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Smart Energy Grids and Complexity Science

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Institute for Energy and Transport

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1. Foreword

This report proposes ideas and an approach to address present and future challenges in future smart energy systems through the particular lenses of complexity sciences.
Complexities arising inside and around emerging energy distribution systems prompt a multilayered and integrated approach in which different disciplines and areas of expertize are pooled together. The interfaces between system layers and intellectual disciplines are the focus, rather than on the details of any individual layer or the particularities of one approach.
A group of people sharing this view and willing to procede in this way organized a workshop at the Joint Research Centre of the European Commission, Petten, the Netherlands on 24th June 2012.Experts from different field of expertise convened to present their current research and discuss the future challenges of emerging smart energy systems via the afore-mentioned perspectives.

2. Background

Growing concerns over energy sustainability, security of power supply, and market competitiveness—and the resulting need to integrate increasing shares of renewable energy and dispersed energy resources—are impacting the energy system operationally and architecturally.

Smart energy grids represent one of the key means for the decarbonisation and decentralisation of the electricity system. Their implementation will change the way we live our lives and how we interact socially and culturally. In this scenario, the business and social actors in the energy landscape will need dramatically to adapt their behaviours, strategies and means of producing, delivering, storing, and consuming energy.

The existing paradigm of passive distribution and one-way communications and power flows from large suppliers to final consumers will be replaced by an active and responsive system. . In the future, smart grids—enabled by pervasive information and communication technologies (ICT) withbidirectional communication, and power exchange between suppliers and consumers will be established. Many end-users will become independent *prosumers*, interacting within a physically constrained network through various ICT systems.

A smart energy grid is not only a diverse set of dynamic, distributed energy suppliers, it is also an energy system which connects smart (i.e., responsive, energy efficient, and variable) users to sustainable (i.e., low carbon, renewable) energy sources. And the grid itself is smart whenever it is able to modify its output, and able to monitor, control and meter the energy demands of consumers in a regulated and fair way.

In many ways, the concept of the smart grid can be extended to other (virtual and physical) complex networks characterising the urban environment, such as the transport of water, fuels, wastes, passengers and packages. Which of the aspects of complexity science, characterizing a smart energy grid, are potentially applicable to these other networks?

To further explore the background and the various areas of expertize some talks presented and discussed relating to:

- The practical application of complex science to energy (electric) systems within a broader context including economic shifts and volatility, consumer behaviour, weather and climatic uncertainty, and the growing need to address climate adaptation including emergency response. Furthermore a path was proposed towards the application of complexity science in these areas through research and explicative applications;
- The verification of current developments in related fields;
- Analysis of the links/synergies between different approaches;
- Consideration of the possibility of establishing a working group of experts, research institutions, stakeholders, policy decision makers with different backgrounds and expertise; ranging from the social sciences to power systems engineering, and from ICT to economics. The aim would be to develop and share a common systemic view of the problems;

2.1 Robin Bloomfield: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Robin E Bloomfield
Adelard LLP and CSR City University London

JRC Institute for Energy and Transport
25 June 2012

Adelard

Evaluation and research

Safety, security and assurance cases
Independent assessment

Software assurance, including formal methods and static analysis

Development, interpretation and application of standards and guidelines

Applied research in safety, security, critical infrastructure interdependencies

Policy to technology

Products ASCE – the Assurance and Safety Case Environment

Scope - clients in nuclear, defence, financial, transport sectors

CSR City University

- Evaluation of socio-technical systems
  - technical, interdisciplinary
- Research
  - with international community and users
- Education
  - placements, internships, scholarships, courses, MSc and CPD
- Innovation

Ongoing activities/projects relevant for Smart Energy systems and/or complexity

Focus on evaluation and communication of risks, resilience

Interdependency analysis

Policy and tools (Cetifs, IRRIIS, TSB innovation, After) including research landscape

Member of UK EIEG, UK Infrastructure Plan

Security vulnerabilities and methodology

ERTMS, rail, CPNI

embedded systems – Sesamo, Artemis

Systemic risks – computer based trading (Foresight UK)

Complexity science approach to energy system

Evaluating complex adaptive systems

What can we learn from swans, cats, dragons, toads, bugs and oxymorons?

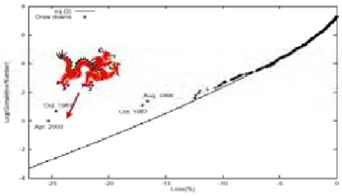


Fig.15 Distribution of drawdowns D for the Nasdaq Composite index, showing several "outliers" in the tail, that qualify as dragon-kings. It turns out that these anomalous events are

How to approach future smart energy systems & complexity and future research

Interested in how much these systems need to be trusted and how to evaluate that trust

- Interworking with existing methodologies
  - Not all issues complex science ones, indeed engineering complexity out of a system
- Adaptation, understand regulation, governance and shaping of systems
  - Part system designed, part grow and evolve
- Importance of soft or intangible infrastructures
- Performative models
- Small changes
  - Possible driver questions
- Risk frameworks
- Viability domains

Engineering complex adaptive systems

Developing intervention strategies for different time bands

- Circuit breakers and trip protection
- Forced diversity in ecology, disrupt correlation
- Alignment of economic incentives

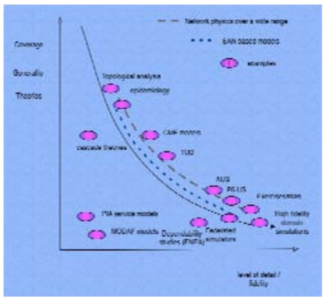
New approaches to resilience assessment and communication

- Investigate viability domains and recovery
  - Of socio-tech systems
  - Specification for single, group and collective
- Deriving risk targets for properties - failure and success
- Possible separation of conventional and complex risks
  - (Fukushima vs flash crash)
- Emphasis on stability as a dependability attribute
  - The risk of change or not
- Methodology issues
  - Abstraction, data, extrapolation

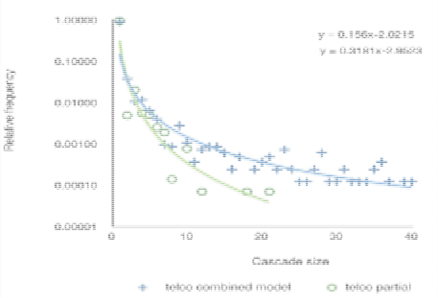
Research landscape and abstraction

- A plethora of research on infrastructure interaction modelling from diverse research communities
- Partial review and classification available from this study
- A variety of related research areas: visualisation, simulation architecture, decision support, human factors
- Any focused research programme is likely to be highly multi-disciplinary, multi-model.

- Issue of what abstraction brings you and what is misses; research methodology questions e.g. US vs Eu?

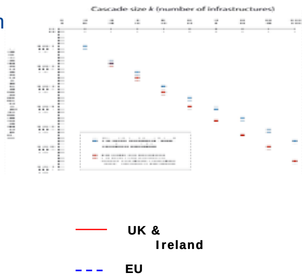


Impact of interdependencies



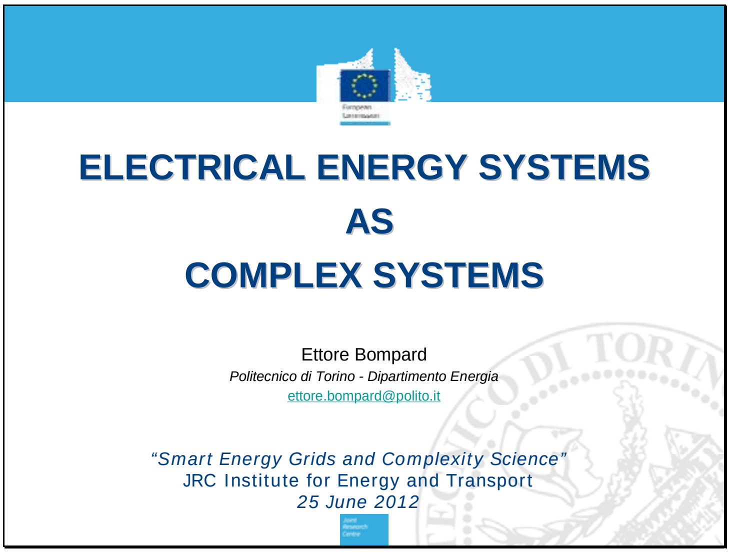
Where are we starting from?

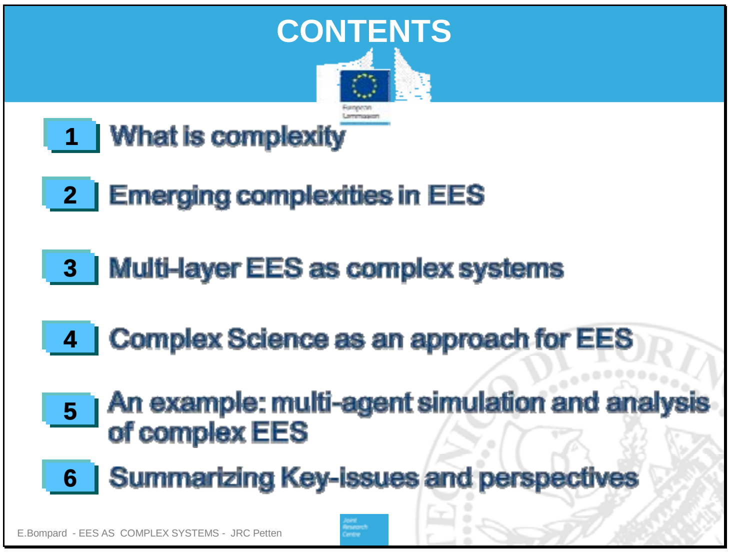
- Evaluating smart grid risk and policies need an understanding of present position.
- Incident data on cascade between infrastructures
- Analysis by CSR of dataset collected by TNO of UK and other European incidents
- Issues of completeness, representativeness etc.
- Estimated Cascade Size Probabilities

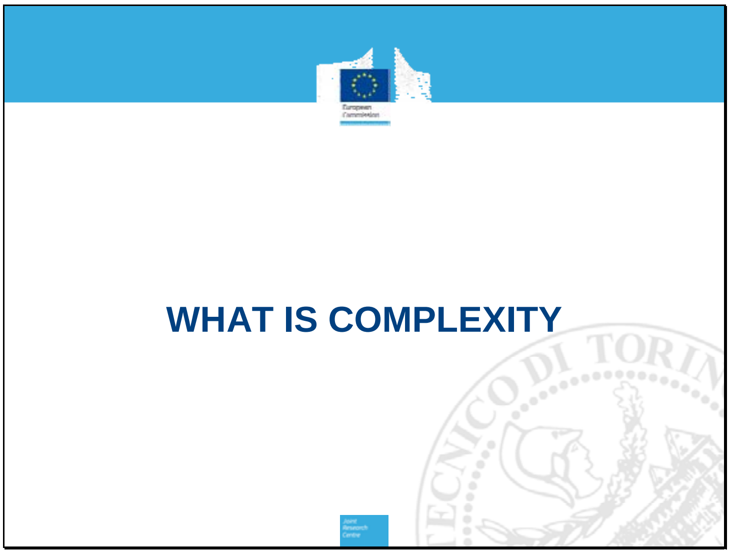


Issues of data collection and analysis as systems evolve

2.2 Ettore Bompard: Electrical Energy Systems as Complexity Science







DEFINITIONS OF COMPLEXITY

- "Complexity is that property of a model which makes it difficult to formulate its overall behavior in a given language, even when given reasonably complete information about its atomic components and their inter-relations."
  -- Bruce Edmonds, Syntactic Measures of Complexity [doctoral dissertation], Manchester Univ. 1999
- "Complexity: the greater the extent of inter-connections between components of a system, the more difficult it is to decompose the system without changing its behavior."
  -- RAMAMOORTHY, CV. An analysis of graphs by connectivity considerations. Journal of the Association of Computing Machinery, 1966, 13, 211-222.
- "Complexity in economics has simply meant not assuming that an economic agent acted as if it had the computational resources to completely cope with the demand placed on it by its environment."
  -- HOLM, HJ. Complexity in Economic Theory. Lund, Sweden: University of Lund: Lund Economic Studies, 1993.

DEFINITIONS OF COMPLEXITY

- "Complexity is the relations weaving the parts together that turn the system into a complex, producing emergent properties."
  --Francis Heylighen. Complexity: 5 questions, Automatic Press/vip, 2008
- "The philosophy of complexity is that this is in general impossible: complex systems...has properties -- emergence properties -- that cannot be reduced to the mere properties of their parts."
  --Francis Heylighen. Complexity and self-organization. Encyclopedia of library and information sciences, 2008.
- "Complexity can emerge in a system when the whole cannot be fully understood by analyzing its components."
  -- P. Cilliers. Complexity and post modernism: understanding complex systems.Psychology press, 1998.
- "Complexity is concerned with how the nature of a system may be characterized with reference to its constituent parts in a non-reductionist manner."
  --S.M. Manson. Simplifying complexity: a review of complexity theory. Geoforum 32, 405-414

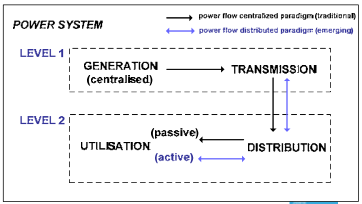
OUR UNDERSTANDING OF COMPLEXITY

"A system, that can be decomposed in a set of elementary parts with autonomous behaviors, goals and attitudes and an environment, is complex if its modeling and related simulation tools cannot be done resorting to a set of whichever type of equations expressing the overall performance of the system, in terms of quantitative metrics, or of a function on the basis of state variables and other quantitative inputs."

EMERGING COMPLEXITIES IN EES

EMERGING PARADIGM OF EES

- **Traditional paradigm**: four subsystems. ① Generation (centralized) ② transmission ③ distribution ④ utilisation. The first three subsystems are devoted to assure “quality electricity” to the fourth.
- **Emerging paradigm**, “generation” is no longer only associated to subsystem 1 (with a limited number of large-sized generators) but also with subsystem ④ as the users become “prosumer” (producer / consumers - huge number of small-sized generators from renewable sources). Subsystem ③ becomes active (capable of injecting power) with the possibility of bidirectional power flows.



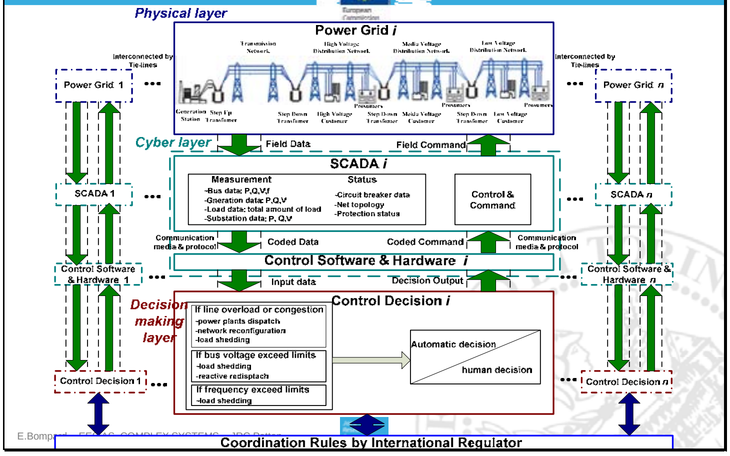
Level 1: Generation (centralised, large scale – hundreds of MW) + Transmission

Level 2: Distribution + Utilisation (small scale – down to KW)

EMERGING FEATURES

- Market structure based on *competition* (self-interested players interacting in competitive markets).
- Achievement of the objective of *energetic efficiency* and *environmental protection* based on market mechanisms.
- Aggregation of *distributed generation and storage* (small size, low predictable, connected to distribution system).
- Shift from centralised decision making (regulated monopoly) to *distributed decision making*, based on the maximisation of the individual utilities of a multitude of self-interested players that interact with a physically constrained network through various ICT technologies

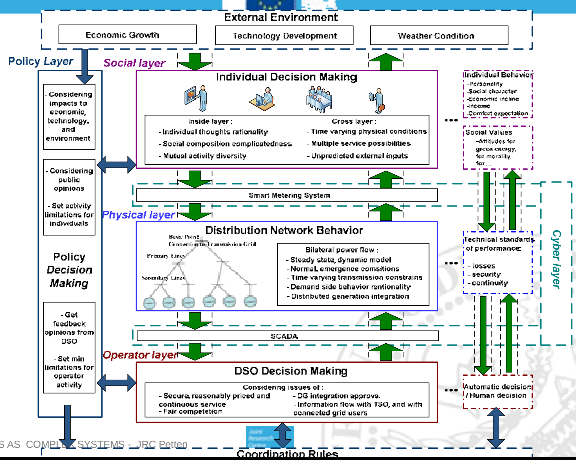
COMPLEXITY IN EES-LEVEL 1



COMPLEXITY IN EES-LEVEL 1

- The *physical layer* is the electrical power grid (wires, transformers, circuit breakers…) to transfer electrical power from generators to customers.
- A widespread change of the electrical network may result from decisions of system operators made in the *decision-making layer*.
- The *cyber layer* acts as an interface between the decision-making and the physical layers and vice versa.
- Electricity *markets* require efficiently exploiting available resources to supply customers, which causes more complex interactions within the above layers.
- The *performance* of the power system depends on a multitude of self-interested decision makers, each of them acting on a portion of the EU interconnected power transmission grid.

COMPLEXITY IN EES-LEVEL 2



COMPLEXITY IN EES-LEVEL 2

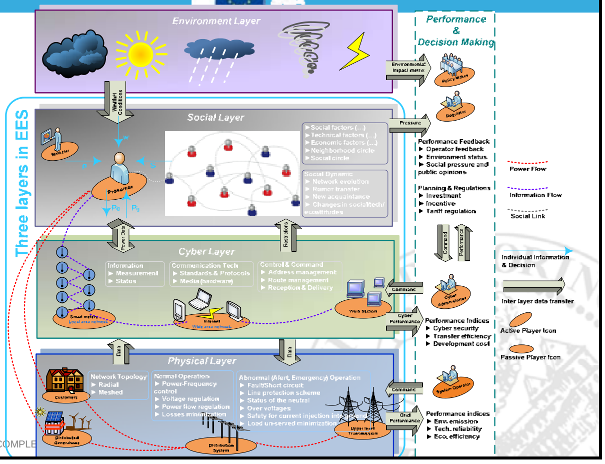
- *Distributed generations from renewable energy resources* such as wind power, solar energy, fuel cell and so on are drastically emerging and developing in Level 2 of EES.
- Shift in the paradigm from *"passive"* distribution, unidirectional flow (generation - final users) to *"active"* distribution with bidirectional flows with active users (prosumers).
- Emergence of bilateral power flow in Level 2 has enormously incorporated complexity into the *physical layer*.
- Initiatives have been laid upon the shoulder of traditional passive end-users, among whom tremendous *social complexity* can arise as a result.
- Appropriate sets of *policies and coordination rules* need to be set for the whole social welfare (economic growth, security and environment sustainability).

MULTI-LAYER EES AS COMPLEX SYSTEMS

EES AS MULTI-LAYER INTERACTING COMPLEX SYSTEMS (MLICS)

- EES operation and performances are related to various interacting aspects that may be *social*, *psychological*, *technical*, *economic* and *environmental*.
- EES may be schematized by three layers: *social*, *cyber* and *physical*.
- The layers interact among themselves and with external inputs to determine the overall performance of the system that can be measured by a set of meaningful metrics (energy savings, environmental pollution, market efficiency …).
- The overall "system control" can be exerted only in terms of policy actions, implemented by laws and regulations (compelling, prohibiting, incentivising or de-incentivizing) to influence the behaviour of the various players.

MULTILAYER EES WITH EXTERNAL INTERACTIONS



LAYERS IN EES: PHYSICAL

- *Physical layer* is the layer in which power is flowing.
- In the layer, are included power grids (radial or meshed) with (active and reactive) *power injection/withdrawal* at specific locations (nodes) which generated (real and reactive) power flow depending on the “electrical” *topology of the network* in terms of connections among nodes and their admittances.
- The grid needs to be operated under a set of strict *operational constraints* (voltage profile, max line flow limits, steady state and dynamic security constraints)

LAYERS IN EES: CYBER

- *Cyber layer* is the layer in which information (for technical/economic operations) are flowing over ICT supports.
- The operation of the grid relays on an ICT communication/command/control systems that *transfer technical data* for the field, in terms of digital and analogue information to human/automatic decision makers and, vice versa, *provide command and control action* to the fields.
- The *information exchange* is also key in a smooth functioning of electricity *markets* for real time price information (retail market) and *power exchange* operation (wholesale market)

LAYERS IN EES: SOCIAL

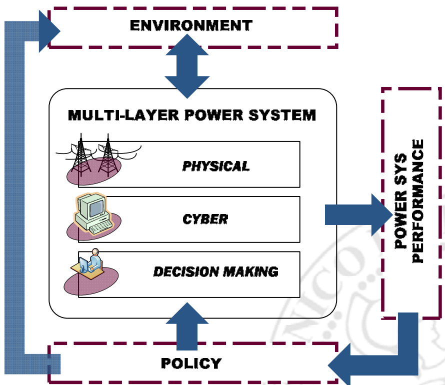
- Social layer: is the layer in which, individually and within a social network, people makes decisions
- The decision making incorporates human and automatic *procedure to control* the status of the players and their interactions with the system at various levels (from a national Transmission System Operator to a single prosumer) with reference to the *physical/economic flows.*

TIMEFRAMES FOR MULTILAYERS EES

- *In the short term* EES interact with an external environment, in terms of social, economic (market) and environmental conditions, subject to some constraints and incentives provided by the policy/regulation.

- *In the mid/long term* the change in the policy/regulation, considering possible changes in the environment strive for an improvement of the expected performances (economic efficiency, energy sustainability, security of supply).

EXTERNAL INTERCATIONS TO MULTILAYER EES



COMPLEX ISSUES IN EES

- *Multitude of self-interested individuals* with different expectations and utility functions that provide a distributed decision making context with different goals:
- Policy makers with considerations for global environment, energetic problems, social expectations, economic efficiency and security of supply metric to create sets of targets, laws, rules and instruments for *achieving global goals*.

COMPLEX ISSUES IN EES

- Individuals with *constraints from policies and technical possibilities*, and with considerations of economic terms from the other parts of the system to decide on the behaviour of himself so that he can get what is needed as both easy and economic as possible.
- The system operator, operates with *constraints from policy makers and operational feasibility*, and considering gathered information and expectations from individuals, to do the most reliable and economical operation for the system.

COMPLEX ISSUES IN EES

- The distributed decision making interacts with the network structure with physical (Kirchhoff's law) and operational constraints defining its *(active and reactive) flows (flow networks).*
- The states of the system (feasible/unfeasible, secure/unsecure reliable and unreliable, stable and instable, vulnerable and resilient, survivable and un-survivable performance) built in real time and in medium/long term are *based on those distributed devices over its physical layer with a set of communication/control channels provided by its cyber layer.*

COMPLEX ISSUES IN EES

- The modelling of the system comprises the *model of each individual* (SO, DSO, prosumer…) *for the technical* (power profile, ICT channel …) and *economic* (profit, cost), defining a utility and interactions among themselves and with the cyber and physical layers. Providing study case and running simulation on the interactions with desired time frame, the *global performance can be derived.*

COMPLEX SCIENCE AS AN APPROACH FOR EES

WHY WE NEED COMPLEX SYSTEM METHODOLOGIES IN EES

- Difficult to capture all the interactions with traditional "closed form" models (analytical equations).
- Traditional models are mainly focused only on one layer or in one of its subsets.
- Need for cross-boundary analysis in which the focus is more on the interactions (connecting variables) among the layers than on the layer itself.
- Provide a realistic simulation of the EES and their interactions (internal and external) as a tool for policy decision making support.
- Testing and assessment "in vitro" of legislative and regulation measures ex-ante

COMPLEX SCIENCE AS THE KEY FOR MODELING AND POLICY DECISION MAKING

- Physical model of power flow
- Cyber layer protocol design
- Decision making of individuals and social interaction
- Market arrangements and performance
- Policy decision making

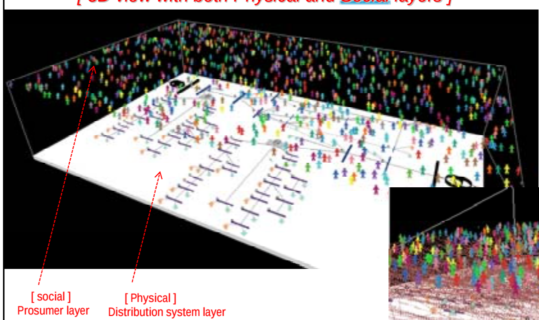
Multiple problems involving several disciplines need to be solved in power system as one complex problem

Complex Science Approach

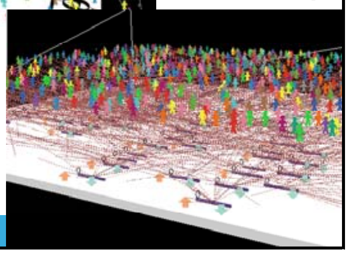
AN EXAMPLE: MULTI-AGENT SIMULATION AND ANALYSIS OF COMPLEX EES

SOCIAL AND PHYSICAL LAYERS INTERACTING

[3D view with both Physical and Social layers]

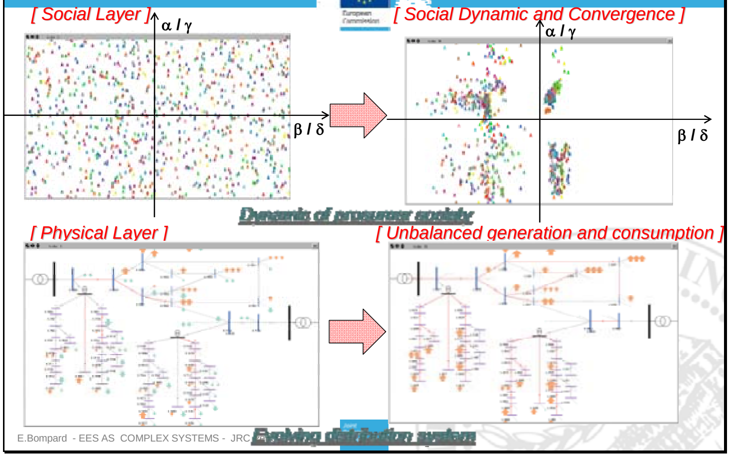


[prosumers linking with their nodes]



A 3D view of the game

SOCIAL AND PHYSICAL LAYERS INTERACTING



SUMMARIZING: KEY-ISSUES AND PERSPECTIVES

GENERAL GOAL: *SUSTAINABILITY*

- Sustainability is the ability to meet the present needs and to make ready to meet future ones without compromising, in the short and long term, any fundamental resources (air, water, food) while meeting social, economic and technical levels of performance.

THE CONTEXT

- A complex world with distributed decision makings, characterized by a multitude of self-interested individuals considering specific psychological and social profiles, interacting among themselves and with the environment to produce global system performance .
- Competition and markets, is the key word to achieve the goal (as economic efficiency, social welfare - education, health, social security, satisfaction of energy needs, reduction of environmental impacts).
- A huge amount of information, coming from different levels of the system, has been made available to decision makers through massive uses of the ICT technology
- The context is complex and not complicated; what arouses complexity is the interplay of all the "layers" and not in each layer itself

CONTROL AND SYSTEM GOVERNANCE

- Regulatory level decision making (policy decision making) may affect the sought global performance "exciting" with (rules, constraints, incentives,...) and let the system evolving (hopefully in the right direction).
- The decision makers for making proper rules for driving the "complex world of interacting systems" toward the desired performance need both theoretical framework and simulation tools for assessing the impacts of new decision/s rules ex-ante, through simulating "in vitro" the overall environment.
- In complex systems both "economic" and "physical" layers are coexistent. Physical variables and constraints are related to physical laws that rule the world; they are "nature based" and cannot be altered. Economic variables are "man-made", a little bit more artificial and, to a certain extent, can be decided and changed.
- Which are the relations among the two types of variable?
- "Capture complexity to rule the world" ?

A CHANGE IN THE FOCUS

- Focus has been inside each layer traditionally; it is time to shift the focus from "inside" the layers to the interface variable among the layers to capture the complexity;
- There is a need for interdisciplinary "coordinated approach" in which different specialists work together to model the world unified by the same "complex view".
- Complexity may have a tremendous impact on cultural paradigm. Human knowledge has been divided into many disciplines with their own theoretical tools and paradigm. Complex science techniques and theoretical tools are used from literature to physics from sociology to medicine.... Might complexity overcome this separation and unify somehow again the knowledge ?

2.3 Malika Chawla: Smart Grids and Complexity Science: Smart Grids and Complexity Science

UNIVERSITY OF CAMBRIDGE | Electricity Policy Research Group

Workshop

Smart Energy Grids and Complexity Science

JRC Institute for Energy and Transport
25 June 2012

www.eprg.group.cam.ac.uk

Organization

Mallika Chawla
Research Assistant for Dr. Michael G. Pollitt (Assistant Director)
Electricity Policy Research Group
University of Cambridge
Email: mc669@cam.ac.uk
Tel: +44 (0) 1223335258

Focus of the Group has remained in conducting rigorous independent research on important questions from electricity and energy industry

2

UNIVERSITY OF CAMBRIDGE | Electricity Policy Research Group

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Ongoing activities/projects relevant for Smart Energy systems and/or complexity

Current Research: International Benchmarking of Electricity Transmission System Operators for efficiency in System Operation Functions

- Funded by the EPSRC (Engineering and Physical Sciences Research Council)
- Part of the Autonomic Power System (APS)
- Academic team comprises of PhDs and RAs from the University of Cambridge, Durham, Manchester, Strathclyde, Sussex and Imperial College London

3

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Complexity science approach to energy system

Objective: Examine the efficiency of different transmission arrangements that exists across the world with a view to estimate costs and incentives associated with an autonomic world

Methodology: Quantitative benchmarking using Frontier Efficiency Analysis (applying Data Envelopment Analysis and/or Stochastic Frontier Analysis) on an international dataset collected from different transmission system operators

How to approach future smart energy systems & complexity and future research

Contribution:

- Highlight the challenges involved in conducting such a benchmarking analysis
- Add to the skewed literature of defining inputs/outputs/environmental factors for different System Operation Functions
- Broaden our understanding of the transmission arrangement that would be best suited for a more autonomic world

2.4 Steve Connors: : How Smart should a smart grid be if a smart grid could be smart?

Smart Energy Grids and Complexity Science
JRC Energy and Transport, Petten NL

How Smart Should a Smart Grid Be If a Smart Grid Could Be Smart?

Stephen R. Connors
MIT Energy Initiative
MIT, 400 Main St. Room E19-341p
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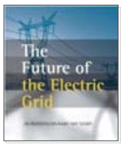
email: connorsr@mit.edu

MIT Energy Initiative

25 June 2012 – pg. 1

No Single "Smart Grid"



web.mit.edu/mitei

- Which Smart Grid are You?
  - Large Scale Renewables Integration (HV/MV)
    Throw in True Baseload Generation too (Nuclear, Geothermal, CCS)
  - Distribution System/Microgrids (MV/LV)
    *Including DG, Storage and "Storage Substitutes" like **xDR***
  - The Smart Meter-Smart House Smart Grid (LV/EU)
    Including Net-Zero Buildings, Smart Electric Vehicle Charging and "V2G"
  - All of the Above? If so, **When**, **Where** and **How**?
- How Smart is Your Smart Grid?
  - The "**Genius Grid**"
  - The "**Not Dumb Grid**"
  - The "**Not as Smart as it Thinks it Is Grid**"
- Innovating for the Smart Grid?
  - Who's Smart Grid is It? (Access and use of Information)
  - Who Invests? Who Pays? Who Benefits?

S.R. Connors – MITEI / AGREA (connorsr@mit.edu) *25 June 2012 – pg. 3*

Smart Grids in Context

The Cambridge-MIT Institute

- *Recommendations to the 2006 UK-DTI Energy Review to simultaneously meet Climate Change and Energy Security goals...*
  - ***Aggressive End-Use Efficiency***
    - Requires a detailed understanding of energy use patterns, to deploy the "three classes of energy efficiency."
  - ***Diversify Domestically***
    - Requires a detailed understanding of the size, temporal and spatial variability of energy sources and sinks.
  - ***Modernize Energy Networks***
    - Requires a detailed understanding of the above and network thresholds and important infrastructure "nodes and modes"

S.R. Connors – MITEI / AGREA (connorsr@mit.edu) *25 June 2012 – pg. 4*

Higher Resolution Research – "GIST"

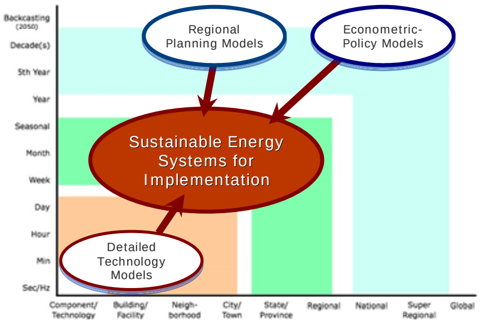
GIST = Graphical Information Systems + Time Series

Meso-Scale Modeling

"Designing for the Dynamics"

- Aggressive End-Use Efficiency
- Diversify Domestically
- Modernize Energy Networks

- 50-80% Reduction = Local Energy



The Convergence of Planning and Operations in Energy Systems Design and Implementation

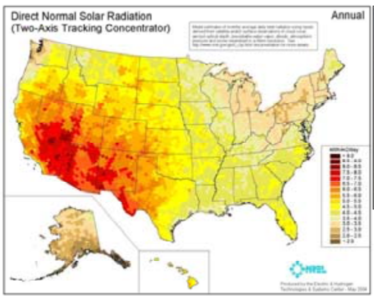
The Role of "Enabling Information?"

- Designing for the Dynamics
  - » In Space & Time (GIST)
  - » "Nodes and Modes of Systems Operation"
- The Value of the Investment Comes from Understanding Planning & Operations
  - » Inter-Annual Dynamics
  - » Daily and Seasonal Variability, Intermittency, etc.
  - » Cycle-Second-Minute-Hour Variability and Volatility
- Which Infrastructure Investments are Leading vs. Lagging?

Matching Supply-and-Demand

Where and When is it Sunny?

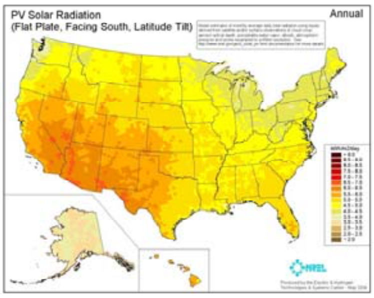
(Definitely more than just latitude)

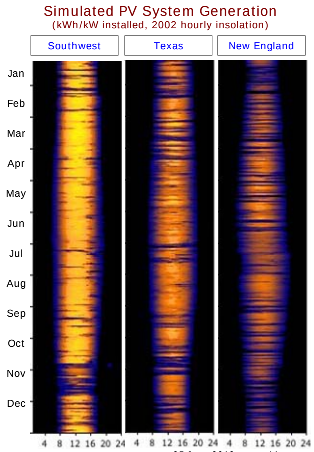


Centralized Solar Power (CSP)
Abengoa Solar Plant PS10 [11 MW]

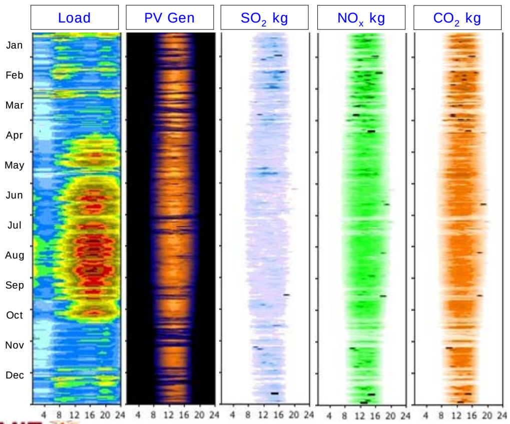
Matching Supply-and-Demand

Where and When is it Sunny?
(Definitely more than just latitude)





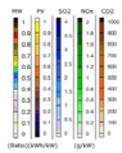
Texas–Avoided Emissions



Texas
(ERCT-2002)

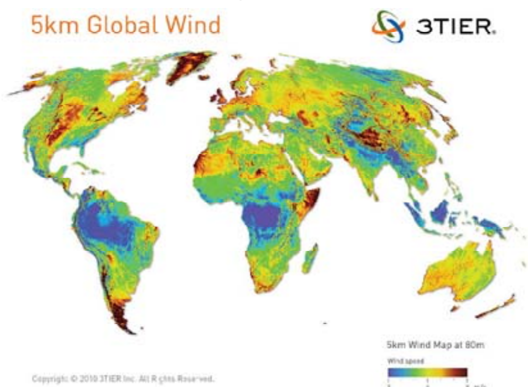
- 365 days x 24 Hours
- Total Load/Elec. Demand
- PV Generation
  (**Monitored** Systems, normalized to 1 kW of installed PV capacity)

\+ Avoided LSF fossil emissions from PV generation (kg per hour)



The Wind Resource

- *Where is it Windy?* (on land)



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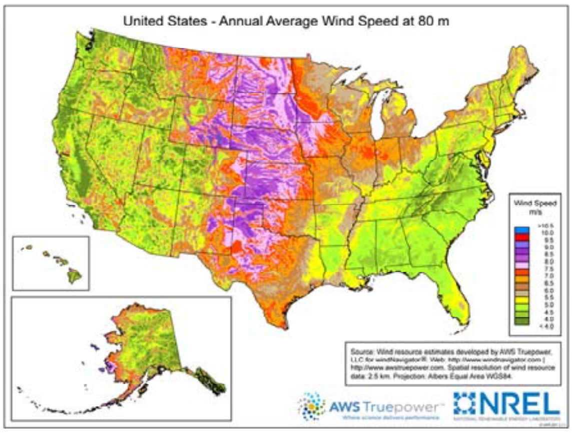
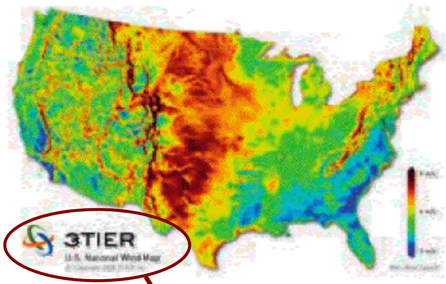
Where is it Windy?



Where is it Windy?

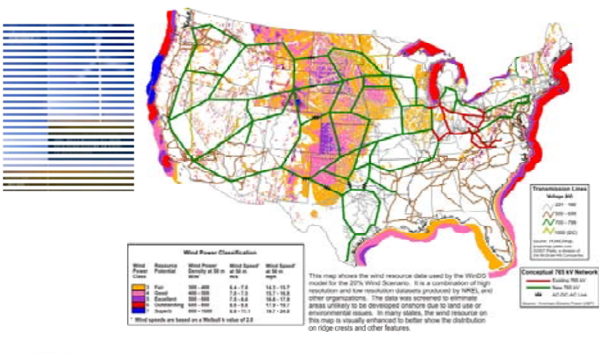
- Trees and Hills, Matter



- AWS Truepower
- Second Wind
- NCAR
- WindLogics
- WSI + GE Energy
- NRG Systems

How Far Away?

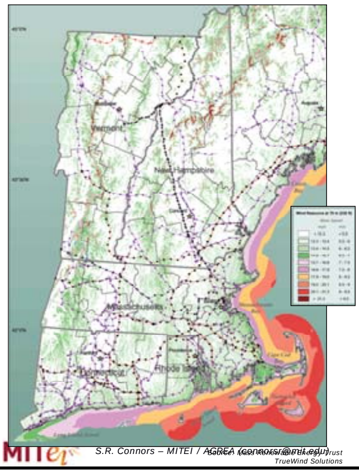
- Trees and Hills, Matter



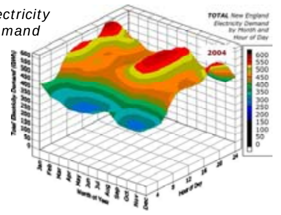
How Variable is the Wind?

Earlier this Year – Visualization Artists “hint.fm/wind”

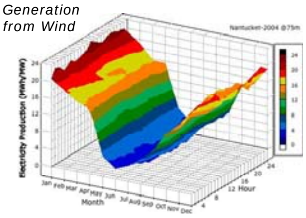
Wind in Space and Time (GIST)



Electricity Demand



Generation from Wind



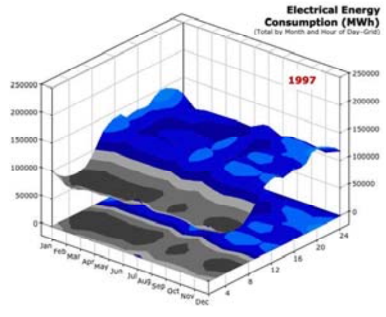
Lessons from MIT-Portugal & Beyond

- New, Smart Technologies Need to “Talk to One Another,” So Real “Field Tests” Are Essential.
- We Need to Move Beyond
  - » Technology Demonstrations
  - » Integration Demonstrations
  - » Commercial Demonstrations

MIT Portugal

Lots of “Integration Demonstrations”

- Mainland Portugal Electricity Demand (REN)

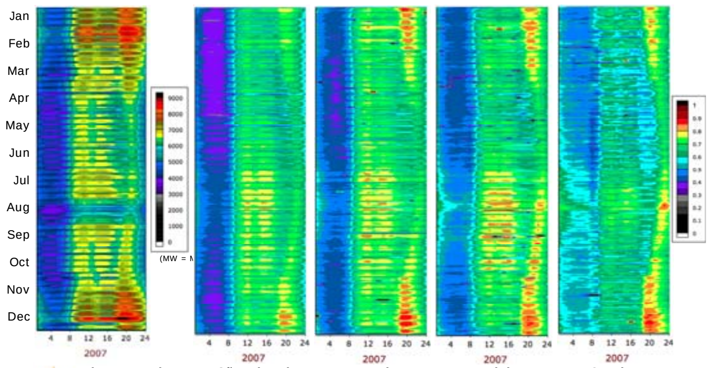


Mainland Portugal Electricity Demand
(REN Data)

S.R. Connors – MITEI / AGREA (connorsr@mit.edu) 25 June 2012 – pg. 21

Higher Resolution/Better Design

- Mainland Portugal and the Azores - 2007



REN Hourly Demand | São Miguel | Terceira | Faial | Graciosa

Source Data: EDA

S.R. Connors – MITEI / AGREA (connorsr@mit.edu) 25 June 2012 – pg. 23

What Flavor of Storage?

- What’s It For? (Early Adopters)
  » Power Quality?
  » Reliability? (Backup Generation)
  » Balancing Renewables
  » Balancing Other Generation?
  » Deferring T&D Investments?
  » Extending the Reach of Electricity as an Energy Carrier?
- How Much for How Long?
  » And Other Key Performance Criteria
- Are There Competing Solutions?
  » Demand Response and “V2G”
  » Competing or Complementary?
  » The Role of “Enabling Market Regulation?”

S.R. Connors – MITEI / AGREA (connorsr@mit.edu) 25 June 2012 – pg. 24

Steve's Key Questions…

- For ***Sizing Up Storage*** *(Energy Side)*
  - » How Much for How Long? (e.g. energy value)
    - Charge/Capacity Retention Rate?
  - » At What Charge/Discharge Rates?
    - How many will I need? How "useful" are they?
  - » At What Cycle Efficiency?
  - » At What "Spark Spread?" (e.g. economic value)
  - » At What Capacity/Capital Cost?
- ***All Energy is Situational*** *(Local)*
  … in Space and Time ….

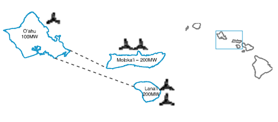
Value of "Fast" Grid Resources

- Recent Lessons Regarding the Value of Storage, DR, Smart EVs
  - › Reduce "Spilled Wind"
  - › Charge EVs at the "Right Time"
  - › Size and Location of Storage
  - › Efficiency Gains in Fossil Operations
- What Flavor of Demand Response?
  - › Emergency (EDR), Power Quality (PDR), Balancing (BDR), and Market (MDR)
  - › Expanded Definition of DR includes Fast Storage, "Grid-Aware" EV Charging (& V2G)

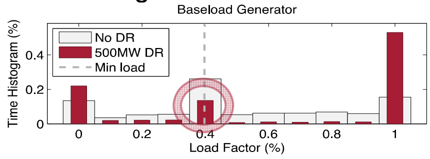
Demand Response for Hawai'i

JISEA Joint Institute for Strategic Energy Analysis

- How might DR Help Hawai'i accept more wind as it ramps up renewable generation?



O'ahu Wind Integration and Transmission Study
500MW Wind Configuration

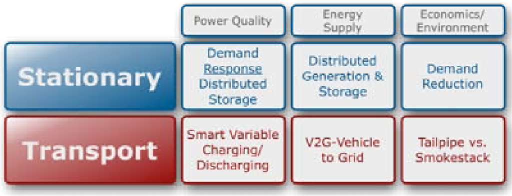


Change in Baseload Generator
Load Levels

- Flexible resources such as DR and storage may help the entire system run smoother.
- How do we guarantee that these types "balancing" options are "real" to local system operators?

Value of IT in Smart Energy Techs

- Smart/Responsive End-Uses
  - » Levels of Smart Meters/Energy Boxes
    - › Zero-Way Communication (end-use load reduction only)
    - › One-Way Communication (energy price-responsive/storage)
    - › Two-Way Communication (includes end-use generation)
      - Asynchronous - respond to price/performance signal
      - Synchronous - especially to be a "grid resource"

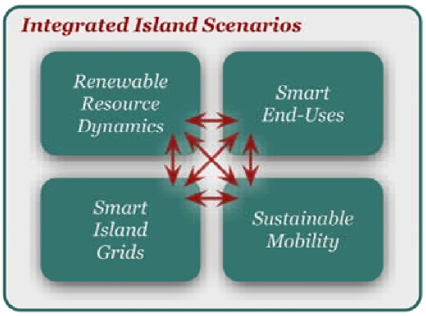


Green Islands Research Themes

- Five Innovative Research Areas

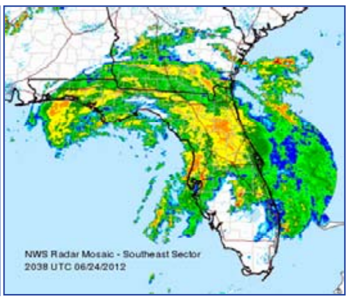
Meso-Scale Modeling
"Designing for the Dynamics"
- Aggressive End-Use Efficiency
- Diversify Domestically
- Modernize Energy Networks

- 50-80% Reduction = Local Energy



Asking the Right Questions?

- Climate Change**d** – Adaptation vs. Mitigation
  - » What are we designing *for*...



Asking the Right Questions?

- Climate Change**d** – Adaptation vs. Mitigation
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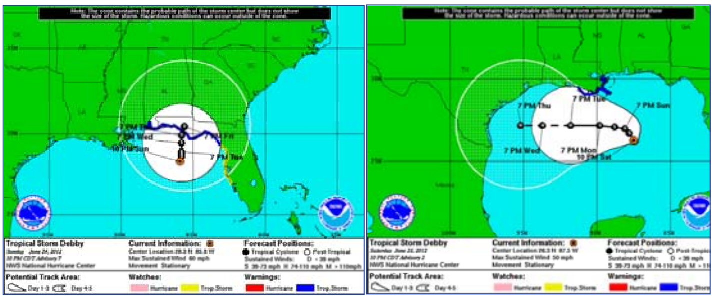
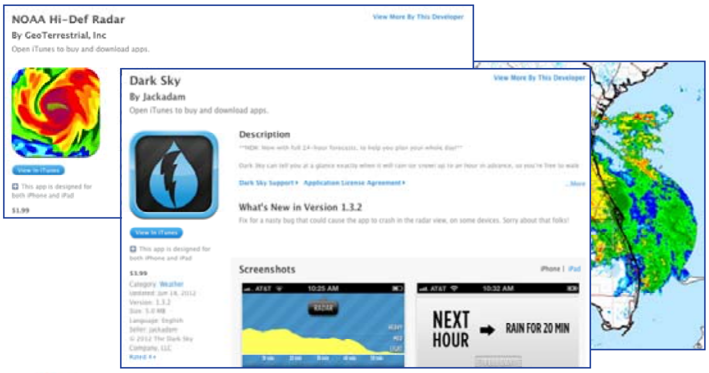


Asking the Right Questions?

- There's an App for That…



Smart Grids and Complexity

- Complexity Science, Complex Systems, Chaotic Systems, etc.
  - » **Energy Security and Climate Change *Adaptation***
    High Resolution **GIST** Data Sets for High Penetration Renewables and Weather Related Warnings (& Emergency Response)
  - » Reliable, Robust, Resilient **Socio-Technical Systems**
    At **All Scales** (International, National, Regional and Local)
  - » Building Informative and **Responsive Capacity**
    Human Capacity, Infrastructural Capacity, Informative Capacity
- "Big Data" and Complexity Science
  - » **Collecting**, Transmitting, (Cleaning), and Processing Data – for Short-Term and Long-Term uses.
  - » **Public Goods Value** of High Resolution Energy Supply & Demand Data – **Stationary & Transport**
  - » Expand Meteorological and Agricultural Data Collection, including Water, to Support Renewable Energy Deployment (and Climate Change Adaptation)
    - Also True for Carbon Management Technologies, e.g. Geotechnical Information for CCS

CSAIL bigdata.csail.mit.edu

2.5 Andre Grebenc: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Andrej GREBENC, European Commission, REA

JRC Institute for Energy and Transport
25 June 2012

Your organization

European Commission, REA, Brussels

- FP7 and Horizon 2020 research projects in security of infrastructures and utilities

Ongoing activities / projects relevant for Smart Energy systems and / or complexity

- Financing the European research on smart grids from security perspective
- Research on complex systems in innovation and knowledge management

Complexity science approach to energy system

Complexity in energy systems is in general a vague concept. It is often used as a synonym of complicated systems.

I suggest a strong complexity approach:

- **Study of nonlinear, emergent, self-organized, resilient dynamic properties in new types of energy systems**

How to approach future smart energy systems & complexity and future research (1)

- **Technological-technical complex systems**
- **Sustainability as a complex smart energy system**
- **New types of energy business models as complex systems**

How to approach future smart energy systems & complexity and future research (2)

- Technological-technical complex systems
  a) Energy point of view (distributed generation (DG), demand side management (DSM))
  b) Topological (network) point of view (small-world, scale-free networks)
  c) Cyber point of view (Broadband Distribution PLC, Internet of things)

How to approach future smart energy systems & complexity and future research (3)

Ad a) Energy point of view:

Research on new architecture of smart energy systems and networks

- mixed: large scale and scattered small scale generation
- transition of radial → meshed networks
- new type of power protection systems
- robustness of energy part of systems (double network power injection points)
- end-user intervention to demand side management

How to approach future smart energy systems & complexity and future research (4)

Ad b) Topological point of view

- Architecture and dynamics of fused **power-cyber networks**
- Dynamics of new type of **power networks-** power flow control and optimisation under new conditions- possible emergence and chaotic behaviour
- Dynamics of **cyber networks** – data flow research and possible emergence and chaotic behaviour

How to approach future smart energy systems & complexity and future research (5)

Ad c) Cyber point of view

- Network fusion (power, cyber- Broadband DPLC) and systemic service robustness (DPLC - only one fused network)
- Separate networks (power, cyber)

How to approach future smart energy systems & complexity and future research (6)

- Sustainability as a complex smart energy system

  - **Mix of energy sources** and its architecture as a complex system (emergence)
  - **Energy storage and stored energy injections** as a complex system (emergence)
  - **Eco-energy system** as a complex system

How to approach future smart energy systems & complexity and future research (7)

New type of energy business models as complex systems

- **local energy communities** as complex systems
- **new stakeholder mix models** (power producers, prosumers, power network operators, cyber net providers, energy communities, regulators and policy makers) – their interplay as a complex system
- **economy energy models** (internalisation of costs) as a complex system (emergency, chaotic models??)

Thank you

andrej.grebenc@ec.europa.eu

2.6 Nouredine Hadjsaid: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Nouredine Hadjsaid

JRC Institute for Energy and Transport
25 June 2012

Your organization

Group, location

- Grenoble Institute of Technology/G2ELAB– France
- IDEA (Schneider Electric, EDF, G2ELAB/Grenoble Institute of Technology
- Smartgrids chair ERDF
- More than 80 people +industry research engineers
- Partners: EDF, Schneider, Nexans, RTE, ERDF, Alstom, Orange Lab, ATOS worldgrids, EADS, GEG, CEA, …

reference/contact person

- Prof. Hadjsaid (Nouredine.Hadjsaid@g2elab.grenoble-inp.fr)

Focus (*application of complex networks***)**

- Smartgrid mostly at distribution level (design, operation, planning, experimentation….)
- Power grids/ICT common model (complex network theory)
  - Interdependency
  - Vulnerability assessment
  - Performance, impact and risk assessment
- Experimental platform to support the

Ongoing activities/projects relevant for Smart Energy systems and/or complexity

- **FINSENY** (Future Internet for Smart Energy systems)
  - Funded by EU/FP7
- **GREENLYS**: large scale pilot project on Smartgrids involving Lyon and Grenoble
  - Funded by ADEME and CGI (ERDF, GDFSUEZ, ALSTOM, SCHNEIDER, ATOS, …)
- **SINARI** (Sécurité des Infrastructures et Analyse des RIsques)
  - funded by the French National Research Agency ANR
- **SensCity:** sensors and ICT for energy efficiency in buildings and cities
  - Funded by ADEME
- **DMS** vulnerability analysis
  - Funded by ATOS Worldgrid
- **Smartgrids experimental platform**: assessment of ICT performances for self healing functionalities from an experimental perspectives
  - Funding: IDEA + different funding channels
- **IDEA projects**: Observability, smartmetering data for load modeling & observability , …

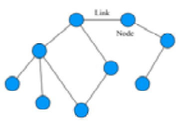
Complexity science approach to energy system

- **Complex network** theory for:
  - *Modeling* coupled infrastructures (Energy/ICT) – integrated approach
    - model large systems
  - *Interdependency*, vulnerability, common mode identification
    - identify weak connections, and understand the interactions between different system components
  - *Performance*/gravity and cascading effects assessment
    - answer the most challenging and fundamental questions about the interactions between Critical Infrastructures and the risk involved
- **Critical aspects**:
  - Model validation vs coupled models
  - Incorporating dynamic (electrical) aspects
  - Need cross disciplinary approach and collaboration

Power Systems and ICTs
New Modeling Approach

We focus our studies on: COMPLEX NETWORK THEORY

A new science that has been used to: Model, analyze, and understand large systems **with** non-trivial topologies **and hidden** interdependencies**.**



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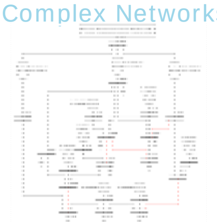
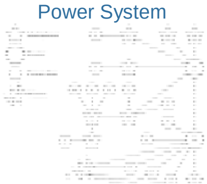
Complex Networks Approach

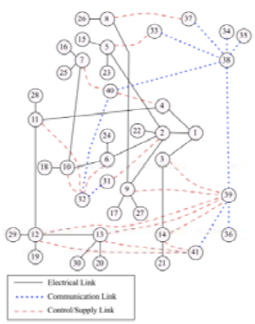


Power System



ICT Network

Undirected Complex Network



- **Evaluating Topology**
- **Identifying weak connections**
- **Comparing infrastructures**
- **Studying cascading phenomena**

• 6

Complex Networks approach

Adjacency Matrix (*A*)

- *A* is the mathematical representation of a Complex Network

$$a_{ij} = \begin{cases} 1, & \text{if link } (i,j) \text{ is type 1} \\ 1i, & \text{if link } (i,j) \text{ is type 2} \\ 1+1i, & \text{if link } (i,j) \text{ is type 3 and 4} \\ 0, & \text{otherwise} \end{cases}$$

We proposed 2-dimensional Complex Networks to understand and identify inherent vulnerabilities of coupled infrastructures

Degree

- The degree of node *i* is the number of nodes incident with the node

$$k_e = \operatorname{diag}\left(A_r.A_r{}^T\right) - (1-\alpha)^T.\operatorname{diag}\left(A_i.A_i{}^T\right) \leftarrow \text{Power System's Influence}$$

$$k_c = \operatorname{diag}\left(A_i.A_i^T\right) - \alpha^T.\operatorname{diag}\left(A_r.A_r^T\right) \leftarrow \text{ICT's Influence}$$

$$k_{in} = k_e.\alpha^T + k_c.(1-\alpha)^T \leftarrow \text{Interconnections Influence}$$

$$\alpha_i = \begin{cases} 0, & \text{if } i \text{ is an electrical node} \\ 1, & \text{if } i \text{ is a communications node} \end{cases}$$

Betweenness Centrality

- The ratio between the number of shortest paths between *i* and *j* that passes through *h* and the total number of shortest paths between *i* and *j*

$$C_e(h) = \sum_{i,j \in V, i \neq j} \frac{\sigma_{e_{ij}}(h)}{\sigma_{e_{ij}}}$$

$$C_c(h) = \sum_{i,j \in V, i \neq j} \frac{\sigma_{c_{ij}}(h)}{\sigma_{c_{ij}}}$$

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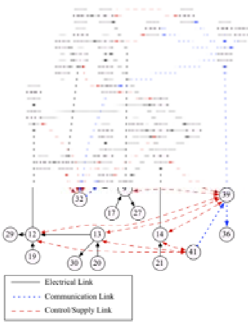
Complex Networks approach

Directed Complex Network



Node Degree:

$$k_i^{in} = \sum_{j \in V} a_{ij}$$

$$k_i^{out} = \sum_{j \in V} a_{ji}$$

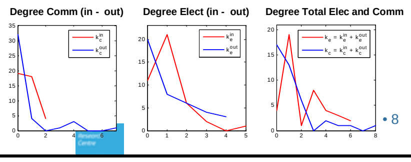
$$k_i^{in} = \boxed{k_{e_i}^{in}} + i\,\boxed{k_{c_i}^{in}}$$

$$k_i^{out} = \boxed{k_{e_i}^{out}} + i\,\boxed{k_{c_i}^{out}}$$

Power System's Influence

ICT's Influence

- **Electrical Directions according to Load Flow.**
- **Bi-directional links between Electrical-Communication nodes (energy supply and control)**



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How to approach future smart energy systems & complexity and future research

- **Progress** achieved in the application of complex network theory to energy/ICT infrastructures:
  - Modeling, cascading failures, threat detection, ….
  - Operational vs. planning (including decision making)
- **Much more work** needed for:
  - Model validation – take advantage of demo projects
  - Unknown graphs? (external observability & behavior)
  - Beyond topology analysis, Dynamic aspects of electrical systems
  - Control systems and human behavior
- **Collaborative:** involve industry
- **A real potential…**

2.7Tooraj Jamasb*:* Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Tooraj Jamasb
Heriot-Watt University
T.Jamasb@hw.ac.uk

JRC Institute for Energy and Transport
25 June 2012

Heriot-Watt University, Edinburgh

Tooraj Jamasb
Prof., Energy Economics:

- Reform and liberalisation
- Innovation and technology economics and policy
- Household energy demand and spending
- Networks

HW Energy Theme / Academy:

- Advanced energy materials
- Asset condition monitoring
- CO_2 capture and storage
- Energy modelling, use, logistics
- Low-carbon buildings
- Petroleum engineering
- Solar energy
- Sustainable development
- Wave and tidal energy
- Wind and marine energy.

Ongoing activities/projects relevant for Smart Energy systems and/or complexity

Networks:

- Incentive regulation,
- Service quality,
- Weather/geography,
- Electric vehicles
- Public engagement
- Critical infrastructure,

Ongoing Projects:

- SESAME – Securing the European Electricity Supply Against Malicious and Accidental Threats (FR7)
- CfSRF - Centre for Sustainable Road Freight (UK Research Councils)
- SusGrid – Sustainable Grid Development (Norway Research Council)

Complexity science approach to energy system

Your viewpoint, your activities and interests,...

- Smart grid - Not just a technical concept
- The interface - where the user/society meets the network/technology
- Socio-Economic and Technical Complexity
  i. Customers, ii. citizens, iii. loads
- Empowering the consumer/user (sovereignty):
  - Technology,
  - Economic incentives,
  - Information.

How to approach future smart energy systems & complexity and future research

Vision, what to do and how, ...

- Challenge: Complexity to be translated/operationalized into "simplicity"
- Complexity science: "Resilience" for the networks (broadly speaking)
- Complexity science: "Versatility" for user (multi need/purpose)
- Key words: i. New regulatory approaches, ii. Investments, iii. Innovation, iv. New business models

2.8 Marko Milovanovic*:* Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Marko Milovanović MSc

rijksuniversiteit groningen / groningen energy and sustainability programme

JRC Institute for Energy and Transport
25 June 2012

Faculty of Behavioral Science / Social Psychology

Steg Group
prof. dr. E.M. (Linda) Steg
with: 11 PhD students, 2 post docs, 1 assistant professor

Topics of interest
Understanding and changing environmentally significant behavior, in particular household energy use.
Understanding factors that promote acceptability of innovations.

Approach
Environmental psychology, social psychology, and interdisciplinary approaches.
Questionnaires, field studies, experimental studies, gaming.

Ongoing activities / projects

Project	Activities	Funding
Macredes	Mapping the **contextual conditions** of resilient decentralized systems	EDGaR
Smart grid: rendement voor iedereen!	Behavioral factors that are crucial for **acceptance**, and succesful implementation, of smart grids	Utrecht
BARENERGY	**Barriers** for energy changes among end consumers and households	EU
GILDED	Governance, Infrastructure, **Lifestyle Dynamics** and Energy Demand: European post-carbon communities	EU
Energy transitions	Psychological factors influencing the **early adoption** of electric vehicles	NWO
LOCAW	**Modelling agents** and organizations to achieve transition to a low carbon Europe	EU
CRISP	Sustainable consumption and **quality of life**	EU
INTEWON	**Smart feedback systems** to promote household energy conservation	Agentschap NL
i-PriSM	**Dynamic Pricing** for Sustainable Mobility	NWO
...	...	...

Complexity science approach to energy system

Innovations are developed on the basis of many assumptions with regard to consumer responses (acceptability, behavior)

Invalid assumptions lead to poor in(ter)ventions

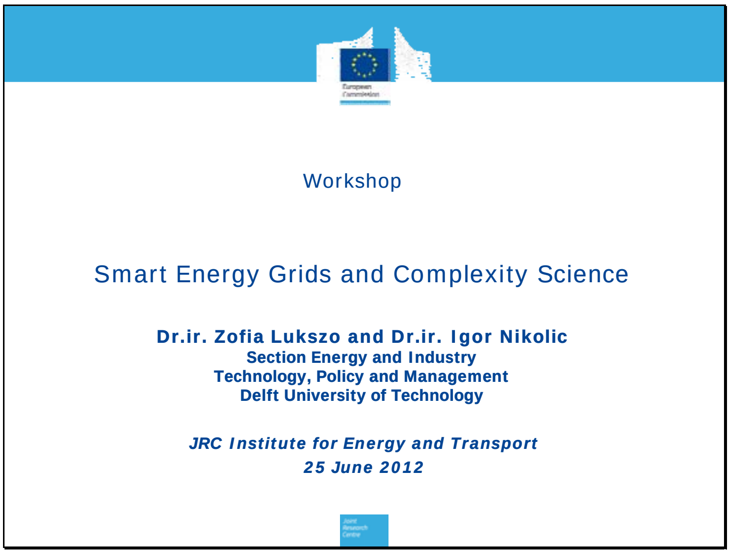
Understanding how innovations influence human behavior is key for the success of smart energy grids

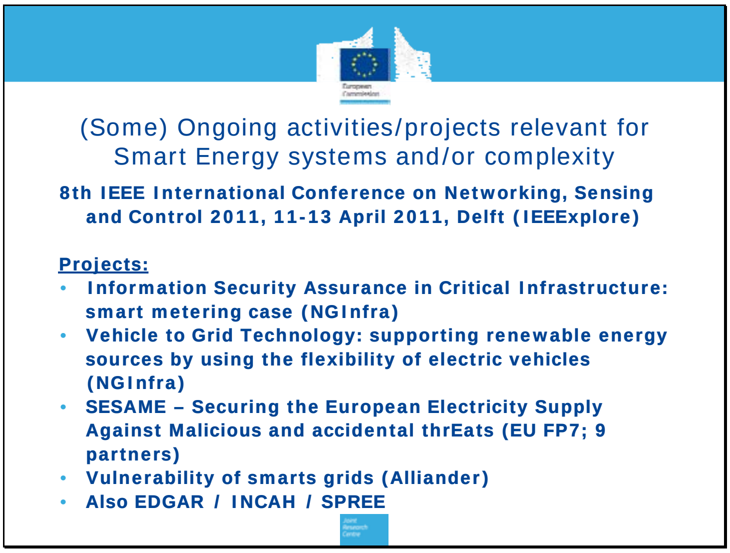
How to approach future smart energy systems & complexity and future research

Understanding the unique characteristics of a smart energy grid

- **Community of co-dependent prosumers**
  - Community processes (scarcity)
  - Game theory?
- **Energy use becomes transparent**
  - Type of information (feedback) shapes our motives
  - Individual motives
  - Social motives

2.9 Zofia Lukszo, Igor Nikolic: Smart Grids and Complexity Science





Complexity science approach to energy system

Strong Complex Adaptive Systems perspective

- Socio-technical complexity
- Evolution / coevolution / dynamics
- Multi-level / Multi-actors / Multi-criteria / Multi-time scale

- **Tools / approaches**
  - Socio-technical ABM of systems evolution *and* operation
  - Gaming
  - Mathematical modeling and optimization
  - Network theory / topology

How to approach future smart energy systems & complexity and future research

- Understanding the multilevel/distributed character of future energy systems by modeling the evolution and operation
- Steering by Multi-optimization
- Security-by-design
- Big data / Open data
- Democratization of modeling energy systems (enipedia)

2.10 William J. Nuttall: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

William J. Nuttall
University of Cambridge
wjn21@cam.ac.uk

JRC Institute for Energy and Transport
25 June 2012

Electricity Policy Research Group

The EPRG is a multidisciplinary research group based at the University of Cambridge in the UK

It is known as one of the world's leading energy economics research groups (first or second by citations), but EPRG activities extend beyond economics to include energy law, political science, technology policy and innovation studies.

The work of the EPRG is supported by UK research councils, EU Framework Programmes and a stakeholder club known as the Energy Policy Forum. EPRG has excellent links to the energy industry, UK government, market regulators and EU institutions

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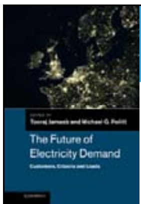
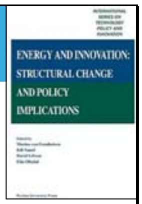


EPRG activities



Much prior work on aspects of smart electricity systems. Putting the phrase 'smart' into the EPRG search facility reveals:

- Six working papers
- Seven conference/seminar presentations
- Two edited books
- Several other publications

and there is much more than that ...

Related past and present funded projects include:
Supergen and Flexnet (EPSRC, UK)
Project TransmiT (OfGEM, UK)
The Autonomic Power System (EPSRC, UK) - Mallika Chawla

Prof. Ross Anderson (EPRG Associate) brings EPRG much insight on information technology issues

Me and complexity

My background is in physics (PhD MIT 1993 -experimental condensed matter – phase transitions)

My interest in complexity dates back more than 20 years. It predates my interest in energy and technology policy.

In the 1980s my PhD introduced me to experts in the emerging discipline of complexity science, but frankly I did not fully appreciate it at the time.

In recent years I have been a founding committee member of the Nonlinear and Complex Physics Group of the Institute of Physics

Complexity science approach to energy system

Much of my energy technology and policy work has connected to physics in a different way. I am mostly known for my work on policy for civil nuclear power.

Arguably nuclear power favours, and is favoured by, electricity systems that lack scientific complexity. Nuclear power today is a base-load technology well suited to conventional notions of electricity transmission and distribution.

By working on nuclear power I have grown to understand issues in electricity policy. Separately, I see how complexity insights can shape the future of the electricity business.

How to approach future smart energy systems & complexity and future research

I strongly support and welcome the agenda of this workshop.

Numerous other conferences have considered the complexity within the future smart electricity system and some are still attempting to define it. I am attracted to this meeting because it also considers the complexity that will sit around the future smart electricity system.

I would like to mention some issues that come to mind, which relate to broader complexity to varying degrees.

Complexity around, not just within, the future smart grid

I see this in various domains:

- *Technological Complexity*
- *Social Complexity*
- *Business Complexity*
- *Environmental Complexity*

Whether my remarks use the phrase 'complex' in a scientific or a metaphorical sense remains unresolved. At this stage they are merely ideas that interest me

Technological Complexity

The future electricity distribution has the potential to become an 'inverse infrastructure' in the spirit of the recent book edited by Tineke Egyedi and Donna Mehos of TU Delft. That is: 'bottom up, user driven, self-organising networks'.

Furthermore users will not just adopt new technologies, they will adapt them to uses never imagined by their developers ('appropriated technologies').

New sources of value will be found, but also previously unimagined risks will emerge. These risks will complement the already known (and hence managed) safety risks in distribution system maintenance that arise in shifting from one source point for power, easily interrupted at the sub-station, to a world of distributed generation and prosumers each of which must be disconnected before maintenance can safely be undertaken [with thanks to Ignacio Perez-Arriaga]

Social Complexity

The shift from electricity consumers to 'prosumers' will bring with it new issues of legal complexity. Previously the electricity system developed as directed by policy and the law (e.g. unbundling following liberalisation). In the future regulation and the law will need to catch up with issues driven by technological change [with thanks to Hamilcar Knops TU Delft]

Community initiatives in electricity self-reliance can run up against the legal right for consumers to switch supplier [M. Pollitt, chapter in *Competitive Electricity Markets [...]* Ed. F.P. Sioshansi, 2008]

Social complexity will involve both expanding and declining cities. To what extent will smart grid innovation be associated only with communities with obviously bright futures? How does the notion of universal quality of service survive in the smart grid world? Could this be worse than the perhaps over-hyped 'digital divide' in information services?

Business Complexity

Unbundling has led to separated businesses of generation, transmission, distribution and in some cases 'supply'.

The future smart grid brings with it the possibility of new business models such as stronger brokers and aggregators acting on behalf of consumers or prosumers.

Smart system data will have a value and could be traded, albeit constrained by legal restrictions, such as those relating to privacy concerns.

It is noteworthy that neither SMS messaging nor Apps markets were fully understood by telecoms policy makers before they appeared. I wonder what businesses might appear from the interaction of a complex electricity system with empowered prosumers.

Environmental Complexity

Here we turn to aspects of the changing climate and changing weather, with complex and slow-burning linkages to energy choices.

These matters have already been introduced by Steve Connors,

So I shall stop …

Thank you

2.11 Andrea Pagani: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

university of groningen

G.A. Pagani – University of Groningen

JRC Institute for Energy and Transport
25 June 2012

Your organization

university of groningen

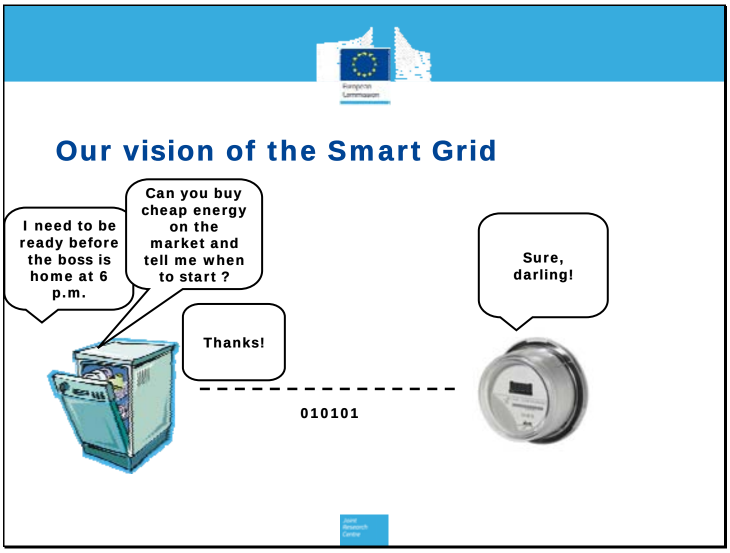
Distributed Systems Group in Faculty of Mathematics and Computer Science
Contact: Prof. Marco Aiello (m.aiello@rug.nl)
G.A. Pagani (g.a.pagani@rug.nl)

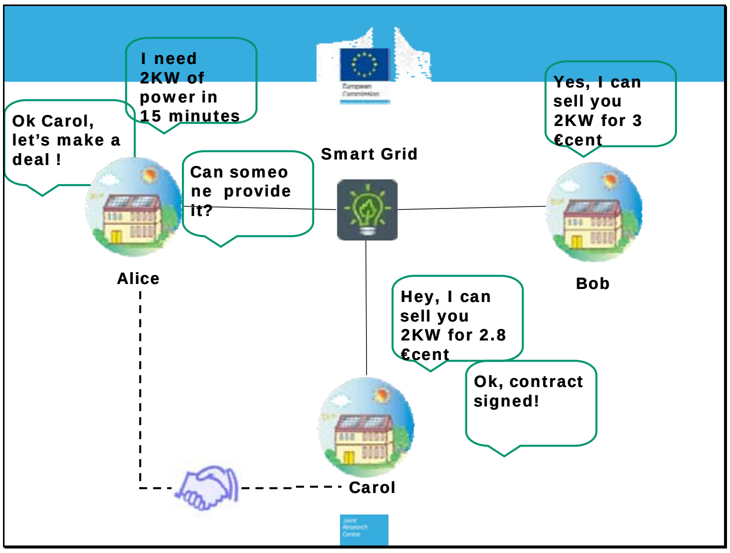
RUG themes strategic research themes:
-**Energy**
-Healthy aging

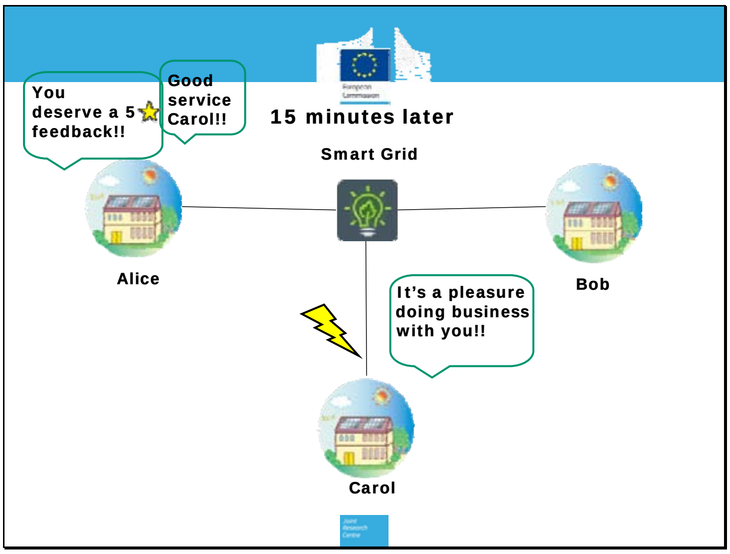
Apply CS and DS in these two strategic themes

Ongoing activities / projects relevant for Smart Energy systems and / or complexity

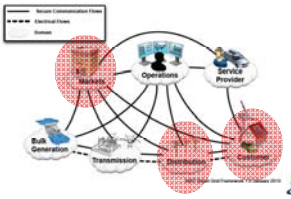
Project name	Focus	Partners	Funding mechanism	Duration	Completion	Publications so far
GreenerBuildings	**Building adaptation for energy saving**	**RUG, Philips, Tu/E, UoR,2 SMEs**	**EU-FP7 Strep**	**3 years**	**Oct. 2013**	**16**
EnSo	**Smart Office optimization**	**RUG, Philips, IBM, TU/E**	**NWO**	**4 years**	**Jun. 2014**	**6**
Sparc	**P2P Energy exchange**	**RUG**	**RUG Ubbo Emmius scholarship**	**4 years**	**Nov. 2013**	**6**


Our vision of the Smart Grid
I need to be ready before the boss is home at 6 p.m.
Can you buy cheap energy on the market and tell me when to start ?
Thanks!
Sure, darling!
010101


I need 2KW of power in 15 minutes
Ok Carol, let's make a deal !
Can someone provide it?
Smart Grid
Yes, I can sell you 2KW for 3 €cent
Alice
Bob
Hey, I can sell you 2KW for 2.8 €cent
Ok, contract signed!
Carol


You deserve a 5 feedback!!
Good service Carol!!
15 minutes later
Smart Grid
Alice
Bob
It's a pleasure doing business with you!!
Carol

Complexity science approach to energy system



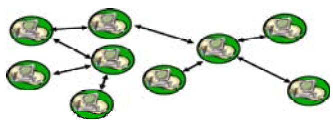
Power Distribution Grid

Green Buildings

Smart Meters and Local Interactions

Smart and Local Interactions

Scenarios of open markets (modeling)
Agent-oriented simulations (with hundred agents)
Agent strategies based on game theory (minority games)

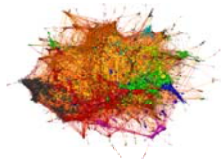


N. Capodieci, G.A. Pagani, G. Cabri, and M. Aiello (2012) An Agent-based Application to Enable Deregulated Energy Markets", IEEE Computer Software and Applications Conference (COMPSAC 2012)

Distribution Grid

Energy exchanges happen locally (M/L voltage)
Is the current Grid suited?
Repressor or enabler?

Distribution Grid

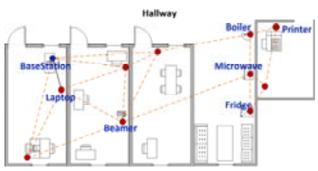


- Complex Network Analysis
- Real M/L Voltage Grid Analysis
- Effects of topology on electricity distribution costs
- Design of best suited networks

G. A. Pagani and M. Aiello. Towards Decentralized Trading: A Topological Investigation of the Medium and Low Voltage Grids (2011) in IEEE Transactions on Smart Grid, 3(2): 538 - 547.

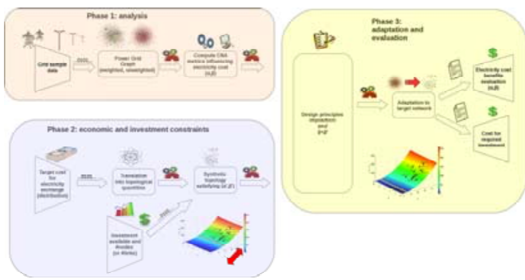
Green Buildings

Appliance turn on in accordance user needs and dynamic energy pricing
Saving money
Saving energy



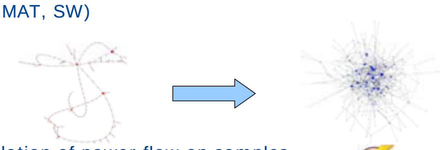
I. Georgevski, V. Degeler, G.A. Pagani, T.A. Nguyen, A. Lazovik and M. Aiello. Optimizing Energy Costs for Officies Connected to The Smart Grid (2012) under review process for IEEE Transactions on Smart Grid.

How to approach future smart energy systems & complexity and future research

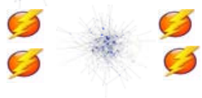


How to approach future smart energy systems & complexity and future research

Adaptation of a graph (real PG graph) to a literature model (e.g., R-MAT, SW)



Simulation of power flow on samples



How to approach future smart energy systems & complexity and future research

- Smart Meter and local interactions:
  - Further exploration of market dynamics with different models, strategies and auction systems
- Green Buildings:
  - User activity inference based on sensor fusion and appliance usage
  - Building automation based on energy dynamic pricing

2.12 Bikash Pal: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Bikash Pal, Imperial College London

JRC Institute for Energy and Transport
25 June 2012

The group

- Prof Alessandro Astolfi (Group Head)

- Prof A Astolfi
- Prof. Richard Vinter
- Dr David Angeli
- Dr Simos Evangelou
- Dr. Imad Jaimoukha
- Dr Eric Kerrigan
- Dr. Balarko Chaudhuri
- Prof Tim Green
- Dr. Paul D. Mitcheson
- Dr. Bikash Pal
- Prof. Goran Strbac

- 15 Post-Doctoral Research Associates
- 20 Graduate Research Assistants
- 65 PhD students

Relevant Research Topic

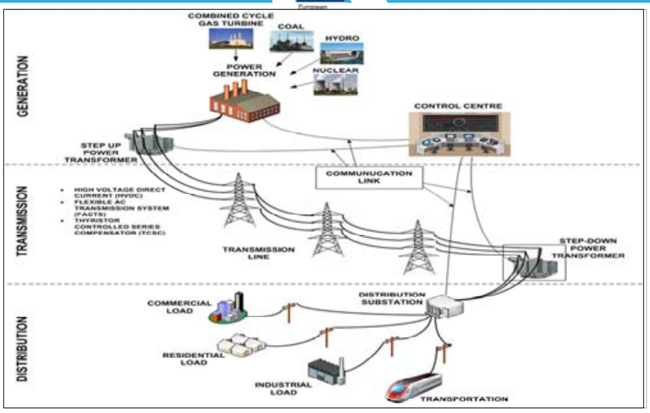
- Robust Power Transmission Control
- State Estimation for Distribution Network
- Wide Area Monitoring and Control
- Dynamic Modelling and Analysis of wind generation

REAL-SMART

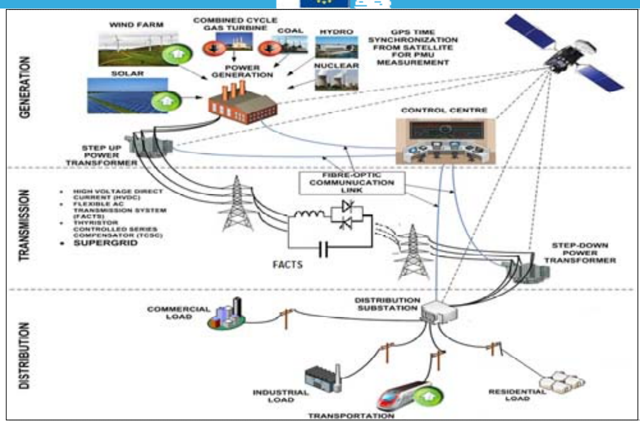
- **Research Theme 1**: Enhanced power transmission system security
- **Research Theme 2**: Monitoring and modelling of wind generation systems
- **Research Theme 3**: Electrical systems in large industrial sites

- FP7 Marie Curie IAPP
- Started September 2010
- €1M between ten partners
- Imperial hiring two postdocs

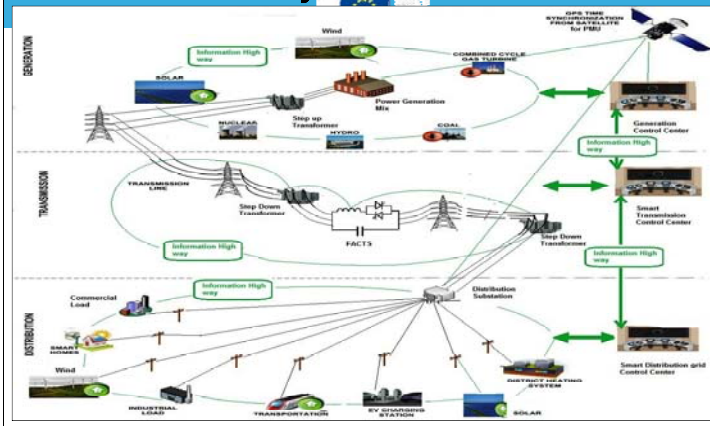
Electricity Network 20 years back



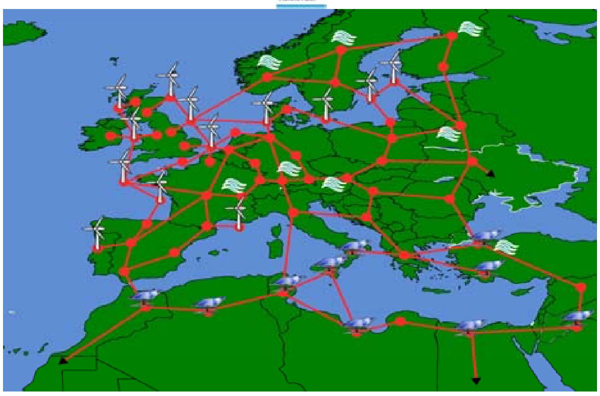
Electricity Network Today



And 20 years in future



European Supergrid in 2050



New technologies and anticipated research questions

Generation (Asynchronous)
- Will the new generation be able to maintain the frequency?

Transmission (AC and DC)
- Is power transmission control through telecom network effective and secured?

Distribution (New forms of demand)
- Will much talked about demand control be in place?

Topic of Research Interest

- Network voltage stability
- Dynamic demand control
- Centralised and distributed storage
- Dynamic interaction between the market and the system
- Frequency stability
- Security/stability of coupled cyber physical energy systems

Frequency stability

- How will the system respond to disturbance with new technologies?
- Dynamics of new generation, demand and storage are not well understood

Approaches

- Multi scale modelling
- Spatial and temporal scale
- One unified simulation tool
- Robust control

How are we positioned to undertake?

Who shall we work with?

- System theorists
- Applied statisticians
- Communication experts
- Information theorists

2.13 Angele Reinders: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Prof. dr. Angèle H.M.E. Reinders
Professor of Energy-Efficient Design, Design for Sustainability
Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands
e-mail: a.h.m.e.reinders@tudelft.nl
& Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands
e-mail: a.h.m.e.reinders@utwente.nl

JRC Institute for Energy and Transport
25 June 2012

Two organizations

Energy-Efficient Design **at** *Design for Sustainability*, **Faculty of Industrial Design Engineering, Delft University of Technology**

Focus: **evaluation and development of energy-efficient product-service combinations, in the context of renewable energy technologies, end-users and new energy infrastructures**

http://www.io.tudelft.nl/over-de-faculteit/afdelingen/design-engineering/design-for-sustainability/

Sustainable Energy Design **at** *Department of Design, Production and Management*, **Faculty of Engineering Technology, University of Twente**

Focus: **integration of new sustainable technologies in products and infrastructures with a focus on solar photovoltaic energy**

http://www.utwente.nl/ctw/opm/

Ongoing activities/projects relevant for Smart Energy systems and/or complexity

1. Power Matching City 1 & 2

1 fte PhD at TU Delft, in framework of Smart Grid pilot in Hoogkerk, cooperation with KEMA, Essent, Enexis, Humiq, TNO, Hanzehogeschool and TU Delft, subsidy Agentschap NL. (2011 >)

2**.** Smart grids on and near the water.

1 fte PhD in framework of University Campus Fryslan, cooperation with NHL and TU Delft, subsidy Province of Fryslan. (2012 >)

3. *International Research and Education Network for Sustainable and Resilient Smart Electric Power Grids*

SRN-NSF project lead by Virgina Tech, cooperation with > 30partners

from academics and industry, subsidy US gov.*(in the pipeline* 2012>)

Power matching city 1 & 2

PMC is a living lab Smart Grid demonstration in Hoogkerk (NL) consisting of 25 interconnected households. (Bliek et al. IEEE ISGT, 2010)

PowerMatcher algorithm
Hybrid heat pumps, electric cars
μ-HCP, PV systems, wind turbine
Smart washing machines, dish washers
User portal for information supply

- **Analysis of performance network and the algorithm**
- Evaluation energy use households

Power matching city 1 & 2

End-users and smart energy systems

(Reinders, ECD, 2011)
(Geelen et al. IASDR, 2011)

End-users in smart energy systems are supposed to change from passive consumers to co-providers in the system of energy supply and demand: prosumers

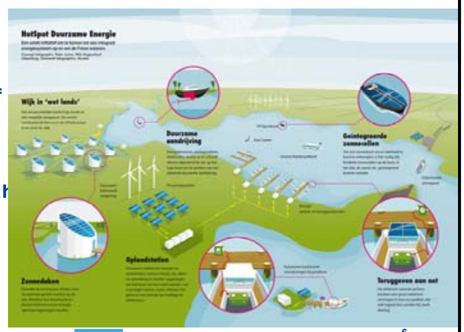
Do we need a need mind set?

Yes, of course because end-users have to

1. Understand the mechanisms in Smart Grids 2. Use the system and appliances appropriately 3. Understand the communication through interfaces		User / Product-services
4. Use electricity and heat 5. Save electricity and heat	Existing experiences	User / Energy
6. Produce electricity and heat 7. Trade electricity	New experiences	

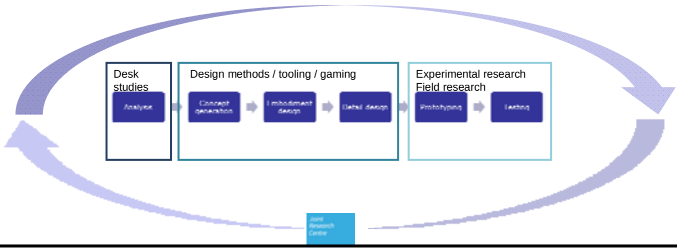
Smart grids on and near the water

Development of potential scenarios for smart grids with a high penetration of sustainable energy around lakes in Fryslan.
- **Linking supply with demand**
- **Costs**
- **CO_2 emission red.**
- **New product-service combinations**



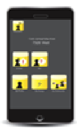
Complexity science approach to energy system

Our viewpoint is design-driven practice based research:
research in and around interdisciplinary smart energy grid projects
with a focus on product-service combinations.

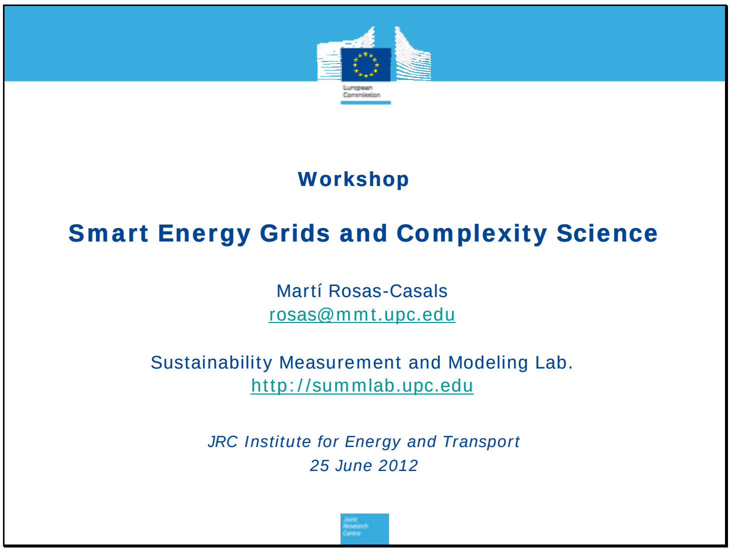


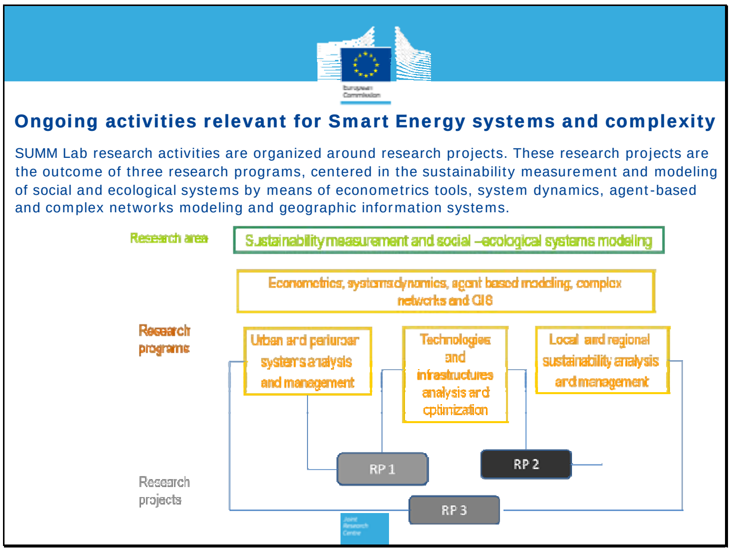
How to approach future smart energy systems & complexity and future research

Identifying new developments with regards product-service combinations
Evaluate these new product-service combinations and their effects on
Energy performance by monitoring and evaluation
Development of user-centered smart energy grid models



2.14 Marti Rosas-Casals: Smart Grids and Complexity Science





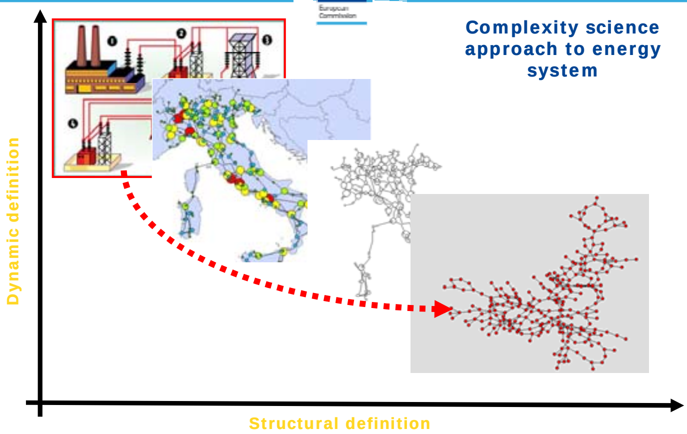
SUMM Lab is actually involved in the following research projects and with the following partners:

Assessment of topological vulnerability of infrastructural systems based on extended complex network techniques. Partners: Politecnico di Torino, Universitat Pompeu Fabra, Vermont University and JRC Institute for Energy.

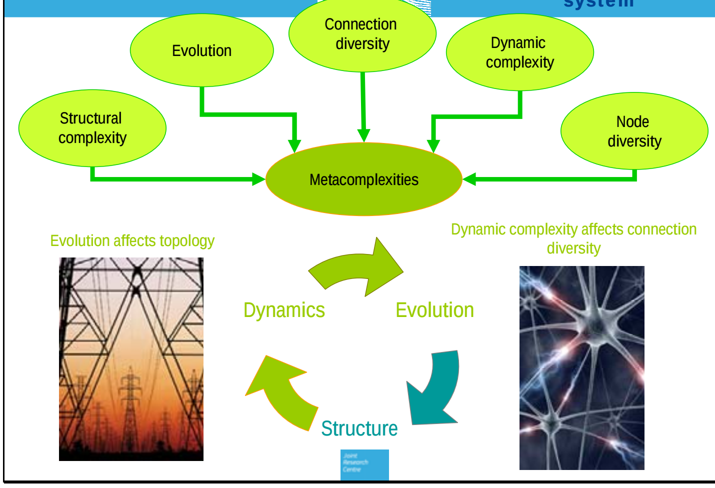
Climate change impacts on economic activities in mountaineous regions. Partners: Observatori de la Sostenibilitat d'Andorra and Institut Català de Ciències del Clima.

Verification of compliance with the CTE - DB-HE, securing and improving the energy qualification of dwellings. Partners: Energy Engineering Dept., Universidad de Sevilla.

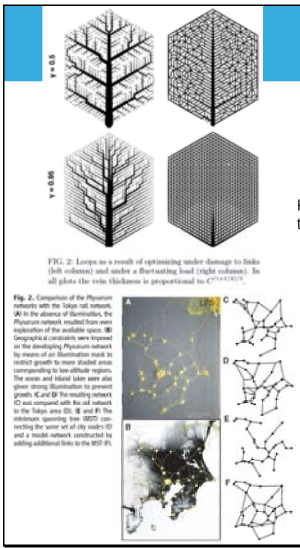
Complexity science approach to energy system



Complexity science approach to energy system



1. Topology and optimality



Topological disorder permits circulation in case of obstacles, but may also confer superior deliverance to fluctuating loads.

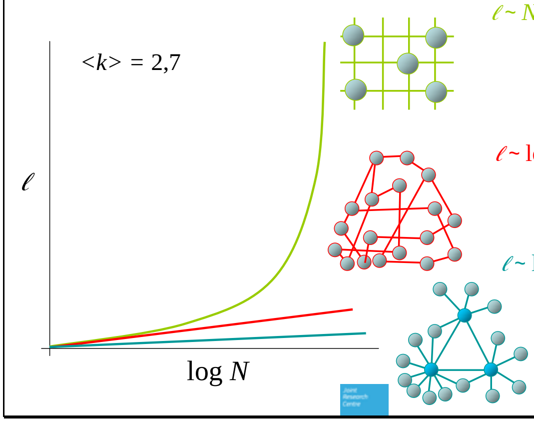
Katifori et al. (2010) Damage and fluctuations induce loops in optimal transport networks. *Phys Rev Lett* 104: 048704.

Biologically inspired mathematical models capture the basic dynamics of network adaptability through iteration of local rules & produce solutions with properties comparable to those of real-world infrastructure networks. This may provide a useful starting point to improve routing protocols and topology control for self-organized networks.

Tero A, *et al.* (2010) Rules for biologically inspired adaptive network design. *Science* 327: 439-442.

1. Topology and optimality

Efficiency, cost and grid design



$\ell \sim N / 2\langle k\rangle$

$\ell \sim \log N / \log \langle k\rangle$

$\ell \sim \log N / \log \log N$

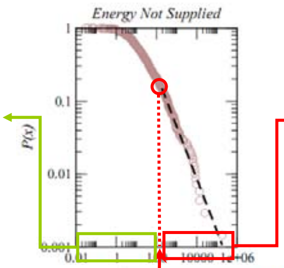
2. Probability distributions and criticality

Failure risk estimation → $R \sim p(E)\, c(E)$

$x < x_{min}$

$p(E) \sim a - \log E$

$R \sim Ea - E \log E$



$x \geq x_{min}$

$p(E) \sim E^{-\alpha}$

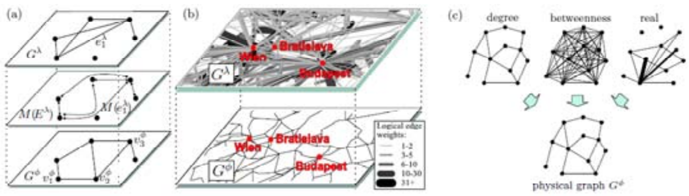
$R \sim E^{(-\alpha+1)}$

Data set	n	$\langle x\rangle$	σ	x_{max}	$\hat{x}_{min}$ (Maximum likelihood)	$\hat{\alpha}$ (Maximum likelihood)	n_{tail} (Maximum likelihood)	p (Maximum likelihood)	Support for PL
ENS	690	552	7004	180000	185±72	1.7±0.1	104±120	0.24	Moderate
TLP	576	400	1790	26746	615±244	2.1±0.2	57±96	0.36	Moderate
RT	897	510	3328	44640	150±68	1.69±0.07	157±115	0.73	Ok

Rosas-Casals et al. (2011) Analysis of major failures in Europe's power grid. *Int. J. E. Po. En. Sys* 33, 3.

3. Multiscaling & ABM

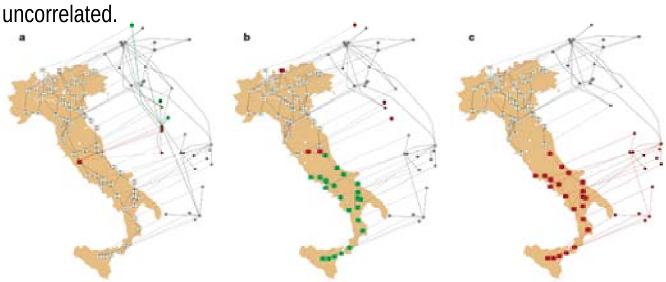
There is a need for new robustness measures that capture not only purely topological aspects, but also the functionality of the system as a whole, from different scales in time and space.



Kurant M & Thiran P (2006) Layered complex networks. Physical Review Letters 96: 138701-138701.

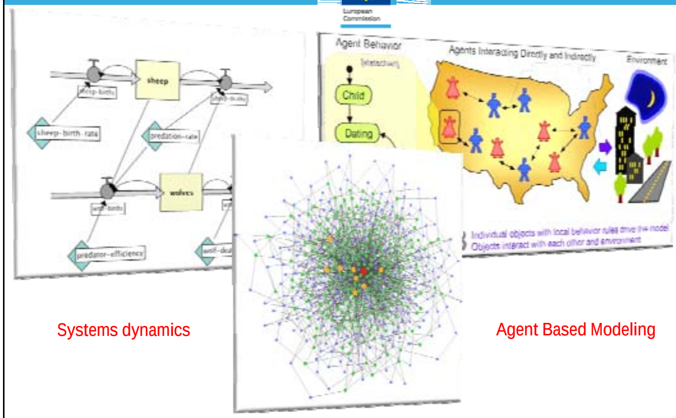
3. Multiscaling (& ABM)

The model captures the important phenomenon of a cascade of failures in interdependent networks that results in the first-order percolation phase transition. The model can be generalized and treated analytically by using generating functions, provided the networks are randomly connected and uncorrelated.



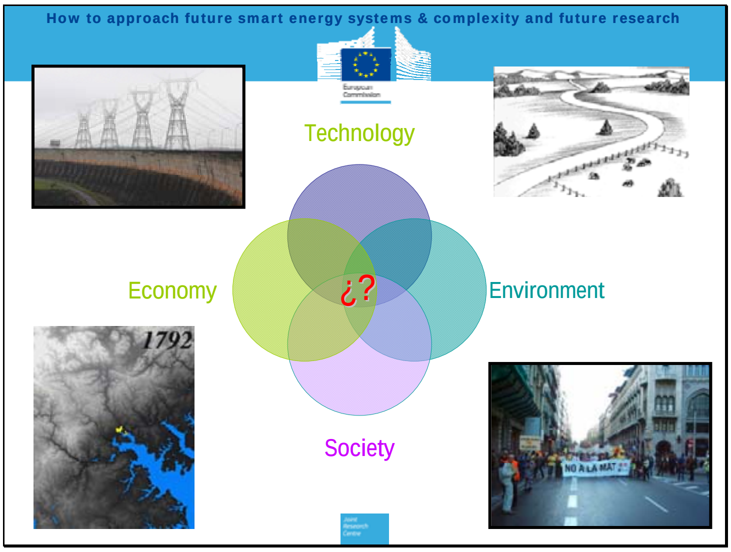
Buldyrev SV, Parshani R, Paul G, Stanley HE & Havlin S (2010) Catastrophic cascade of failures in interdependent networks. Nature 464: 1025-1028.

3. Multiscaling (& ABM)



Systems dynamics

Agent Based Modeling


How to approach future smart energy systems & complexity and future research
Technology
Economy
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Society
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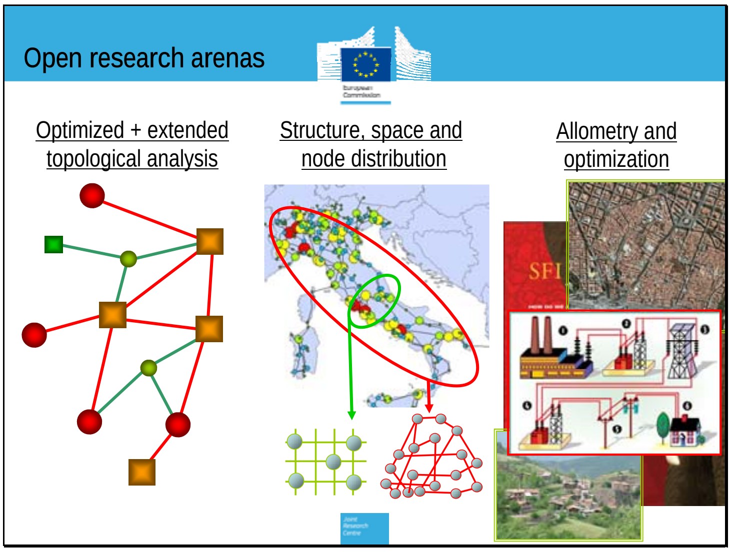
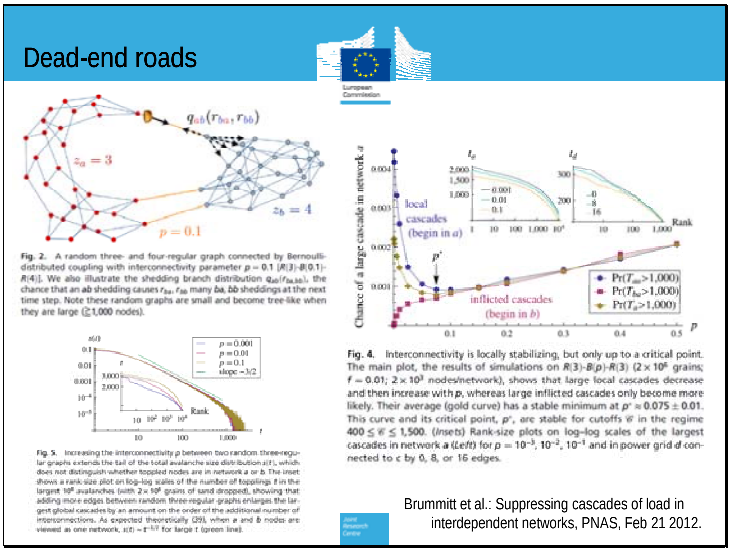

Open research arenas
Optimized + extended topological analysis
Structure, space and node distribution
Allometry and optimization
SFI


Dead-end roads
$q_{ab}(r_{ba}, r_{bb})$
$z_a = 3$
$z_b = 4$
$p = 0.1$
Fig. 2. A random three- and four-regular graph connected by Bernoulli-distributed coupling with interconnectivity parameter $p = 0.1$ [$R(3)$-$B(0.1)$-$R(4)$]. We also illustrate the shedding branch distribution $q_{ab}(r_{ba,bb})$, the chance that an ab shedding causes r_{ba}, r_{bb} many ba, bb sheddings at the next time step. Note these random graphs are small and become tree-like when they are large (≳1,000 nodes).
$p = 0.001$
$p = 0.01$
$p = 0.1$
slope −3/2
Rank
Fig. 5. Increasing the interconnectivity p between two random three-regular graphs extends the tail of the total avalanche size distribution $s(t)$, which does not distinguish whether toppled nodes are in network a or b. The inset shows a rank-size plot on log-log scales of the number of topplings t in the largest 10^4 avalanches (with 2×10^6 grains of sand dropped), showing that adding more edges between random three-regular graphs enlarges the largest global cascades by an amount on the order of the additional number of interconnections. As expected theoretically (39), when a and b nodes are viewed as one network, $s(t) \sim t^{-3/2}$ for large t (green line).
Chance of a large cascade in network a
local cascades (begin in a)
inflicted cascades (begin in b)
p^*
$\Pr(T_{aa}>1{,}000)$
$\Pr(T_{ba}>1{,}000)$
$\Pr(T_a>1{,}000)$
Fig. 4. Interconnectivity is locally stabilizing, but only up to a critical point. The main plot, the results of simulations on $R(3)$-$B(p)$-$R(3)$ (2×10^6 grains; $f = 0.01$; 2×10^3 nodes/network), shows that large local cascades decrease and then increase with p, whereas large inflicted cascades only become more likely. Their average (gold curve) has a stable minimum at $p^* \approx 0.075 \pm 0.01$. This curve and its critical point, p^*, are stable for cutoffs $\mathscr{C}$ in the regime $400 \le \mathscr{C} \le 1{,}500$. (Insets) Rank-size plots on log-log scales of the largest cascades in network a (Left) for $p = 10^{-3}, 10^{-2}, 10^{-1}$ and in power grid d connected to c by 0, 8, or 16 edges.
Brummitt et al.: Suppressing cascades of load in interdependent networks, PNAS, Feb 21 2012.

Drawbacks

Complete database accessibility

Union for the Co-ordination of Transmission of Electricity (UCTE)

2005: N = 2783 / E = 3762

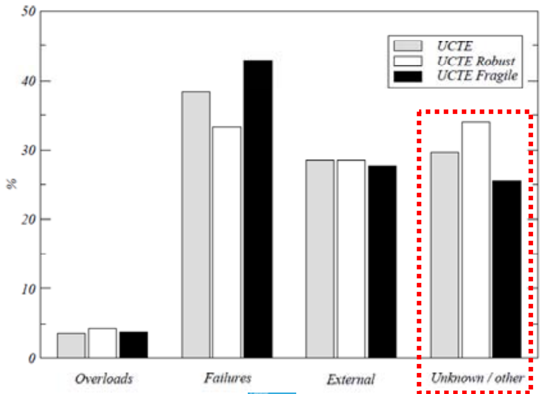
Gestionnaire du Réseau de Transport d'Electricité (RTE)

1962: N = 10 / E = 13

2006: N = 170 / E = 213

Drawbacks

Reliable and accurate field data collection



Other pressing questions

Is there a way to design a reliable power grid with a modified (N-X) criterion?

How can this criterion be adapted to the evolutionary development of a power grid? How can this be related with distribution and consumption grids?

Where is the optimal tradeoff between reliability and fragility in terms of topology? Does it exist?

Is there a way to develop planning tools with topological as well as other sustainable criteria, rather than reliability alone, like energy equity and land fragmentation? And how this fact would affect the aforementioned tradeoff?

2.15 Giorgio Sonnino: Smart Grids and Complexity Science

Workshop

Smart Energy Grids and Complexity Science

Giorgio SONNINO

Can Smart Energy Grids be Analysed by Statistical Thermodynamics ?

JRC Institute for Energy and Transport
25 June 2012

My organization

Giorgio SONNINO

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1049 Brussels (Belgium).

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Bvd du Triomphe, Campus de la Plaine C.P. 231
1050 Brussels (Belgium).

SMART ENERGY GRIDS IN FEW WORDS

- A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.
- A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies to:
. better facilitate the connection and operation of generators of all sizes and technologies;
. allow consumers to play a part in optimizing the operation of the system;
. provide consumers with greater information and choice of supply;
. significantly reduce the environmental impact of the whole electricity supply system;
. deliver enhanced levels of reliability and security of supply.

Smart Grids deployment must include not only technology, market and commercial considerations, environmental impact, regulatory framework, standardization usage, ICT (Information & Communication Technology) and migration strategy but also societal requirements and governmental edicts.

3

Complexity science approach to energy system

What Do We Want ?

-To perform a transition from the traditional energy supply to multiple decentralized energy resources.

-We want less energy-production with fossil fuels.

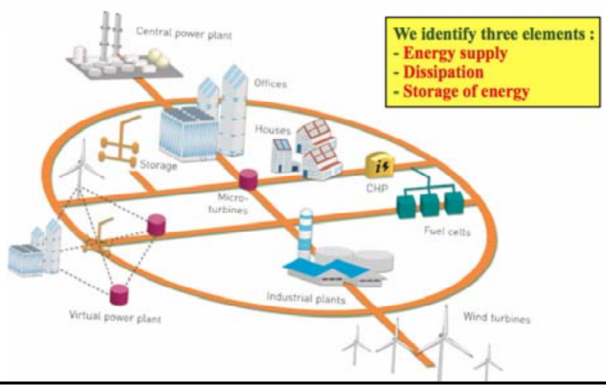
-To generate a "*two-way flow*" in the integrated system , *i.e.* :

ENERGY ←→ INFORMATION

I mean by this

Energy supply ←→ Rate of consumption, forecast of energy production etc.

SMART ENERGY GRIDS



We identify three elements :
- Energy supply
- Dissipation
- Storage of energy

Complexity science approach to energy system

PROBLEM 1

- Integrating large amount of renewable energy sources like wind and solar power introduces fluctuations in the power production.

PROBLEM 2

- The smart energy grid emerges from the collective interaction of the single parts, and the system cannot be predicted from the dynamics of the, non interacting, single parts (Complex Phenomenon).

6

How to approach future smart energy systems & complexity and future research

Complex Systems are very difficult to analyse for several reasons :

- **Heavy numerical simulations;**

- **Difficult mathematical treatment (in general, complex systems are treated by nonlinear dynamics).**

An Example of Organized Complex System: The Bénard Cells
(Prigogine's Nomenclature : Dissipative System)

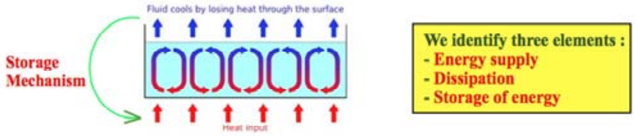
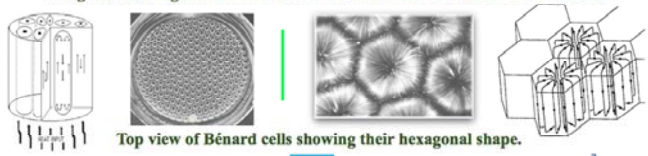


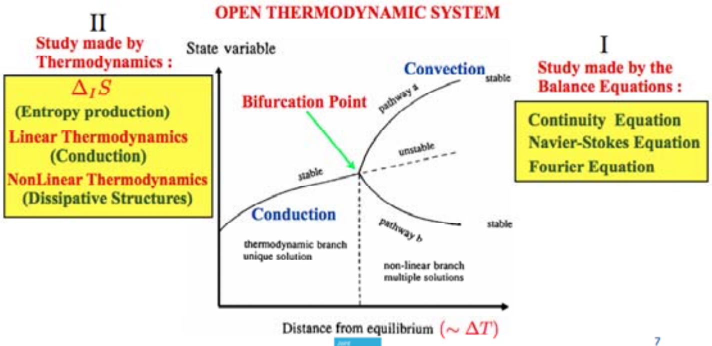
Diagram showing the internal movement of the heat flow of the Bénard cells.



Top view of Bénard cells showing their hexagonal shape.

7

Complexity science approach to energy system



7

How to approach future smart energy systems & complexity and future research

MY SUGGESTION

Statistical thermodynamics (Prigogine's statistical thermodynamics).

- **We renounce to a local description and we adopt a statistical approach;**
- **We assume that our network is composed by a very large number of branches and nodes;**
- **The first approximation consists in considering a branch between two nodes as "*a unique and single point*".**

How to approach future smart energy systems & complexity and future research

A Brief Introduction of the Idea

Our network is an open thermodynamic system (*i.e.*, submitted to external energy supplies);

The branches are so "dense" that we can assume that the system is "quite"-continuous in space;

We introduce a probability density of finding a state with value of the power production P_E lies between P_E and $P_E + \Delta P_E$.

How to approach future smart energy systems & complexity and future research

A Brief Introduction of the Idea

Let us consider a system characterized by n degrees of variables $A_1,\ A_2, \cdots A_n$. The (local) equilibrium values are $A_1^0,\ A_2^0, \cdots A_n^0$. Denoting by $\alpha_\mu = A_\mu - A_\mu^0$ $(i = 1 \cdots n)$ the n deviations of the thermodynamic quantities from their equilibrium value, Prigogine proposed that the probability distribution of finding a state in which the values α_μ lie between α_μ and $\alpha_\mu + d\alpha_\mu$ is given, up to a normalization constant, by [1]

$$\boxed{\mathcal{F} \propto \exp\left(\frac{\Delta_I S}{k_B}\right)} \quad ; \quad \boxed{\frac{\partial s}{\partial t} + \nabla \cdot I = \frac{d_I s}{dt}}$$

A model should be adopted for estimating $\Delta_I S$.

How to approach future smart energy systems & complexity and future research

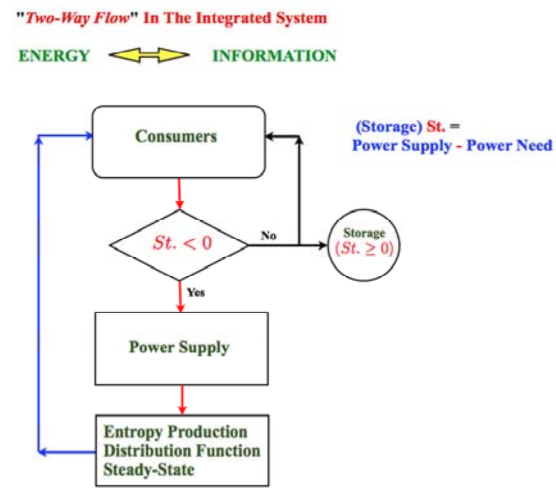
Advantages of this approach

The system can be described by a relatively low number of variables.

We can use the thermodynamic theorems for systems out of equilibrium:

Minimum Entropy Production Theorem:
"The steady state configuration corresponds to an extreme of $\Delta_I S$ ".

General Criterion of Evolution governing the relaxation law towards the steady-state configuration.



How to approach future smart energy systems & complexity and future research

A Brief Introduction of the Idea

Example of Calculation: Tokamak-plasmas

The equilibrium state corresponds to the values $\alpha_1 = 0$ and $\alpha_2 = 0$ for which the entropy production tends to reach an extreme.

$$-\Delta_I S = g_0(w) - \frac{1}{2}\sum_{i,j=1}^{2} g_{ij}(w)\alpha_i\alpha_j + h.o.t.$$

with

$$g_0(w) \equiv -\Delta_I S\,|_{\alpha_1=\alpha_2=0}$$

How to approach future smart energy systems & complexity and future research

A Brief Introduction of the Idea

Example of Calculation: Tokamak-plasmas

Coefficients g_{ij} are determined by the particular system we are analyzing [see, for example, the distribution function for tokamak-plasma out of equilibrium "*General Approach for Deriving Reference Distribution Functions for Systems out of Equilibrium by Statistical Thermodynamics*" G. Sonnino, A. Cardinali, G. Steinbrecher *et Al.*, Phys. Rev. E (2012)].

3. Challenge

Smart grid design and implementation needs to be coupled with broader social and cultural considerations in order for smart grids to be successful. Indeed, while smart grids need to be studied and understood as complex techno-socio-economic systems with multiple physical, cyber, social, policy, and decision making layers, these layers also interact with changing *external* conditions (economic cycles, technological innovation, and prevailing and changing weather and climatic conditions). Many actors interact within this broader “system of systems”, such as prosumers, distributors, retailers, brokers, regulators and policy makers. They act via distributed decision making processes which impact the physically constrained network via diverse electronic means (from control and command systems to smart meters).

The complexity of the smart grid system rests on the multiplicity of interacting players that operate with, and within, a defined environment as independent decision-makers, with autonomous behaviours, goals and attitudes. These broader socio-technical networks form a community with high levels of interaction and integration among its actors.

While much research has looked at the purpose and functionality of smart grid systems, smart grids themselves are merely one system in a “system of systems”. As such, complexity is not just an attribute of the smart grid alone, but also the systems interacting with it. For example, the increasing complexity of weather and climate, the increased complexity of social behaviour and the interaction of individuals guided by narrow economic rationality, the complexities of crisis management and emergency response (including the need to envisage and militate against such events and risks), and the overall organisational structure needed to manage all those complexities, must all be studied and modelled to adequately meet the emerging challenges to modern society.

In this context, in order to understand the complexity of future smart grids, there is the need to move focus and attention from a component-oriented to an interaction-oriented view of the electric power system. The goal of this systemic understanding is to identify tools and techniques for optimal decision-making that will enable society to achieve its energy, environmental, economic and social goals. The framework that should be developed will enable the identification of emerging problems and will provide new solutions and approaches.

4. Research questions

In this context, the research questions to be address are:

- Can complexity sciences help in understanding, modelling and simulating the emerging smart grid environment within a broader sustainability context including changes in economies, consumer and social behaviour, and climate variability and adaptation?
- Can sound policy decision making be based on theoretical models and simulation tools derived in the framework of dynamic multilayer interacting complex systems?
- How can the multi-layered, multi-actor energy system satisfy economic, environmental, security and social requirements? (The lessons learned from complex systems, social sciences and advanced ICT tools can help in answering these questions.)
- How might future energy systems be affected by different threats and risks?
- How can complexity science help in better addressing those threats and risks?
- How can future technological and social changes be anticipated, managed and integrated in policy and decision making?
- How can complexity science help in addressing these socio-technical challenges?
- What is the role played by “contextual” complexity due to the social environment, climate scenarios etc.? How can we properly to address such complexity?

5. Conclusion: Future Smart Energy Systems

6.1 Context

Our proposal aims at investigating the present and future challenges in, and around, future smart energy systems (FSES), employing complexity sciences for modeling and analyzing the dynamics and interactions of a broad range of actors and components constituting the technical (physical and cyber), socio-economic, and environmental aspects of those systems.

The FSES includes both local smart distribution grids (characterized by numerous independent participants like prosumers, retailers, distributed-generators, energy storage, EVs as well as technologies still to be invented) and transnational super grids (e.g. connecting large-scale time-varying renewable sources to national power grids and markets).

The main characteristics of these systems are:
- pervasive deployment of information and communication technologies (ICT);
- integration of renewable generation in support of energy, environmental and other policies;
- bidirectional communication and power exchange between suppliers and consumers/prosumers;
- multiplicity of interacting players operating with, and within, a defined architecture/market;
- enhanced network flexibility and reliability in a future smart energy system;
- newly required approaches for the monitoring, control and protection/defense of power systems in both space and time.

Why complexity sciences? Complexity of the FSES arises from the multiplicity of interacting players operating as independent decision makers with autonomous behaviours, goals and attitudes. Furthermore technical power systems will operate under varying environmental conditions, exchanging transactions in the power markets. A key concept in complexity science is 'emergence'. At this early stage in the development of FSES some emergent properties can already be anticipated. However, noting the complexity of the field we expect that important emergent properties remain unforeseen. Research resting on a robust complexity science foundation will allow stakeholders to rapidly identify and interpret emergent phenomena.

The hypothesis is that complexity sciences can help in identifying tools and techniques for optimal decision making encompassing policy and regulatory design, planning and investment, as well as real time operations. FSES research incorporating complexity sciences can provide models and guidelines for future developments, and for recognizing emerging behaviors and challenges.

6.2 Proposed view for research initiative

Our view on the proposed research agenda is based on the following points:

- *Unified and unifying approach to FSES studies based on a complex systems view and methods*. We propose an approach that will embrace the technological, social, business and environmental complexity of smart grids in a unified view, aiming at promoting sustainability and resilience through model based problem solving. While much of current research concentrates on the technical functionality of smart grids, these should be treated as *"system of systems"* with many self-governing components that respond to different economic and environmental issues beyond the pure operational ones. Modeling needs to take the broader techno-socio-economic context into account.

- *Complexities in and around FSES*. The electricity system infrastructure and its evolution are strictly intertwined with a wider set of contexts (social, technical, economic, environmental). These contexts interact with FSES and each other through patterns that are difficult to represent through traditional approaches. Differently from some current research exploring complexity within future smart electricity systems, our approach will also include the complexity of the interactions with the context. As such we take our consideration to the level of *"system of systems within systems"* We are interested in the complexity that will surround the future smart electricity system as the means towards a full understanding of its overall sustainability. For example, the dependence on the evolution of weather and climate change, the increased intricacies of social behaviours related to the active participation and the acceptance of different energy paths, the requirements of crisis management and emergency response, and the overall organizational structure required to manage all of them contemporaneously must all be taken into consideration.

- *Multi-scale modeling*. The challenges coming from the multiscale phenomena in technology, society, business and environment have to be properly addressed with multiscale modeling. The system behaviour needs to be modelled using information or models from different levels. In the end, the approach should include the growing set of links and correlations in, and around, the FSES: how society and technology co-evolves, how new business and social models will enable new patterns for the generation, distribution and consumption of electricity, how huge investments can be affordable confronting rapid technical shifts, etc. The availability and relevant use of data is crucial in this step.

- *Evolutionary scenarios for societies: towards sustainability and resilience*. Complex systems are simultaneously robust and fragile. The FSES will possess abilities to self-heal and adjust so as to cope with shocks that would cause a traditional distribution system to fail. These benefits, however, will come at the expense of new vulnerabilities and the risk that relatively small proximate triggers (perhaps from outside the FSES itself) could cause, through a cascade or combination of factors, severe disruptions to operations. The timescales of change are interesting and relevant. Sudden shocks are not the only concern, slow-burning trends and shifts can generate challenges. Will cities be able to cope with such complexities and potentially disruptive scenarios? To what extent will smart grid innovation be associated only with communities with vibrant futures? Social complexity will involve both expanding and declining cities. It is important to consider the needs of those without access to the FSES. How will those communities respond? How does the notion of universal quality of service survive in the smart grid world? Could this be worse than the perhaps over-hyped 'digital divide' in information services? What will be the social and energetic model be in the next 50 years? Which sustainable options will be available in 2050? Which role can be played by the emerging energy smart systems in stabilizing various scenarios? We need to fit FSES in the foreseeable future anticipating lifestyles and adaptation. There is the need for new approaches to resilience assessment. New opportunities and scenarios will encompass new risks that need to be taken into account, while calling for the separation of conventional and complex risks. Finally FSES brings benefits and vulnerabilities in the related areas of system safety and security with concern for the protection of individuals but also for systems themselves.

- *Complexity vs. simplicity. The challenge of our approach is to suggest, by means of a complexity science strategy, ways of simplifying the representation and understanding of the system (e.g.: consumers are ready to pay more for simpler solutions). We promote a complexity science approach that strives for simplicity. Through understanding the heterogeneous characteristics in FSES with complexity science and theories, simple rules and strategies can be designed and tested for a set of representative phenomena and scenarios. Complex global system behaviors can be related to the responsibilities and capabilities of individual system participants, which would be clearly recognized and characterized through models. This type of analysis can influence standardization and regulation at all stages of system evolution.*

- *Empowering stakeholders*. The objective is the empowerment of stakeholders, such as: consumers, governments and other institutions. Co-dependency of individuals will promote the creation of communities that will share benefits, while receiving and paying fair tariffs for the electricity generated and consumed. There is a need to better understand the energy consumers and anticipate lifestyles in light of their adaptation to new social and economic settings. How easily will users adapt or adopt the new system? Which kind of support will they require from authorities and utilities? How long might it take for a fully functional "smart powered" society? In addition, one can foresee that emerging behaviors of prosumers/consumers will require and force the development of new mindsets, which could parallel the emergence of social networks around the Internet. Some key questions could then be posed to society, e.g. How to change environmentally important behaviours?

6.3 Research agenda

Our research agenda will be organized as follows:

1) Formalization of the framework:
    - Identification of relevant components, goals and interactions
    - List and analysis of the proposed framework in terms of players, stage/scenarios, metrics to measure performance-dependability, environment/contextual factors

- Identify and assess the possible interactions among all actors

2) Definition of a formalized environment for studying FSES:
   - definition of "agents" and interactions
   - make possible integration and comparison among various models proposed and implemented by various researchers
   - common interface among social models/simulators of power systems/cyber systems/environmental predictions

3) Development (theoretical and practical implementation), according to the identified evolutionary scenarios, models on various scales of the various layers and integrate for serving general purposes in developing FSES:
   - Checking the interoperability of the various modules developed by different R&D groups
   - Integration across layers
   - Integration at different scales (geographical, temporal)

4) Application to case studies, and verification and validation with model comparison with different real benchmark cases
   - Checking sustainability and resilience
   - Checking simplicity and completeness,
   - Checking empowerment of stakeholders (modes of use, benefits, and dialogue)
   - Feedback: gaps and new research openings.

7. Contributors

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Abstract

This report proposes ideas and an approach to address present and future challenges in future smart energy systems through the particular lenses of complexity sciences.
Complexities arising inside and around emerging energy distribution systems prompt a multilayered and integrated approach in which different disciplines and areas of expertize are pooled together. The interfaces between system layers and intellectual disciplines are the focus, rather than the details of any individual layer or the particularities of one approach.
A group of people sharing this view and willing to proceed in this way organized a workshop at the Joint Research Centre of the European Commission, Petten, The Netherlands on 24th June 2012. Experts from different field of expertize convened to present their current research and discuss the future challenges of emerging smart energy systems via the afore-mentioned perspectives.

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