# Toward a Complex Adaptive Grid

## A Systems Innovation Approach to Grid Modernization

IEEE eGrid 2024 – *Power Plant of the Future*

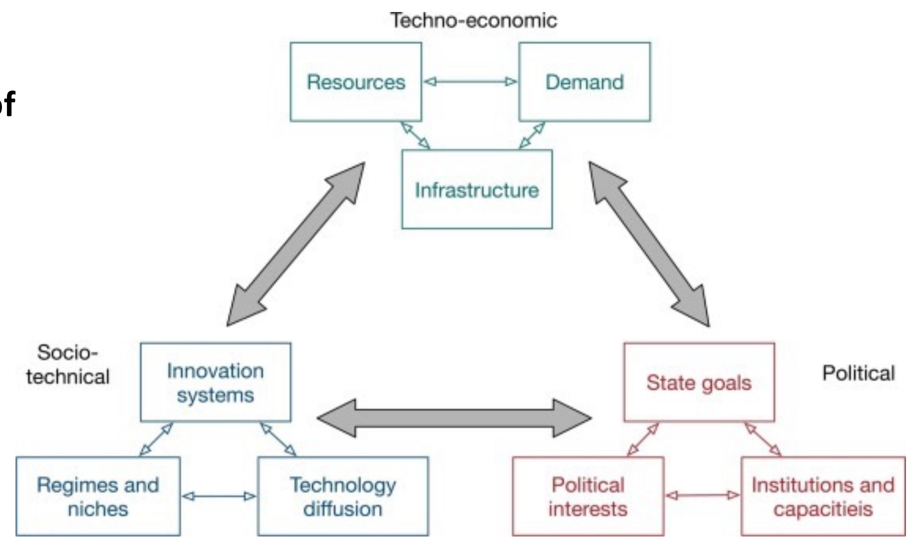
MICROGRID
Systems Laboratory

eGRID 2024

# Proposition

1. **The Power Plant of the Future will be the holistic, interactive, complex grid system – in its entirety**

2. **This will bear on the planning, design, and operation of Power Electronics devices and sub-systems**



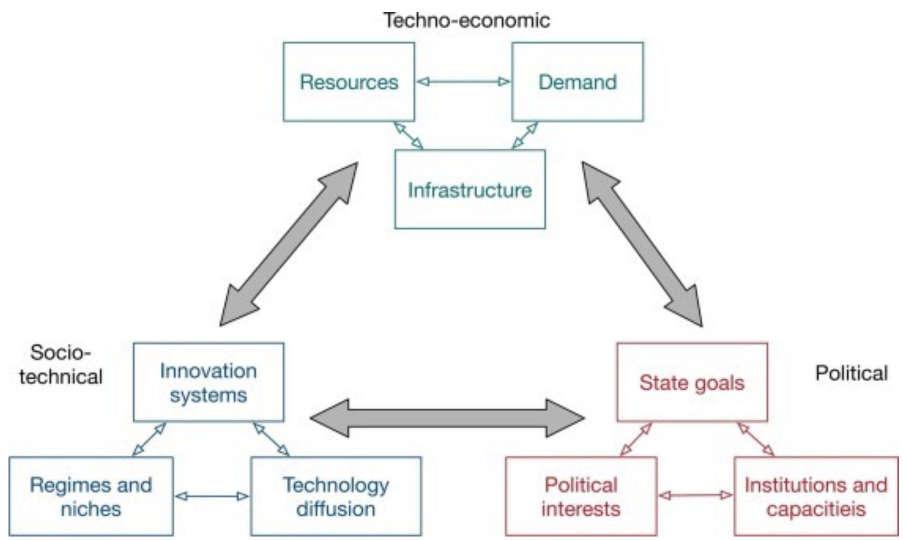

From “Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework”

# Organizing Principle

**How (and why) might we understand the grid as one fully integrated socio-techno-economic system?**

By applying three deeply integrated components:

- A *Systems Innovation* approach…
- informed by *Trans-Disciplinary* Research…
- seen through a *Complexity Science* lens




From "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework"

# Agenda

**Part One**

- Needs & Challenges
- Systems Innovation

**Part Two**

- Complex Adaptive Systems & the Grid
- Promising Developments
- An Inflection Point?

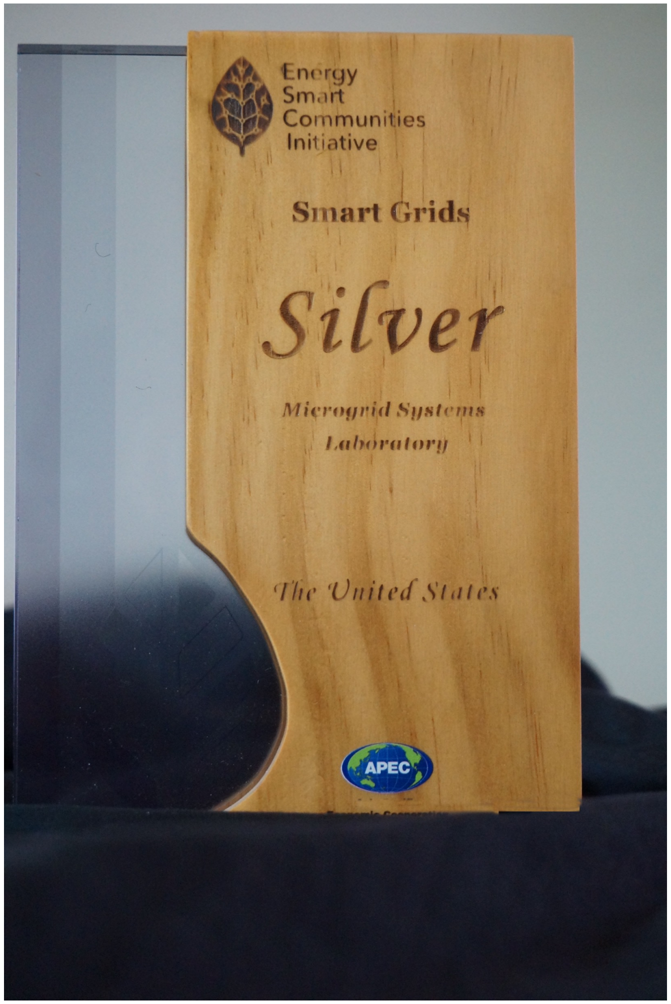
**Part Three**

- Toward a Complex Adaptive Grid

# About MSL

**A non-profit energy innovation consortium:**

- *Mission*: accelerate the energy transition
- *Three Program Pillars*: Grid Modernization (U.S.), Energy Access (Africa), Energy Sovereignty (Tribal Nations)
- *Four Project Activities*: Research, Innovation, Demonstration, Education




Asia Pacific Economic Cooperation innovation awards, 2022

# Part One

## Conceptual Basis

# Needs and Challenges

"...the grid we have today does not have the attributes necessary to meet the demands of the 21st century and beyond."

--DOE Grid Modernization Initiative

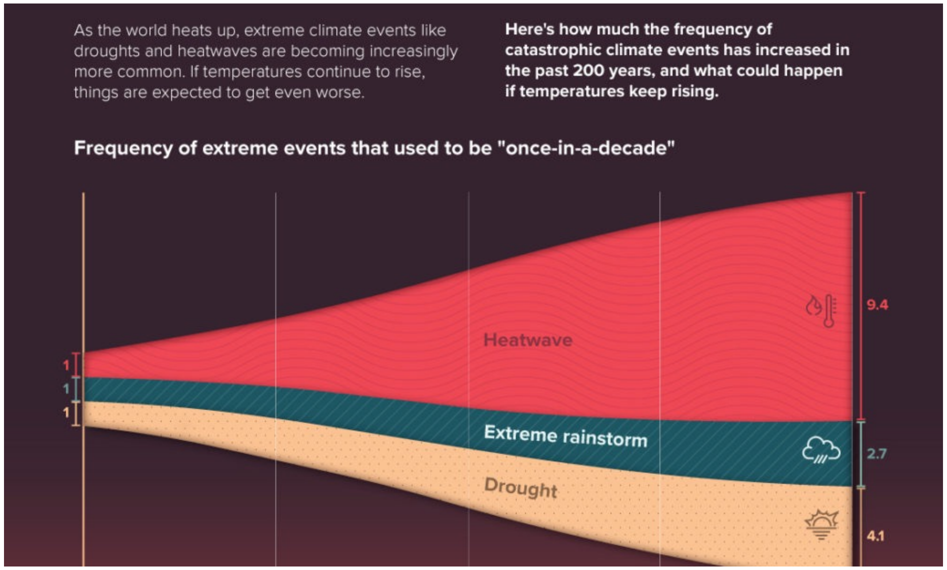
GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

# Systemic Challenges

**High-Level Current Challenges and Future Trends:**

- Reliability ⬇
- Resilience ⬇
- Resource adequacy ⬇

- Extreme weather ⬆
- Load growth ⬆
- Heterogenous, stochastic DERs ⬆
- Variable generation ⬆
- Cyber vulnerability, threats ⬆




From "The Changing Landscape: Impact of Climate Change on Construction Sector"

# Paradigmatic Shifts Underway

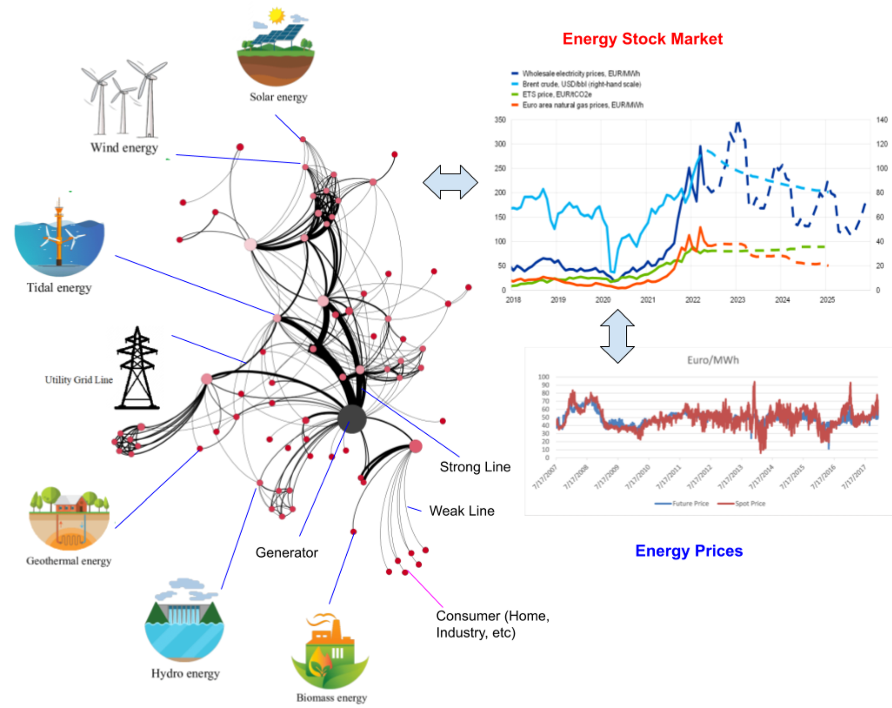
**Trends are complicated by rapid changes in grid structures:**

- Power flows ⟺
- Data flows ⟺
- Financial flows ⟺

**In sum:**

- System complexity ⬆⬆⬆

*Our natural response:* reduce a problem to more manageable sub-systems, disciplines, or parts…




From "Artificial Intelligence and Mathematical Models of Power Grids Driven by Renewable Energy Sources: A Survey"

# Systems Thinking

**"We can't solve problems by using the same kind of thinking we used when we created them."**

--possibly Albert Einstein


We will need new tools and techniques that are *additive* and *complementary* to current practice

# Systems Innovation

"The electrical grid… [is] the largest and most complex ***machine*** ever made.

Yet the system is built in such a way that the bigger it gets, the more inevitable its collapse."

--The National Academies of Sciences, Engineering and Medicine

**How might we understand this "machine" as:**

- A ***networked system…***
- producing ***emergent behavior…***
- requiring a ***whole-systems*** approach…

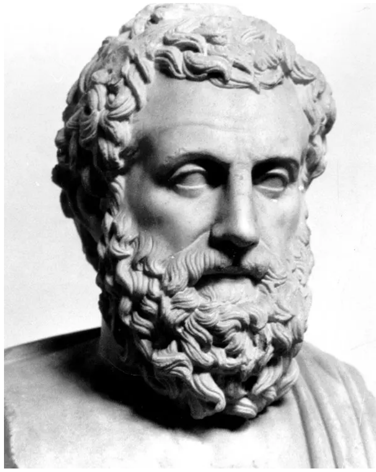
From "Toward Norms in Cyberspace: Recent Progress and Challenges"

And view these *challenges* as *opportunities*?

# Systems Innovation: Key Attributes

**Enables a shift in thinking, leading from *incremental* to *transformational* innovation:**

- Complicated => Complex
- Reductionist => Holistic
- Mechanistic => Networked
- Linear => Emergent
- Analytic => Synergistic



"The whole is *greater* than the sum of its parts"

"The whole is *different* than the sum of its parts"

"The whole is *something besides* the parts"

--Aristotle

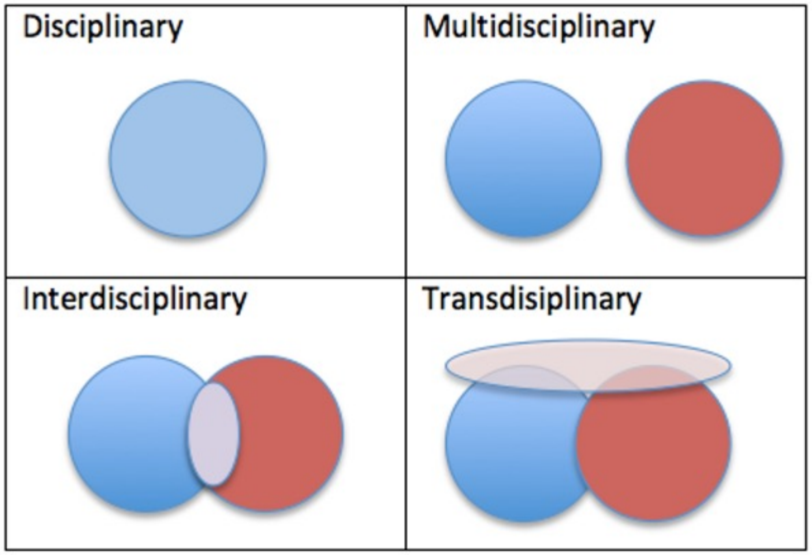
# Trans-Disciplinary Research

**To explore systems' shared patterns and structures, cross-pollinate ideas, develop new conceptual frameworks**

*Multi*-disciplinary: communicating across boundaries

*Inter*-disciplinary: collaborative effort between researchers, but no blending of fields

***Trans*-disciplinary:** deep mutual immersion, yielding new understandings, questions, research cultures, and disciplines




From: "Transdisciplinary Approach - What Does It Mean?"

See "Transdisciplinary Electric Power Grid Science," PNAS July 23, 2013

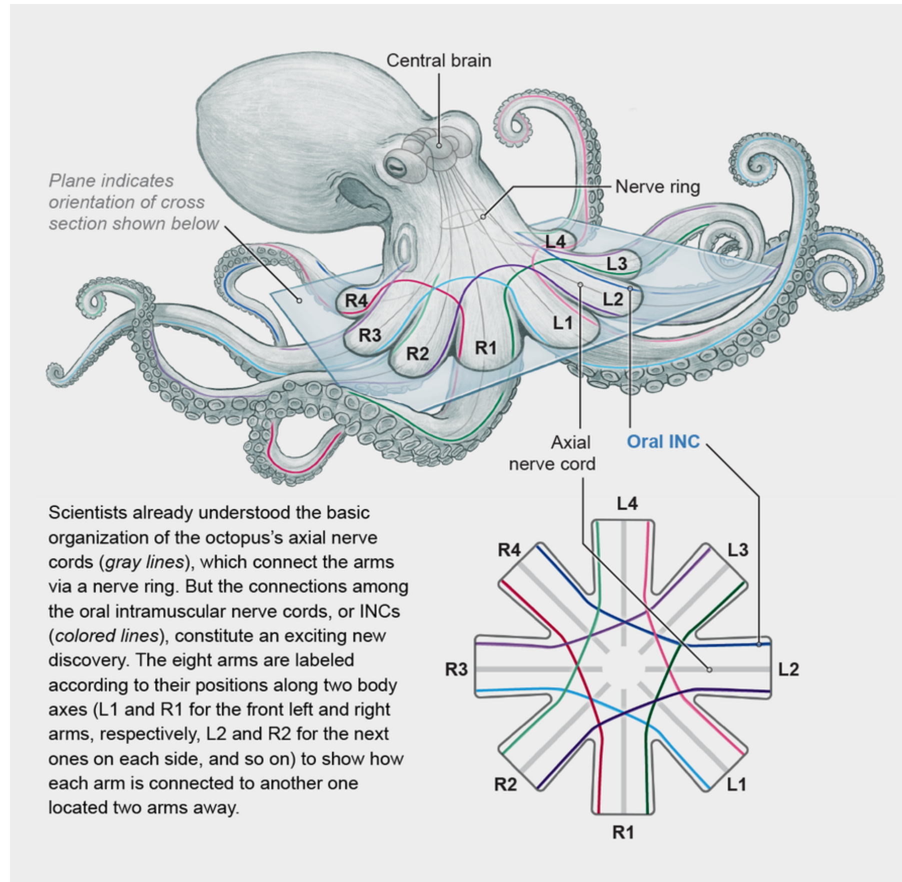
# Relevant Disciplines

- Engineering, power systems
- Physics
- Complex networks
- Computational science
- Economics, finance
- Social science
- Law, public policy
- Ecology

**Example: the Neuroanatomy of the Octopus:**

- ~60% of neurons are in the tentacles
- ~30% in the optic lobes
- ~10% in the central "brain"

*Key question*: what problem is evolution trying to solve?




From "How Octopus Arms Bypass the Brain," Scientific American March 1, 2023

# Complex Adaptive Systems

## As pioneered by the Santa Fe Institute & LANL's Center for Non-Linear Studies:

**Multiple interacting components:** a relatively large number of actors or elements

**Intelligent and adaptive agents:** elements can adapt their behavior in response to new information

**Decentralized control:** No single actor has complete information or control

**Nonlinear interactions:** elements interact dynamically in often nonlinear ways

**Emergence:** behaviors emerge as a result of interactions at different levels of organization

**Self-organization**: spontaneously develop new structures without external control

**Co-evolution:** The system evolves in conjunction with and feedback from its environment

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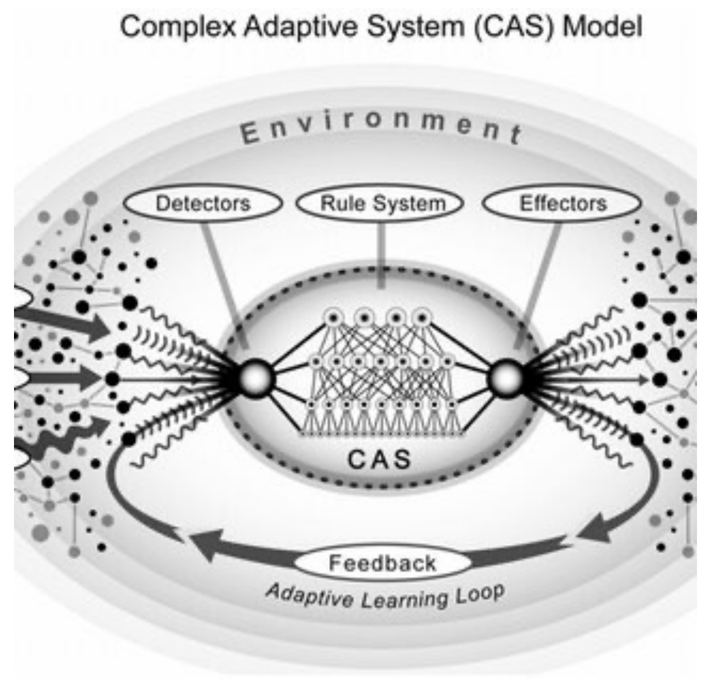
# Part Two

Proposed Solution

# The Grid as a Complex Adaptive System

**Current and evolving attributes and trends:**

- Dynamic pricing
- DER proliferation
- Load flexibility
- Stochastic actors at vast scale
- Pervasive data networks
- Transactive (peer-to-peer) energy
- Adaptive, multi-level architectures
- Regional grids, connectivity, and network effects
- Inter-region and inter-RTO interactions
- Multiple governance layers <> Distributed decision-making




From "Integrative Systems View of Life: Perspectives from General Systems Thinking"

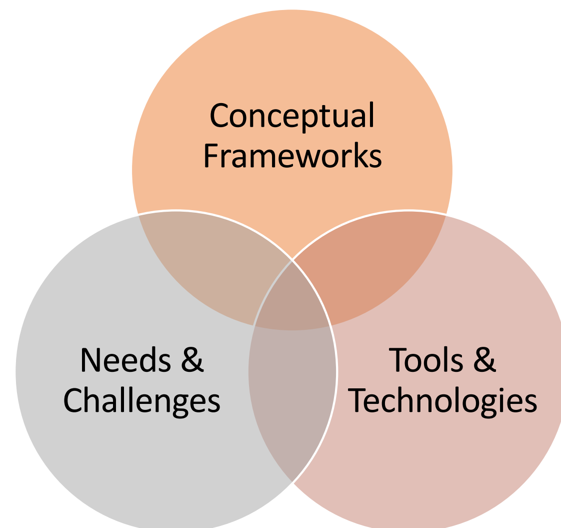
# An Inflection Point?

**Are we converging on a new paradigm, the "Complex Adaptive Grid"?**

Are we approaching a critical inflection point?'

What might this shift demand, and enable?

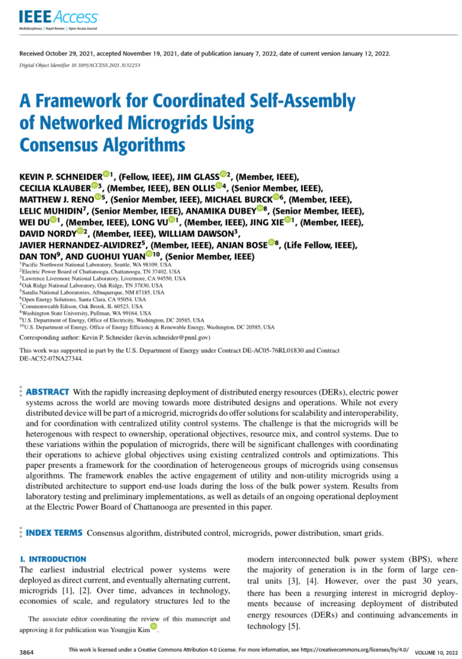
1) *We'll need different methods and tools to meet the challenge*
2) *It's an extraordinary opportunity to influence the future grid*




> "The best time to effect large-scale system change is when a system is in transition"
>
> –Systems Innovation Network

# Related Prior Art: Complex Systems & the Grid

- “A Framework for **Coordinated Self-Assembly** of Networked Microgrids Using Consensus Algorithms”
- "The Studying of Power Grid Planning Based on **Complex Adaptive System** Theory"
- “**Agent Based Modelling** for Smart Grids”
- "An Integrated Optimization and **Agent-Based Framework** for the U.S. Power System"
- "Modeling Power Systems **as Complex Adaptive Systems**"
- "Simulating the Behavior of Electricity Markets with an **Agent-Based Methodology**
- "Complex **adaptive systems**: concepts and power industry applications"
- “**Complex System Science** for Smart Grids”
- “Knowing power grids and understanding **complexity science**”
- “**Complex Systems** and the Electric Grid”
- “Electricity Market **Complex Adaptive System**”
- “An Integrated Optimization and **Agent-Based Framework** for the U.S. Power System”
- “Complex Adaptive Systems, **Cognitive Agents** and Distributed Energy
- “Modeling Power Systems as **Complex Adaptive Systems**”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## A Framework for Coordinated Self-Assembly of Networked Microgrids Using Consensus Algorithms

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**ABSTRACT** With the rapidly increasing deployment of distributed energy resources (DERs), electric power systems across the world are moving towards more distributed designs and operations. While not every distributed device will be part of a microgrid, microgrids do offer solutions for scalability and interoperability, and for coordination with centralized utility control systems. The challenge is that the microgrids will be heterogenous with respect to ownership, operational objectives, resource mix, and control systems. Due to these variations within the population of microgrids, there will be significant challenges with coordinating their operations to achieve global objectives using existing centralized controls and optimizations. This paper presents a framework for the coordination of heterogeneous groups of microgrids using consensus algorithms. The framework enables the active engagement of utility and non-utility microgrids using a distributed architecture to support end-use loads during the loss of the bulk power system. Results from laboratory testing and preliminary implementations, as well as details of an ongoing operational deployment at the Electric Power Board of Chattanooga are presented in this paper.

**INDEX TERMS** Consensus algorithm, distributed control, microgrids, power distribution, smart grids.

### I. INTRODUCTION

The earliest industrial electrical power systems were deployed as direct current, and eventually alternating current, microgrids [1], [2]. Over time, advances in technology, economies of scale, and regulatory structures led to the modern interconnected bulk power system (BPS), where the majority of generation is in the form of large central units [3], [4]. However, over the past 30 years, there has been a resurging interest in microgrid deployments because of increasing deployment of distributed energy resources (DERs) and continuing advancements in technology [5].

The associate editor coordinating the review of this manuscript and approving it for publication was Youngjin Kim.

# Promising Elements: *Technical*

- AI/ML real-time dynamic optimization
- Federated Machine Learning
- Large-scale simulation, digital twins (ESIF, ARIES, Advanced Grid Modeling Program)
- Exascale Computing Project
- Dynamic microgrids (DynaGrid, RONM, Citadels)
- Autonomous Energy Systems (NREL)
- Grid edge innovation (V2X, VPPs, orchestration)
- Energy Internet of Things; Packetized Energy

From "Future cities: taking a smart approach to infrastructure"

**Advanced power electronics-based solutions** as a key *enabling* technology (e.g., DERs at scale, digitization, optimization, controls, IBRs, grid-forming devices)

# Promising Elements: *Institutional*

- Integrated Resource Plan innovation (integrated T&D, extended time horizons)
- Performance Based Regulation
- Clean Transition Tariffs
- Distribution System Operator frameworks
- Federal-State collaborations


# Promising Elements: *Organizational*

- DOE Grid Modernization Initiative, GMLC
- European Union JRC Smart Electricity Systems
- GridWise Architecture Council
- WSU-PNNL Advanced Grid Institute
- Santa Fe Institute: multiple grid workshops, working groups

# Part Three

Implementation

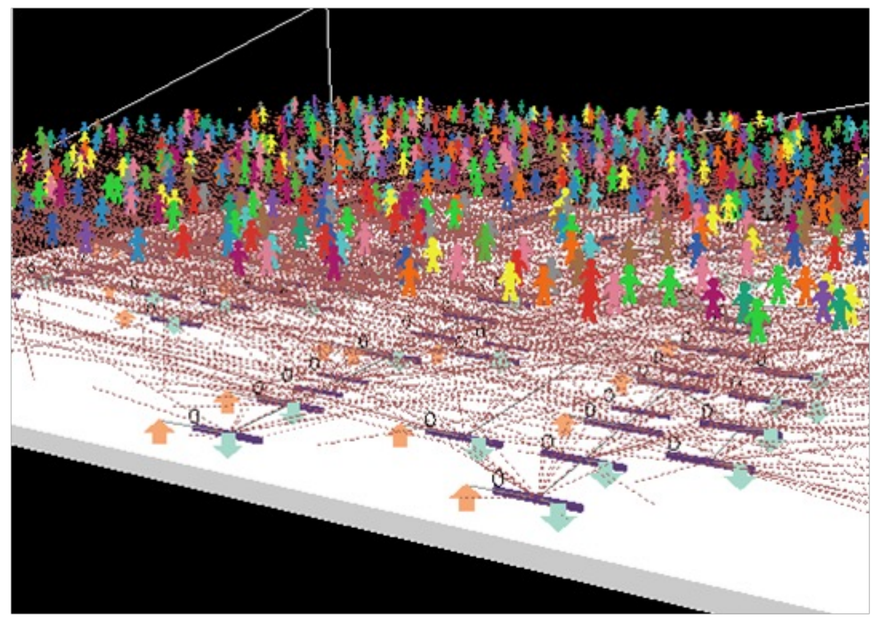
# Toward a Complex Adaptive Grid

***Goal*: a sustained, well-resourced structure to support and incentivize ongoing systems innovation and CAG work:**

*Catalyze* a field of trans-disciplinary research

*Collaborate* with cross-sector teams (e.g., governance, utilities, technology, finance, workforce)

*Complexity Science* as a lens



From "Agent Based Modeling for Smart Grids," EU Joint Research Center

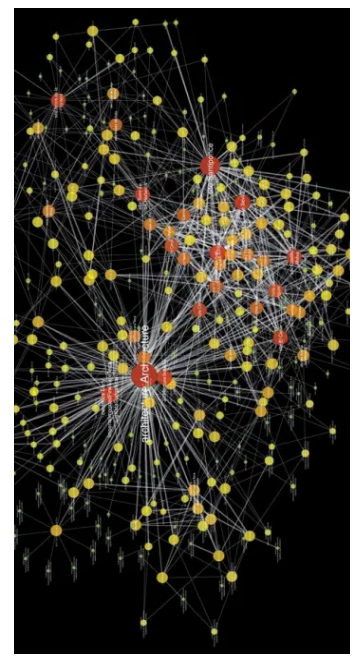
# Useful Complexity Science Methods

**Agent-based modeling**: Computer simulations of interacting agents to study emergent phenomena

**Network theory**: Analyzing the structure and dynamics of interconnected systems

**Nonlinear dynamics**: Studying systems with feedback loops and chaotic behavior

**Information theory**: Examining how information flows and is processed in complex systems



From “Complex Systems Theory: Exploring Complex Phenomena”

# Practical Path Forward

***Process*: Workshop => Consortium => Structure => Resources**

- Engage key cross-sector stakeholders, researchers
- Convene a planning workshop
- Develop funding and resources
- Incentivize trans-disciplinary work
- Establish a center and a field of CAG studies
- Gain insights into system leverage points
- Develop specific recommendations

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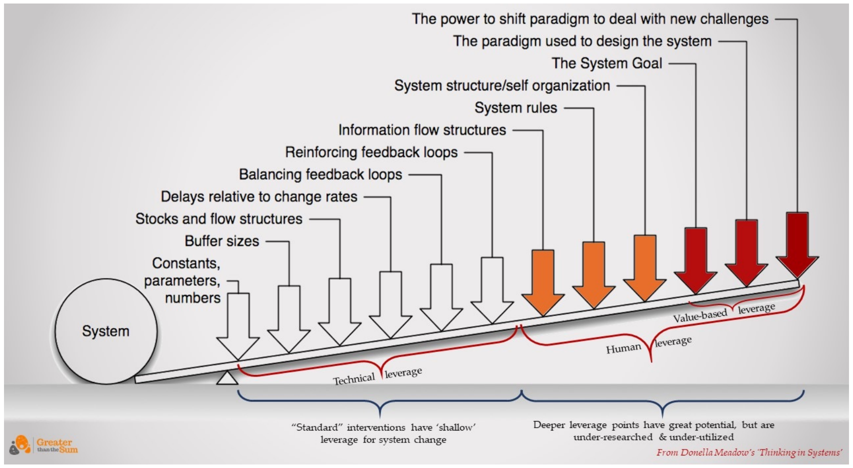
# Illustrative Applications & Impacts

**Potential System-Wide Leverage Points, e.g.:**

- New paradigms (e.g., CAG conceptual framework)
- Enable multi-level interaction (FERC/NERC, ISO, PUC, IOU, DER)
- Analyze feedback interactions over multiple levels and time scales, mixed ownerships




From "Leverage Points: Places to Intervene in a System," Donella Meadows

**Potential Practical Use Cases, e.g.:**

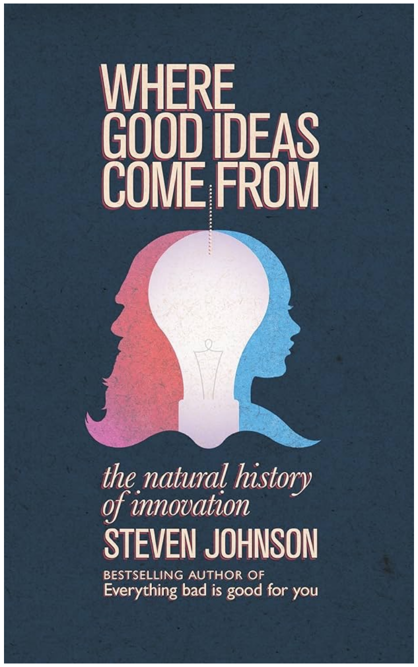
- Self-optimization at very high dimensionality scales (massive DER growth, extreme variability)
- Stochastic & human factors in power flow engineering (behavioral economics, load flexibility, price signals)
- PE implications: design, planning, operations for optimal CAG performance

***Then continually sense and learn from the system and adapt accordingly…***

# The "Adjacent Possible"

"...the adjacent possible is a kind of shadow future, hovering on the edges of the present state of things... its boundaries grow as you explore them, which inspires continuous exploration to emerge what's next."

--Steven Johnson



# Thank You!

**Questions, comments, and discussion are welcome**

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