

IDAES
Institute for the Design of
Advanced Energy Systems

Progress on Dynamics & Control in the IDAES Framework

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IDAES Stakeholder Meeting, May 16, 2019



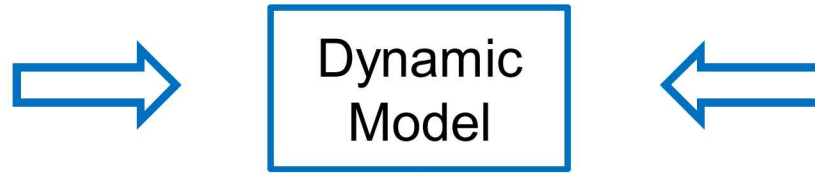
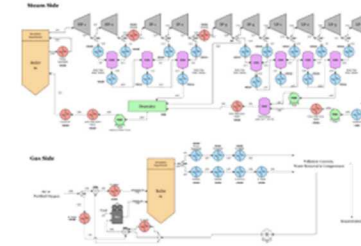
Process dynamics are important

Existing Plants



https://en.wikipedia.org/wiki/TECO_Energy

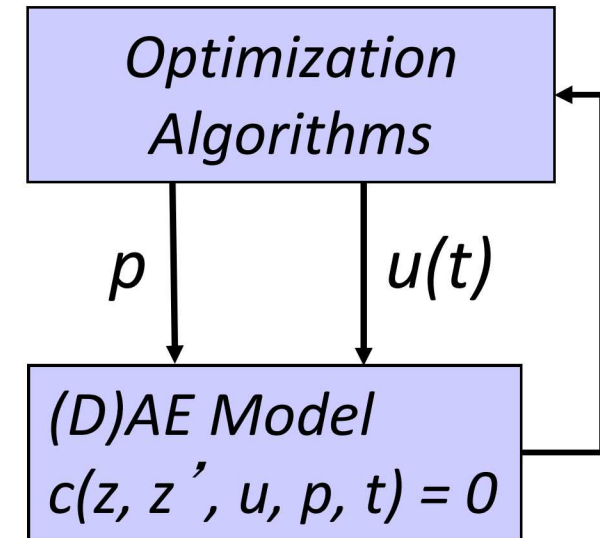
Future Energy Systems



- Improve process:
 - safety
 - profitability
 - reliability
 - adaptability
- Predict, understand, and exploit:
 - process dynamics and limits
 - complex interactions between process units
- Optimize operation during:
 - start-up
 - ramps & transitions
 - range of operating conditions
- Respond to real-time electricity pricing

How process dynamics are handled in current tools

- Focus on forward simulation and not optimization
- Wrap process simulator in an optimization algorithm
- Limited support for custom dynamic model/algorithm development
 - Data reconciliation
 - Parameter estimation
 - Advanced state estimation and control



How process dynamics are handled in current tools

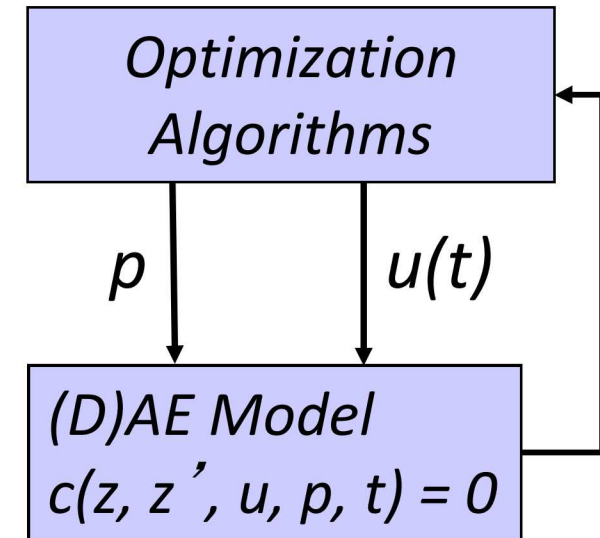
- Focus on forward simulation and not optimization
- Wrap process simulator in an optimization algorithm

Our approach:

Simultaneously converge the process dynamics and the optimization problem

Optimization
 $Min f(x)$
 $s.t. x \in X$

(D)AE Model
 $c(x) = 0$
 $x = \{z, z', u, p, t\}$



Evolution of NLP Algorithms & Tasks

' 80s: Flowsheet optimization
~ 100 variables and constraints

' 90s: Static real-time optimization (RTO)
over 100 000 variables & constraints

' 00s: Simultaneous dynamic optimization
over 1 000 000 variables and constraints

' 10s: Sensitivity-based dynamic on-line
optimization for large NLPs: < 1 CPUs

SQP



rSQP



IPOPT



sIPOPT

The most efficient NLP tools now handle millions of variables and constraints with modest computational effort

Dynamic optimization challenges in practice

- **Dynamic model formulation**
 - fidelity?
 - well-posed-ness? (singular, high-index, etc.)
 - scaling?
- **Applying a discretization**
 - which scheme to use?
 - discretization resolution? (trade-off between accuracy and problem size)
- **Large-scale nonlinear programming (NLP) problem**
 - model initialization?
 - ill-conditioning?
 - solution time? (suitability for on-line application)

Optimization

Min $f(x)$

s.t. $x \in X$

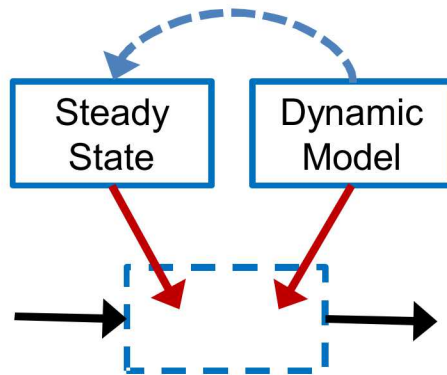
(D)AE Model

$c(x) = 0$

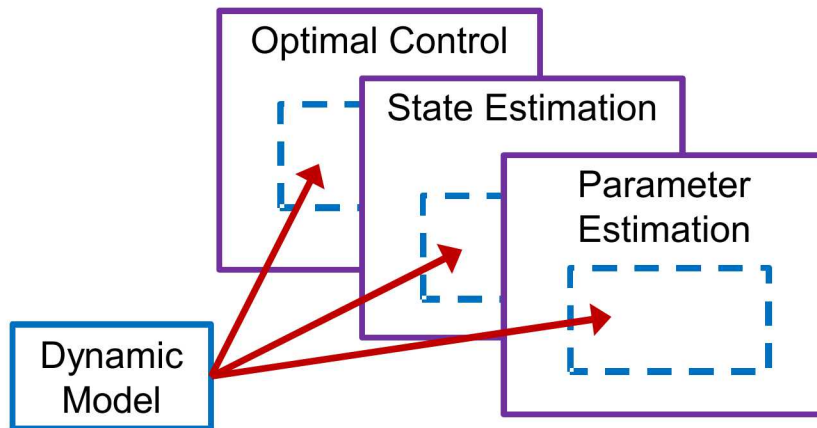
$x = \{z, z', u, p, t\}$

Vision of the IDAES Dynamic Optimization Framework

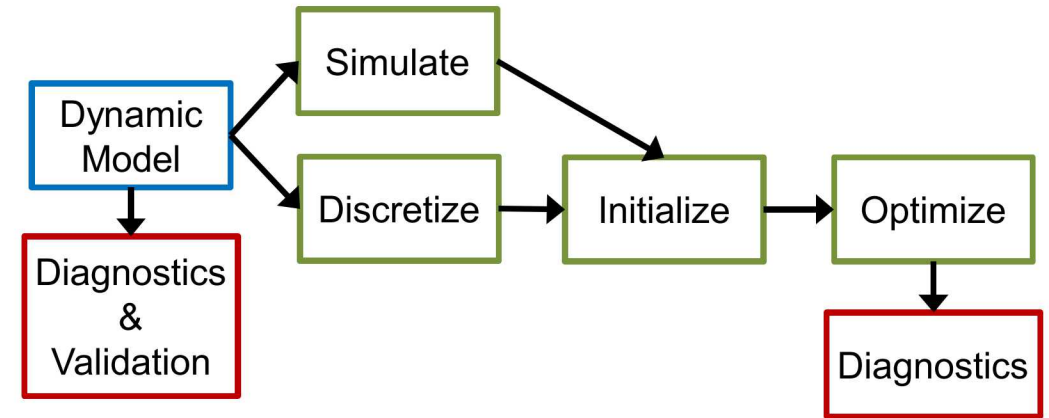
Unit model infrastructure



“Plug-and-play” formulations

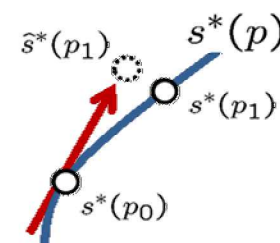


Dynamic optimization solution tools



Novel algorithms

Sensitivity-based approaches



New formulations

- MHE
- NMPC
- Economic NMPC

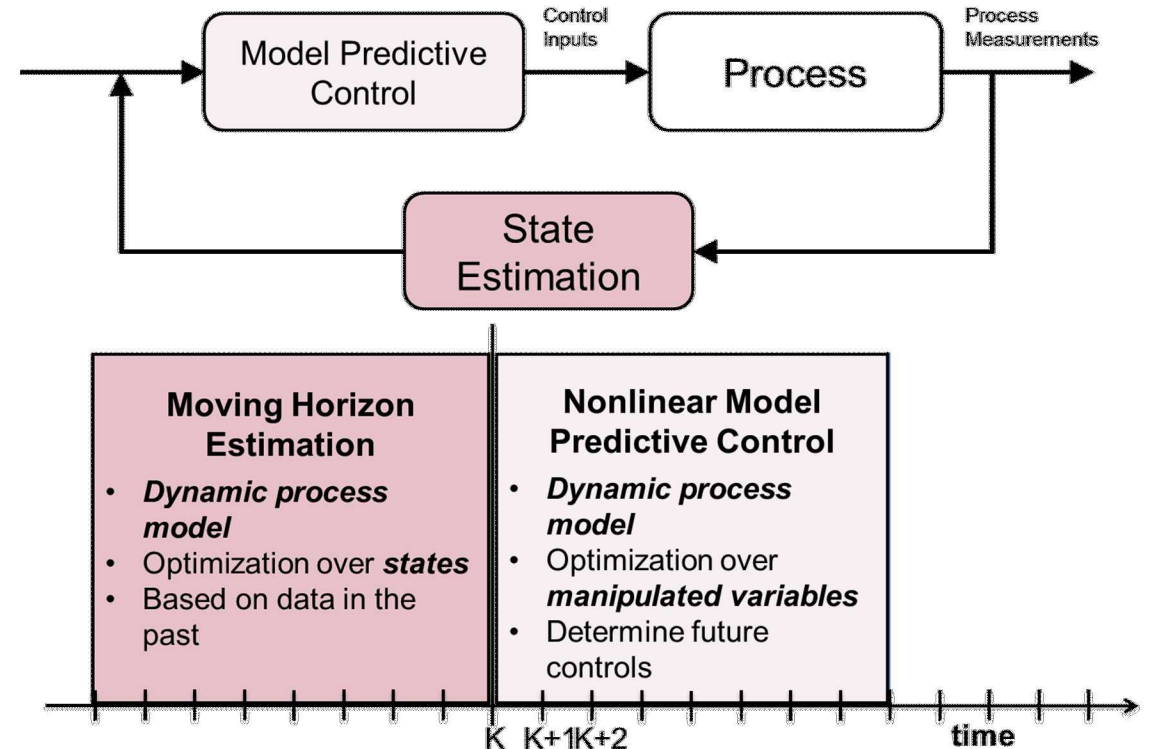
Parallel solution approaches

$$\begin{bmatrix} K_1 & & & & A_1 \\ & K_2 & & & A_2 \\ & & \ddots & & \vdots \\ & & & K_N & A_N \\ A_1^T & A_2^T & \dots & A_N^T & D \end{bmatrix}$$

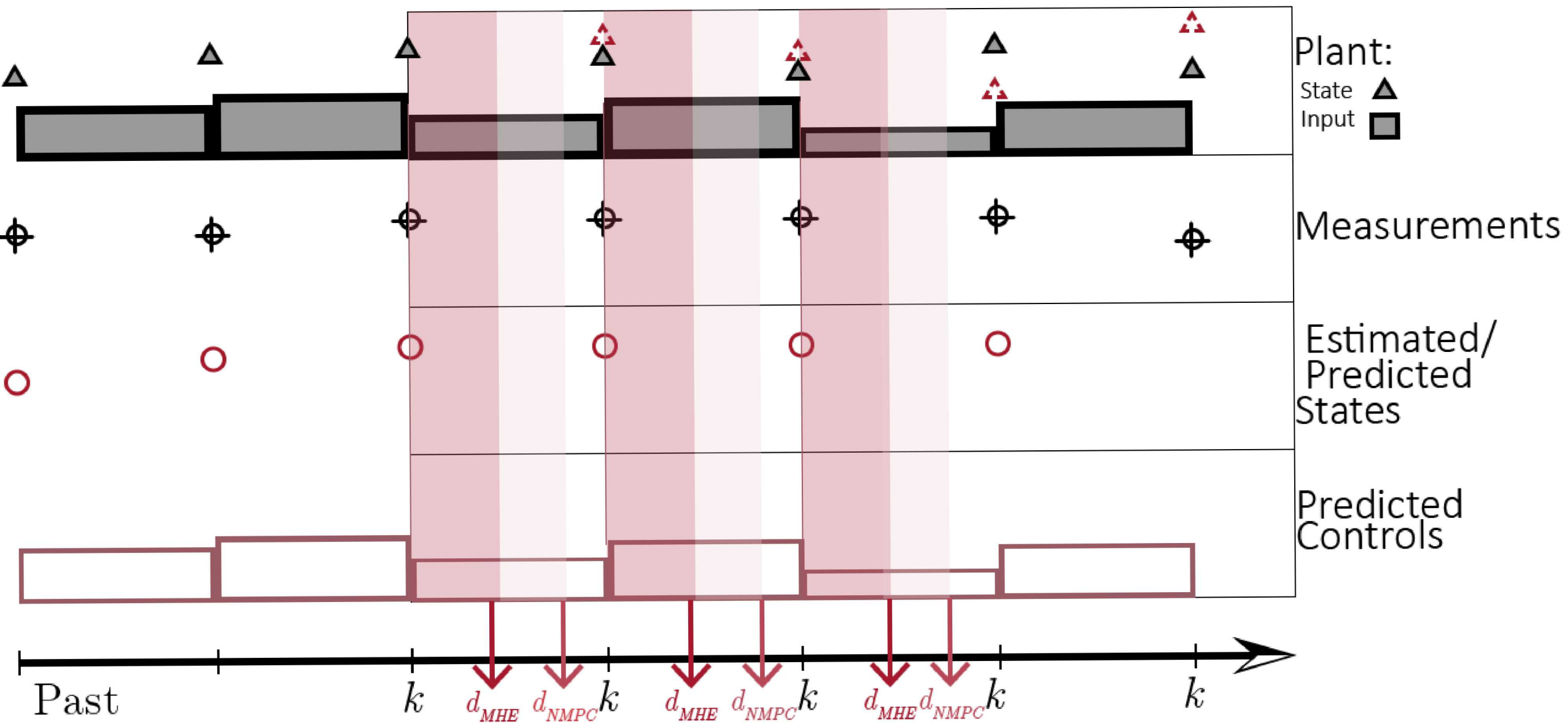
$$\begin{bmatrix} D_1 & U_1 & & & \\ L_2 & D_2 & U_2 & & \\ & & \ddots & & \\ & & & L_{N-1} & D_{N-1} & U_{N-1} \\ & & & & L_N & D_N \end{bmatrix}$$

Advanced state estimation and control

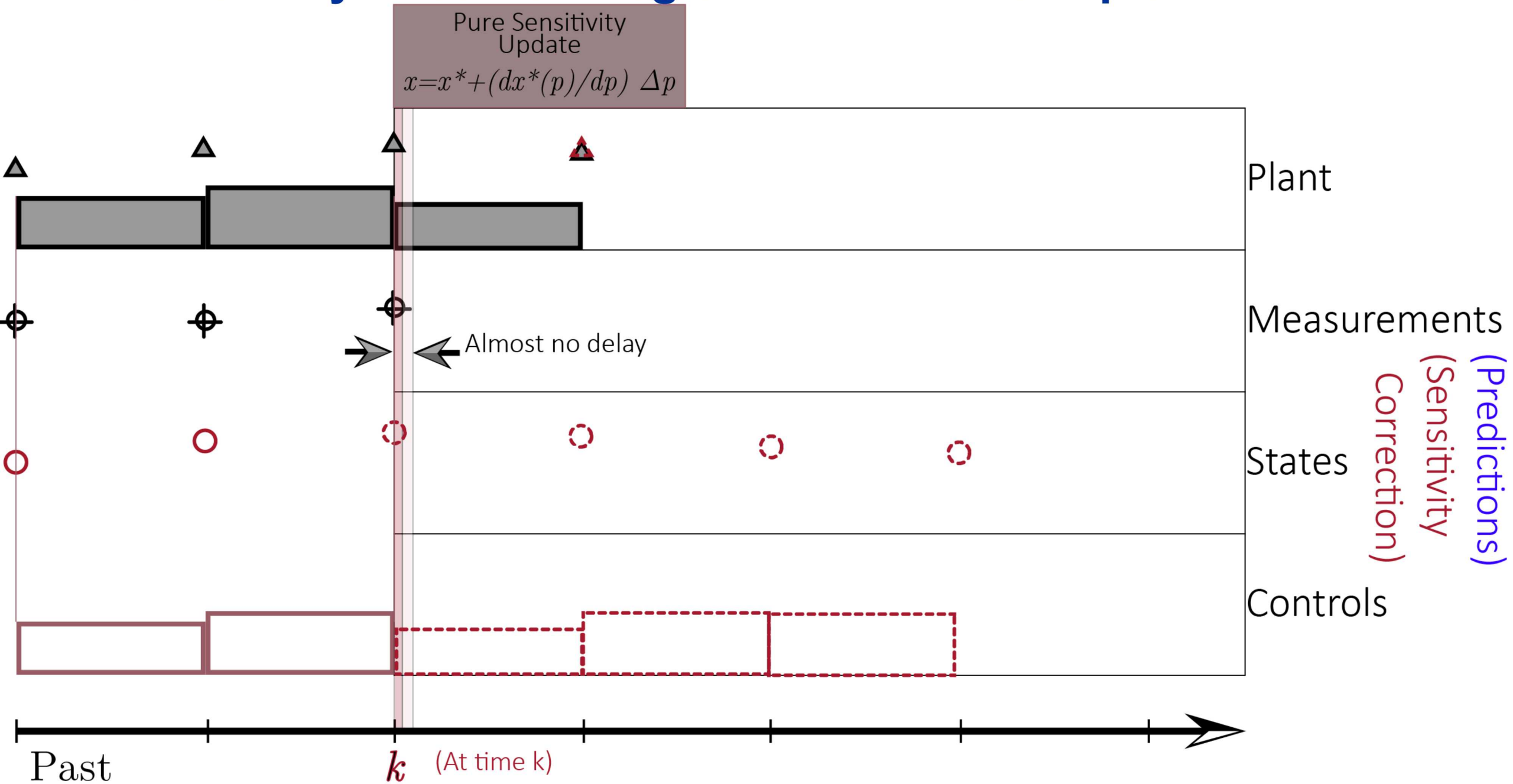
- Explicitly incorporate process dynamics
- Require repeated solves of large-scale nonlinear optimization problems
- Can be difficult to implement
- IDAES framework will provide:
 - “Plug-and-play” frameworks for advanced problem formulations to simplify and streamline the implementation process and enable code re-use by separating the dynamic model from the specific problem formulation



Computational delays with MHE and NMPC

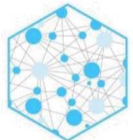
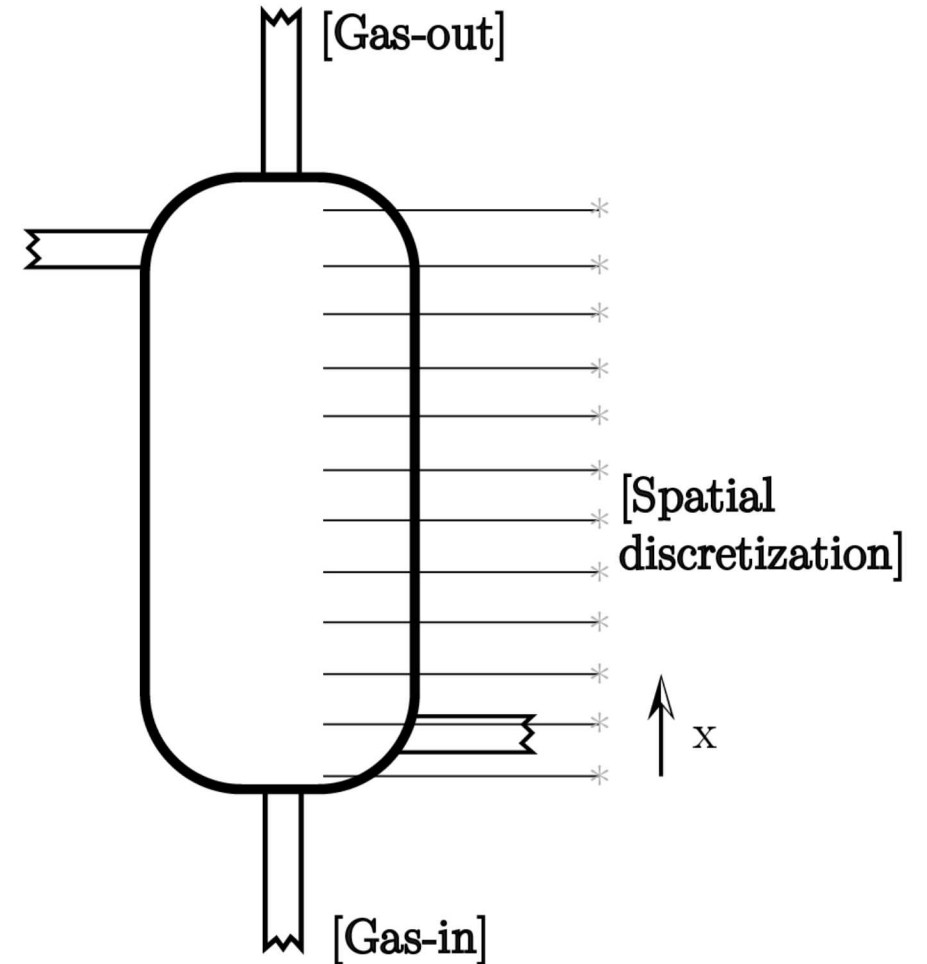


Sensitivity-based strategies for real-time implementation

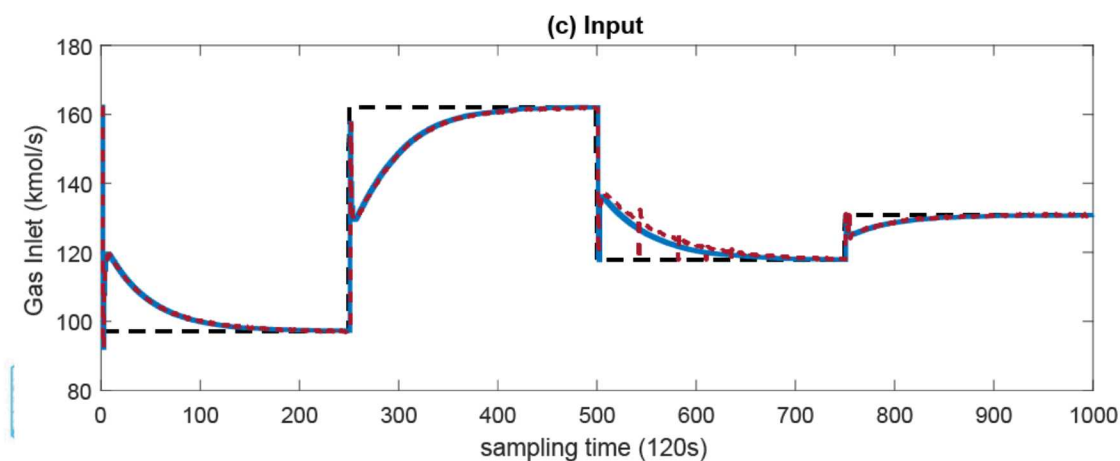
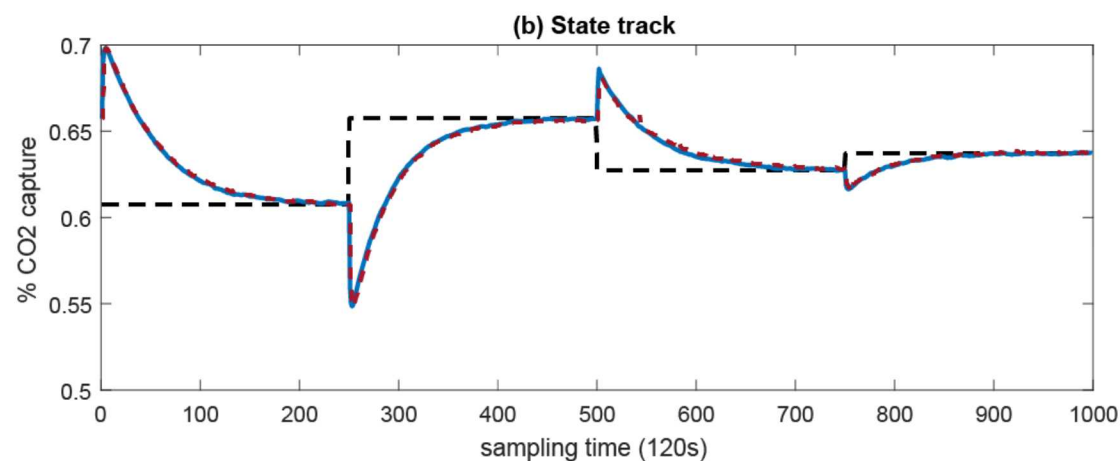
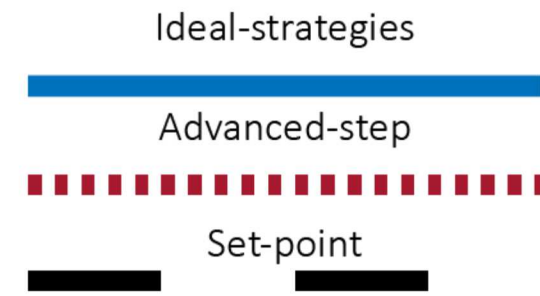
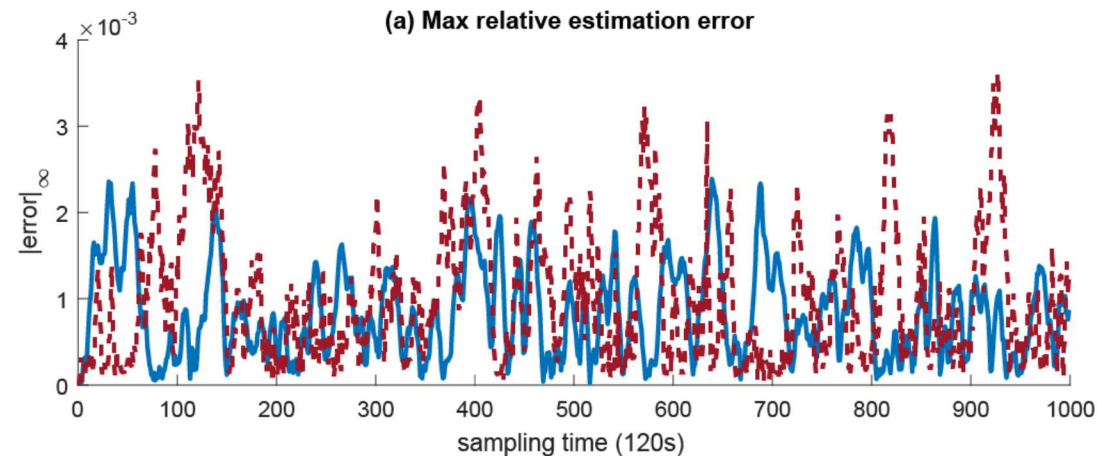


Case study: Bubbling Fluidized Bed Reactor

- Originally based on the Kunii-Levenspiel 3-region 2-phase model.
- Partial-Differential Algebraic model with 1-D mass, energy and momentum balances + empirical correlations.
- Set-points: CO₂ removal fraction
- Measure: inner temperature and gas velocity
- Controls: gas input flow
- Discretized with orthogonal collocation (time-space)
 - 5, 3 finite elements & collocation points (Legendre) in space
 - 10, 1 finite elements & collocation points (Radau) in time
- 32810 variables and 31300 equations
- 150 states for the current discretization
- **Full-state feedback control**
- Random state noise with $\sigma_w = 10^{-4}$



Case study BFB



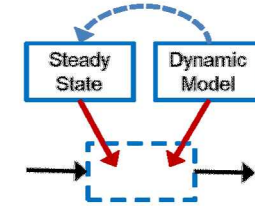
Ideal MHE+NMPC (delay): 29.91 seconds
 Overall online (delay): 0.65 seconds

		BFB CO_2	
		NMPC	MHE
Offline	NLP (Ipopt)	6.83	9.45
	Red. Hessian (k_aug)	-	13.63
	Sens. Matrix (k_aug)	12.49	7.94
Online	<i>Sens. step (dot_sens)</i>	<i>0.13</i>	<i>0.52</i>

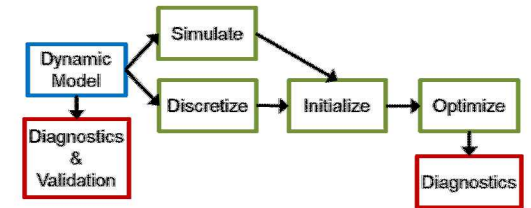
Advantages of the IDAES Dynamic Optimization framework

- A single framework for dynamic process model development, simulation, and optimization
- Tools for dynamic model development including:
 - Model identification and parameter estimation tools
 - Sensitivity analysis tools
 - Model reliability and convergence testers
 - Timescale based model reduction

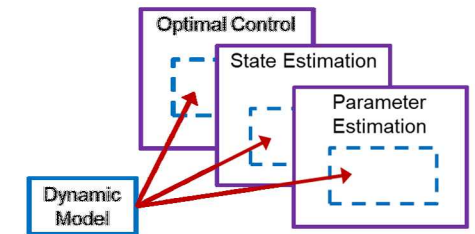
Unit model infrastructure



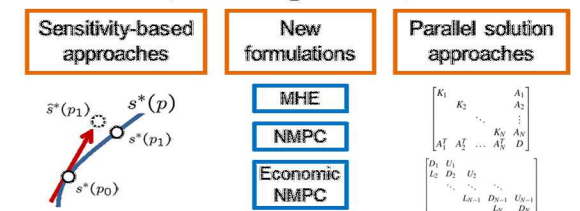
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“Plug-and-play” formulations



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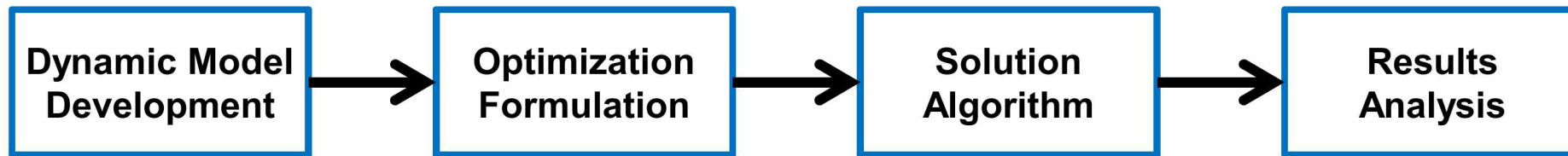


Related Posters

- Process Dynamics and Advanced Process Control (Bethany Nicholson)
- Advanced Dynamic Modeling for Fluidized Beds (Rob Parker, David Thierry)

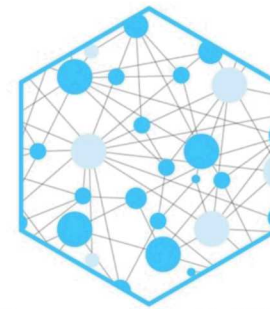
Conclusions and Next Steps

- Explicitly modeling process dynamics creates opportunities for:
 - improving the operation of existing plants
 - designing efficient and flexible future energy systems
- Dynamic optimization tools being developed with emphasis on:
 - ease of use, flexibility, complete life cycle support



- Future development:
 - Demonstrate Caprese on dynamic IDAES models
 - Framework for creating reduced order models
 - Complete dynamic power plant unit models and flowsheets of subcritical/supercritical plants
 - Develop infrastructure for lower-level control loops

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We graciously acknowledge funding from the U.S. Department of Energy, Office of Fossil Energy, through the Crosscutting Research Program and the Advanced Combustion Systems Program.

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- **National Energy Technology Laboratory:** David Miller, Tony Burgard, John Eslick, Andrew Lee, Miguel Zamarripa, Jinliang Ma, Dale Keairns, Jaffer Ghose, Emmanuel Ogbe, Gary Kocis, Ben Omell, Chinedu Okoli, Richard Newby, Grigorios Panagakos, Maojian Wang
- **Sandia National Laboratories:** John Sirola, Bethany Nicholson, Carl Laird, Katherine Klise, Dena Vigil, Michael Bynum, Ben Knueven
- **Lawrence Berkeley National Laboratory:** Deb Agarwal, Dan Gunter, Keith Beattie, John Shinn, Hamdy Elgammal, Joshua Boverhof, Karen Whitenack
- **Carnegie Mellon University:** Larry Biegler, Nick Sahinidis, Chrysanthos Gounaris, Ignacio Grossmann, Owais Sarwar, Natalie Isenberg, Chris Hanselman, Marissa Engle, Qi Chen, Cristiana Lara, Robert Parker, Ben Sauk, Vibhav Dabadghao, Can Li, David Molina Thierry
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