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COMMENTARY

Macro-Energy Systems: Toward a New Discipline

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Macro-Energy Systems: A Discipline for Energy Transitions

Humanity is faced with the need for two massive, interrelated energy transitions, and there is considerable uncertainty about the best way to undertake them. A transition to low- and no-carbon energy technologies underpins all realistic climate solutions.[1] Simultaneously, the reach of modern energy services must grow substantially to reach more than a billion people who currently do not have access.[2] Solving these intertwined challenges will require changes of an unprecedented scale occurring over multiple decades, and a substantial number of researchers are working to understand and advise these transitions. We believe that these efforts could be aided by cultivating a community of scholars—a new discipline—that focuses on the large-scale, systems-level, long-term aspects of sustainable energy planning. We call this discipline "macro-energy systems."

Macro-energy systems can be distinguished by common questions and methodologies that are honed to grapple with very large-scale energy systems. The common element of large scale drives key methodological choices arising from

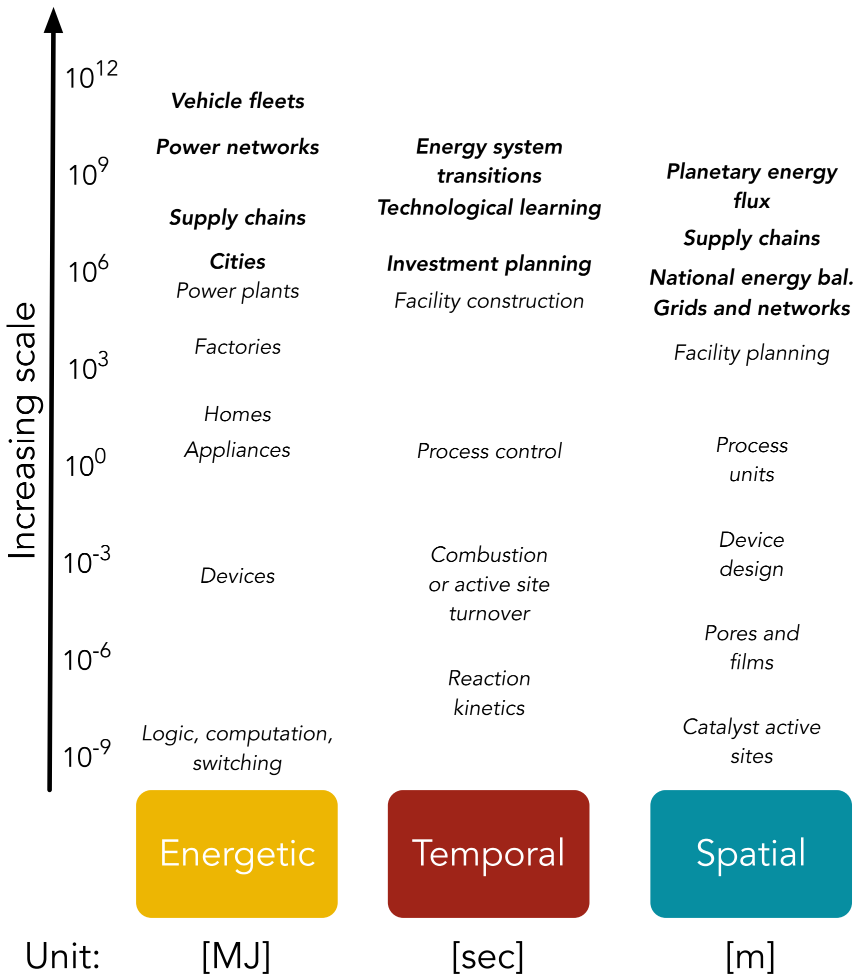

Figure 1. Three Dimensions of Scale in the Human Energy System
Phenomena of interest to macro-energy systems are listed in bold.

the difficulty of modeling these massive systems, and of conducting controlled experiments on them.

The aim of macro-energy systems is to understand the dynamics, benefits, costs, and impacts of large-scale energy systems and energy system transitions. It focuses on phenomena that are large when measured by time span, spatial scale, energy flow, or any combination of the above. Co-analysis of economic, engineering, environmental, and social factors is often critical for answering societal-scale questions. As a result, this discipline combines methods from many fields spanning the natural, social, and engineering sciences.

The study of large-scale human energy systems is not new; researchers have expended decades of dispersed intellectual effort, and climate change has driven an explosion of interest in the subject in recent years. Advances in computation have enabled increasingly sophisticated methodologies. The result is a growing area of study with an increasingly rich set of tools and questions. These efforts would greatly benefit from being united under a common umbrella.

What Defines Macro-Energy Systems?

Scale and Complexity

As fields of inquiry mature, they have historically split into sub-disciplines to maintain a coherent research community. Often this differentiation is based on scale. Biology has split many times over centuries into multiple scale-differentiated disciplines including molecular biology, cell biology, organismal biology, and ecology. Even though all of these communities are biologists, they pose distinct questions and require different research methods, making them distinct areas of research. Economics has bifurcated into microeconomics and macroeconomics, formalizing a long-standing divergence in questions and methods. Sub-disciplines divided by scale have emerged naturally multiple times because they provide common ground for researchers who are interested in similar phenomena and create a sense of coherence in a complex scientific field.

We believe that research on sustainable energy systems is ripe for a scale-based differentiation. There is a great volume of active research on energy systems over a wide range of scales and topics (see Figure 1). At the molecular and device level, basic science and engineering is used to design novel materials and energy technologies like improved batteries and solar cells. Machine- and facility-scale engineering joins many such components and devices to create automobiles, airplanes, solar panels, and even power plants.

The new discipline of macro-energy systems considers even larger and more complex systems. It addresses questions concerning topics like the structure of potential low-carbon energy systems;[3,4] market and policy solutions for reducing greenhouse gas emissions and their economic, environmental, and distributional impacts;[5] the environmental and economic impacts of different approaches to forecasting energy demand and improving energy access;[6,7] the economic and environmental value of new technologies;[8] dynamics of the development and adoption of new technologies;[9] environmental impacts of current and future energy technology;[10] and validation and improvement of the modeling paradigms used to address these questions.[11,12]

Figure 1 illustrates the scales that macro-energy systems is concerned with. Only one of the dimensions of spatial extent, energy flow, and time must be large to introduce the type of complexity that characterizes macro-energy systems.

Methodologies to Cope with Complexity

The sheer complexity and high dimensionality of the phenomena studied by macro-energy systems demands specialized research methods. Simulation, abstraction, and modeling are required approaches in macro-energy systems work. It is difficult to conduct macro-energy systems experiments (though not impossible) and simulating or optimizing the system in full is likely to be computationally intractable. Even if it were technically tractable to model every detail, a simpler model is often preferable for providing intuition about a system. Indeed, much of the challenge of macro-energy systems research is to identify which phenomena are worth representing in detail and which can be abstracted.

These practical constraints, coupled with a common set of problems and questions about sustainability, stability, equity, and cost effectiveness, result in researchers in disparate departments and fields drawing on a common set of tools. For example, general and partial equilibrium models; optimal unit-commitment, dispatch, and capacity expansion models;[12] life-cycle assessment;[13] and technological learning curves are widely used and understood.[9]

As with other disciplines defined by their scale, macro-energy systems research involves abstractions of sub-processes that are subjects of study in their own domains. For example, macroeconomics aggregates and abstracts the actions of individuals and firms, and the micro-economic rules describing them. Similarly, macro-energy systems necessarily parameterizes away the chemical or physical phenomena involved in engine design, combustion chemistry, or solar cell material properties. Such abstraction of detailed domain knowledge—although always imperfect—is a natural and necessary feature of knowledge generation at large scales. To create useful abstractions, it is essential that macro-energy systems remains in good communication with other scales of energy systems research even as it distinguishes itself. Likewise, smaller scales of research can be informed and guided by bigger-scale issues identified by macro-energy systems; for example, macro-energy systems can help identify what types of electricity storage would be most valuable for basic R&D to improve for a future low-carbon grid.

Quantitative and Interdisciplinary Approach

Macro-energy systems research is built around quantitative analyses and supported by a holistic understanding of the systems in question. The engineering complexity of many of the underlying systems often demands a quantitative model. Additionally, a quantitative approach encourages a thoughtful weighing of tradeoffs against each other, since the researcher must carefully think through how each attribute should be valued.

The problems addressed by macro-energy systems, including energy access or decarbonizing energy systems, are multi-faceted. They may involve several complex systems such as power systems, transportation, and even political or financial systems. An understanding of several systems may be needed to usefully frame and interpret research.[1,6,7] As a result, macro-energy systems draws on knowledge and methods from a range of disciplines including engineering, environmental science, operations research, finance, and economics. Macro-energy systems researchers must be familiar with the approaches of several disciplines, so that they may usefully combine them or collaborate when appropriate.

Disciplinary Infrastructure Fosters Better Research and Progress

Scientific infrastructure—broadly conceived as a set of discipline-specific journals, meetings, funding bodies, and communication fora—is key to developing a mature discipline. Such infrastructure results in more rigorous peer review, allows for more efficient collaboration, and facilitates effective communication of results to a broader community. Defining macro-energy systems as a discipline will enable the creation of a specific scientific infrastructure and all of the benefits that it entails. Such benefits are described in more detail below.

Gaining Credibility

Fields of inquiry begin to mature when they have a critical mass of experts working on a common set of problems, using common nomenclature, and sharing core methodological approaches. This community of scholars can credibly review and evaluate the veracity and novelty of research outputs.

The creation of macro-energy systems will also enable practitioners to more convincingly represent the value of their research to outsiders. Disciplinarians may have difficulty valuing the perspectives and skill-sets of an interdisciplinary researcher. Uniting under a common banner will allow others to more consistently value the skills of macro-energy systems researchers.

Increasing Communication

A common identity fosters communication through conferences, journals, and the simple ability to identify and seek out other practitioners. Current journals and research centers focusing on human energy systems do not differentiate based on scale. The result is a combination of large-scale energy systems analysis with other research, like device-scale and molecular-scale technology development, consumer preference experiments, and energy finance research. While it is important to have these broad umbrellas so that micro- and macro-level research can inform each other, more specific fora are also needed to facilitate communication within macro-energy systems and ensure a high quality of review. Formal recognition of macro-energy systems as its own discipline could encourage researchers to support more specific academic infrastructure, which supports macro-level research.

Avoiding Repeated and Redundant Effort

A united discipline can help researchers avoid redundant effort that arises from knowledge being too widely scattered. Increased communication means that researchers are more likely to hear about related work that might be of interest. Moreover, a common terminology can arise, making it easier for researchers to seek out the information they need. An example of this pitfall is the sphere of "energy analysis," which is also variously called "net energy analysis," and "energy return on investment analysis." This concept has been re-invented numerous times over decades from multiple directions by multiple actors[13] but still lacks a consistent methodology.

Establishing Accepted Methodologies

Macro-energy systems research is published in many different disciplinary journals, making it difficult to easily assess the state of the art and determine common methodologies. As a result, macro-energy systems has little formalized ''textbook'' material that can serve to transmit prior learning to new researchers or establish best practices. Codified and vetted methodologies (or methodological schools) for studying and teaching about macro-energy systems phenomena would improve research rigor.

Encouraging the Next Generation

Unification of disparate areas under the umbrella of macro-energy systems will make it more identifiable to new students, as well as to job seekers and hiring managers. Currently, it is difficult for interested students to identify the existence of a research community around the questions of long-term, large-scale energy choices and to determine the skills and experience needed to succeed in this area. A consolidated discipline, with an established methodology and pedagogy, will be much better at recruiting and training the brightest students. Job seekers will be able to advertise their skills more effectively and hiring committees will be able to formulate their job posting more clearly.

Moving Forward

Establishing a new discipline, especially one that pulls from several existing fields, is not trivial. It requires changing minds and creating a formal infrastructure befitting of a formal discipline, including new pedagogy, standardized nomenclature, an infrastructure of conferences, academic institutions, and interpersonal relationships. We propose to start in two places.

First, academics and researchers who believe that their work fits with what we have outlined above can identify their discipline as macro-energy systems and can champion macro-energy systems to their peers. Second, we envision a workshop in which participants will chart the scope and direction of macro-energy systems research and discuss key educational components for budding macro-energy systems researchers. Those interested in helping put together or participating in such a workshop are invited to contact the authors.

Eventually, we hope that this new discipline will lead to a new pedagogy of teaching large-scale energy system issues, increasingly standardized nomenclature and methodologies, a network of conferences, journals, and academic infrastructure, as well as exciting new interpersonal relationships. We hope that you want to work with us on the transition toward a low-carbon future.

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COMMENTARY

An Energy Transition That Relies Only on Technology Leads to a Bet on Solar Fuels

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Oscar Kraan obtained his PhD in 2019 from Leiden University on the thesis entitled "On the Emergence of the Energy Transition." His thesis work, done in collaboration between Leiden University and Shell, focused on the development and application of agent-based simulation models for the energy transition. Oscar holds a bachelor's degree in physics from Leiden University and a master's degree in energy science from Utrecht University. Currently Oscar works as Senior Strategy Consultant at Monitor Deloitte in Amsterdam, the Netherlands, where he focuses on strategic questions in the energy industry.

Gert Jan Kramer holds a PhD in physics from Leiden University (1988). After his PhD, he joined Shell, and since 2000 his work has increasingly focused on alternative fuels (notably hydrogen) and renewable energy. Since May 2016 he is Professor of Sustainable Energy Supply Systems at the Copernicus Institute of Sustainable Development at Utrecht University. From January 1, 2018 onward Gert Jan is head of the Energy & Resources group within this institute. His interest is in the energy transition as a technical and a socio-technical phenomenon.

Martin Haigh has been working in Shell's Scenarios Team for the last 15 years. Martin's background is in mathematics, with experience in mathematical and economic modeling in the energy industry. He has led the development of Shell's World Energy Model, which has underpinned all recent Shell scenario rounds, including the Sky scenario. He has jointly authored papers on energy technology deployment, and the long-term potential for renewables. Martin works with many institutions, including MIT's Climate Science team, the IEA, and a UK universities group focused on energy systems modeling. He is a Fellow of the Royal Geographic Society.

Chris Laurens holds an MSC and PhD in physics from Groningen University (1999). After his PhD, he joined McKinsey & Company, where he was leader of the Energy Practice and the Abu Dhabi Office. He served over 30 clients in the energy sector on topics ranging from strategy, investments, energy markets design, and decarbonization. After McKinsey, he joined Shell, where he focused on new energy technologies, the energy transition, power market fundamentals, and Shell's investments in power, hydrogen, and biofuels. Recently, he joined ADNOC, where he focuses on long-term strategy and growth.

Introduction

The task to build out and reshape the world's energy system is central to two of the greatest challenges for the 21st century: fulfilling the economic aspirations of a growing world population, while drastically reducing CO_2 emissions to limit global warming. Even in a net-zero-emissions world, significant demand for hydrocarbon fuels will persist. This will require that the CO_2 emissions from fossil fuels be captured and stored (carbon capture and storage, CCS) and that remaining emissions are offset by negative emissions from bioenergy CCS (BECCS), afforestation, etc. by deploying existing technologies. In all cases, governments need to be proactively involved to coordinate and support the transition. A radical alternative exists in the form of solar fuels, carbon-neutral fuels produced from renewable electricity, water, and the circular use of CO_2. If and when solar fuels could be produced at affordable cost and scaled, their market introduction could be market led, needing no more than price protection in the form of a carbon price. While a cost target of 200 US$ per barrel is potentially achievable in the long run if strong cost reductions can be met in all component elements, it is a high-risk bet for policy to rely on it in place of other technologies that are available today yet difficult to implement for non-technical reasons.

The Choice at the Heart of the Energy Transition

Since 2000, the world has made progress on the energy transition by the rapid deployment of "new renewables," notably solar photovoltaics (PV) and wind. This expansion appears likely to continue apace as costs continue to fall and decarbonization efforts increase under the pressure of "Paris." Any future scenario therefore