Cyber-Physical Energy System Modeling

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AMES LABORATORY
Creating Materials & Energy Solutions
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Goal

- Codify and define 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 academic, national lab, and industry partners who can participate in the development of this approach,
- work with these partners to identify needed cyber-physical models of energy systems, and
- start to develop an initial open source software base to support the integration of cyber-physical systems.

What is the purpose of models?

"In modern engineering practice, scarcely any new type of structure or machine, whether it be a long-span bridge, a canal, a jet engine, or a supersonic speed airplane, is constructed until a model of it has been built, tested, redesigned, and retested, often several times."

…

The observations may be made on models, or entities which are usually smaller, less expensive, and more easily altered than the one for which the characteristics are to be established."

Glenn Murphy, *Similitude in Engineering*, 1950

Cyber-physical systems

- Engineered systems that are built from, and depend upon, the seamless integration of computation and physical[1]
- Physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core[2]
- The integration of computation with physical processes whose behavior is defined by both cyber and physical parts of the system[3]
- Networks of tightly integrated physical processes with computation components designed to monitor and control the physical world intelligently[4]

[1]National Science Foundation, “National Science Foundation Cyber-Physical Systems Solicitation.” (2021)
[2]Rajkumar et al., “Cyber-Physical Systems: The next Computing Revolution.” In *Proceedings of the Design Automation Conference*, 731–36, (2010).
[3]Seshia et al., “Design Automation of Cyber-Physical Systems: Challenges, Advances, and Opportunities,” *IEEE Trans Computer-Aided Design of Integrated Circuits and Systems* 36 (9): 1421–34.(2017)
[4]Eskandar et al., “Human-in-the-Loop Cyber-Physical Systems for Construction Safety,” In *Cyber-Physical Systems in the Built Environment*, 161–73, (2020)

Cyber-physical models

- Intelligent models whose behavior is driven by cyber and physical parts that are seamlessly integrated by a computing and communication core.
- These models can be are less expensive than the engineered system tested and can be quickly and easily altered, tested, redesigned, and retested, multiple times to enable co-design of complex or entangled systems.

Models constructed using cyber-physical systems to accurately predict the performance of a specific detail or aspect of an engineered system or component.

Energy system development

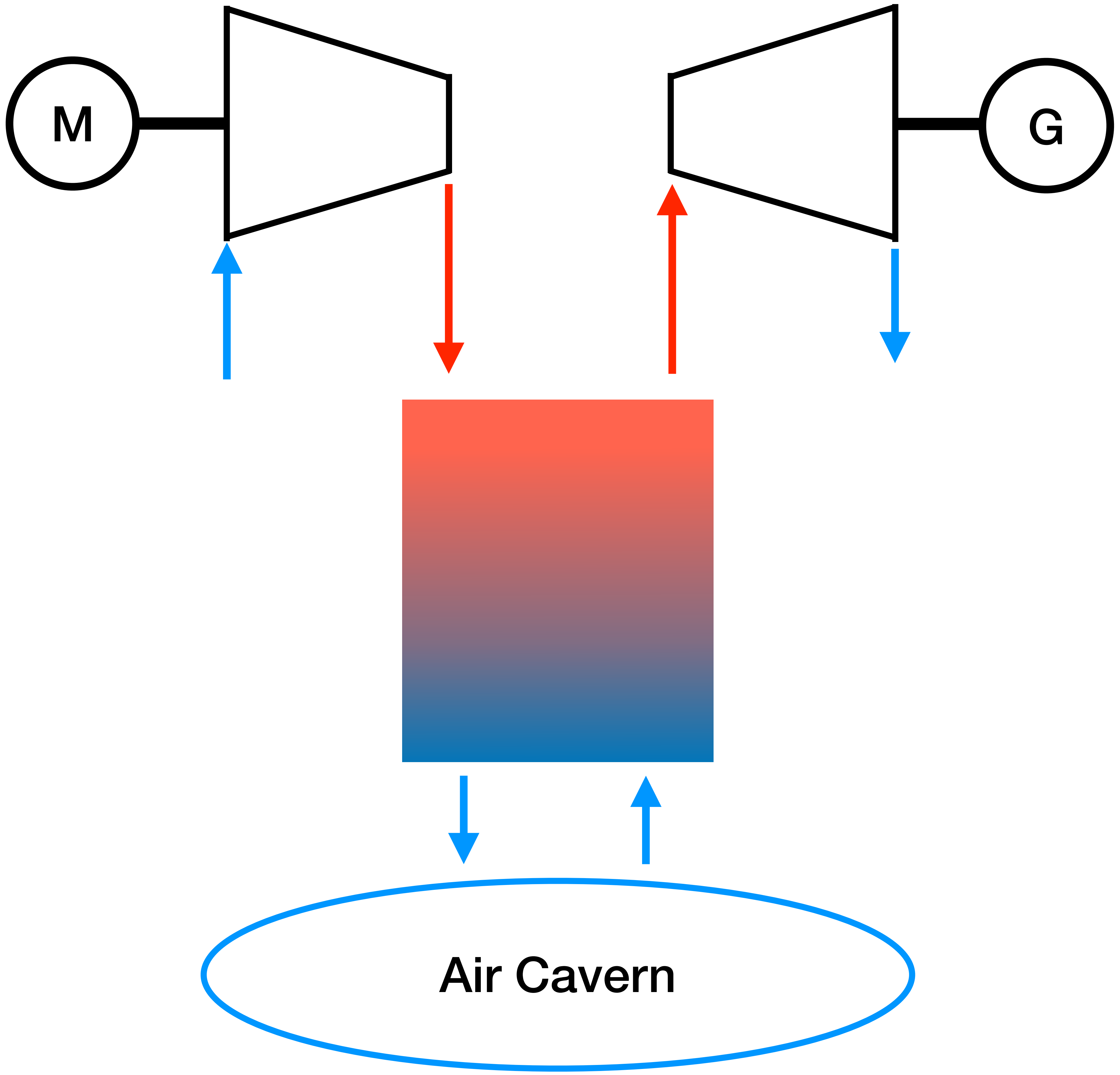
- Today, much of physical modeling has been replaced by computational modeling
- with the benefits cost, flexibility, and time;
- however, the “ground truth” of physical modeling is now provided by an extensive (time consuming and expensive) pilot plant program.

Cyber-physical modeling can provide the flexibility of computational modeling and the “ground truth” of physical modeling at much lower cost while substantially reducing the time from concept to realization.

Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.

Compressed air energy storage

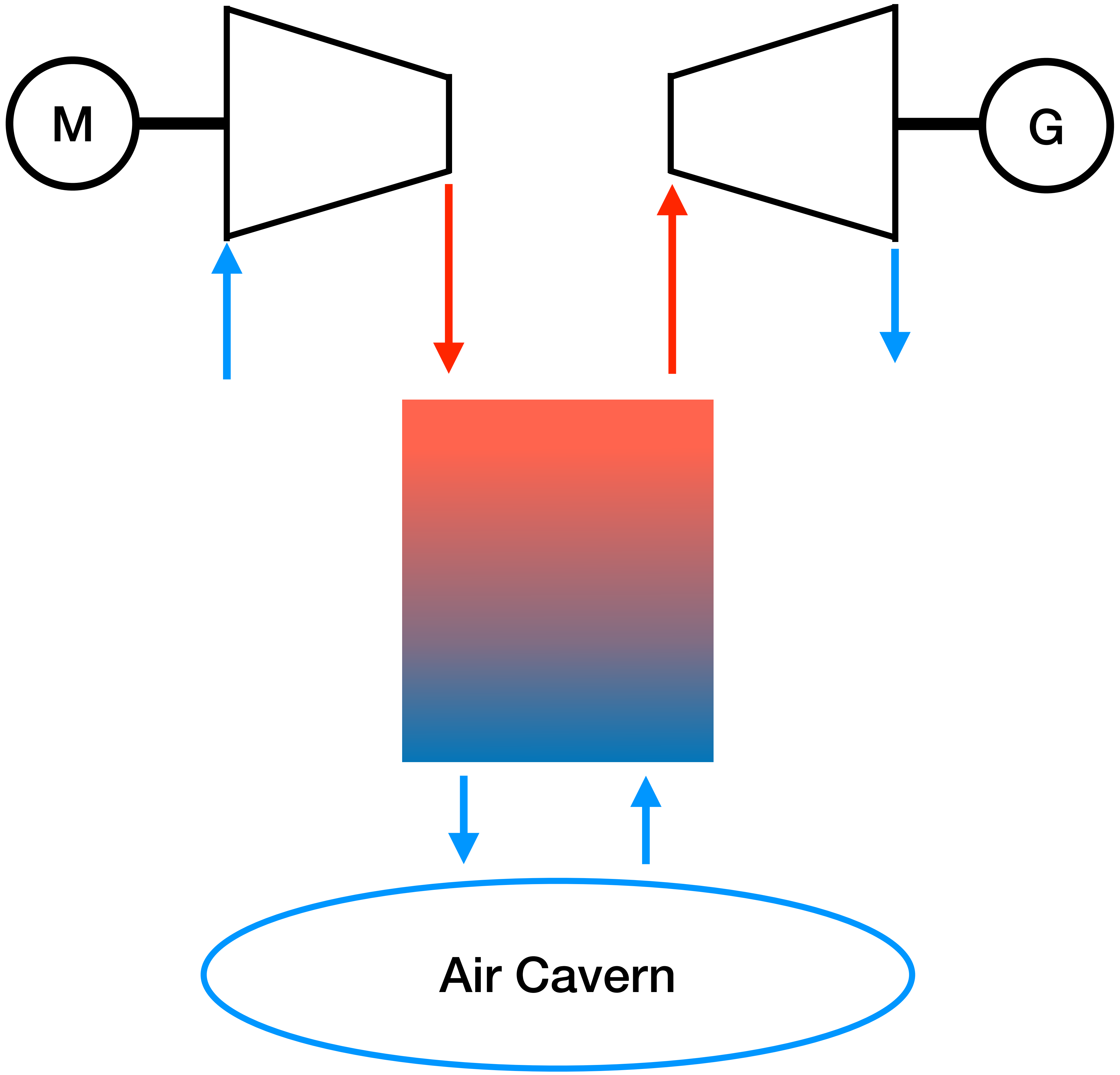


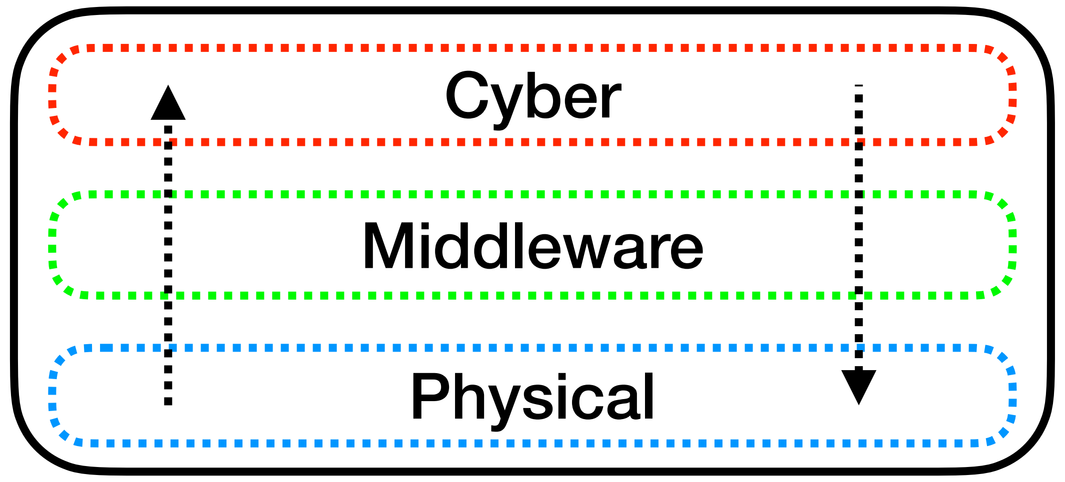
Challenges
- Improve round trip efficiency
- Reduce cost
- Enable heat addition from various sources (natural gas, solar, geothermal, …)
- Dynamic controls and integration

→ **Co-design**

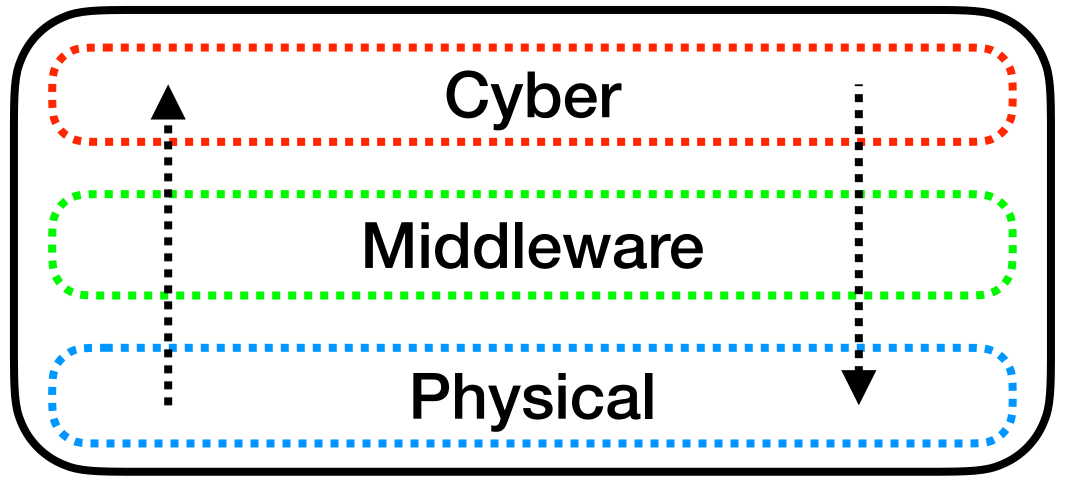
Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.





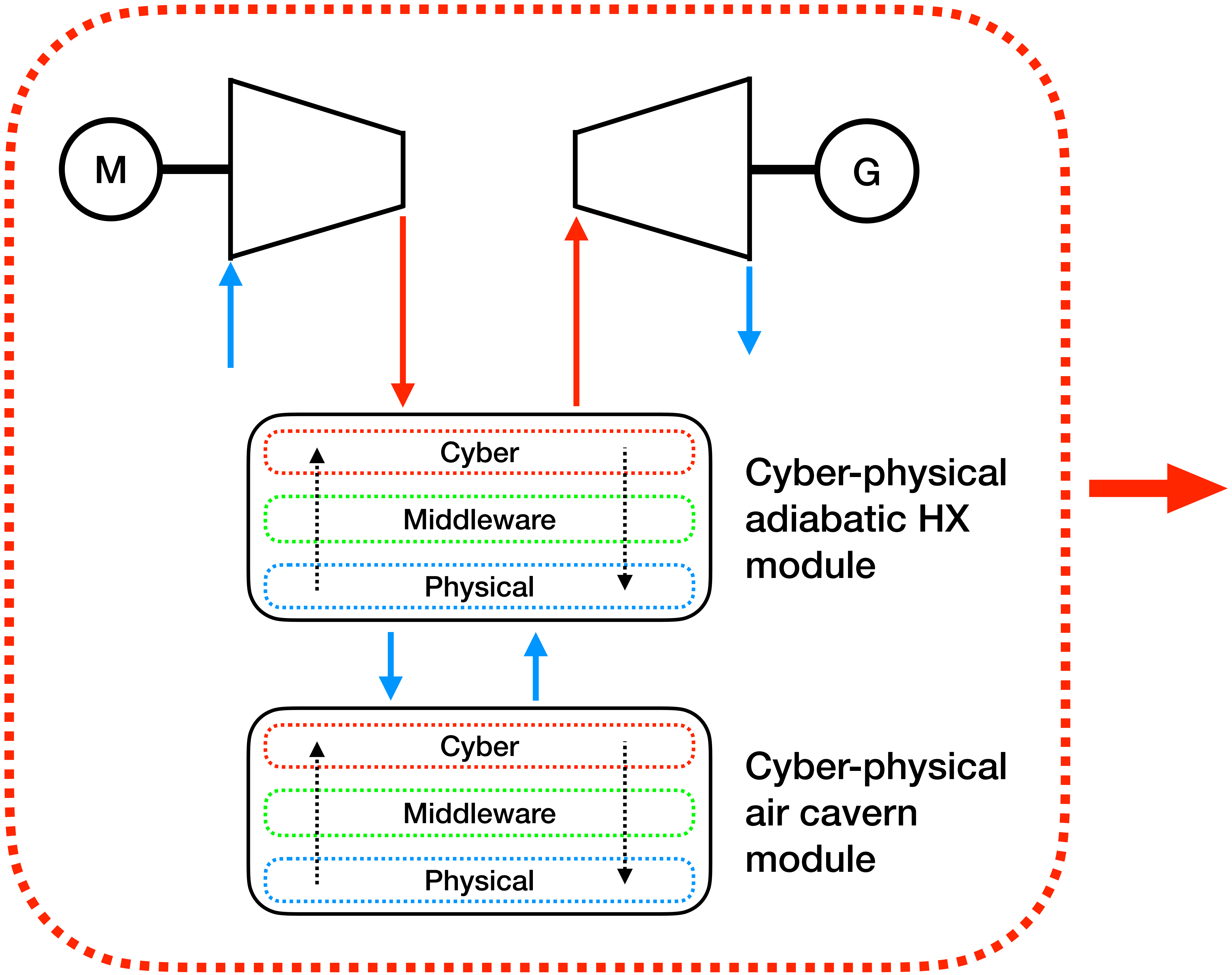
Cyber-physical adiabatic HX module



Cyber-physical air cavern module

Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.

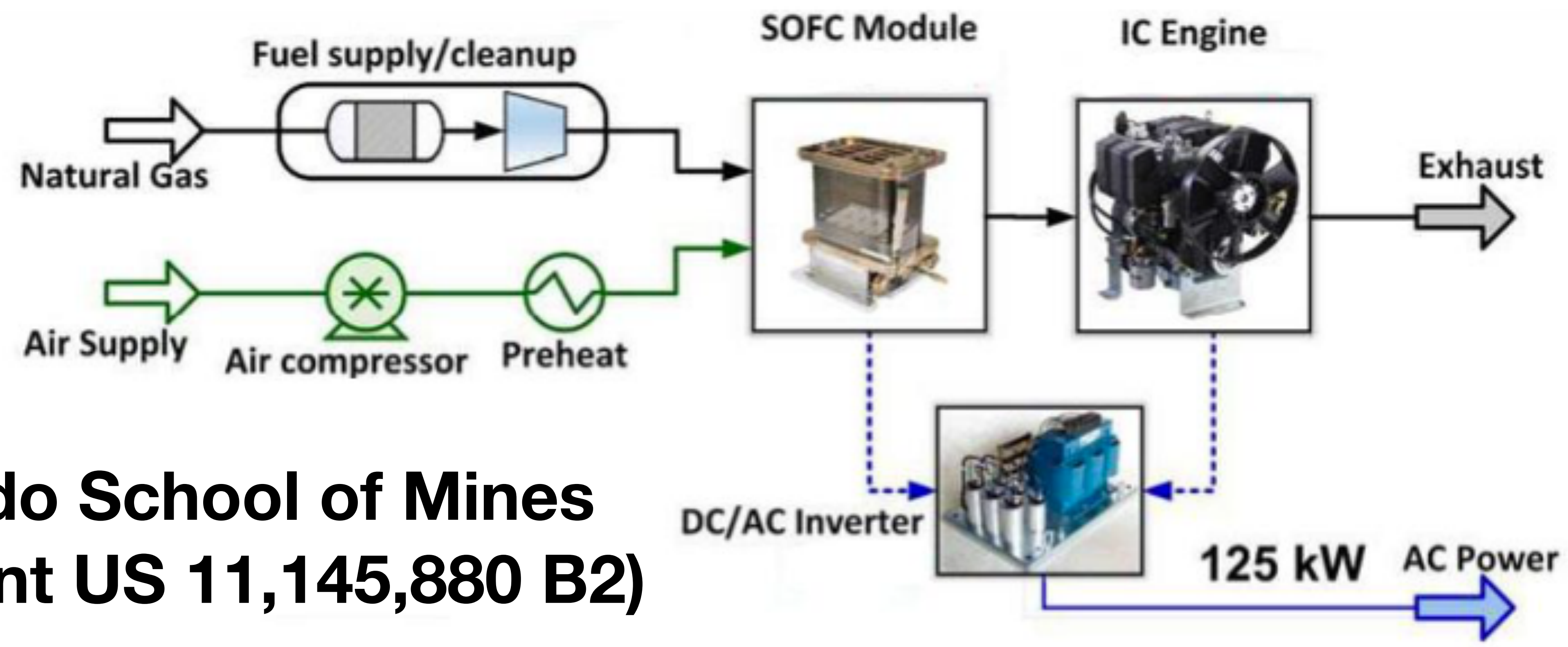


Cyber-physical energy system model

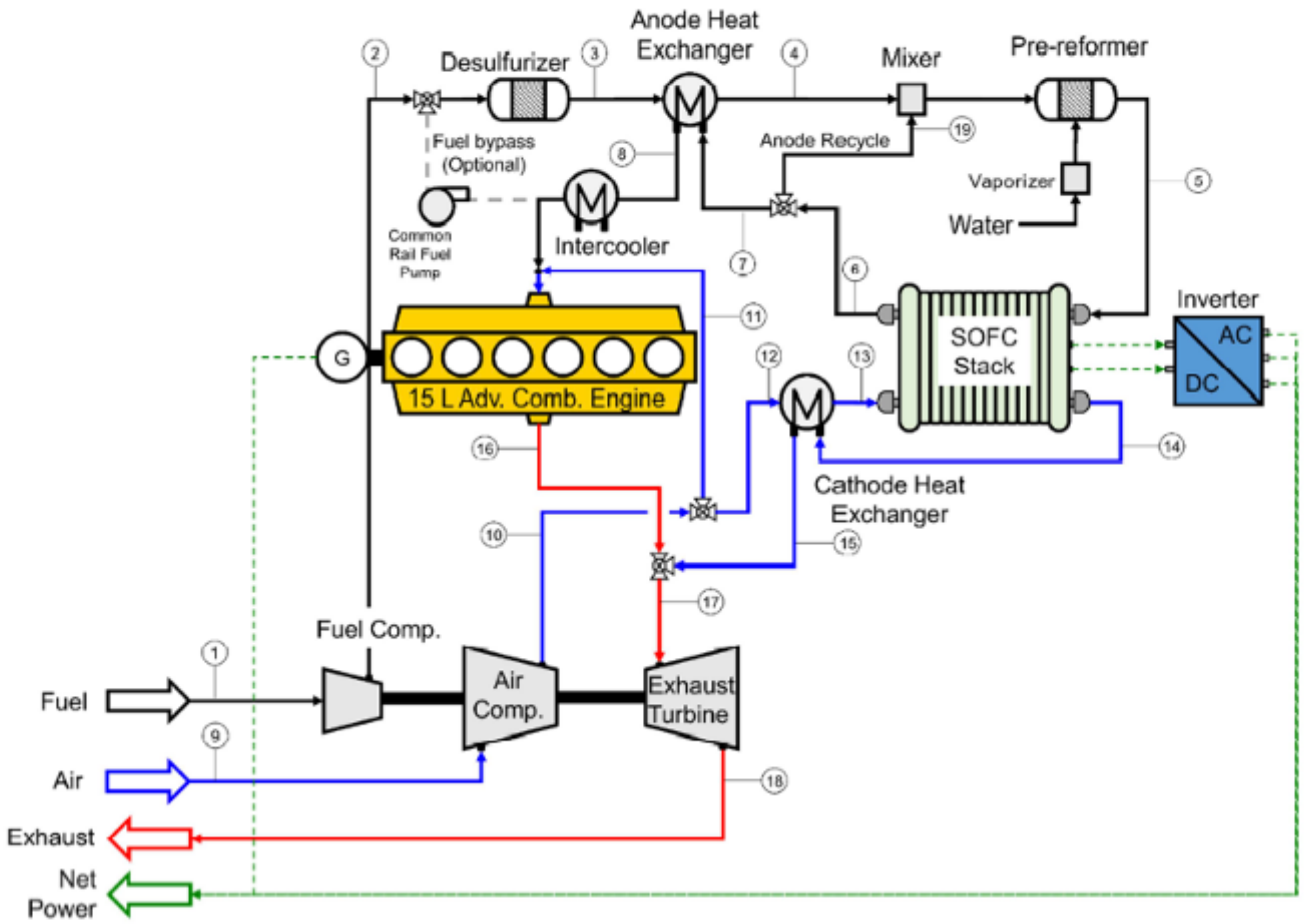
Developing a cyber-physical model

1. Define the purpose of the cyber-physical model
2. Identify the essential functions of each component of the system
3. Determine how to best represent each component of the system
   [Physical, computational or cyber-physical]
4. Determine the system requirements and the interface requirements between the components
5. Build the physical, computational, and cyber-physical components
6. Assemble and build the cyber-physical model

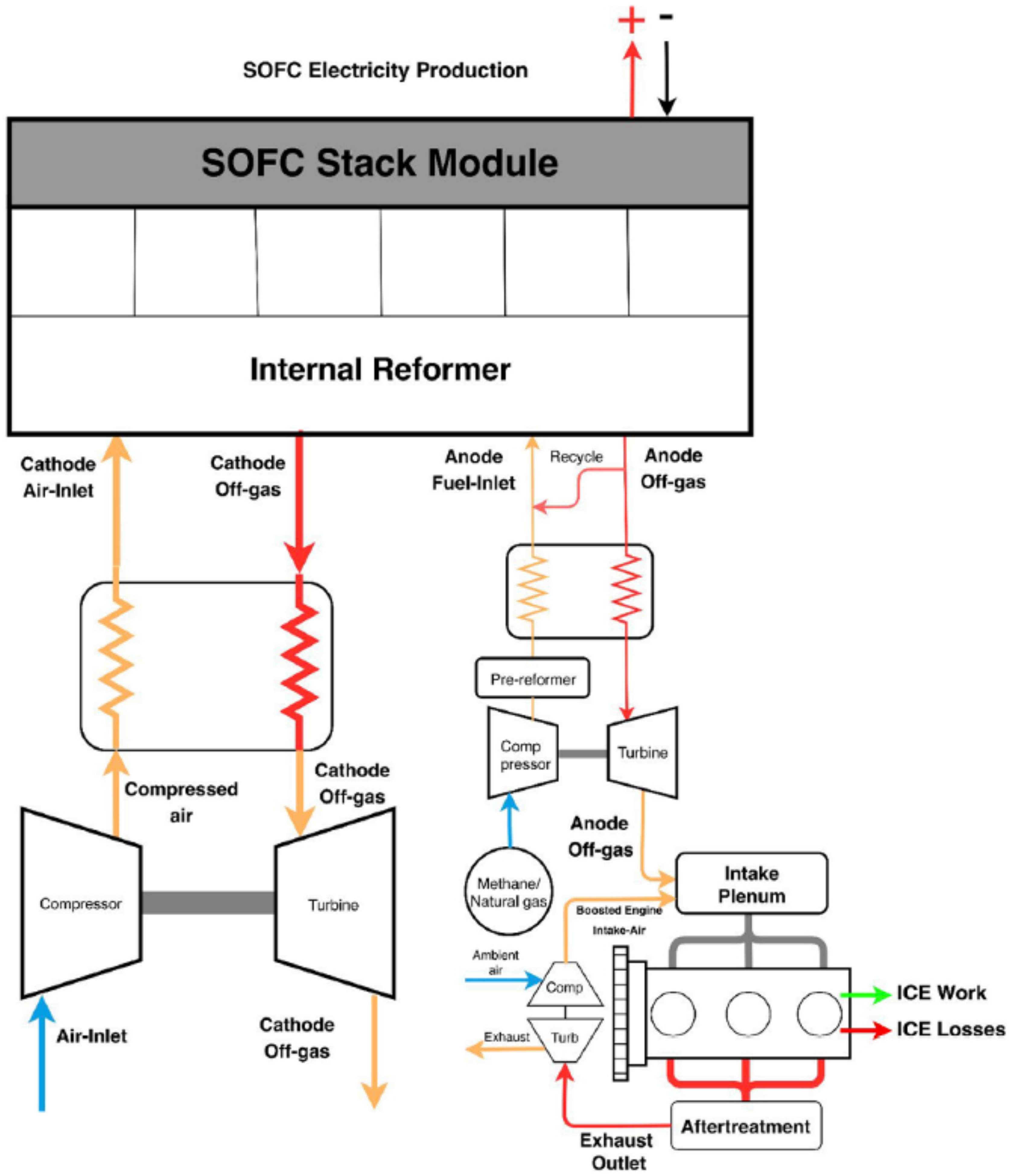
Solid oxide fuel cell - internal combustion engine hybrid



Colorado School of Mines
(US Patent US 11,145,880 B2)

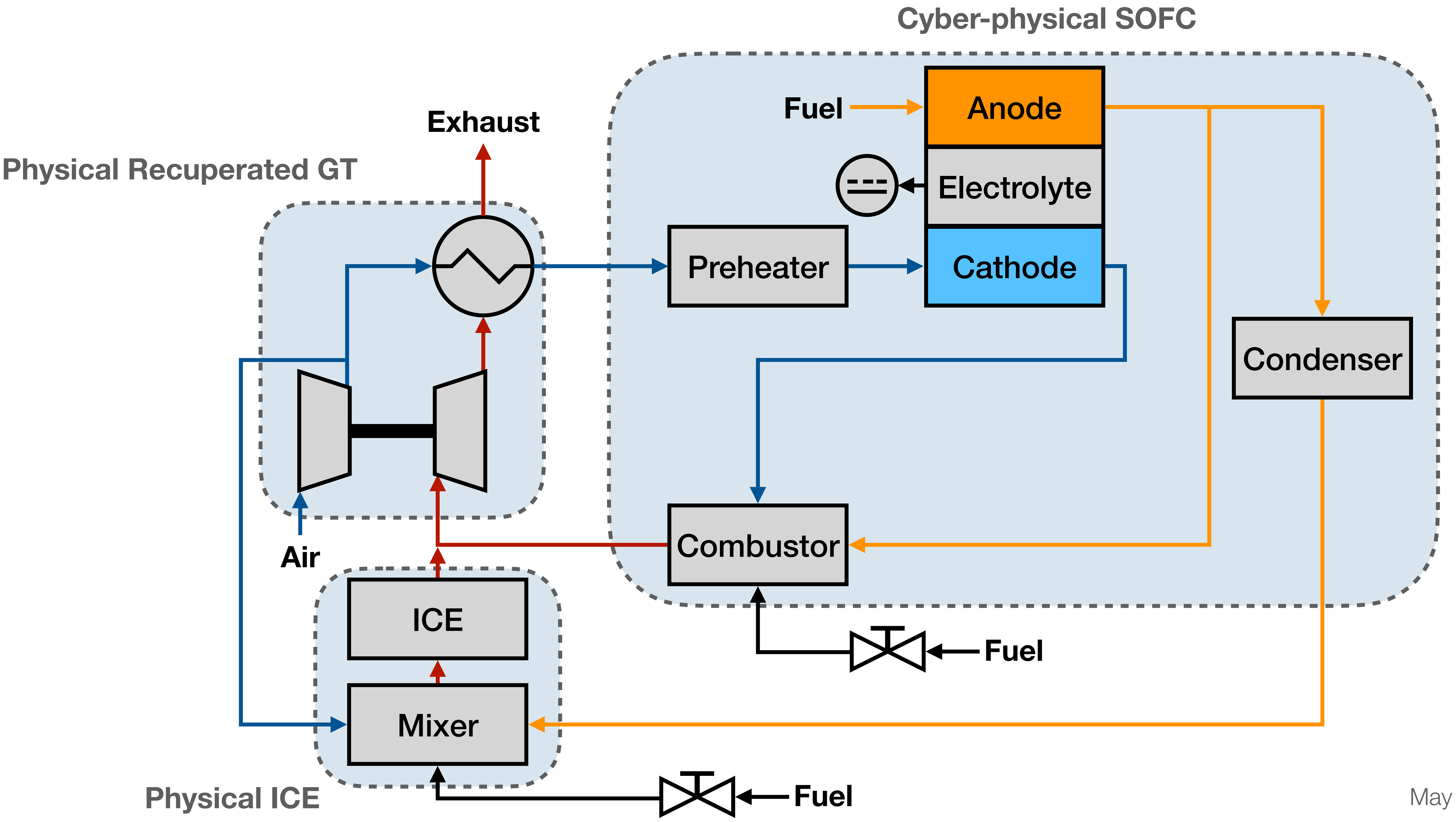


University Wisconsin-Madison
Chuahy and Kokjohn et. al., 2018

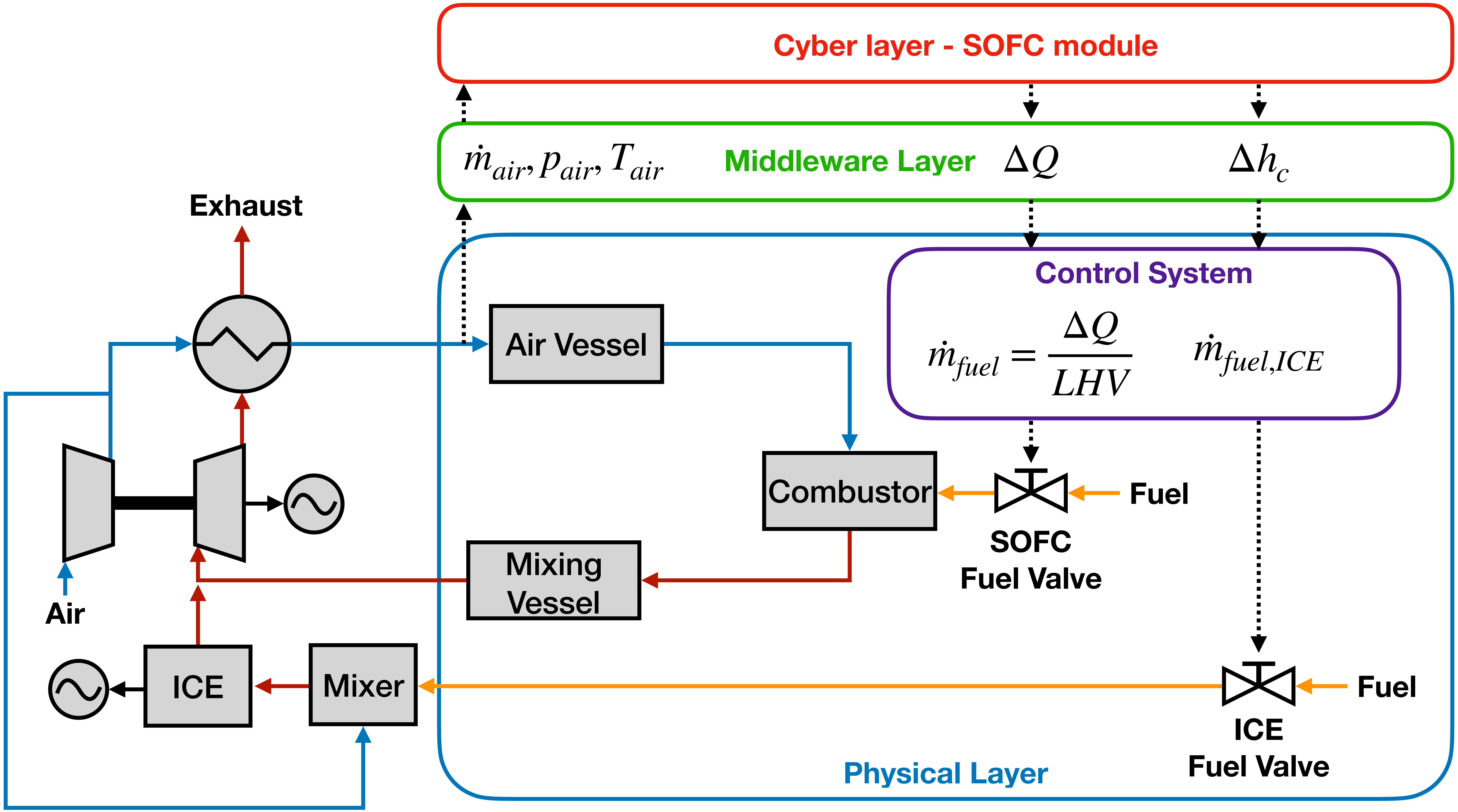


Stony Brook University
Ran et. al., 2021

Solid oxide fuel cell - internal combustion engine hybrid



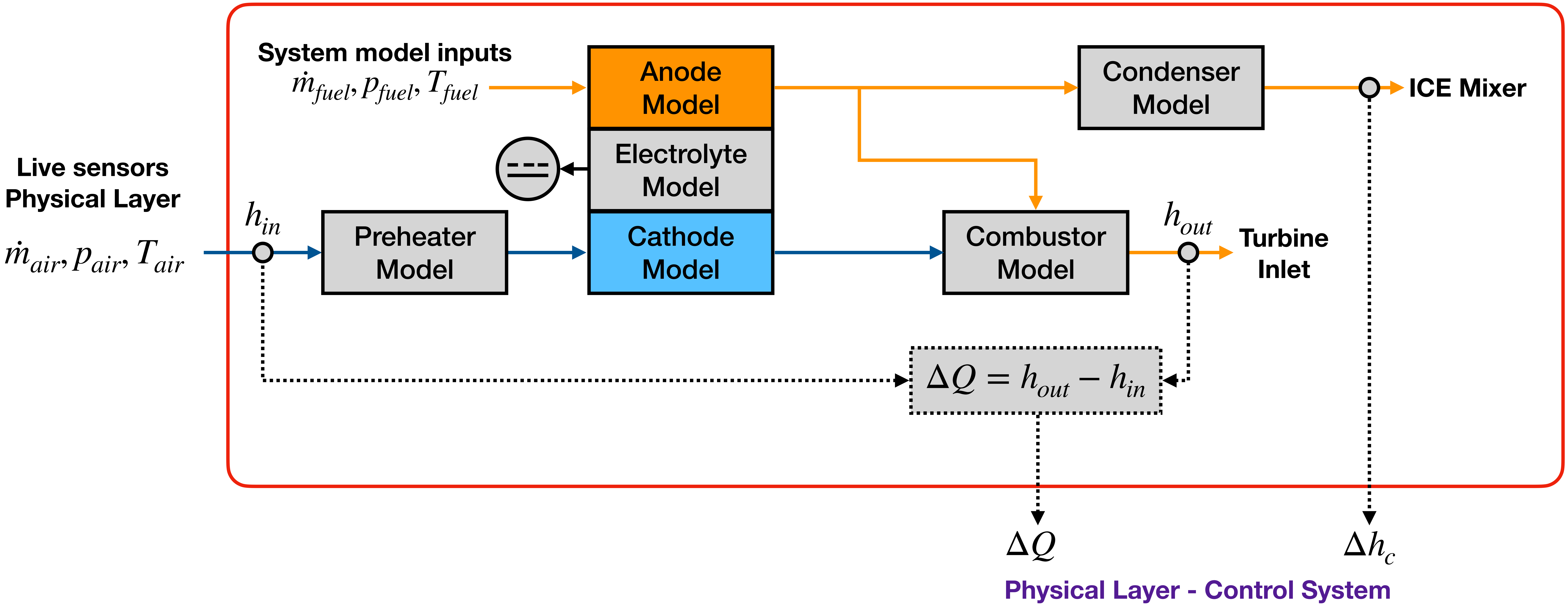
SOFC-ICE Cyber-physical model



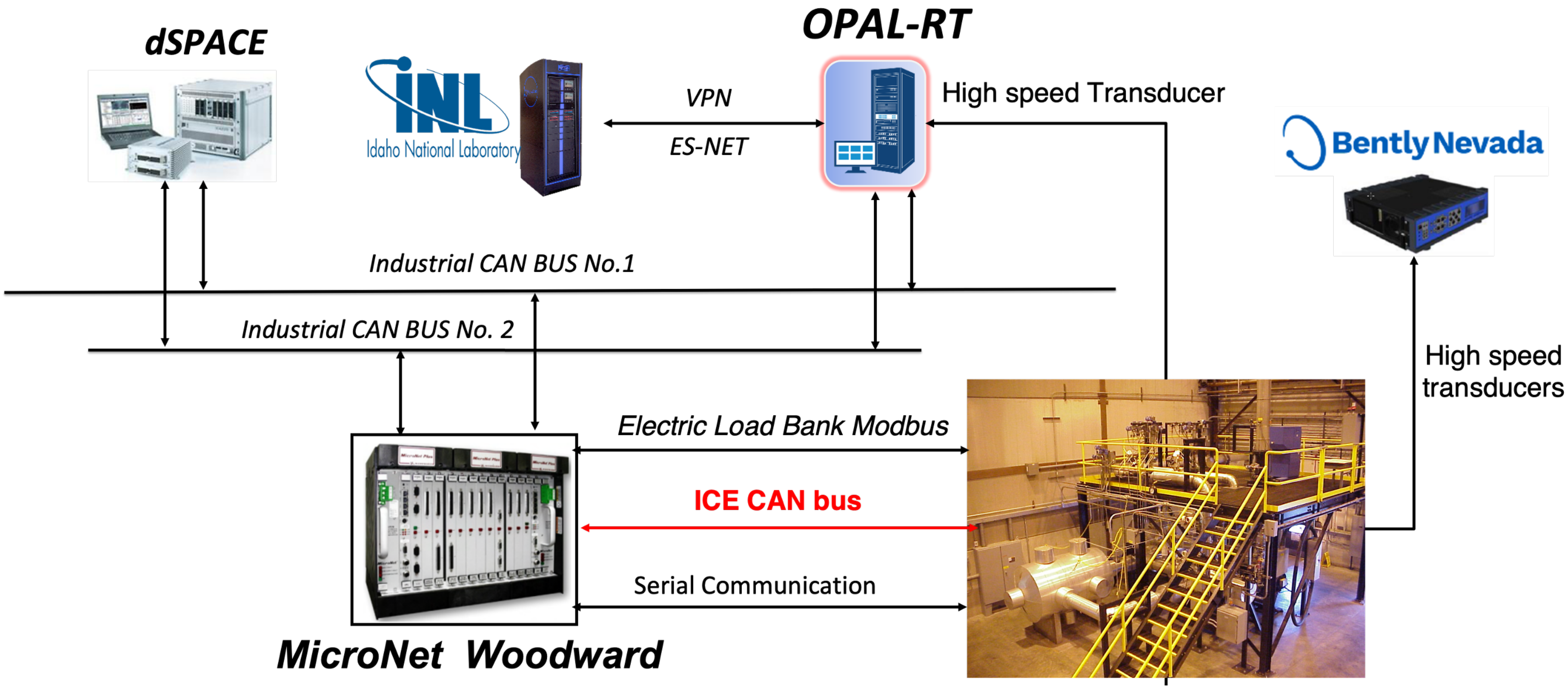
- Thermal

- Pressure
- Mass flow
- Thermal

Cyber Layer - SOFC module



Middleware Layer



What about hardware-in-the-loop?

Hardware-in-the-loop …

… a real-time simulation that contains both computational and physical components that share information. Generally, this information share is focused on the performance of one of the components that is being tested and often does not fully address the performance of other components within the system

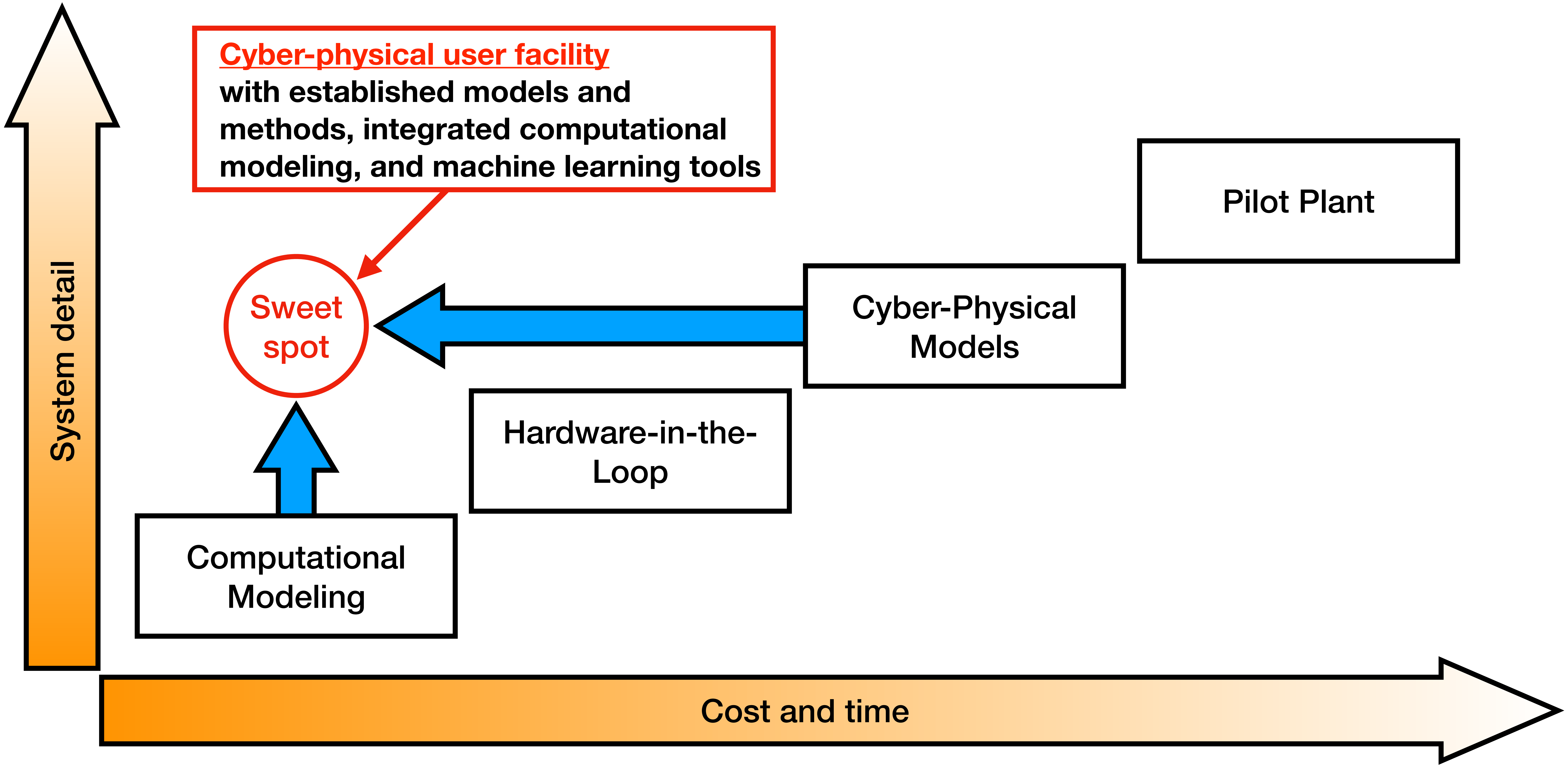
What about digital twins?

Digital twin …

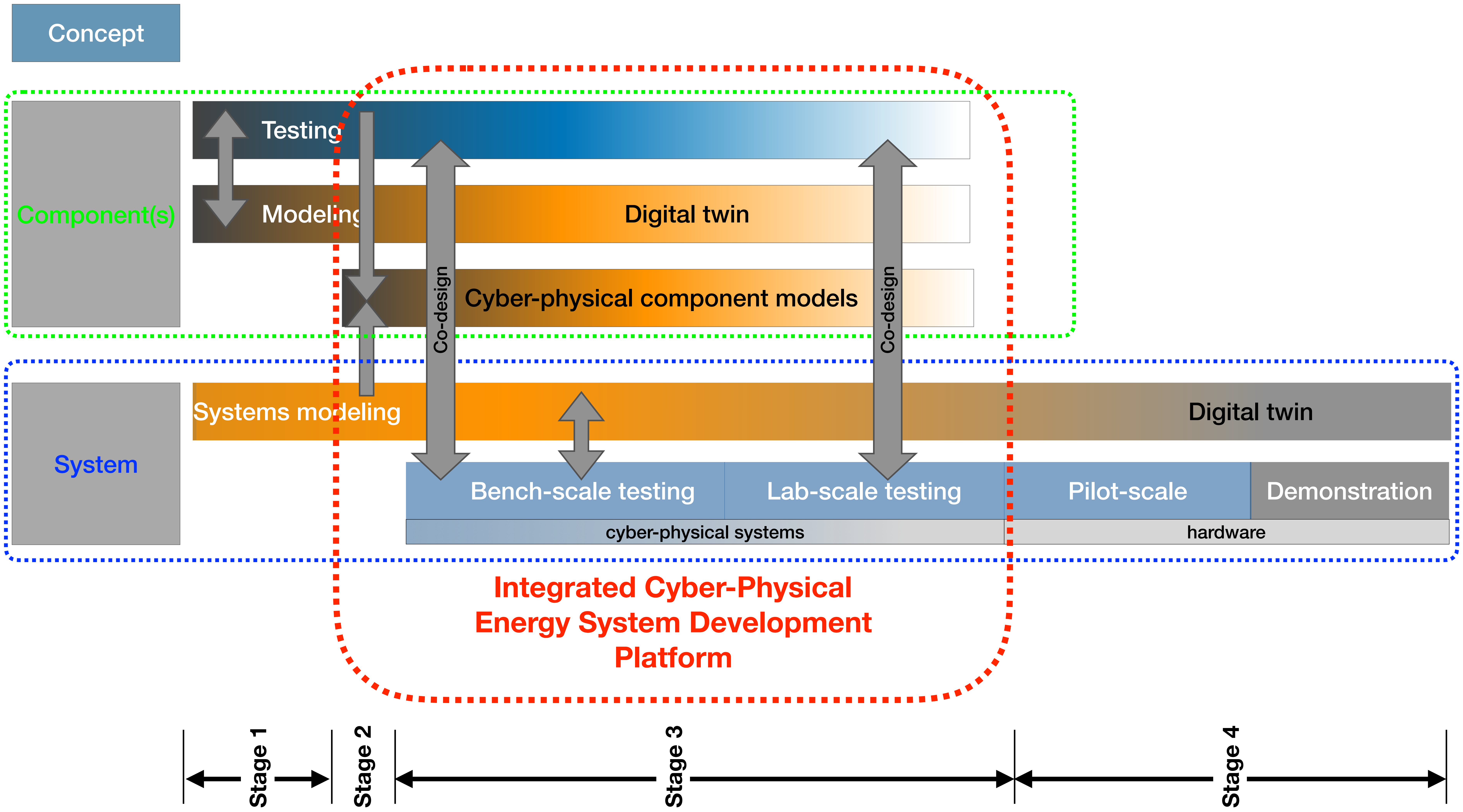
… a term used to describe a virtual model that accurately mimics (twins) a physical system, such as a power plant. The goal is that this digital twin is tightly coupled to the physical power plant during operation and information is shared bidirectionally in real time to provide a mirroring response to real-time changes in either the physical or virtual plant.

The virtual representation is developed concurrently with the physical plant and is deployed alongside it, changing throughout the lifecycle of the plant.

A trade-off between ‘ground truth’ and flexibility



Energy system development platform



Questions?

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