ancillary services
Desired operating Condition?
yes
no
Unacceptable operating conditions
Acceptable operating conditions

Something new: Operating and planning in the changing industry

- Distributed performance metrics, associated with the candidate new technologies and/or unbundled entities
- IT and software capable of accommodating these distributed performance metrics, and extracting their value-added to the performance metrics at (various) layers of the shell
- Definitive need for extracting value-added through distributed JIT an JIP performance within the given contextual, spatial and temporal interplay
-


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

Software specifications for the changing industry

- Need for flexible protocols (easy-to-reconfigure) to provide bundled services (energy, delivery, Quality of Service ("QoS"))
- Multi-layered protocols are essential to create software and hardware development incentives, providing compelling value proposition to customers

- We are working toward protocols and software for dynamic (electric) energy control, allowing "true" customer choice and enhanced, sustainable business models for distributors, utilities and markets

The underlying change of paradigm [1]

- The electric power industry processes are a result of numerous small decisions/actions; sharp contrast to the old industry
- Micro-level actions contribute to significant change at the macro-level
- Economies of scope gradually replacing economies of scale
- New opportunities are based on this change; however, current operating/planning/design practices do not support this change

[1] Jelinek, M., Ilic, M., ``Strategic Framework for Electric Technologies:Technology and Institutional Factors and IT in a Deregulated Industry'', NSF Workshop, 2000.

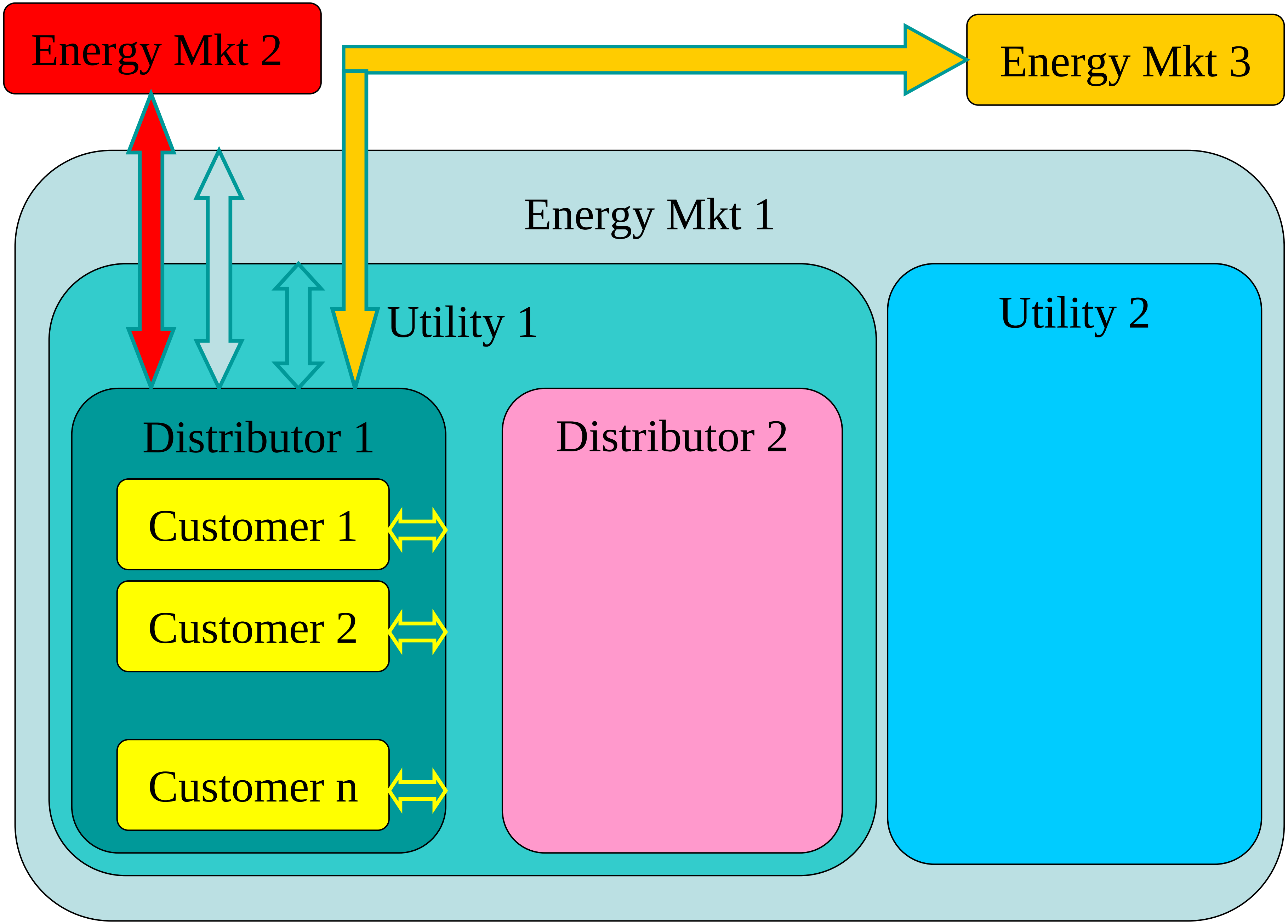
A Dynamic Energy Control Protocol to support the new paradigm [2]

- Defines relations between physical, information and financial processes, across entire industry;Allows for flexible, creative decision making within these well recognized relations; Software based, with various degrees of automation; could accommodate many users
- Without these, the customer choice is not sustainable – “market is not ready”; many business consequences
- 2] Ilic, M and J.., Dynamic Energy Control Protocols for the Changing Electric Power Industry, Power Systems Computations Conference (PSCC), Barcelona, Spain, July 2002 (submitted)

The Role of Multi-Layered Dynamic Energy Control Protocols (DECPs) and Software

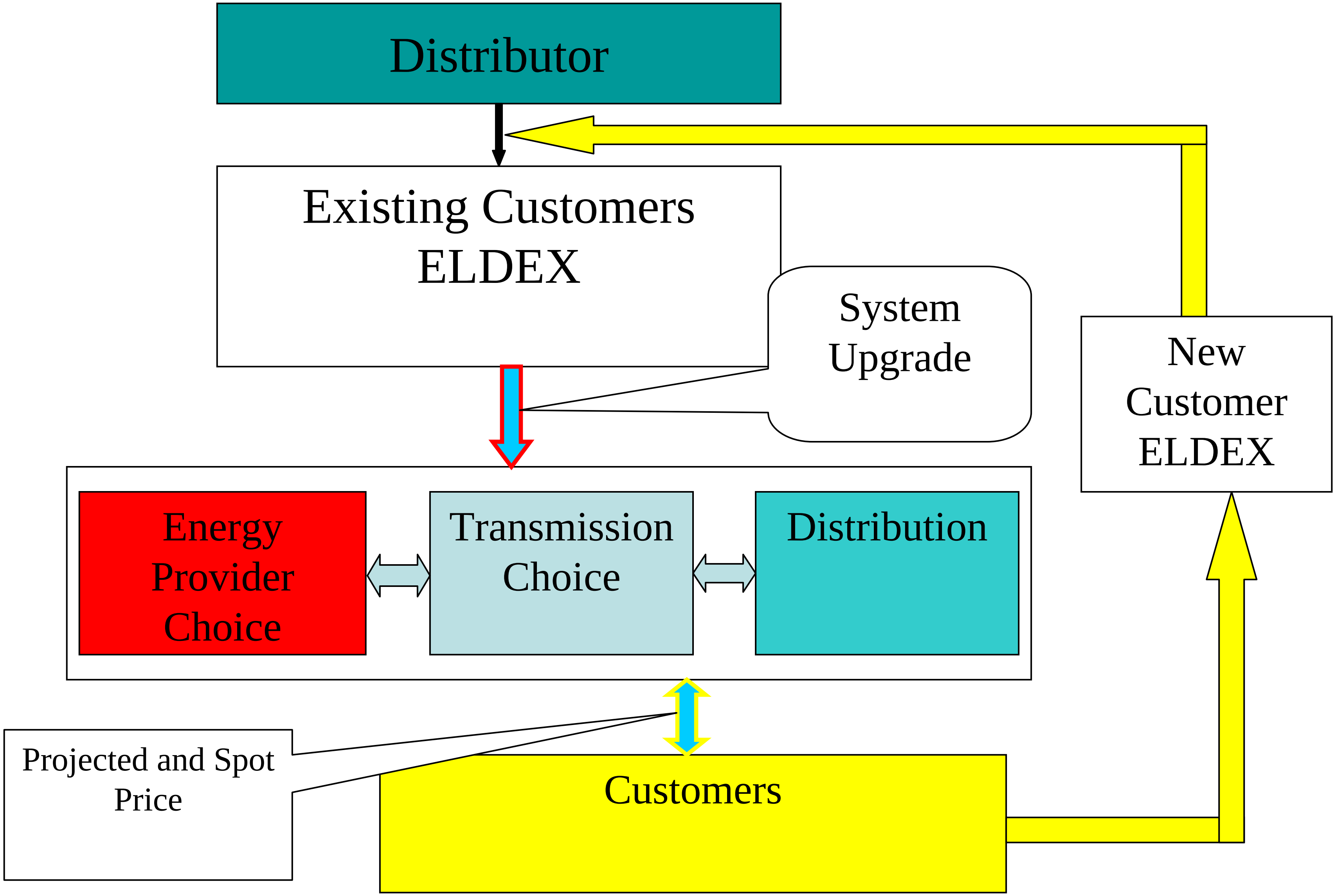
- To be used by the customers, as well as by the various providers of services to the customers in identifying right incentives

- Focus on proactive distributors for facilitating true customer choice

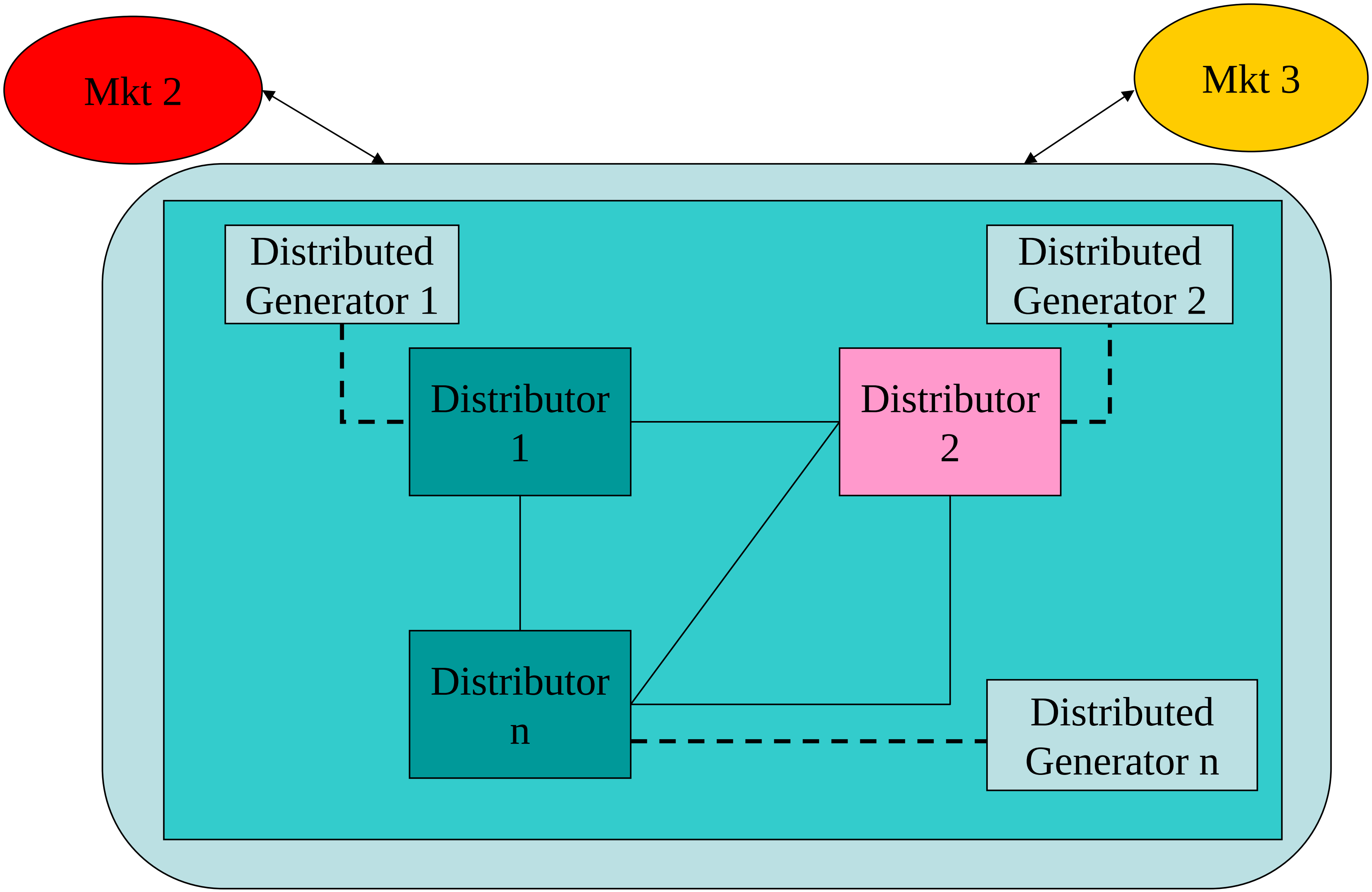


Energy Mkt 2
Energy Mkt 3
Energy Mkt 1
Utility 1
Utility 2
Distributor 1
Distributor 2
Customer 1
Customer 2
Customer n

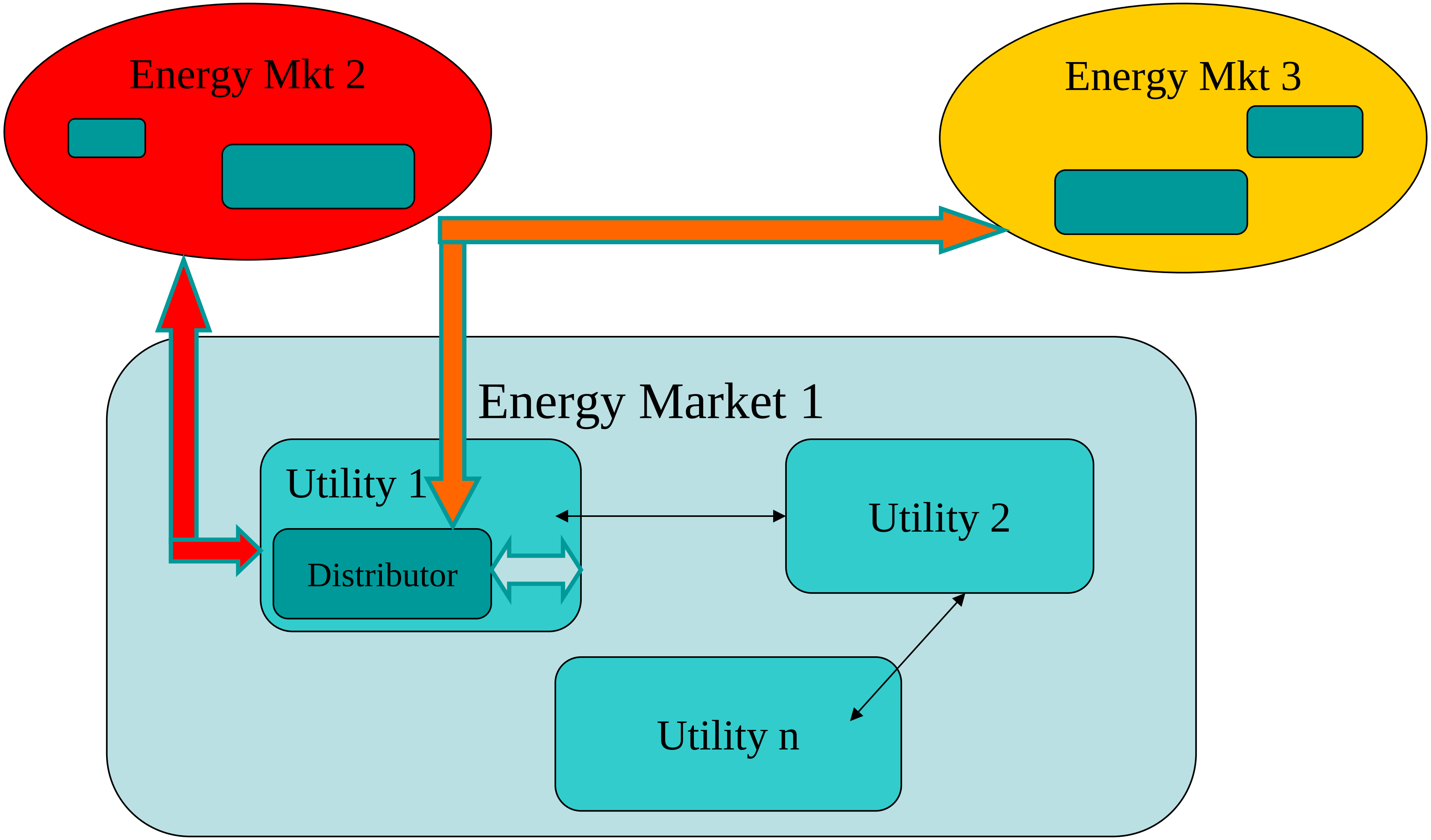
Dynamic Protocol --- Distributor Level



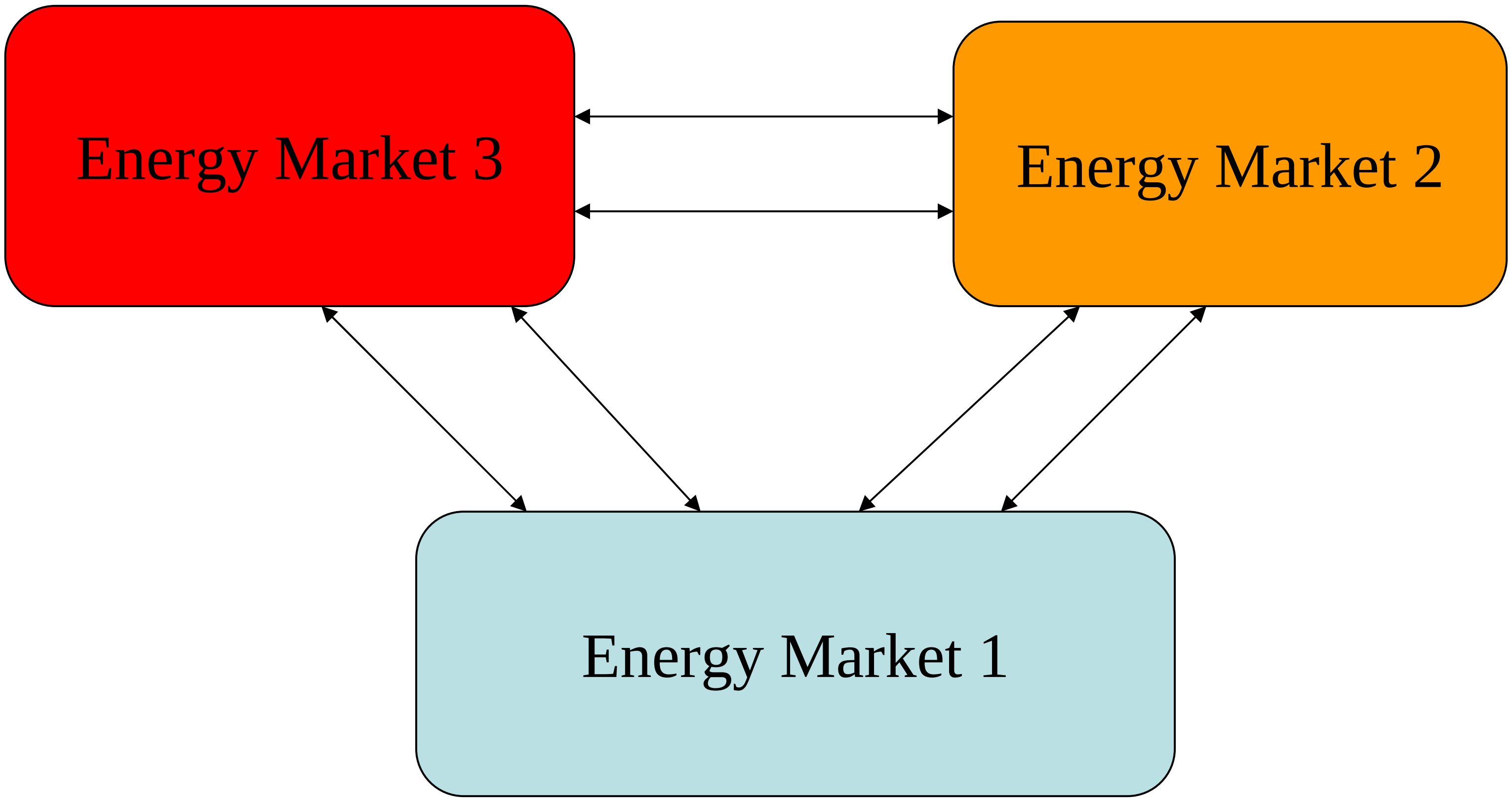
Dynamic Protocol --- Utility Level



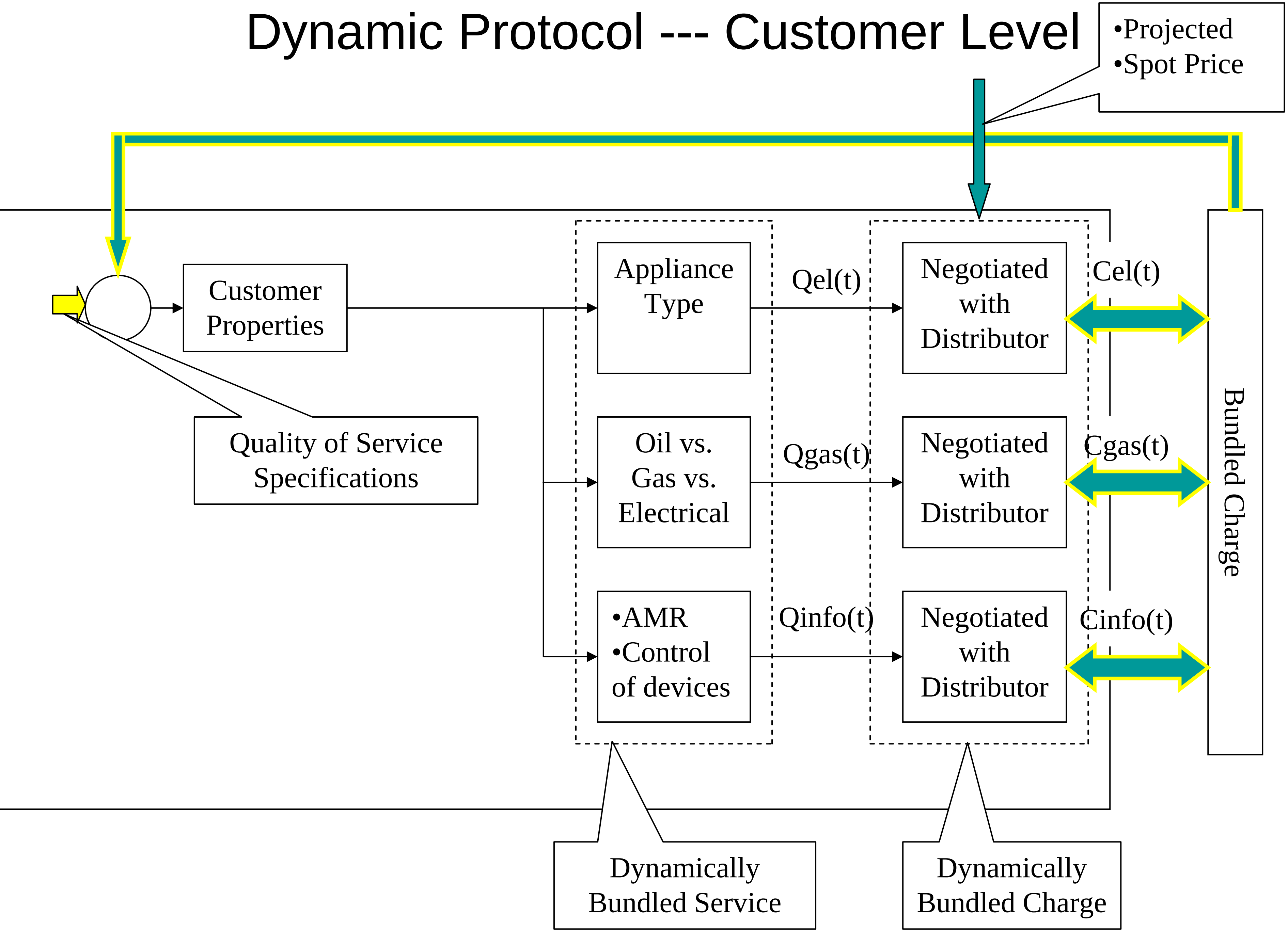
Dynamic Protocol --- Energy Market Level



Dynamic Protocol --- Multi Market Level



Dynamic Protocol --- Customer Level



Summary (technological challenges)

- Understand the value of various technologies under specific paradigms/architectures
- Not one size fits all!!! It is not all distributed, flooded by data, poor in information.
- Domain application-specific concepts, instead of fully general.
- Requires interdisciplinary team work.
- Need to learn how to “translate” real-world problems into design problems for cyber-physical (energy, and other) ecosystems.

Summary (Regulatory Challenges)

- Possibly the most immediate problem is a design of new regulation of systematic information concerning (1) needs of customers to have long-term assured electricity services, as well as (2) the offers to build generation and transmission. These protocols would provide basic mechanisms for adjusting energy utilization while reconciling the key tradeoffs.
- This is essential for risk allocation associated with impossible to predict long-term future demand. Risk should be distributed over time and all industry participants. The only sustainable solution is the one which reflects the scarcity of resources and their actual costs in the future. Otherwise, false expectations concerning price of services and the effects on the environment.

Summary (2)

- The main R&D challenge is design of new regulatory policy which recognizes

  -- THE NEED TO REPLACE CONSTRAINTS BY TRADEOFFS, WHOSE RECONCILIATION WOULD TAKE PLACE IN AN ITERATIVE EXCHANGE OF INFORMATION AMONG THE INDUSTRY PARITCIPANTS

  --STUDY PERFORMANCE AS A FUNCTION OF TYPE OF INFORMATION AVAILABLE

  --PROPOSE DYNAMICALLY ADJUSTABLE INFORMATION EXCHANGE PROTOCOLS FOR WELL-UNDERSTOOD INDUSTRY PERFORMANCE

  -- DECIDING ON THE TYPE OF INFORMATION EXCHANGE (EX POST AND EX-ANTE) SHOULD BE A MATTER OF QUANTIFIABLE MODEL-BASED DESIGNS WHICH LINK ENGINEERING, REGULATION AND ECONOMICS
- NEED TO POSE THESE PROBLEMS IN OUR CLASSROOMS

References

- **[1] Ilic, M., *“Engineering Electricity Services of the Future”,* Springer, December 2007.**
- **[2] Ilic, M., Black, J.W., Prica, M. “ Distributed Electric Power Systems of the Future: Institutional and Technological Driversfor Near-Optimal Performance”, Journal on Electric Power Systems Research (EPSR), Special Issue on Distributed Systems, May 2005 (invited). Available online Nov 2006 at www.sciencedirect.com**
- **[3] Ilic, M., ``Model-based Protocols for the Changing Electric Power Industry'', Proceedings of the Power Systems Computation Conference, June 24-28, 2002, Seville, Spain.**
- **[4] Ilic, M., “From Hierarchical to Open Access Electric Power Systems,” Special Issue of the IEEE Proceedings on Modeling, Identification, and Control of Large-scale Dynamical Systems. Guest Editors: Simon Haykin and Eric Mouines, April 2007.**
- **[5] Ilic, M., “Engineering Energy Services of the Future by Means of Dynamic Energy Control Protocols (DECPs)”, Proc. Of the IEEE SMC’2007, Montreal,CA.**
- **[6] Ilic, M., Software Needs and its Valuation in the Electric Power Industry, http://www.ece.cmu.edu/electricityconference, Jan. 2006.**
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