Evaluation of microreactor requirements and performance in an existing well-characterized microgrid

Project 20-19693

Alvin Lee, Dimitri Kalinichenko, Lucas Wodrich, Caleb S. Brooks, Tomasz Kozlowski
University of Illinois

March 8th , 2023

Project Purpose:

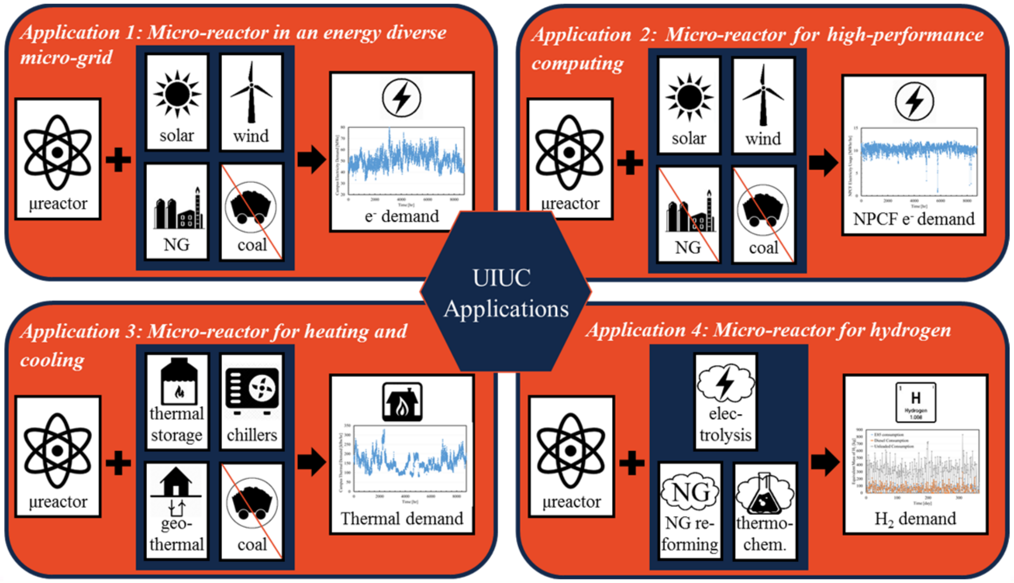
To quantify the opportunities and challenges of operating micro-reactors in populated, decentralized power generation environments and the potential for deployment in established micro-grids with diverse power generation sources.

Project Objectives:

1) Develop integrated system modeling of micro-reactor applications.
2) Incorporate available data to validate modeling.
3) Simulate normal and bounding events.
4) Determine economic performance requirements across applications.
5) Identify operational requirements and opportunities across applications.
6) Determine the scalability of microreactor deployment at campuses and other existing microgrids.

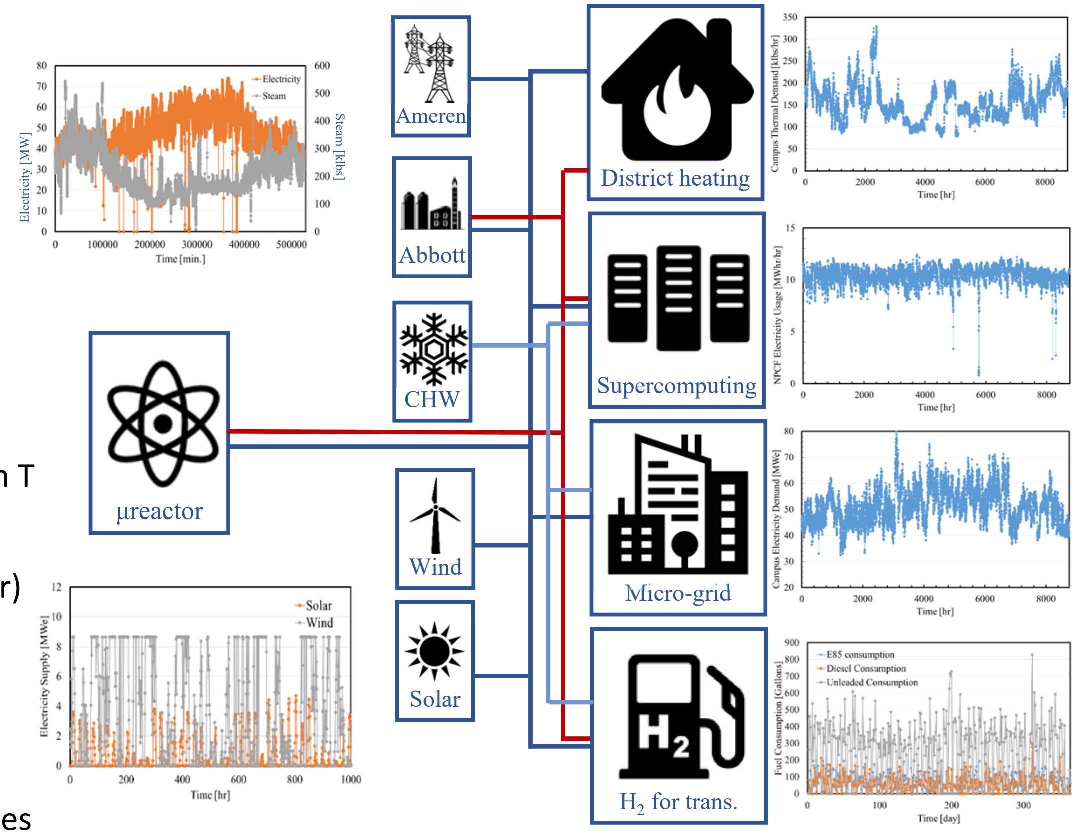
Project Outcomes:

1. Detailed analysis of the market potential for micro-reactors in existing microgrids
2. Expansion of the Modelica-based hybrid energy system modeling to include the existing well-characterized environment of a functioning microgrid with diverse energy generation and dispatch portfolio,
3. Economic target for microreactors deployed as electricity producers, thermal energy producers, and hydrogen producers,
4. Identification of specific economic and technical opportunities to guide technology development efforts,
5. Foundational training of the next generation of nuclear engineers in the critical path for the wide adoption of clean, safe, reliable nuclear power.



Overview of UIUC Microgrid

- Electrical
  - 55 MW_e average demand (Peak 80 MW_e)
  - Blue Waters Supercomputer up to 15 MW_e
  - Wind: ~25,000 MWhr/yr
  - Solar: ~7,200 MWhr/yr (20,000 MWhr/yr new installation)
  - Chillers: ~20 MW_e peak
- Thermal
  - 50 MW_{th} average demand
  - High P steam constant, Low P steam varies with T
  - 6 Chilled water plants (2 steam, 21 electric)
  - Energy storage (6.5 million gallons chilled water)
- Transportation
  - Campus fleet ~ 800 gallons/day
  - Campus bus system: up to 3,400 gallons/day
  - Bus system already investing in 10 new H_2 busses



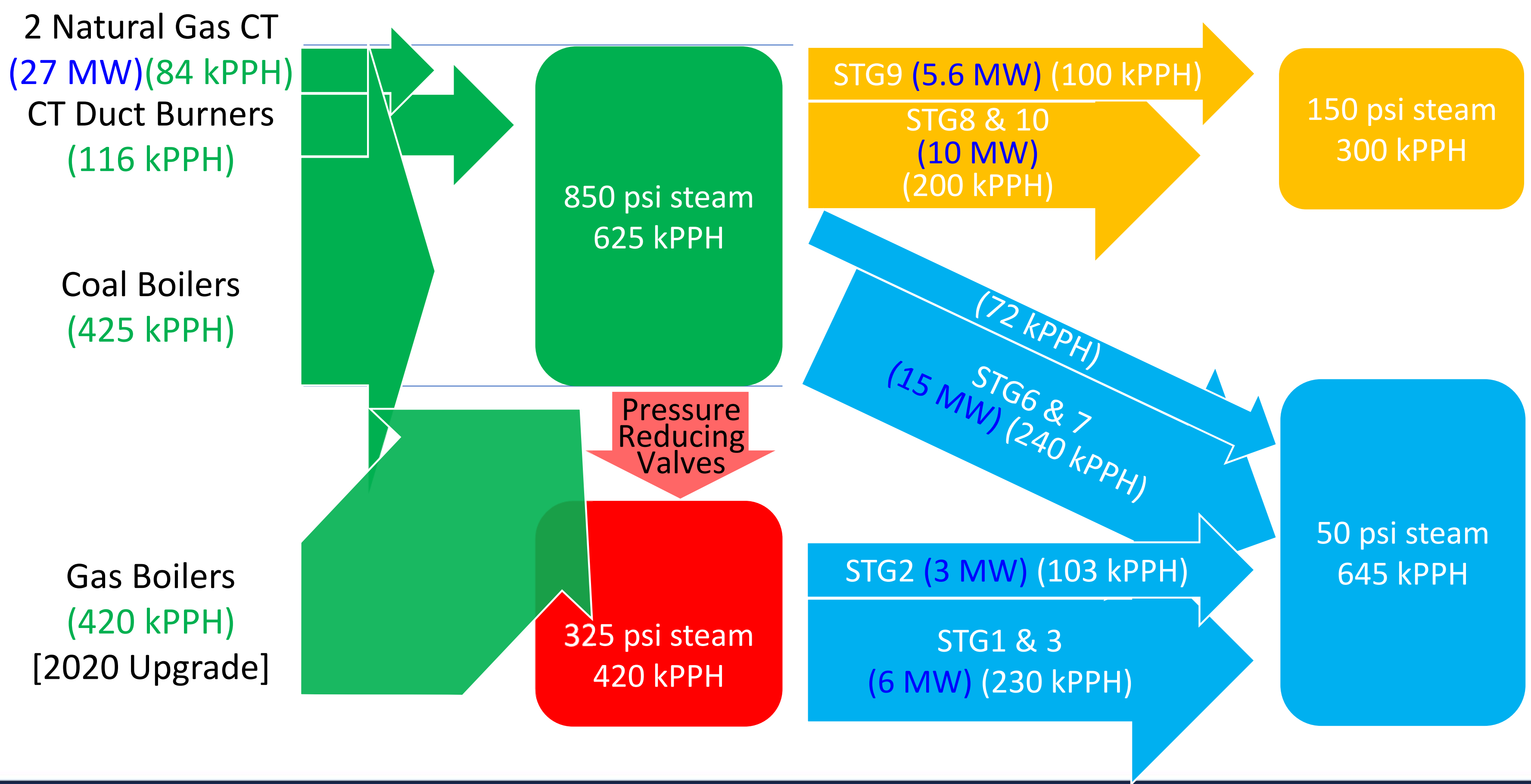
Overview of UIUC Microgrid

- 2019 UIUC emission sources:

Scope	Scope Definition	Emissions ($MTCO_2e$; %)	Campus Energy Source %	Campus Electricity %
1	Emissions produced on campus within UIUC control	195,459; 45.1%	80%*	43.10%
2	Emissions from purchased electricity	183,595; 42.3%	20%	56.90%
3	Emissions from off campus university activities	54,743; 12.6%	N/A	N/A

*Calculated from fuel consumption

Overview of UIUC Abbott Power Plant

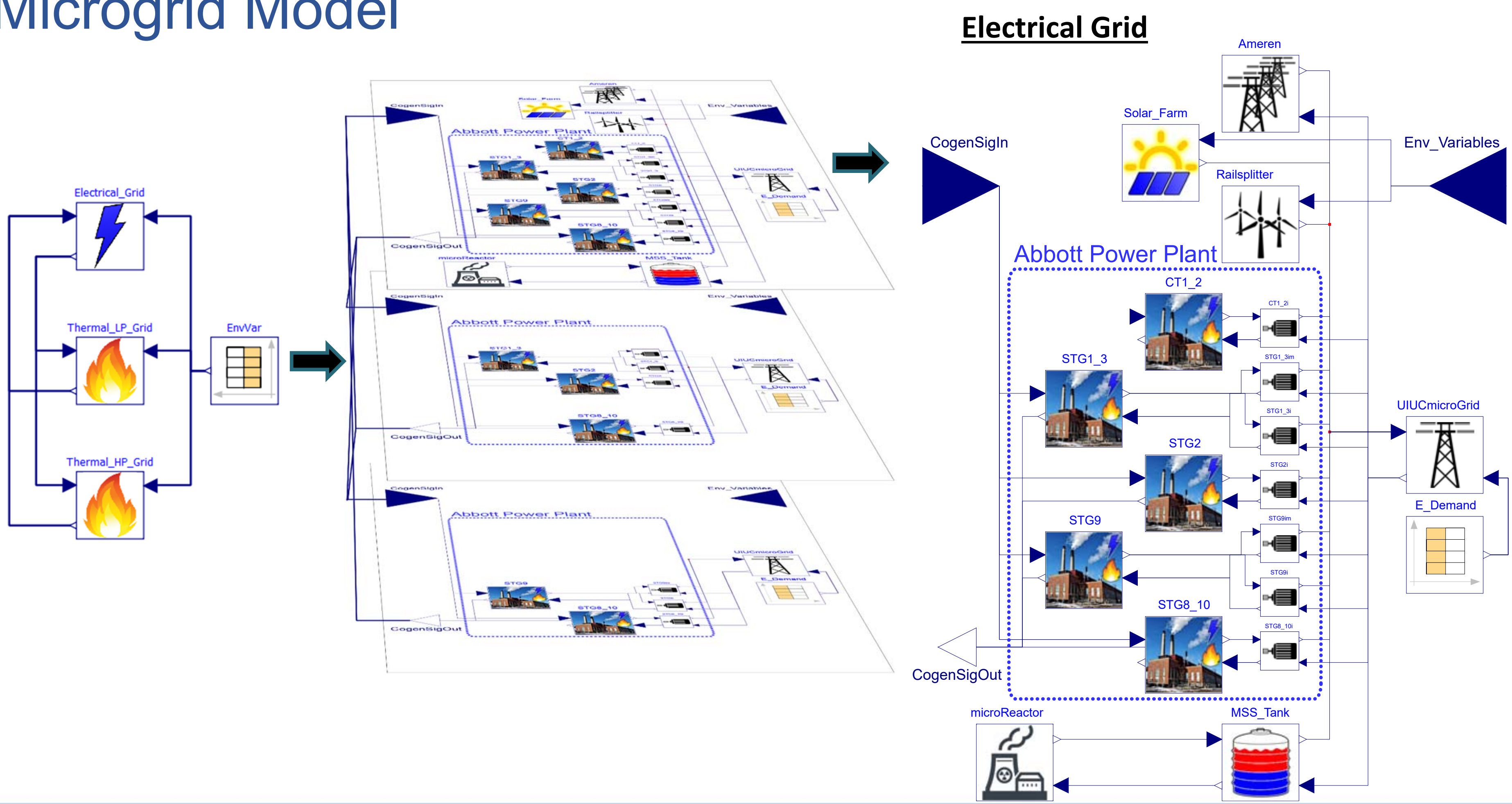


Approach – Microgrid Modeling

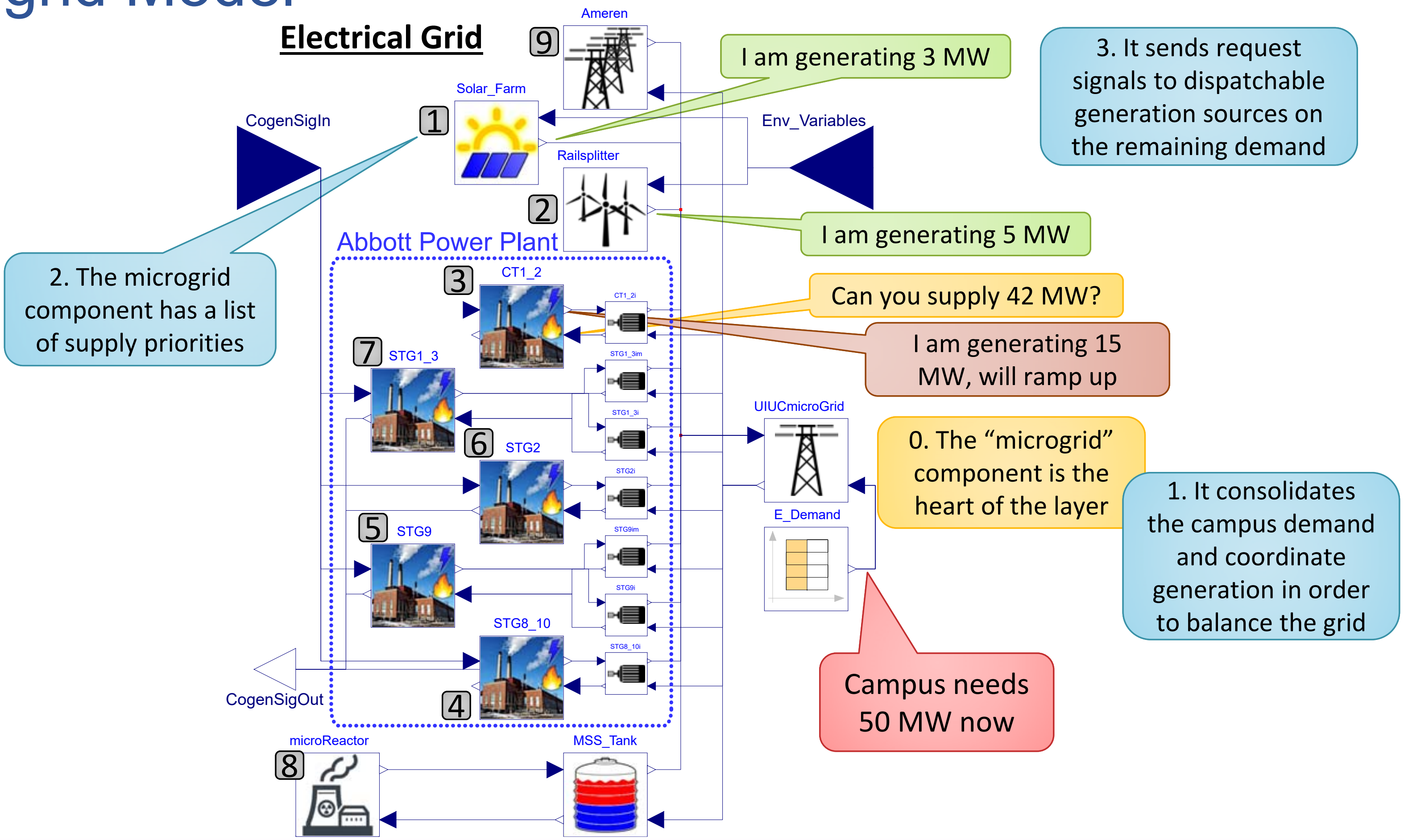
- Main idea: Create a simplified model of the microgrid to provide information on the minutes scale and perturb component parameters and configurations to obtain optimal solution

- Simplified in terms of variables used
  - E.g. For electrical grid: MW and MWhr for power and energy exchange instead of the more fundamental variables (Volt, Ampere, Hertz)

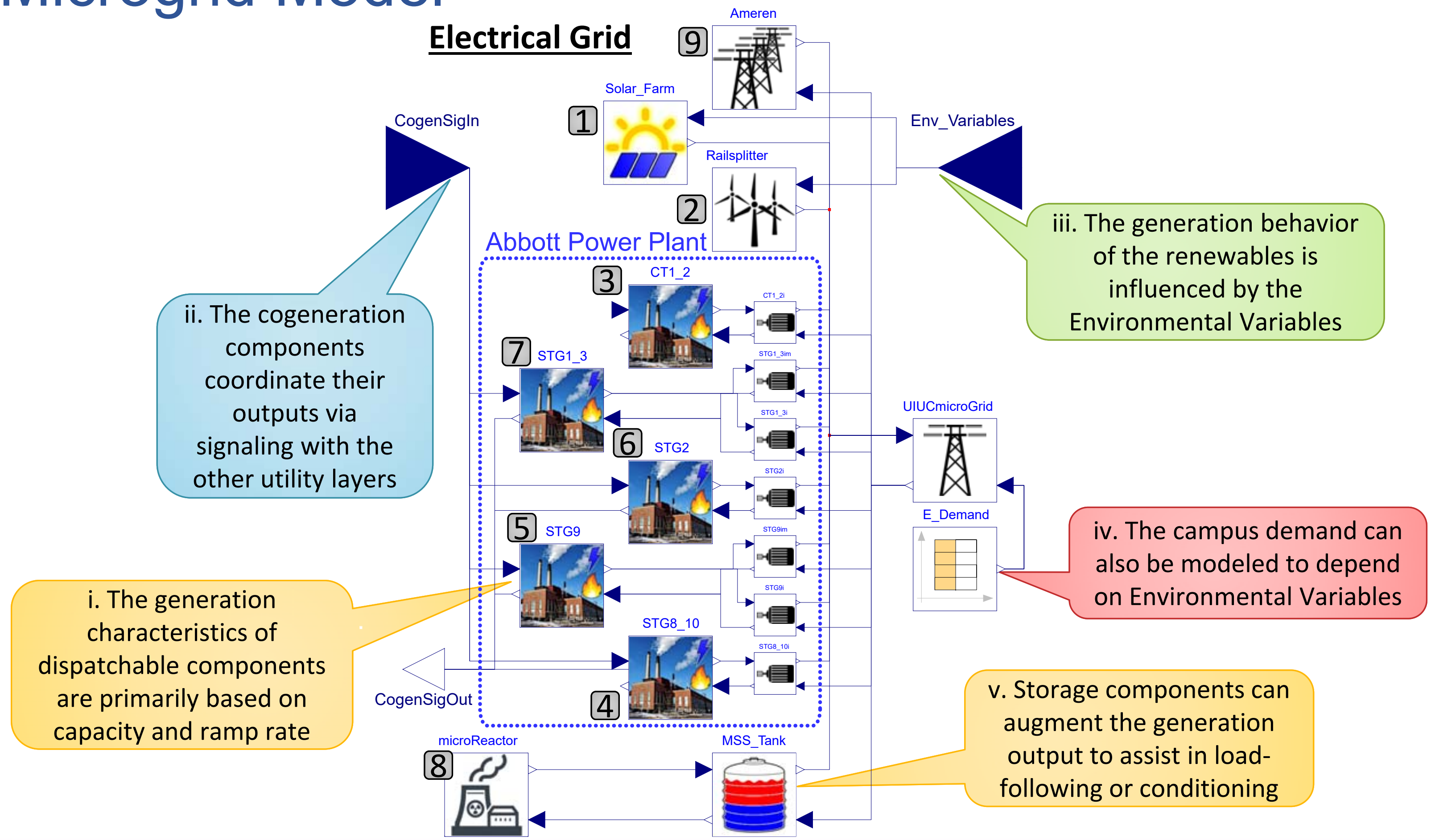
Microgrid Model



Microgrid Model



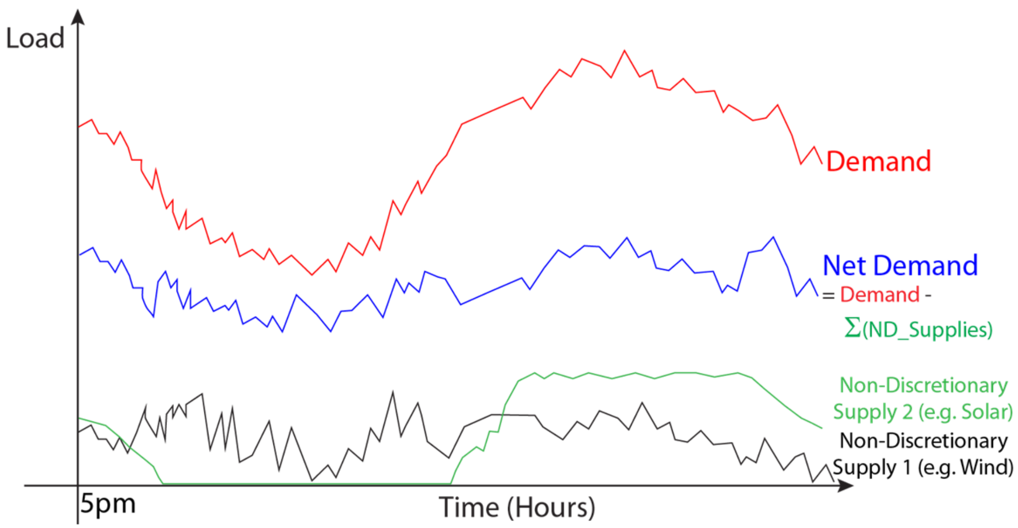
Microgrid Model



Microgrid Model

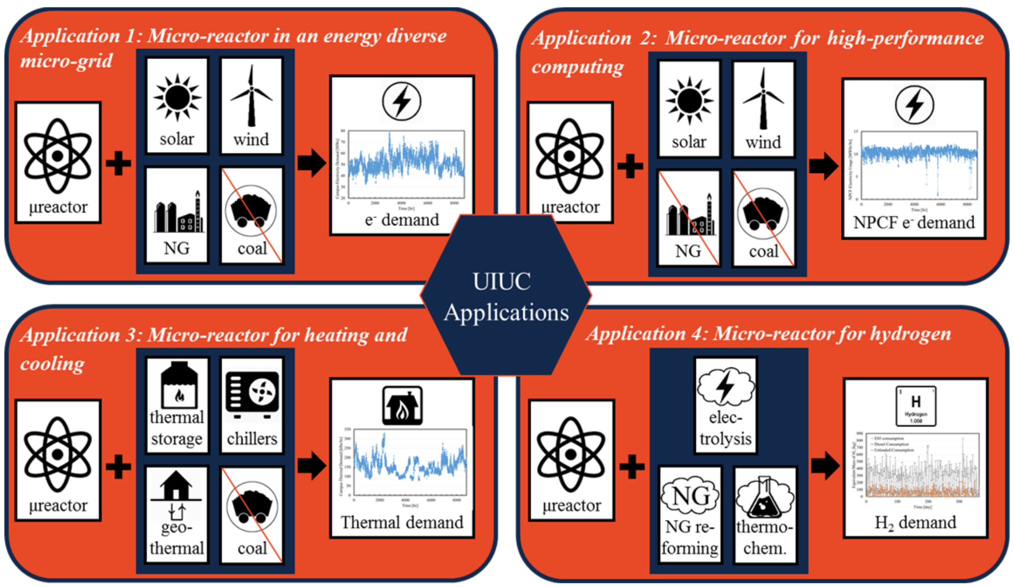
With a sufficiently accurate model, we can determine:

i. Demand, based on environmental variables such as temperature, time of year, etc.
ii. Supply behavior, in response to demand and other internal system complexities such as cogeneration.
iii. Tally total demand & supply, fuel usage, costs, greenhouse gas emissions, etc.



Overview of Subtasks 2.1 and 2.3 Results

- Task 2.1: Use of microreactor solely for electricity generation in an energy-diverse UIUC microgrid.
- Task 2.3: Use of microreactor for steam (and electricity) generation with a focus on heating and cooling.



Select Key Scenarios From Subtasks 2.1 and 2.3

Task	Configuration	Cost Savings[1] [$M/y]	Emissions Reduction [MTCO2/y]	Key Findings
2.1: Electricity Generation ($5\ MW_e$)	Baseload CT with load-following µR	1.98	UIUC: 0 Grid: 28.4 Total: 28.4	• CTs baseload while µR+MSS provides load-following • µR+MSS helps to condition power by reducing fluctuations and provide some electricity arbitrage
	Baseload µR with load-following CT	1.10	UIUC: 11.3 Grid: 9.0 Total: 20.3	• µR baseloads with load-following CT to minimize fossil fuel usage • Some emissions reduction but less cost savings due to lower export of excess electricity • Resistant against increase in natural gas prices, esp. above $3.86/MMBTU
2.3: Steam & Electricity for UIUC ($15\ MW_{th}$)	Boiler Retrofit	1.45	UIUC: 25.1 Grid: 1.2 Total: 26.3	• µR retrofitted onto existing coal boiler in APP to produce boiler steam • Relegates production to APP using existing APP infrastructure • 1.9 MW_e + 36.8 kPPH steam, or throttle up to 3.7 MW_e + 0 kPPH steam (condensing mode)
	Cogeneration 50 psi with MSS	1.60	UIUC: 24.1 Grid: 4.3 Total: 28.4	• STG exhaust as 50 psi steam for campus heating • MSS enables load-following • 2.3 MW_e + 35.3 kPPH steam

[1]Cost savings refer to the reduction in electricity and fuel expenses as compared to the current UIUC microgrid without a microreactor.

Some Key Takeaways From Subtasks 2.1 and 2.3 Results

- Ideal microreactor deployment approach depends on the specific goal and scenarios

  E.g., If reduction of local emissions is a priority, then cogeneration is better than sole electricity generation which only offset grid emissions.
  E.g., If existing infrastructure is available, then retrofit may be better than cogeneration due to cost and complexity reduction.

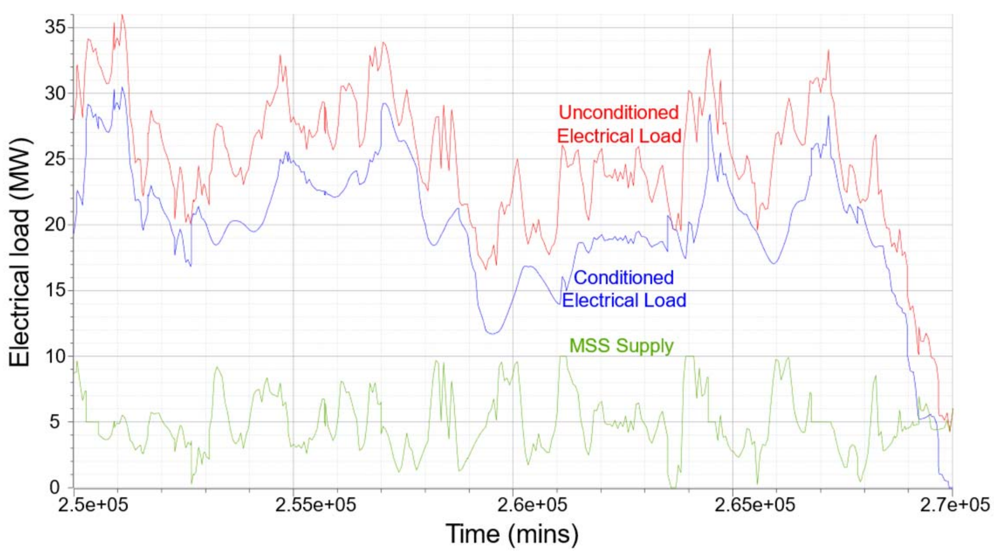
- Potential cost reduction from a microreactor is highly dependent on price of electricity and the fuel it replaces (i.e. natural gas). In the simulated period, the average electricity price was about $25/MWh and $2.87/MMBTU for gas.
  The prices have increased significantly over the years and would result in much greater cost reduction for present microreactor deployments.

- As the electricity grid shifts towards clean energy sources, the focus would be on reducing local emissions generation.

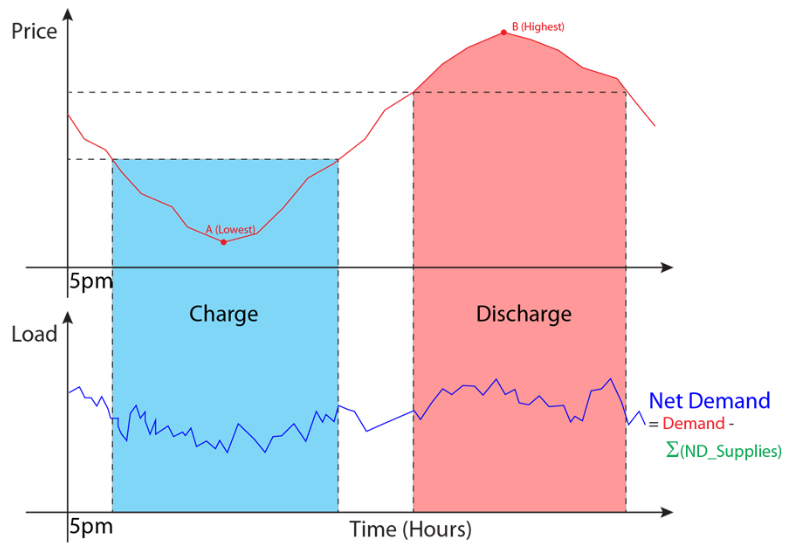
Load-Conditioning and Electricity Arbitrage by MSS

- Load-conditioning by the Molten Salt Storage (MSS) system attempts to smooth the electrical load which is important for achieving a self-reliant microgrid.
- Electricity arbitrage by the MSS allows additional cost reduction by charging the MSS during periods of low electricity prices and discharging during periods with high prices.

<u>Load-conditioning</u>



<u>Electricity Arbitrage</u>



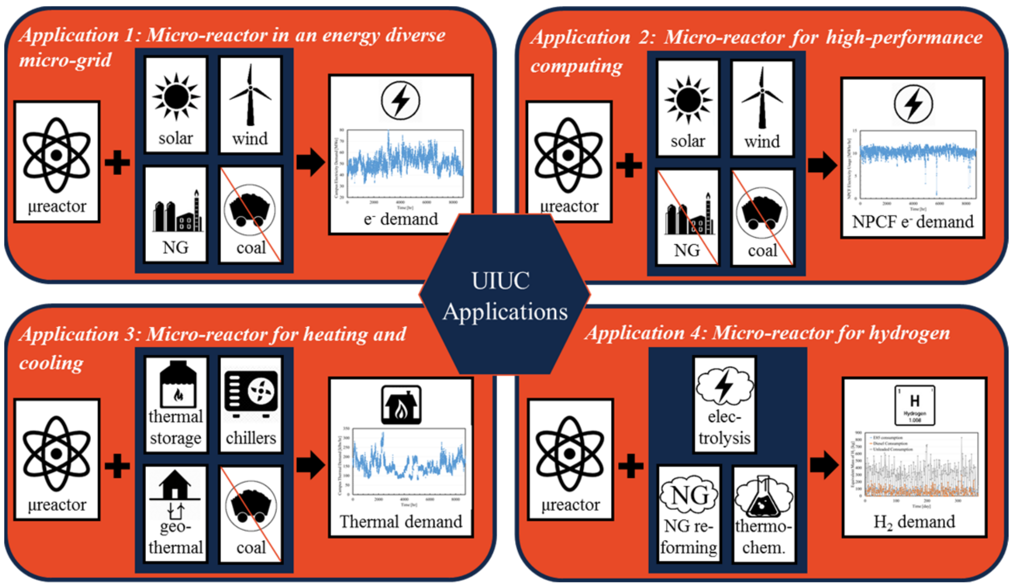
Load-Conditioning and Electricity Arbitrage by MSS

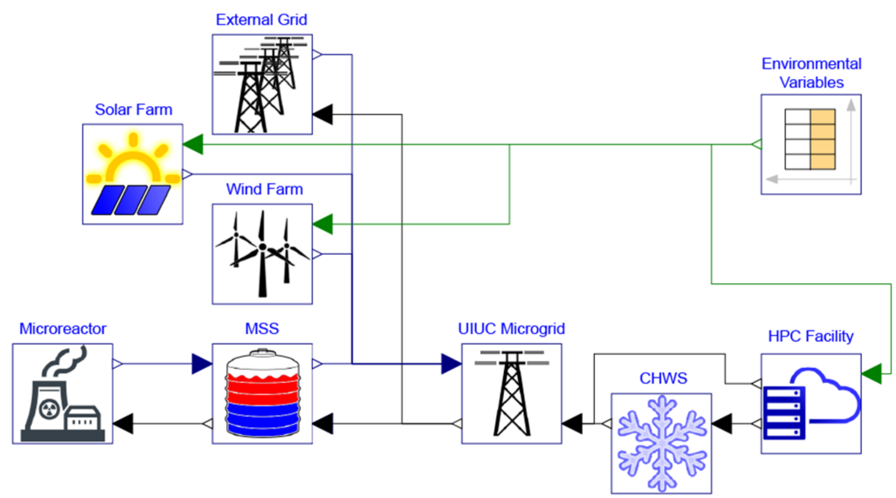
- Load-conditioning and electricity arbitrage provide small amounts of energy cost savings ($60k/y and $90k/y, respectively) as compared to the energy cost savings by the microreactor itself ($1.9M/y).

- However, besides market based optimization, an MSS can provide value through other aspects as well:
  1. An MSS system can decouple the demand load variation from the microreactor neutronics by providing buffer to the load variation. This reduces the number and frequency of control rods maneuvers
  2. An MSS system can enhance the short term load-following capability of a microreactor-MSS system.
  3. An MSS system can serve as a heat reservoir in removing decay heat during SCRAM.

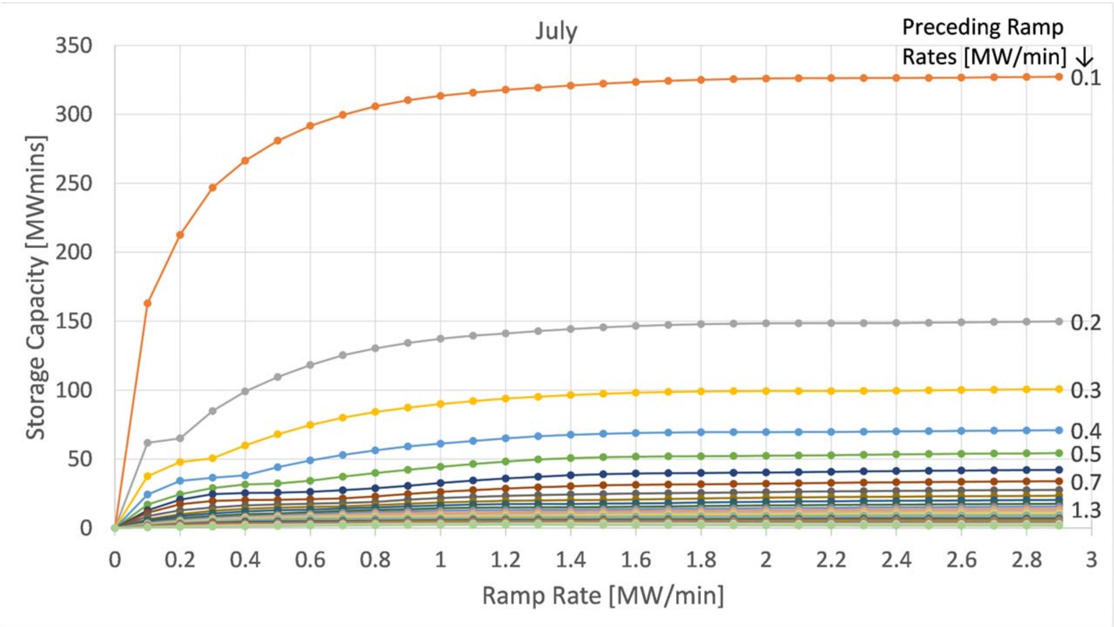
Overview of Subtask 2.2

- Task 2.2: Use of microreactor for High-Performance Computing (HPC).
- HPC is an energy intensive but high-value application.





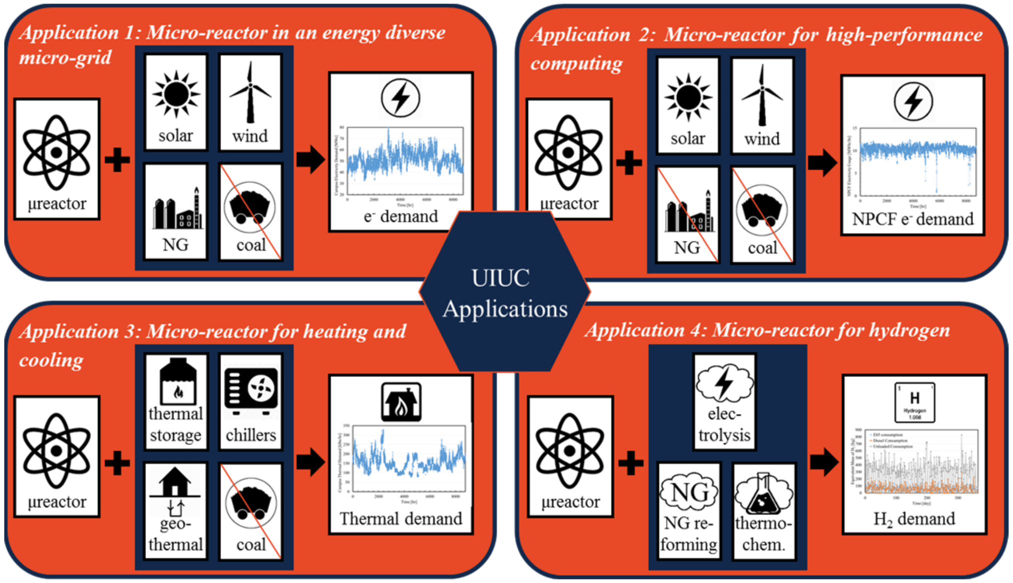
Key Results from Subtask 2.2

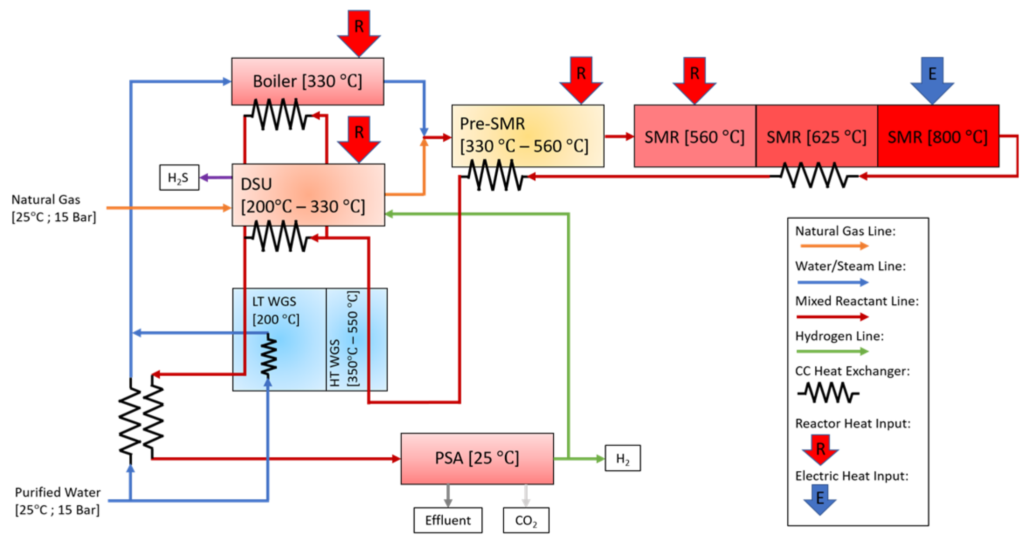


- HPC has very high load variation, requiring up to around 4 MW_e/min of ramping.
- Energy storage devices (MSS, batteries, flywheels) needed for load-following.
- Storage capacity reduced by 2 orders of magnitude if μR can ramp at just 0.3 MWe/min.
- Microreactor designs can greatly enhance versatility and expand use cases by including some load-following capability.

Overview of Subtask 2.4

- Task 2.4: Use of microreactor for hydrogen production.
- Task explored the pairing of a microreactor with low-temperature electrolysis (LTE), high-temperature electrolysis (HTE), and Steam-Methane Reforming (SMR)



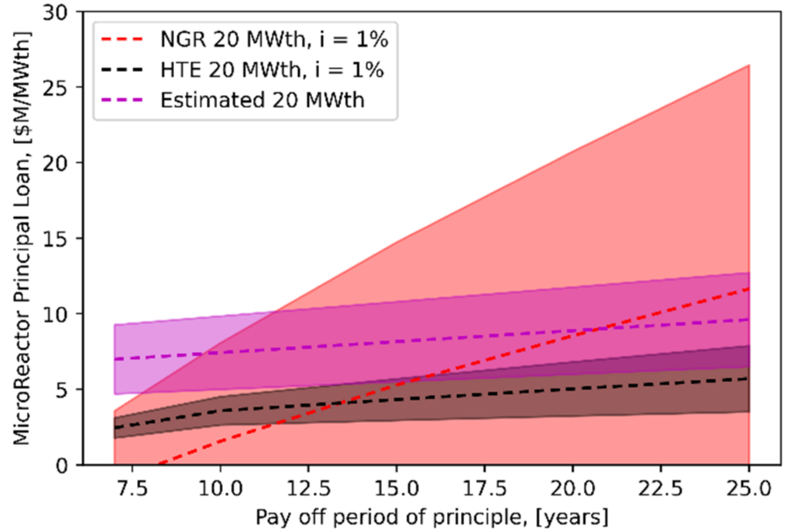


Key Results from Subtask 2.4

Production Method	Yearly H_2 Production [10^3 Tonnes/y]	Emissions Reduction [$MTCO_2$/y]	Emission Reduction Coefficient [$MTCO_2/MWh_e$-equivalent]
LTE	0.93	16.63	0.379
HTE	1.08	19.15	0.437
NGR	4.63	55.21	1.261

- LTE and HTE provide less emissions reduction than if the electricity input was used to offset grid electricity usage (emission coefficient 0.65 $MTCO_2/MWh_e$)
- NGR has process emissions, but the significantly larger production makes for the biggest reduction in emissions
- Hydrogen is a more valuable commodity compared to electricity, provided a demand is available
- All systems are able to fulfill the fueling needs and produce additional hydrogen for sale or export electricity to the grid
- Significant losses in hydrogen yield for transportation occur due to the compression to 700 bar

Stand-alone Hydrogen Systems



- Hydrogen provides a high-value commodity that can help pay off the principal loans required for first-of-a-kind microreactors
- NGR systems are more economically competitive than HTE, with the ability to meet available cost estimates with a 20 year pay-off period
- Tax credits in the Inflation Reduction Act of 2022 provide limited support for the economic viability of hydrogen generating systems

Summary and Conclusion

- A modular modeling framework was developed to simulate the impact of a microreactor deployment within the UIUC microgrid.
  The modeling approach can be extended to other similar microgrids.

- The project explored four main applications for microreactor deployment:
  1. µGrid Electricity Generation 2. Steam & Electricity for Heating/Cooling
  3. Generation for High-Value HPC 4. Production of Hydrogen

- The optimal microreactor configuration depends on the specific application

- In all cases, a microreactor:
  1. Reduces emissions 2. Enhance resiliency from external factors
  3. Could provide process heat, thereby expanding range of possible products

Key Products/Publications

Journal Papers:

- L. Wodrich, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Modeling of an Energy Diverse Embedded Grid for Microreactor Integration, Nuclear Technology, (in-press)
- A. J. H. Lee, L. Wodrich, D. Kalinichenko, C. S. Brooks, T. Kozlowski, Modeling Microreactor Application for High-Performance Computing, Applied Energy, (Under Review)
- D. Kalinichenko, L. Wodrich, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Microreactor Efficacy With Hydrogen Production Methods, (Under Review)

Conference Papers:

- A. J. H. Lee, L. Wodrich, C. Brooks, T. Kozlowski, Modeling and evaluation of micro-reactor deployment within existing microgrids, American Nuclear Society Winter Meeting, Washington D.C., November 30–December 3, 2021
- L. Wodrich, A. J. H. Lee, C.S. Brooks, T. Kozlowski, Determining Economic Efficacy of a Microreactor Within a University Campus, American Nuclear Society Winter Meeting, Washington D.C., November 13–November 17, 2022

Milestone Reports:

- L. Wodrich, D. Kalinichenko, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well characterized grid; Task 2.4: Modeling Hydrogen Production Fulfilled by a Microreactor; Milestone ID: M3NU-20-IL-UIUC-030205-026, December 2022.
- A. J. H. Lee, L. Wodrich, D. Kalinichenko, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well characterized grid; Task 2.2: Modeling Microreactors for High-Performance Computing; Milestone ID: M3NU-20-IL-UIUC-030205-024, September 2022.
- A. J. H. Lee, L. Wodrich, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well-characterized microgrid; Task 2.1: Modeling Microreactors in an Energy Diverse Micro-Grid, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-023, June 2022.
- L. Wodrich, A. J. H. Lee C. S. Brooks, T. Kozlowski, Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid; Task 2.3: Modeling Microreactors for Building Climate Control, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-025, November 2021.
- L. Wodrich, A. J. H. Lee, S. G. Dotson, R. E. Fairhurst Agosta, O. R. Yardas, C. S. Brooks, T. Kozlowski, K. D. Huff, Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid; Task 1: Overview of campus energy portfolio and available data, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-022, May 2021.