An Integrated Approach to Energy Management and Security

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A. Interactions, Variability, and Security in Energy Pathways

Our understanding of sustainable energy utilization has evolved considerably in recent years driven by advances in our ability to observe, measure, analyze, and model the underlying environmental, physical, personal, social, and economic processes. However, as is often the case in scientific disciplines, the evolution has been towards increasing specialization. Illustrative of this is the way we think of sustainable energy usage in terms of distinct pathways. For example, we have developed some insights into energy wasted in transportation due to congestion [Schran11], and have achieved reasonable success at mitigating congestion by regulating highways and city traffic patterns. Likewise, we now have a good understanding of water usage, and have achieved reasonable success in managing water resources so as to provide water for residential and agricultural use at low cost. With significant energy embedded in water during its generation, supply, and use, efficient use of water results in energy savings [Klein09, Ortez09]. While these pathways are largely seen as independent and typically studied in isolation, in reality they are coupled due to the interactions among the underlying processes. Unfortunately, regarding different energy pathways as independent has led to sustainability management practices, economic policies and human behavioral patterns which, although optimal within a single pathway, are sub-optimal or even undesirable when their effects across different pathways are examined. For instance, we have managed to continually improve both fuel economy of cars and reduce emissions per mile of driving several folds since the 1970s, which may suggest transportation has become more efficient. However, from a societal perspective, the social cost of transportation has increased and lead to greater environmental burden. It has been argued that technological gains which reduced the cost of driving have been dissipated through an increase in the size and power of personal vehicles [Knittel11] and an increase in vehicle miles driven leading to greater suburban sprawl, greater congestion, etc. Similar examples can be provided in the case of electricity where lower costs of electricity and improved appliance efficiency standards may in the longer run have contributed to an increase in the size of household appliances such as refrigerators. From a macro-economic perspective, lower cost of energy services have contributed in the long run to greater dependence on fossil fuels, and increased the risk to economic security. It has been argued that the importance of oil to the US economy was an important factor in precipitating the financial crisis of 2008-2009 [Hamilton09].

In this white paper we use the term ***energy*** in a broad sense to refer to both direct forms of energy such as electricity or fuel that we personally buy and use, and to indirect forms of energy that are embedded in goods, resources and services that we consume such as water, food, and transportation. Further, we use the term ***energy pathway*** to refer to all the different ways in which energy can be produced, transported, distributed, and consumed.

As an example of the coupling that can exist between energy pathways that are traditionally managed separately, consider the use of water and electricity in buildings and communities. Water and energy interlock in a complex overall energy sustainability puzzle that is referred to as the “Water-Energy Nexus” [SNL11]. On the one hand, large amounts of fresh water - as much as 40% in the US - are used in electricity generation and extraction of fuel. On the other hand, in water stressed areas large amounts of

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energy are used to provide water - e.g. in California, 19% of the total electricity use and 32% of the total non-thermal power use is on water - with buildings accounting for a disproportionate share because of the higher energy intensity of the water they use. With increasing reliance on water recycling and extraction at the point of use in many water-stressed parts of the world, water is more sensitive to energy prices so that the "water-embedded-energy" is not just a societal level concern but is a visible component of a building's direct energy cost. Moreover, energy used in the water pathway - as much as 30-40% in many mid-size cities - creates a direct spatio-temporal correlation between water use and load on the electrical grid. Consequently, policies and incentives that seek to influence and regulate the usage patterns and behaviors in either the water or the electricity pathway (e.g. dynamic pricing in electrical grid, time-based usage restrictions on water) actually affect the sustainability of the other energy pathway as well. Their optimization would therefore benefit from taking the water-energy nexus into account.

The interactions between traffic and energy usage in buildings are also worth mentioning. Office buildings are characterized by large thermal masses that are slow at changing temperature. For this reason, optimal usage of energy resources for heating and ventilation requires regulating the building temperature hours before the first occupants start their working day. Consider now a traffic event that delays a large percentage of workers. Such an event indirectly results in wasted energy since the cooled office spaces now remain largely unoccupied. Although energy is not directly transferred between the traffic pathway and the building pathway, there is an undeniable interaction between these pathways that should be exploited to increase sustainability. The traffic pathway influences energy usage in buildings in several other ways. If the building occupants commute using electric vehicles that are charged while parked at work, then changes in traffic will inevitably lead to changes in the building's electric load. This coupling provides another example of how the traffic pathway is intimately coupled to the building pathway. Hence, building energy usage decisions are not optimal unless studied in the larger context of all the interacting energy pathways.

The coupling between different energy pathways also has implications for security. For example, by observing one energy pathway and exploiting pathway interdependencies one can infer properties of another pathway thereby leading to potential privacy breaches. Many private activities such as house occupancy or the use of appliances can be inferred by observing the usage of electricity [Quinn09]. The potential compromise of privacy becomes even more serious when one combines observations from multiple energy pathways (electricity, water, etc). Therefore, couplings between different energy pathways also naturally gives rise to information leakage leading to important questions about security/privacy. We argue that we should understand the vulnerabilities arising from these dependencies and devise the architectures and defense mechanisms that can control or at least minimize them.

Besides assuming independence among the processes underlying different pathways, current sustainability practices also consider these processes to be relatively stationary over time and localized. As a result, policies and interventions adapt minimally over time, and focus on spaces (e.g. a building) and stakeholders (e.g. an individual) in isolation without accounting for interconnections among them. For example, [Milly08] noted in the context of water resource management that designing and operating systems while assuming that underlying natural processes (e.g. rain fall) fluctuate with a stationary or annually periodic probability density function is no longer possible due to the magnitude of anthropogenic disturbances and impacts on the natural systems. Similarly, spatial dependency in human and natural processes that underlie energy sustainability pathways is well recognized. For example, Tobler's First Law of Geography ("Everything is related to everything else, but near things are more related than distant things" [Tobler70]) captures the short-range interactions with inverse relationship with distance that exists in processes such as urban traffic distribution. Complementing these are the "teleconnections" [Glantz91] that establish correlations and causalities over long distances and time spans and across different forms of energy use due to shared human agents leading their daily lives. As an example, energy consumption by individuals at their work places has interactions with energy use at their homes due to the obvious correlation in the occupancy patterns at the two locations, and may be leveraged in smarter energy management and conservation incentives. Likewise, insights from research in computational social science indicate that behaviors, thoughts, and feelings are influenced by and spread through their social networks via inter-personal interactions [Christakis09], suggesting that behaviors and choices relating to energy sustainability may similarly be influenced by social connections.

A.2. Harnessing Interconnections and Coping with Variability and Security Challenges

As observed above, energy pathways are neither isolated nor stationary. Building upon these observations, we put forward the following research challenges:

1. How to best use embedded networked sensing, system identification and statistical methods to measure, learn, model, and even predict, at high accuracy and resolution, the interactions and variability that exist among energy pathways along mode, space, and time of energy use?
2. How to harness the synergistic interactions and account for the antagonistic interactions that exist across energy pathways, and combine insights from control theory and economics, to devise more effective and cost-efficient interventions and incentives to improve overall sustainability?
3. How to use models of interactions and variability to engineer better sensing substrates that would let the underlying processes be observed more efficiently? In turn, the sensed quantities should be used to adapt the models, to detect important changes caused by the non-stationarity of the physical processes, and for real-time control of energy management systems.
4. How to use interdependencies to enable robustness and survivability under adversarial attacks? How to shape interactions and develop mechanisms to ensure privacy and security?

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