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New Design Paradigm for Integrated Energy Systems Needed for Sustainability

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INTRODUCTION

Achieving Sustainability

Achieving sustainability in the energy sector requires an economically viable path with a balanced transition that does not aggravate environmental and sociological problems associated with current fossil-based power production. Increasing the grid penetration of intermittent renewables to realize a sustainable energy future without consideration of the balanced transition may result in devastating economic and societal impacts [1]. As we press for the minimization of renewable power curtailment, current fossil-based technology struggles to meet demand under extreme transient and part-load conditions. This results in dramatic reduction of efficiency and a corresponding increase in emissions of not only carbon, but far more devastating pollutants.

Without a doubt, the needs of a sustainable future require new technologies, not only for renewable power like wind and solar, but also for dispatchable power [2]. Ideally, technology to serve the transition would provide a significant increase in the efficiency of fossil fuels conversion under transient and part-load conditions as well as an opportunity to use renewable fuels and integrate with existing wind and solar. To meet the aggressive timelines for decarbonization and transition to a renewable energy sector posed by many world governments, these new technologies would need to be developed with an unprecedented haste not supported by our current technology development paradigm [3].

Integrated Energy Systems

Integrated energy systems provide hope for high efficiency conversion of fuels to electricity, low emissions, load following flexibility, and low-cost carbon management. By integrating a variety of power generation assets, developing technologies can be matched with mature technologies, mitigating risk and facilitating early adoption of novel component concepts.

As an example, the synergies of a solid oxide fuel cell (SOFC) – gas turbine system through thermal integration result in efficiencies that exceed the sum of the individual parts. Through optimizing the integration of fuel reforming in the cycle, theoretical efficiencies over 70% low heating value (LHV) natural gas can be realized at SOFC fuel utilizations below 45% where the fuel cell represents less than half the power of the cycle [4]. Merging developing (SOFC) and mature (gas turbine) technologies mitigates SOFC early adoption risk by lowering the fraction of power generation and associated costs. Even if the SOFC does not function to its fullest potential, higher efficiencies and turndown capabilities can be realized through the thermal energy storage capacity of the SOFC materials, facilitating the transition to a sustainable future. Similarly, concentrated solar power and thermal energy storage can be coupled to the mature gas turbine technology.

Co-Design

Although many benefits of integrated energy systems have been extolled in the literature and even in distributed scale demonstrations, system integration and dynamic control issues inhibit commercial adoption of these technologies. In the current technology development paradigm, integration and control issues are not often identified until the completion of a pilot scale system [3,5], as shown in the abbreviated technology development timeline in Figure 1. Failure at the pilot scale stems further investment and shatters all hope for commercialization efforts. As such, the bridge between numeric models and the hardware of a pilot plant represents the greatest risk in technology development and the opportunity for the greatest gain in accelerating the path to commercialization of new concepts.

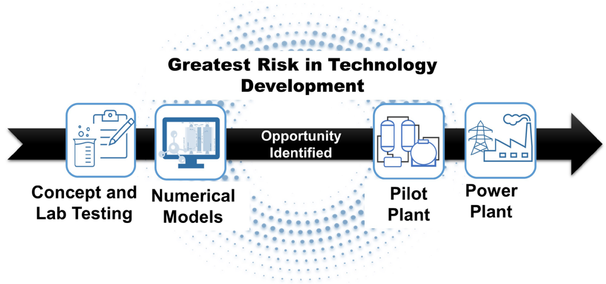

Figure 1. Current paradigm of technology development

The simultaneous co-design of system components, system integration, and dynamic control would be required to minimize development risks. If a pilot plant could be built with some confidence of the operability and potential for automation, the chances for success would be greatly improved. This could be best accomplished if component design could be changed based on identified needs for system integration and controls. To realize effective co-design, the use of new tool would be required [3,6,7].

Cyber-Physical Systems

When considering the design tools needed in the transition from numeric models to pilot-scale hardware, cyber-physical systems (CPS) come to the forefront as a method to model complex integrated energy systems. As shown in Figure 2, CPS interact with a physical environment through a seamless combination of numeric models and hardware through a series of sensors and actuators.

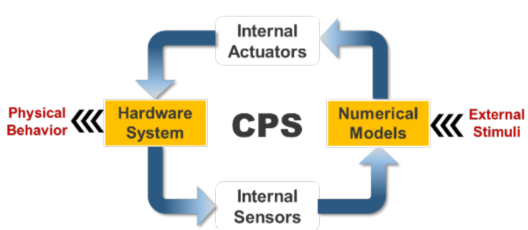

Figure 2. Interaction between physical environment and real-time numerical models in cyber-physical systems

Simulations using cyber-physical models are distinguished from hardware-in-the-loop simulations (HILS) that couple a physical component to a virtual environment for testing. Although commercial digital twin (Twin) products also couple numeric models to hardware, CPS requires the models to converge within the sampling frequency of the dynamic controller. In power systems, Twins generally require convergence within the optimization time of a supervisory controller, or about 5 to 15 minutes. The CPS facility at NETL requires convergence in 5 milliseconds. Concepts of HILS, Twin and CPS are compared in Figure 3.

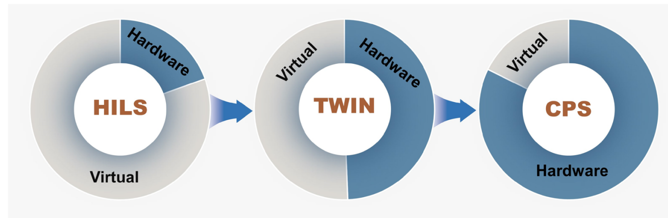

Figure 3. Illustration of the concepts of hardware-in-the-loop, digital twins, and cyber-physical system

Changing the Paradigm

To minimize the highest risk or "valley of death" in the technology development, the current paradigm must be modified to accommodate co-design by including a feedback loop in the highest risk part of the design process [3,5]. As shown in Figure 4, if CPS techniques could be employed before investment in a full pilot scale power system, opportunities to modify materials and bench scale systems would be available to maximize success at the pilot scale.

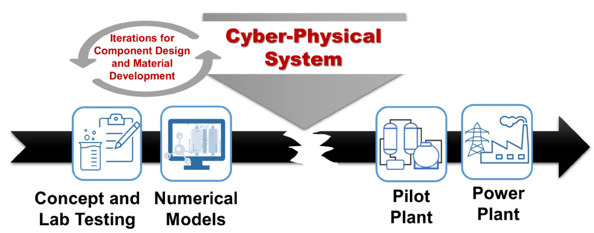

Figure 4. De-risk technology development through cyber-physical systems

The new design paradigm for integrated energy systems of the future must include pathways that make use of dynamic models, hardware-in-the-loop simulation, digital twins, cyber-physical models, and ultimately, cyber-physical systems to support intelligent power generation. As shown in Figure 4, filling the "valley of death" with a continuum of simulation methods between numeric models and hardware models can provide an opportunity to achieve commercialization of new energy system technologies within the time scale needed to realize economically viable energy transitions on an international scale.

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DISCLAIMER

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