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I. Introduction

What is Energy Systems Integration (ESI)?

Energy Systems Integration (ESI) is the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment.

Global energy trends

Energy systems have evolved from individual systems with little or no dependencies into a complex set of integrated systems at scales that include customers, cities, and regions. This evolution has been driven by political, economic, and environmental objectives. As we try to meet the globally recognized imperative to reduce carbon emissions through the deployment of large renewable energy capacities while also maintaining reliability and competiveness, flexible energy systems are required. This flexibility can be attained through integrating various systems: by physically linking energy vectors, namely electricity, thermal, and fuels; by coordinating these vectors across other infrastructures, namely water, data, and transport; by institutionally coordinating energy markets; and, spatially, by increasing market footprint with granularity all the way down to the customer level (Figure 1).

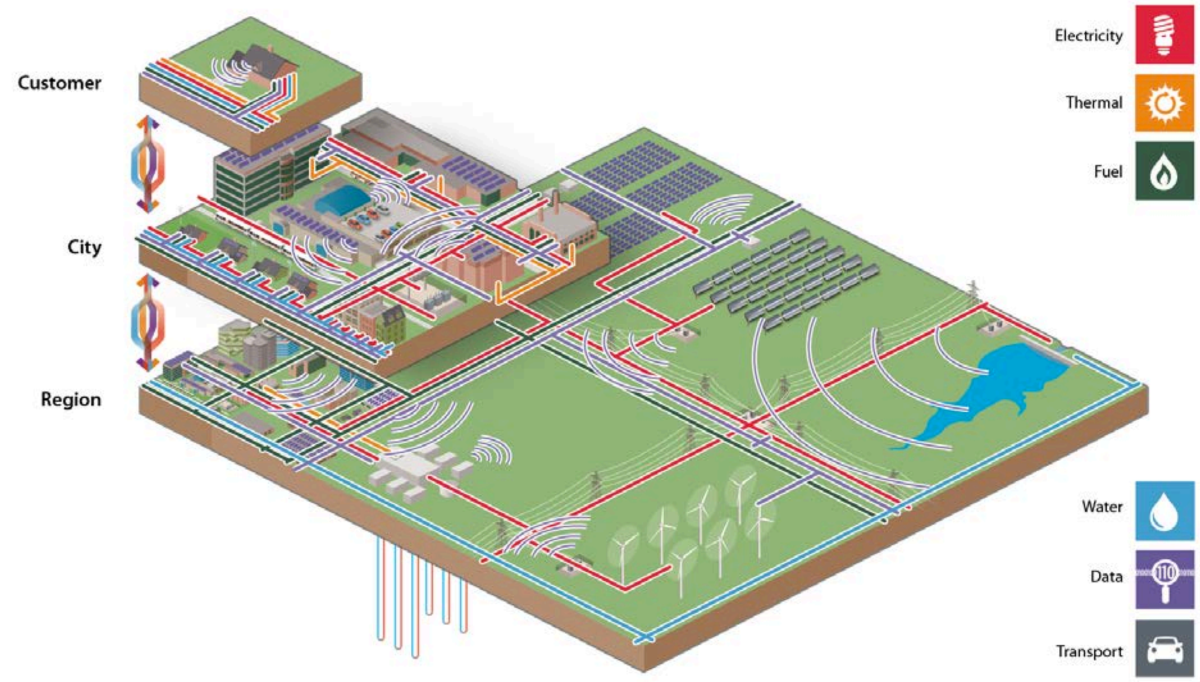

Figure 1: Energy Systems Integration

The International Energy Agency estimates that approximately €7.4 trillion will be invested over the next 25 years in executing the shift to renewable energy sources. This represents only 15% of the total investment in global energy supply and is not enough to meet climate change targets. The recent Conference of Parties 21 (COP 21) agreement has given further momentum to this renewable energy trend—which necessitates the development of flexible, integrated energy systems.

ESI is one of several global social and engineering trends that will shape the solutions to the key challenges of the next decades: resource stress, climate change, megacities, urbanization, cybersecurity, and infrastructure resilience. ESI is an umbrella concept that encompasses activities tackled in the context of smart grids (grid modernization) and smart cities. However, these two approaches are more limited, with one focused on a single energy vector (electricity) and the other limited in geographical scale to a city—so they may miss important opportunities that can arise by considering all energy vectors and all scales.

Policy relevance

The importance of ESI is being recognized globally. Most significantly, ESI is a central theme running through the European Commission's Strategic Energy Technology (SET) Plan Integrated Roadmap. It is also a central theme of the Clean Energy Ministerial and a major research theme with the U.S. Department of Energy national laboratory complex. There is also a new European Energy Research Alliance Joint Programme in ESI.

It is imperative that stakeholders gain a better understanding of what ESI is and how we can use it to achieve a low-carbon energy system with affordable, efficient, and secure supplies of energy. This requires a concerted effort to:

- Communicate the importance of ESI to all stakeholders, which in turn should help focus attention and resources to related challenges and opportunities;
- Encourage and support dedicated education programs, which will help produce the human resources required to deliver on the potential of ESI; and
- Highlight the importance of breakthroughs in ESI and promote knowledge creation and transfer.

This paper defines what ESI is and the value of this approach.

II. Defining ESI

We define ESI in the following way:

Energy Systems Integration (ESI) is the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment.

ESI includes interactions among energy vectors (electricity, thermal, and fuels) and interactions with other large-scale infrastructures including water, transport, and data and communications networks—which are an enabling technology for ESI. ESI is most valuable at the physical, institutional, and spatial interfaces, where there are new challenges and opportunities for research, demonstration, and deployment to reap its commercial and societal benefits. ESI is a multidisciplinary area ranging from science, engineering, and technology to policy, economics, regulation, and human behavior. It is this focus simultaneously on breadth and depth that makes ESI such a challenging and exciting area.

Every system is different

Each energy system will approach ESI from a different starting point (e.g., an urban area in the developed world will have a different approach compared to a rural area in the developing world). It is crucial to define the geographical scope as well as the components, the boundaries, and the influence of the surroundings. For example, renewable integration is the driving force of ESI in many regions, but not all. In some regions, the main drivers are increased combined heat and power (CHP), increased efficiency, a shift from coal generation to natural gas, or simply electrification. Different incentives, decision-making processes, and access to capital due to location or scale will result in very different energy systems and approaches to ESI (e.g., a government can invest in high-voltage transmission, while individuals will not). As each energy system develops, it will be necessary to constantly re-evaluate the system in order to assess how it is best coordinated.

Every actor is different

Developing coordinated systems through ESI analysis requires a proper understanding of the different actors involved, along with their motivations, their incentives, and the information they have access to. From a whole-system perspective, the actors in each energy domain tend to act on the information they have in ways that maximize benefits for their domain, but not for the entire energy system. For example, each user consumes based on their own requirements, each market values certain financial outcomes, and each government serves its own social or political motivations—but there may be no coordination across these domains to determine the best option for all actors involved. Poor outcomes can potentially arise from this lack of information and/or coordination, and may not be monetary in nature; a poorly executed energy transition could result in energy systems that lack technical integrity, social equity, and/or political acceptability.

III. What is the value of ESI

The value of ESI can be summarized as follows:

The value of ESI is in coordinating how energy systems produce and deliver energy in all forms to reach reliable, economic, and or environmental goals at appropriate scales. Analysis and design of integrated energy systems can inform policymakers and industry on the best strategies to accomplish these goals.

Because ESI is a broad topic that includes all types of energy sources and end-use applications, it is helpful to categorize examples of ESI into a few areas. Here we provide several examples of ESI that have been organized into three “opportunity areas”: streamline, synergize, and empower (Figure 2). These categories help differentiate how various ESI approaches can offer solutions to issues that have risen to the top of international energy agendas.

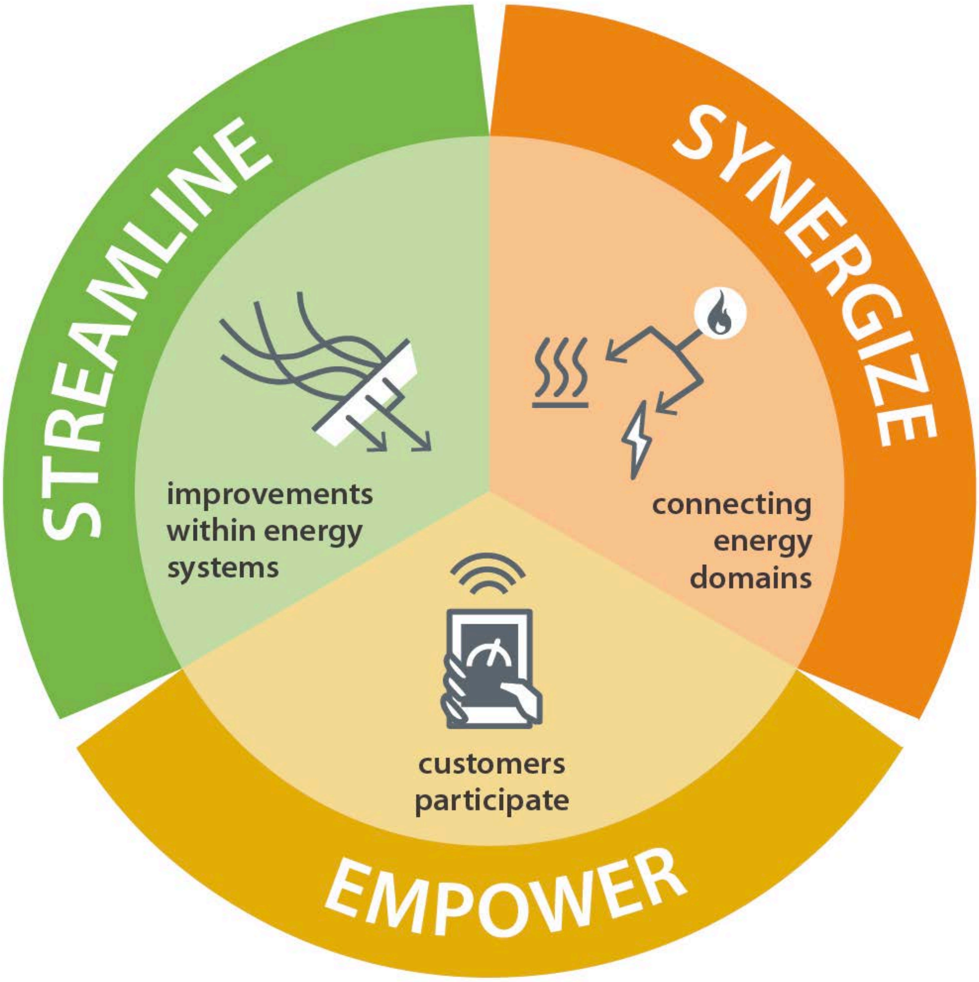

Figure 2: Opportunity areas for ESI

Streamline refers to improvements made within the existing energy system by restructuring, reorganizing, and modernizing current energy systems through institutional levers (i.e., policies, regulations, and markets) or investment in infrastructure. Increasing the flexibility of energy end use has potential system-wide benefits and could create new markets for products and services. However, capturing these benefits will require proper regulatory and market structures, new operational and planning paradigms, physical energy network characteristics, an integrated communications system, and suitably flexible end-use products. Many of these are currently lacking in the existing energy system and require a system-wide understanding to deliver pragmatic and sustainable solutions. Developing more integrated energy system-wide policies will enable better management of uncertainties. More integrated energy networks and proper functioning real-time locational markets will reward capacity and flexibility. In addition, the removal of institutional barriers between distribution and transmission systems will allow better integration of distributed resources and facilitate regional integration. By providing standardized requirements, updated interconnection and interoperability standards and grid codes will streamline the energy sector.

Investment in the appropriate infrastructure within the integrated energy system will improve flexibility. Expansion of the electrical transmission grid will enable flexibility by aggregation across scales. Pipeline infrastructure is required to increase the penetration of bio and/or synthetic fuels. Investment in data infrastructure will enable consumers to more fully participate in the energy system and will improve energy network operations through forecasting and analytics.

Synergize describes ESI solutions that connect energy systems between energy domains and across spatial scales to take advantage of benefits in efficiency and performance. To date, the coupling of heat and electricity sectors has focused on the supply side (e.g., CHP) for fuel-saving purposes. However, at the system level, its inherent inflexibility can lead to sub-optimal overall system performance. A good example of this is wind curtailment in China, which is in part due to the inability of physically inflexible CHP plants to reduce electricity production while providing heat. ESI solutions that integrate heat storage into the CHP plant are being developed and indicate a shift from the supply side to the demand side (e.g., electrical heating of water, thermal storage in buffers and heat pumps). It is possible to capitalize on “virtual storage” where the flexibility in one part of the system (e.g., heat, transport, water, etc.) can be integrated with, for example, the electricity system, and used in a similar manner to electricity storage. This virtual storage can be significantly cheaper than dedicated storage, as it does not require large capital investment—but it does require a more integrated energy system. Demand management (e.g., controlling heating and cooling loads) technologies currently being deployed and developed are in part leveraging this virtual storage. However, ESI proposes that it is at a grand scale where fuel, thermal, water, and transport systems will be systematically planned, designed, and operated as flexible “virtual storage” resources for the electricity grid (and vice versa). There is also the potential to use the natural gas fuel grid to create energy storage through the “power-to-gas” concept.

Empower refers to ESI actions that include the consumer, whether through their investment decisions, their active participation, or their decisions to shift energy modes. Investments in energy efficiency are increasingly recognized as a cost-effective way to reduce energy demand and can lead to system-wide benefits that include upstream capital and operational savings. From an overall energy system point of view, energy efficiency at the level of an individual building may be in conflict with the flexibility that the demand side can provide to the grid. Energy efficiency improvements or targets also contribute to broader social and policy goals, notably macro-economic efficiency, industrial productivity, public budget balance, security of supply, and health benefits. This building-level investment needs to be made by the consumer. The formerly totally separated sectors of transport and electricity may become more integrated through plug-in electric (hybrid) vehicles and car batteries, but the consumer needs to accept this mode of transport. The potential in some regions for thermal grids has been raised, but questions remain as to how large they should be, how best to integrate them into the electricity grid, and, importantly, how consumer requirements will be ensured and whether consumers will accept them. Consumers can also make choices that provide them with the necessary services while using less energy by mode shifting. For example, consumers can choose to take public transport instead of personal transport.

The considerations that govern ESI are numerous and complex, and the outcomes and their value can be difficult to define. One of the first steps to determine this value is to define a set of robust metrics spanning the engineering and social sciences (e.g., financial impacts, emissions costs, resiliency, public health considerations, social utility, etc.) to measure and highlight the various benefits. Any set of definitions or metrics will have to be flexible enough to accommodate a wide range of circumstances. Metrics also need to be simple enough to allow for an overall holistic understanding of how the different aspects interact.

IV. Conclusions

ESI is an important concept to make the energy system more flexible, enable the efficient integration of renewable energy and to reduce carbon emissions. ESI solutions can range from the very simple to the very complex, are system specific, and impact different actors in distinct ways. They can require expertise from a single discipline or from a multitude of disciplines. It is important to understand the ESI value proposition and to communicate it in order to educate energy professionals and foster knowledge creation and transfer.

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