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Global Systems Science and Energy Systems
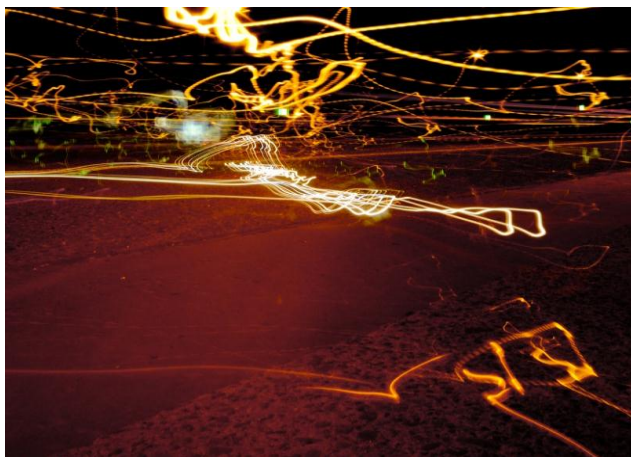
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FOREWORD

In Brussels, on 18th and 19th March 2013, a workshop "Vision in global systems science: energy futures" was held, organized by EC DG Connect in collaboration with the Joint Research Centre, Institute for Energy and Transport. Experts from different fields of expertise convened to present their ideas and discuss the future challenges of emerging energy systems in the context of GSS.

The objective of this document is to summarize the discussions held in the workshop, with special attention on the methods and models that can be used in science based support to policy making.

1. GLOBAL SYSTEMS SCIENCE AS AN EMERGING SCIENCE

Global Systems Science (GSS) comes at the intersection of two major 21st century developments, one societal and one technological: the increasingly global and highly interconnected nature of challenges facing humanity and the pervasiveness of Information and Communication Technologies - ICT - in all human and societal endeavours.

Global systems science studies the possible structural, physical and socio-cultural transformation of the earth, environment and society. The goal is to capture the whole of the interactions of those systems and, given a set of objectives, such as sustainability, security, competitiveness, etc., to study possible future scenarios in order to provide support to the policy decision makers. The challenges that GSS aims at addressing are both borderless and multi-dimensional, therefore they cannot be handled by one single country or by one single discipline, if aimed at providing sound policy support. This can be done in both qualitative and quantitative terms, with a focus on interactions, systemic effects and emergent phenomena.

In particular, Global System Science:

- is an integrated trans-disciplinary approach which uses but moves beyond inter-disciplinarity by trying first to identify the kind of key societal and policy issues which policy makers needs to address through science-based approaches;

- should provide an improved understanding of the interactions - interdependences of multiple socio-physical/technical-ecological systems of systems;

- uses an integrated perspective to address multiple problems at the same time that operate and interact at different scales and domains;

- should support social learning and transformations at institutional and individual levels by focusing on developing new concepts, tools and methods to prevent large-scale systems failures and improve resilience of global systems.

2. EMERGING ENERGY SYSTEMS

Emerging global energy systems can be conceived as a 'complex systems of systems'; they can be conveniently described and represented in terms of dynamic complex multi-layer structure that integrates various different, interacting layers. The different layers of energy systems span from physical/technical (the hardware of the network), cyber (measurement, communication and control), market and business (wholesale and retail, services and operations), social (customers, users, stakeholders…), normative (administrative issues, standards, etc.), and political (local, national and regional decision making and geopolitical implications).

This multilayers structure of emerging electricity systems (as well as general energy systems) increasingly show a "flow networks" structure, spanning over different geographical areas, often on a continental or cross-continental base. This provides to energy systems their "global flavour".

The interconnections between the different layers exhibit an emerging complexity in which it is impossible to abstract the overall behavior by the analysis of the single components. The coupling of the various layers with an incumbent widespread ICT and other systems (urbanisation, financial, etc.) may be a relevant source of the weaknesses of such systems and need to be studied to identify the potential risks, vulnerabilities and benefits of various systems configurations and interconnections.

'Butterfly effects' take place when small events at a local scale may cascade and accelerate to large-scale largely unpredictable effects and 'cascading failure' in which the failure of one or a few nodes in a network can influence the entire network, often resulting in large-scale collapse in the whole network (for example, the largest blackout in US history that took place on 14 August 2003 or the Western North American blackouts in July and August 1996).

Energy systems are constrained by considerations and goals from the environmental layers (environmental impact, climate change and limitation of usable natural resources) and the set of externalities (from local to global; from immediate to long lasting).

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All this results in the co-evolution of the technical, cyber, market and business, social normative and political layers, in a given environmental context. From the policy and industrial perspectives, the analysis of these systems must consider a global standpoint.

The Global dimension is typical of energy systems. There are many examples of situations in which global systemic effects have been observed within the energy domain, the oil crisis in the 1970's being one of the most outstanding one. Another example of the "globality" in emerging energy systems is the July 2012 India blackout, the largest power outage in history, where more than 620 million people were affected (about 9% of the world population). The blackout spread across 22 states in Northern, Eastern and Northeast India. The overdrawn power in the northern region led to the tripping, cascading failure and ultimate collapse of the Northern Grid. One of the possible reasons for overdrawing power was the deficient rainfall which meant increased use of electric pumps to withdraw water for farming in these agricultural states.

Inside the emerging energy systems, the Electric Power Systems (EPS) are an exemplifying case. EPS are multi scale and multi layers systems characterized by two different interconnected and interacting levels, with different scales both in terms of extension and energy (power) involved. The High and Extra High voltage transmission systems (Super Grids) are emerging as global energy infrastructures, spanning over continents (from EU to Russia and China to northern Africa), while, at a smaller scale, the distribution systems (Smart Grids) serve a set of prosumers with local distributed production and storage of electricity with new real-time bidirectional communications. The social networks among prosumers may play a crucial role in the feasibility and sustainability of these systems.

3. GOALS AND POLICIES IN ENERGY SYSTEMS

Policy decision making, at local, national and international level, and regulation provide the rules that constrain the behaviour of the different players in the energy sector (consumers, producers, wholesale and retail traders). It is generally considered that the goal is that of maximizing the system performance (technical, economic, energetic, environmental), striving towards the highest *sustainability*, *efficiency* and *security* of the energy system. The decisions of the players are (conceptually) based on the maximization of individual utilities although social values can determine, for instance, the choice of more expensive options.

Policy decisions in energy will have systemic consequences and need to be properly addressed. Very often policy makes use of many narratives that are not always backed by scientific evidence. The goal of GSS is to provide approaches, models and tools to understand the possible future energy scenarios and enhance sustainability instead of contributing to "building smart futures" that seems a too vague concept. In the current narratives about smart future there is a tacit acceptance that smart future will be a better future.

The logical chain from modelling and simulation of concepts and performance to policy decision processes is the heart of GSS. Feedback between modellers and stakeholders can be facilitated by, among others things, the use of narratives and gamification.

The key stakeholders (supranational, national and local policy decision makers, civil society) should be involved not only in the final stage of the application of the tools but also interactively during the design stage.

Key concepts, describing desirable performance, such as sustainability, interoperability, security…, need to be clearly defined and quantified. The approaches and theories to be used must be identified (complex systems and sustainability sciences). The concepts express goals in the policy decision making that need to be quantitatively defined and linked to the possibilities of the former scientific approaches to provide adequate assessment.

4. KEY POINTS AND OPEN ISSUES IN EMERGING ENERGY SYSTEMS

Key points and open issues in emerging energy systems that can benefit from a Global Systems Science approach are discussed below.

Energy infrastructure: energy infrastructure involves a chain of interacting processes and systems, including resource extraction, generation and production, storage, transmission and transportation, marketing, distribution, consumption and waste disposal. For instance, the interdependency between different carriers needs to be considered. In this context, the contribution of a GSS is needed because it is essential to have a holistic framework and models of the entire energy infrastructure that address the interactions between its components. Such models must incorporate the economic, social, technological and environmental aspects, and provide insights into the effect of policy decisions concerning energy on the well-being of private citizens and society as a whole.

Technological performance and choices: the choice of technology influences all aspects of energy infrastructure and its impacts. Economic models for the mitigation of global warming, for example, are inevitably forced to make assumptions about the likely rate of improvement of different technologies, both in terms of costs and environmental impacts. Models depend considerately on these assumptions. The possibility of implementing a continent wide electricity market needs a proper transmission infrastructure able to minimize the bottlenecks among different countries. The choices that are made dramatically influence all aspects of energy infrastructure; for example, the characteristics of the grid that we will need in the future are very different if we massively adopt nuclear power than if we adopt more renewable energy.   To plan our research, development and investment in energy technologies, it is not sufficient to "leave technology to technologists". This would lead to bad planning: expert forecasts regarding technological improvement have typically been wrong due to a combination of "silo thinking" and biases due to industry advocacy. Here we are not claiming that we should advise technologists in the lab, but rather that we should take global systems science into account when making public investments and in extrapolating the future course of technological improvement for planning purposes.

Understanding the process of technological improvement, in particular as it applies to energy, is essential for planning future energy systems. We must improve our ability to estimate the future cost and performance of energy technologies.   GSS is important because the family of all technologies forms a global system in and of itself, which can be thought of as a *technological ecosystem*, which is best thought of as a network. Individual technologies are built recursively out of their component technologies; this is true both for material inputs as well as the processes of production and manufacture. In the modern world technological manufacture is a geographically distributed and in many cases a global process. Progress in one technology is automatically transmitted to all the technologies for which it is a component; improvements in semi-conductor manufacture, for example, made a substantial contribution in driving down the cost of photovoltaic modules. Global systems science can contribute by giving us a better understanding of technological improvement in energy, by treating the process of improvement as a networked phenomenon that is driven by the physical interaction of technologies as well as the social drivers underlying acceptance, supply and demand.   Doing this properly requires addressing the economic, environmental and social consequences of our choices concerning technological development. Moreover, global system science is not only a tool for analysing the existing situation and providing simulations. GSS can also come into help in designing the future energy systems and as a decision making tool.

Externalities: incorporating externalities is a central problem for energy systems. Climate change is an effect of the way we produce power and should be factored in. Markets do not price in safety or pollution by themselves - these need to be enforced via regulations. There are many different approaches to the same problem. For example, we can reduce carbon emissions via a cap and trade scheme, through carbon taxes (internalization of externalities), by outright bans on technologies that emit too much carbon or by the use of social incentives. We can stimulate low carbon technologies through feed-in tariffs or via public R&D. Moreover, the emergence of ICT can uplift current energy infrastructure, user awareness and control. The effectiveness of these methods depends on interactions between technology and society, and must be evaluated in terms of economic, environmental and social impacts.

Centralized vs. decentralized: is there really a trade-off between centralisation and decentralisation? Or are these two possible complementary configurations and serve different functions at different levels? The degree to which we want to push the global energy systems to a decentralised form is a political issue meeting a series of global objectives. But what are these global objectives? Is this simply a matter of maximising market performances? How to achieve nearly full-automation of energy systems, so that multiple components can run autonomously at multiple layers? Would such automated energy systems have sufficient public support, and which conditions should be fulfilled to enhance public support? In order to answer all this we need to discuss first what kinds of different economic, environmental and social objectives global energy systems are supposed to attain. Also, we need consistent and operational definitions of de/centralised systems and of the different agents that constitute such systems (e.g. individual households).

From a GSS perspective, we want to understand the future potential of various options and of potential trajectories of the global energy systems. The question thus raised is: to what extent are various forms of energy transmission and distribution technically and socially feasible? A decade ago, it was not possible to ask such questions because of the lack of availability of the micro-generation systems and because the economic, technological, social and political landscape was very different. At present, we could say that we have insufficient transmission lines for a global centralised power system. How much do we need to invest in various forms of energy transmission and distribution? Is it really possible to centrally control distribution systems? In an ICT-based system we may not need a centrally controlled system and the data needed for a distributed energy control system may differ from those of a centralized control one. A challenge therefore is to provide dynamic real-time information of prices, stocks and flows of energy to various costumers. To that aim, we need to understand what kind of different tools are needed to solve the different kinds

of problems of the two possible system configurations. And to avoid speaking completely different languages, we need to have some quantitative approach to separate the good solutions from the not-so-good ones, while acknowledging that different groups and people will have different perceptions of the problems at stake, as well as different interests and preferences. In this context focusing on the process is crucial - in particular when generating new models and tools, and the communities of practice that can be constituted to address a particular energy assessment and decision-making problem.

In addition, we need evidence that one system may be better than the other: measures of satisfaction and performance need to be developed, and it is necessary to identify some already existing benchmarks to guide policy action in either direction. A much in-depth relational understanding is also required onto the extent to which the behaviour of prosumers - their motivations, constraints but also their capabilities - are determined by different configurations of the market. Some energy systems actors may need information and price signals on a very short time span - seconds, minutes - to take their decisions, but such information may not be available in a not-fully interconnected system. IT and data from social networks may help to disclose some information that some actors may be resistant to release. Decisions on various technical aspects regarding production, storage, distribution, consumption and waste control and reduction from a full life-cycle energy perspective need to be taken. Then the question is whether and how can we use the information provided by the market price signals and other social networks to integrate and coordinate these decisions and flows.

Multi- scale systems: multiple interconnected time and spatial scales. Decisions regarding energy systems comprise multiple interconnected scales, from very short ones (e.g. milliseconds) to years to even over 100 years as for the case of infrastructure. As in the case of power systems both a continental wide transmission system coexists with small neighbourhood distribution networks.

Uncertainties: what is specific about uncertainty in global energy systems in contrast to other systems? Are there any special approaches required to manage such uncertainties? In this regard, scenarios are often used as a typical policy tool in energy systems assessment. However, one difficulty is that such scenarios usually do not come with any assessment of their probabilities. In this regard, sometimes people refer to a "central scenario" as the most probable. Advanced statistics (e.g. Bayesian methods) can be used to quantify uncertainty associated with a given scenario. Therefore, the problem is how to communicate the resulting uncertainties to politicians and the general public in a language that they can understand and espouse and assist them to deal with

these uncertainties. In this context, we need to ask: What are the various sources and types of uncertainty? What kinds of uncertainties emerge from various models and data dealing with energy systems? What is the role of social science in helping to anticipate, predict or change the behaviours and interactions of the new agents that form new global energy systems (e.g. prosumers, transnational corporate energy networks)?

We should rethink whether the approach taken by climate change modellers whereby numerous climate models are developed and run by different research centres worldwide and in which divergent outcomes are used to derive a statistical measure of uncertainty is the best approach. In fact, it is not true that such models are so different in nature, as most of these models are based on rather similar assumptions and approximations (herd mentality) often deterministic and linear, as it is the case of the single-equilibrium, single rational agent assumptions used in most climate-economic models. These assumptions are simplistic and it is worthwhile to run models based on more realistic assumptions.

Modelling and simulation: proper models, simulation and large data management tools are needed to capture the global dimension of energy and electricity systems (both geographical and multilayer) and the high linkage between different players and systems that integrate economic, social and natural science. The consistency check and the validation prior to their application is a key issue.

In addition, models are usually validated using past data. One can always certainly tweak model parameters to get a good fit to the observed behaviour. But this does not tell us if a prediction made by a model will be good. In other words, models may be good for interpolation but not for extrapolation. Hence, how to assess uncertainty of model-based prediction and in particular with regard to generating a better understanding of global energy system dynamics? The key is to understand sensitivities and to identify which model parameters are most important to understand what drives a system's behaviour, taking a complex perspective able to deal with non-linear behaviours, discontinuities, bifurcations, tipping points and phase changes, and rapid changes in boundary conditions (including changes agents configurations, e.g. from consumers to producers). We should avoid the view which tends to stick to the continuation of the present regime as if nothing would change. While there is the general perception that Agent-Based Modelling is the only way to address and integrate complexity in modelling, this is not true, as we need a portfolio of methods and tools to deal with such different kinds of uncertainties and problems. In this respect, we need to explore whether certain formal statistical methods (e.g. Bayesian statistics) can deal with

the effects of disruptive technologies (such as shale gas) which have a potential to completely change the main model characteristics.

5. QUESTIONS AND CHALLENGES TO GSS APPLIED TO ENERGY SYSTEMS

Science-oriented challenges

- How can we better understand key factors influencing energy systems and identify effective ways to manage these systems in order to prevent a **globally systemic crisis** like the one of 1970s?

- What are the **inter-linkages between** the vulnerabilities of power systems with the vulnerabilities of **ITC systems**?

- How to develop less **vulnerable / more resilient energy systems** in a globally interconnected world? What kind of economic, technological, social and **regulatory innovations** at various scales of action are needed for that?

- What kind of **specific tools, method and science-policy integrated processes** need to be devised to better represent and assess global energy systems dynamics? How can we effectively combine a range of methods to increase our understanding of global system dynamics?

- What **integrated performance indicators and goodness functions** need to be constructed that relate to the whole energy system of systems?

- What kind of **centralised/distributed algorithms** are required to address specific global challenges in the energy sector? Warning: avoid though reducing policy assessment and politics to algorithms.

- What trade-offs or synergies can be identified between various **optimisation procedures** operating at various levels and sectors?

- What kind of **common formal languages** are required to integrate insights from various disciplines to address multiple problems and needs that regard the global energy systems?

- What **kinds of evidence** we need to provide grounded insights about possible trajectories of the global energy system evolution?

- **How to extract sense from the large flows of networks information** in ways which are relevant for the understanding and the integrated assessment of global energy systems?

- **How to incorporate the social, political and behavioural dimensions in the modelling** of global energy systems?

- **What** is the role of other global systems, like **the financial and banking sector**, and the internet in the configuration of global energy systems?

Policy-oriented challenges:

- How to better map out and understand the social, economic and environmental **consequences of unbundling?** Can GSS help to model and quantify the global multi-level effects, as well as the unintended consequences, of the unbundling policies in the energy sector? What is the role of prosumers in yielding extreme forms of unbundling?
- How to achieve **dynamic real-time pricing** of energy flows at global and local (decentralized) level?
- What are effective and acceptable (economic or social) incentives to manage energy demand?
- What **benchmark examples** of existing experiences can already be used to illustrate the role of ICT in fostering transformations and transitions in global energy systems?
- What would be the financial needs and social, ecological and economic consequences of a **Global Green Dea**l in the energy sector?
- What **kind of new business models** are needed to better fit the various innovations, visions and requirements of alternative energy systems? e.g. globally distributed, based on 'servicisation' (not buying energy but energy services) and enhanced 'prosumers' (agents who are both producers and consumers).
- What implications have the present **world population growth** trends and demand for energy in the reconfiguration of global energy systems?
- How to better map out and deal with **global inequalities in energy access**?
- What **extreme global warming scenarios** (e.g. up to a 10º degree warming) would entail the reconfiguration of the global energy systems? In which way can a complexity IT-based approach (e.g., using networks and big data information) help to better assess and to anticipate that?
- What is the role of military systems in the configuration of global energy systems (e.g. nuclear vs. renewables)?
- How can GSS support **energy crises management**? (e.g. Japan)
- How **renewable**s can be introduced globally? What is the role of prosumers in reducing energy consumption or changing energy demand in time and global energy impacts? How can demand and supply matching be best realized?

- What different potential **global transitions** in the energy systems can be identified and to what extent the implications, e.g. in terms of costs and benefits of these different transitions and pathways, can be quantified?

Public communication and engagement challenges

- What kind of **incentives,** including **non-economic** ones, can be most effective in supporting coupled IT - energy innovations and transformations?
- What kind of energy systems configurations can be envisaged so as to be more conducive to **learning, adaptation and flexibility** and in coping with global challenges?
- What is the role of IT, and in particular visualisation, in improving a '**global energy awareness and culture**' and supporting **'energy-smart citizen behaviours'**? How can information on energy demand and supply be best communicated to users to increase the efficiency of energy systems?

6. CONCLUDING REMARKS

In the present globally interconnected world, energy is generated, stored, transmitted and consumed and its related waste disposed of or recycled through a complex and dynamic *system of systems*. A central challenge for GSS is to focus on the multiple interactions of different scales of the energy systems: from smart micro-grids to super grids. To what extent can these two approaches coexist? How do these two apparently divergent trends and configuration relate to each other and be managed for a better coordination and efficiency?

GSS should be able to identify what kinds of factors are most relevant for the global energy systems and to what particular pressures are they more sensitive (e.g. not necessarily prices but perhaps to other variables outside the energy systems). For such a system to improve its long-term sustainability and performance a diversity of tools of analysis and flexible and resilient operational arrangements are required, in ways that are able to address the multiple goals involved. In the context of emerging energy systems, 'global' should better be understood as 'multi-objective', 'multi-connected' (between various systems) and 'multi-functional'. In other words, while this 'global energy system of systems' is growing both in operational size and in interconnectedness, its multiple performances are also increasingly tighten up and depend on the performance of many other non-energy systems (IT, governance, financial, urban, etc).

In turn, GSS could also help to reframe the role of energy systems in the light of societal challenges. A global systems perspective could also be a key driver for Research, Development and Innovation and in particular by coupling IT into the development of alternative configurations of energy systems. For instance, GSS could support innovations and system-level synergies in areas like industrial symbiosis and industrial ecology (e.g. by transforming various forms of waste from one system to become energy for another system). Transformations in the global energy systems will require coupling the synergies of multiple innovations occurring within the energy systems at various scales and processes with innovations being developed outside of them, e.g. with the IT and the urban sectors. While connecting the smart grids with the smart cities development may represent full suite of responses to complex problems that concern the sustainability and optimality of energy-information-transport systems, there are many other options and alternatives that need to be explored. To achieve this, a learning evolutionary approach is called for: individual motives, incentives and learning capabilities of the agents constituting the multiple systems need to be explored, together with their systems' interactions.

In the future, globally smart energy systems, coupled with other systems, can only be composed by 'energy-intelligent agents' who know what is best needed to be done for optimizing their multiple decisions in ways that lead to a secure, sustainable and high quality operational global energy system.

On the one hand, GSS should also help to unveil the assumptions about agents behaviour used in the conventional energy modelling, e.g., moving toward the study of single individuals preferences to 'social practices' (clusters of social interactions, not just individuals). The way we represent real dynamics in energy markets does not often fit the supply-demand model. In this respect, we must avoid the risk of developing one single tool or model, but a diverse array or toolkit comprising a range of complementary methods and models to improve our understanding of the complex energy system dynamics. On the other hand, GSS should be able to produce much better modelling tools on pressing issues such as the costs and benefits of climate mitigation and of the various pathways for a global energy transition, e.g., using agent-based modelling but also other methods while taking into account long-time series of energy trends. This should be able to enhance our capabilities for anticipation of the systemic, unwanted effects of such agents' interactions as well as to understand what kinds of institutional innovations are needed at different levels (e.g. property rights of energy resources, or liabilities derived from energy systems). This could lead to a possible overarching theory to learn how to cope with the dynamics of energy systems of systems in a global scale. And at policy level, it could also help to identify certain policy system attractors and leverage points to support the various multi-level transformations, while trying to map out the possible unintended cascading effects derived from aggregation of single policy interventions (e.g. as in the case of the penetration of the electric vehicles or home insulation policies).

GSS is an open-boundary research, whose results cannot yet be anticipated – that is, in its present nature is mostly goal-searching, not goal performing. There are indeterminacies about what we need to know and thus we are faced with many unknown-unknowns. In this situation, the GSS approach requires a community which is farsighted and creative, but also shows a great capacity for flexibility and independence.

Abstract

In the present globally interconnected world, energy is generated, stored, transmitted and consumed and its related waste disposed of or recycled- through a complex and dynamic system of systems. A central challenge for Global Systems Science is to focus on the multiple interactions of different scales of the energy systems: from smart micro-grids to super grids. To what extent can these two approaches coexist? How do these two apparently divergent trends and configurations relate to each other and can be managed for a better coordination and efficiency? Global Systems Science should be able to identify what kinds of factors are most relevant for the global energy systems and to what particular pressures are they more sensitive (e.g. not necessarily prices but perhaps to other variables outside the energy systems). This report presents the key points and open issues in emerging energy systems and highlights questions and challenges to global systems science applied to energy systems. It is based on the discussions and results of the workshop on "Vision in global systems science: energy futures" held in Brussels on 18th and 19th March 2013 and organized by DG Connect in collaboration with Joint Research Centre, Institute for Energy and Transport, Petten.

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