Cyber-Physical Energy System Modeling

AMES LABORATORY
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

in collaboration with

NATIONAL ENERGY TECHNOLOGY LABORATORY

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Cyber-Physical Systems - NIST

"Cyber-Physical Systems (CPS) comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. These systems will provide the foundation of our critical infrastructure, form the basis of emerging and future smart services, and improve our quality of life in many areas. Cyber-physical systems will bring advances in personalized health care, emergency response, traffic flow management."

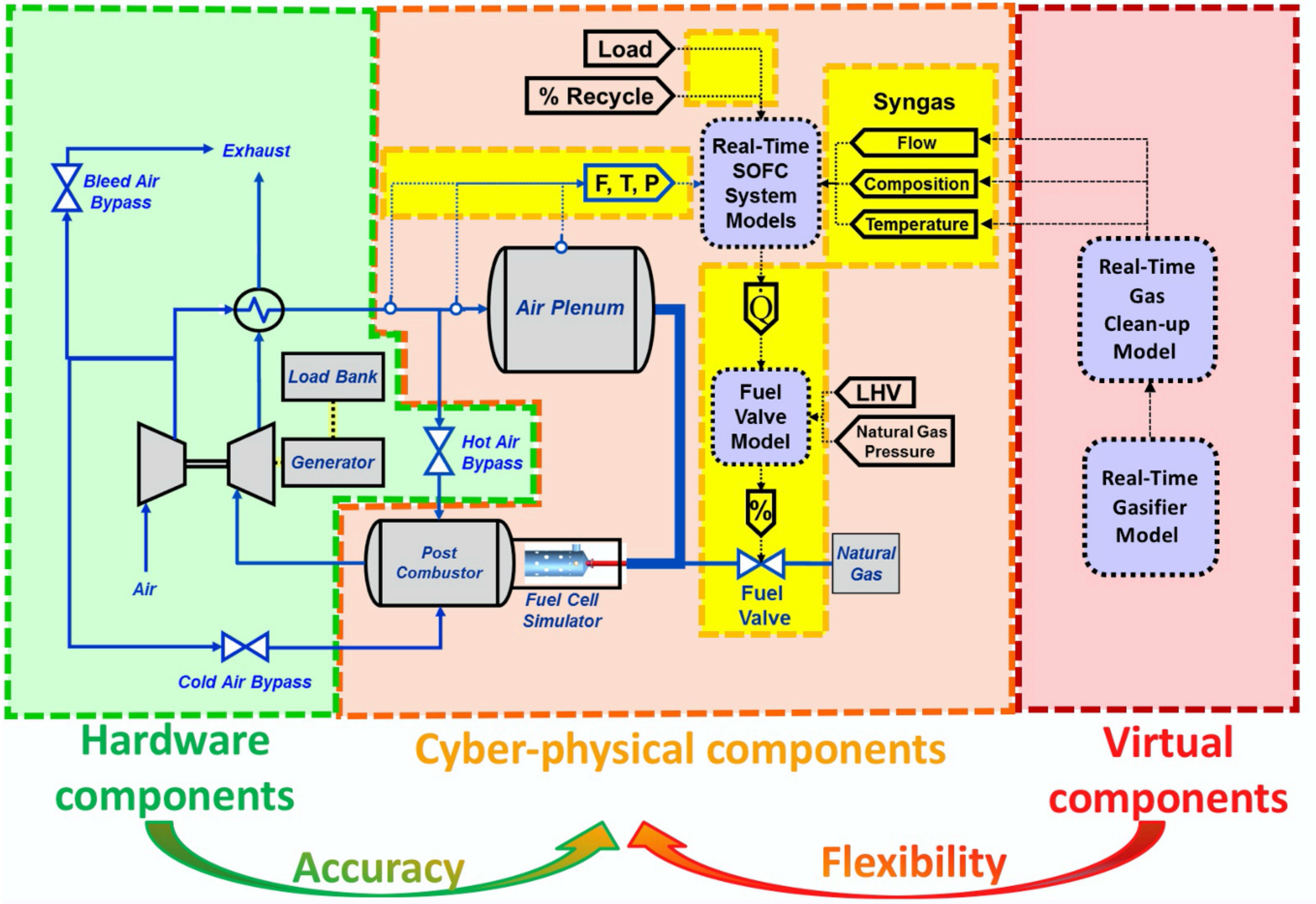
https://www.nist.gov/el/cyber-physical-systems

Hyper - a cyber-physical energy system model

Fuel cell–gas turbine hybrid systems are complex systems and their dynamic behaviors cannot be determined only with models.

- *Cyber-physical fuel cell model* — integrates digital, physical, and analog assets to model the dynamics of a SOFC in realtime.
- *Integration* — SOFC model integrated into a gas turbine system (including the controls) creating a cyber-physical model of the system.
- *Enabling modeling technology* — provides a low cost, flexible lab-scale test system and eliminates the risk that dynamics and controls testing would damage the fuel cell.

Simplified Process Diagram of the Hyper Facility



Background

A **cyber-physical energy system** model has the following characteristics

- *A physical embodiment* — integrated into the physical systems lab-scale model
- *Integration of cyber-physical model* — occurs within the physical domain as well as within the controls system
- *Real-time model(s)* — that control and update the behavior of the cyber-physical component(s) based on the behavior of the overall system
- *Seamless integration of physics and logic* — including the integration of smart sensors, smart actuators, and hardware components as well as computational algorithms.

Motivation

- *Novel concept* — Using a cyber-physical system to model and design a complex energy system is a first-of-a-kind concept
- *Unique modeling tool* — Current modeling techniques are not able to fully address the complexity of large-scale energy systems and physical modeling (lab-, pilot-, full-scale plants) are costly and relatively inflexible.
- *Critical application* — Cyber-physical modeling has the potential to accelerate the design, deployment, and scale-up of advanced energy systems by providing both the flexibility of computational modeling and the accuracy and “hard truth” of physical components.
- *Provides the bridge* — Reduces the cost and time of scaling from lab-scale and full-scale power systems and components, helping innovative energy system concepts transition to products.

Challenge

While cyber-physical systems are becoming increasingly common, they are are not being used as engineering modeling tools in the design and development of engineered products.

Today there is no detailed understanding of how to create a model of a component or system using a cyber-physical strategy.

Goal

Collaborate with NETL to

- Codify the cyber-physical modeling approach developed at Hyper to create an extensible industry-facing cyber-physical modeling approach to complex energy system development,
- identify and develop industry partners that can participate in the development of this approach,
- work with these partners to develop and validate cyber-physical models of energy systems, and
- develop an initial open source software base to support the integration of cyber-physical systems.

Technical Approach

Define & Invite — 2021

- Seminal journal article on cyber-physical energy system modeling
- National Lab-Industry-Academia workshop focused on cyber-physical modeling

Build a Coalition — 2022

- Start to build an industry-facing coalition
- Identify a compelling case for cyber-physical energy system modeling
- Develop one or more industrial partners to assist in developing the software platform that incorporates digital twins and cyber-physical modeling

Demonstrate — 2023

- Release a beta version of the software platform
- Working with NETL and industry to build a cyber-physical modeling demonstration
- Final report

Objectives

1. Codify our detailed and rigorous understanding of cyber-physical modeling and how to utilize cyber-physical modeling in the design and deployment of integrated energy systems

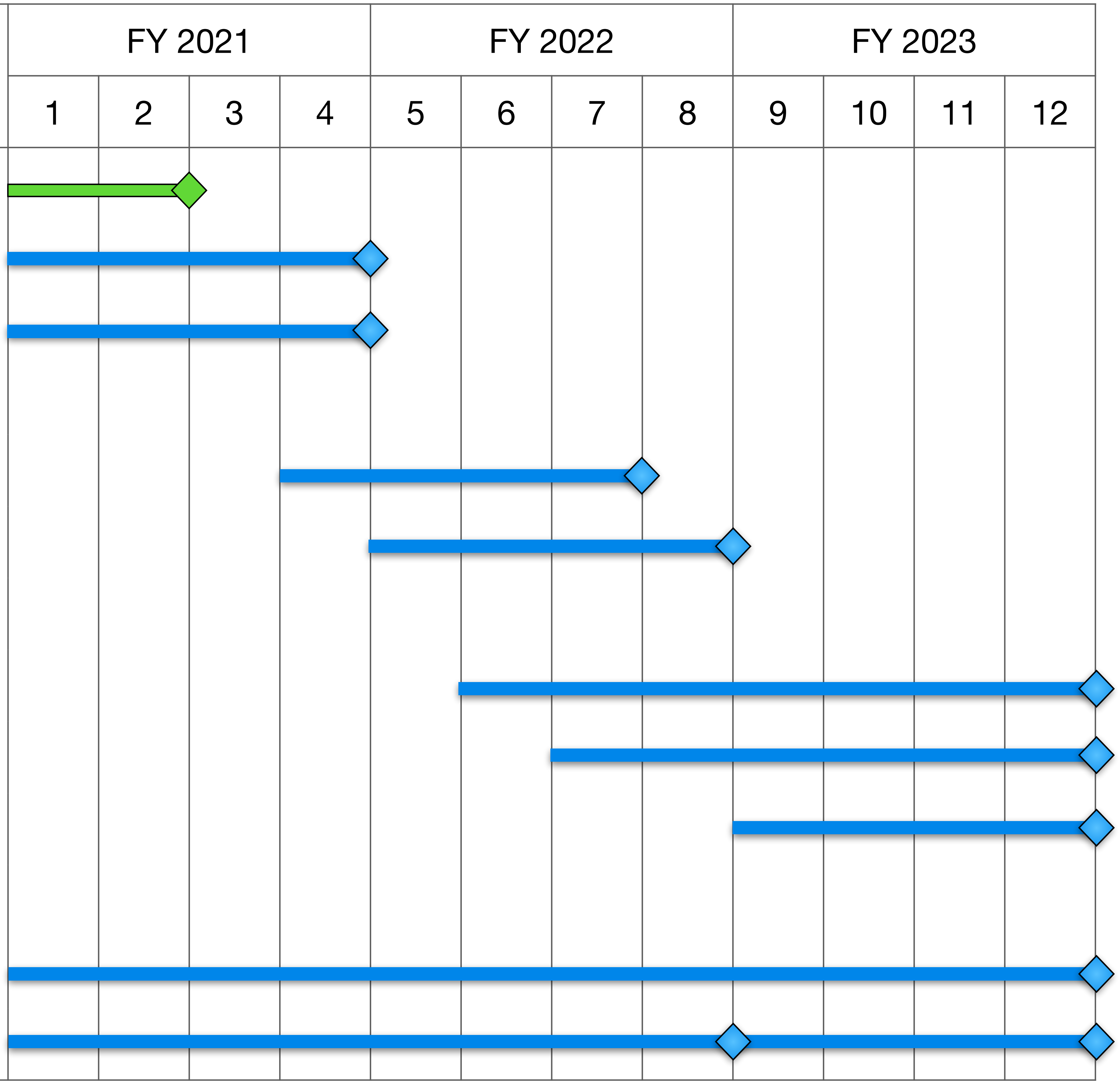
2. Extend and maintain the existing stack of software and controls tools

3. Identify new concepts in support of the Cyber-Physical Energy System Development Platform

Schedule

Task

1. Develop recommendation on cyber-physical platform and submit to NETL
2. Define and organize an industry-lab-academia workshop
3. Prepare a journal article and conference proceedings describing cyber-physical modeling
4. Work with NETL to identify an industrial partner
5. Develop a plan for developing energy system cyber-physical models
6. Develop software platform for integration of cyber-physical systems
7. Collaborate with NETL on the development of a cyber-physical component models
8. Collaborate with NETL to validate the methodology of cyber-physical energy system design
9. Maintain the software repository
10. Reporting



Milestones

FY 2021	**Mar 31**	Integrate the lessons learned from Hyper and the literature to provide a recommendation to NETL on the primary functions and methods needed for the development of a cyber-physical energy system design platform. - **Complete**
	Sept 30	Collaborate with NETL to define and organize an industry-lab-academia workshop on cyber-physical energy system design. - **in progress**
FY 2022	June 30	Work with NETL to identify an industrial partner and initiate discussions to identify a project of interest to industry and NETL.
	Sept 30	Submit to NETL for review and approval a design plan for developing cyber-physical models of energy system components.
FY 2023	Mar 31	Work with NETL and an industrial partner to create one (or more) cyber-physical model(s) of energy components.
	Sept 30	Collaborate with NETL and an industrial partner to test and validate the methodology of cyber-physical energy system design based on a new energy system concept as defined in Task 2 and in alignment with FE goals.

Deliverables

FY 2021	In collaboration with NETL, submit a conference proceeding on the cyber-physical energy system methodology.
	In collaboration with NETL, submit a journal article on cyber-physical energy system model design.
	Conduct an industry-lab-academia workshop co-hosted with NETL focused on cyber-physical energy system design and publish the workshop report/proceedings.
FY 2022	Work with NETL to identify an industrial partner and initiate discussions to identify a project of interest to industry and NETL.
	Summarize the research work completed to date in a report submitted to NETL for review and approval.
FY 2023	In collaboration with NETL and an industrial partner make available the software platform needed to support the integration of a digital twin and cyber-physical devices for deployment testing and validation.
	Summarize the results of the industrial deployment and identify R&D gaps and issues in a technical report with a R&D plan to address them.

Current Status

- The recommendation for primary functions and methods needed for the development of a cyber-physical energy system design platform are in review/discussion with NETL.
- The industry-lab-academia workshop will be included as a part of the LEAP workshop and is scheduled for September 2021.
- Opened an OSF project for maintenance of journal articles and other materials
- Preparing a journal article on the development of cyber-physical energy system model design based on Hyper

Lessons learned - page 1

1. Cyber-physical energy system models can fill in the gap between concept/experiment and pilot plant
   - speeding up the energy system deployment process
   - can provide the missing bridge between concept and deployment

2. Cyber-physical energy system modeling can reveal details that other modeling tools cannot. These include
   - dynamic performance,
   - system integration details, and
   - controls performance.

   This can provide a full co-design platform.

Lessons learned - page 2

3. A cyber-physical model is an engineering model. As a model it can be rerun, changed and modified as our knowledge grows and as we define the design space of interest.
    - Engineering models are technology design and deployment focused.
    - Hyper is a cyber-physical model of a power system, not an experiment nor a small-scale power system.
    - There are many advantages to this and not all of these have been fully explored.

Lessons learned - page 3

4. Integration and dynamics are the sweet spot for current cyber-physical models.
   - This requires real-time models and real-time updates of models
5. Seamless integration of hardware and software are essential.
   - The middleware is more important and harder that it seems at first glance
   - The component models need to be discrete and stateless
6. Cyber-physical models can be used to build/improve the tools needed for a digital twin.
   - Need to partner with industry to build industry-compatible digital twin tools
7. Cyber-physical models have the potential to enable full co-design of energy systems

Lessons learned - page 4

8. Large amounts of data can be generated very quickly.
    - Therefore, scientific machine learning tools, visualization tools and other tools that can be used to examine and understand the data are critical.
    - The focus of these tools need to be on creating actionable, industry facing tools (i.e., tools that support moving from the cyber-physical model to the power system and digital twin).
    - The system network must be able to support realtime data capture and storage.

Recommendations

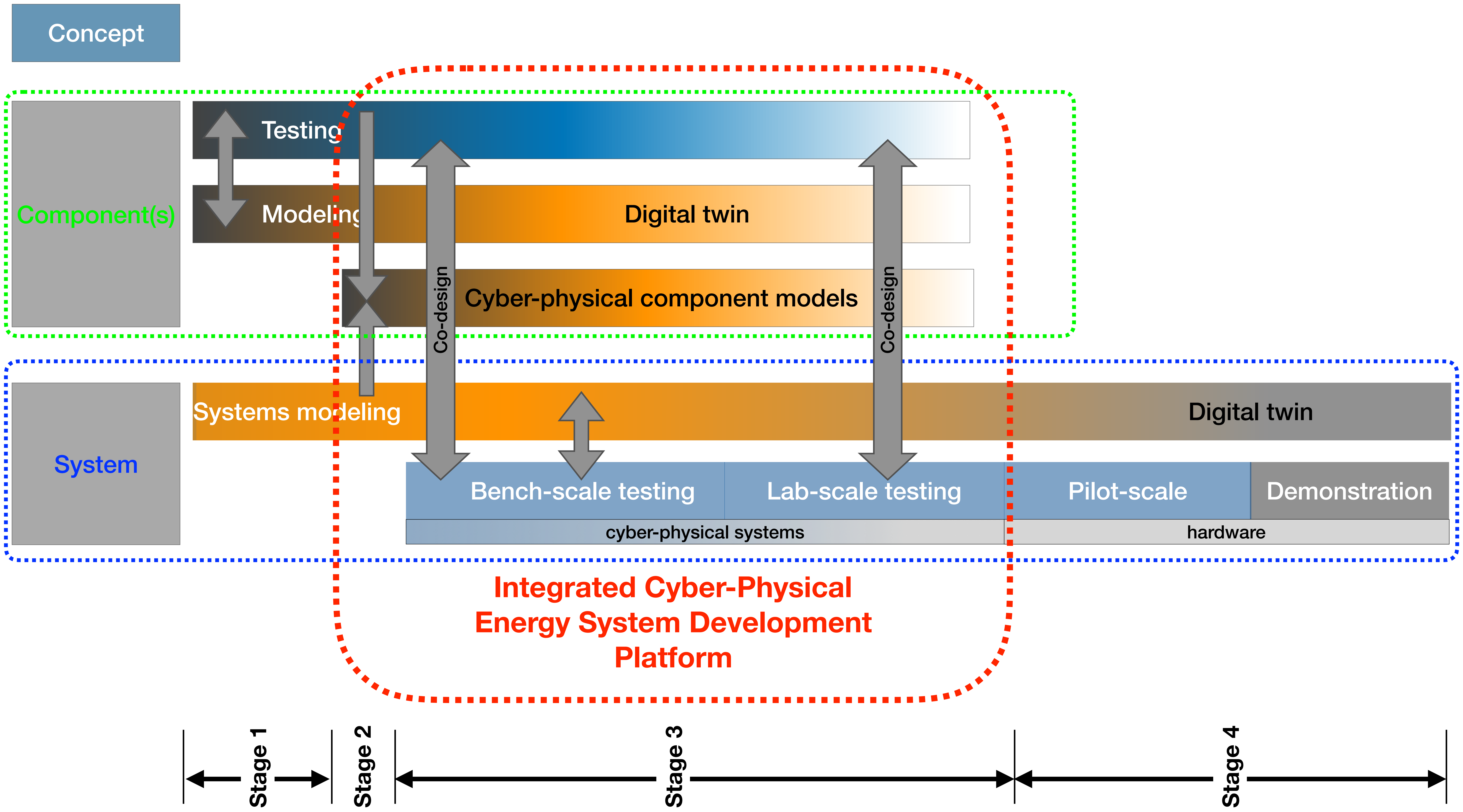
1. Redesign/update of the Hyper facility to enable the rapid reconfiguration of Hyper to model multiple types of integrated energy systems. These components should include physical hardware, cyber-physical models of components, and computational models.

2. Initiate work to more fully define of how cyber-physical modeling can enable the full co-design of integrated energy systems and the tools needed to support this.

3. Define the needed middleware platform and initiate development of an open source software that acts as a middleware platform enabling the seamless integration of models, scientific machine learning (sciML), and hardware in support of cyber-physical energy system modeling.

4. Define the needed the data gathering and storage facilities, sciML tools, visualization tools and other facilities needed to examine, understand, and reduce to actionable knowledge the results of cyber-physical energy system modeling.

A Cyber-Physical Energy System Development Platform



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Questions?

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