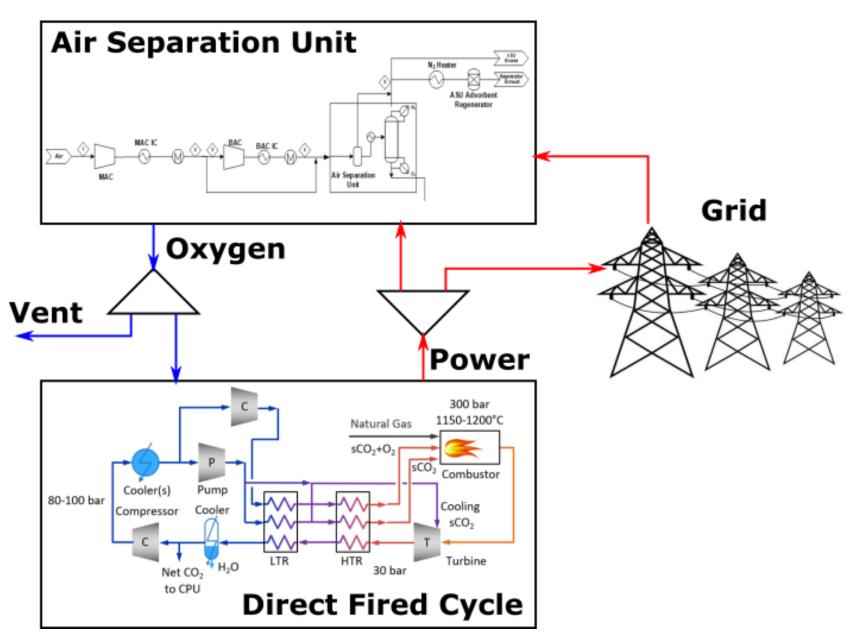




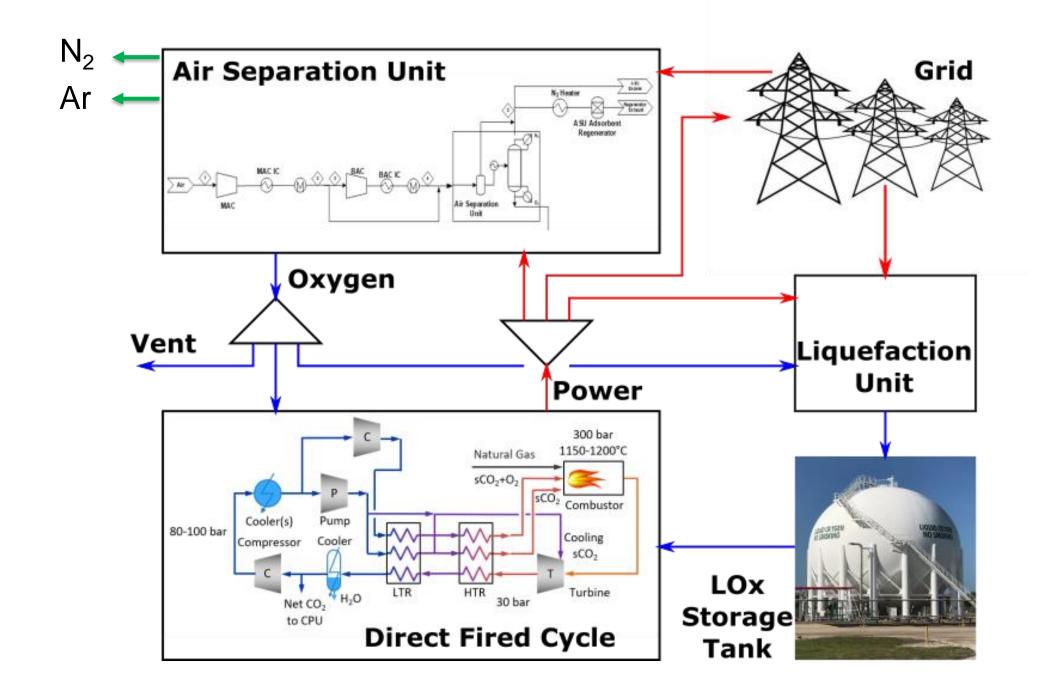
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## **Motivation**

- Increased penetration of intermittent renewables requires fossil generators to be "flexible" in order to respond to the grid conditions
- Some of the low-carbon fossil generator technologies, such as direct-fired supercritical CO<sub>2</sub> power cycle, require oxygen for combustion
- Required oxygen is produced onsite by an Air Separation Unit (ASU)



- Slow dynamics and long startup time associated with the ASU makes the entire system less "flexible" and additional capital expenditure for the ASU makes it less economical
- Propose inclusion of a liquefaction unit and a liquid oxygen (LOx) storage tank as a potential solution to improve the flexibility of the system



- During off-peak periods, the ASU can continue to operate by liquefying and storing oxygen and during high-peak periods it can ramp down, while the DFC runs off of the stored oxygen.
- Co-production of air products such as nitrogen and argon, introduces more revenue, which improves the overall economics







## **Optimal Design of Flexible Co-production Systems with Storage for Grids Containing High Variable Renewable Energy**



- Is the system profitable without co-production? If not, does the addition of n revenue streams from co-production improve profitability?
- Does liquid oxygen storage improve flexibility and justify the capital expendi a liquefaction unit and tank?
- Does either help in reducing the frequency of shutdowns, the size, and the of the ASU?

## **Technical Challenges and Solution Approa Challenges:**

- High intra-day and inter-day variability in the locational marginal price (LMI requires a dynamic operation and frequent startups and shutdowns
- Startup/shutdown procedures, which take place over the span of a few hou different for the power cycle and the ASU
- Optimal size of individual units is not known a priori

## Approach: Simultaneous design and operations optimization in IDA

Rigorous Models



Surrogate Models + ramping, startup, shutdown, uptime, ...

Multiperi **Optimizat** in IDAE \_MP

signal **Co-production Without Storage Results** LMP Signal\* Market DFC ASU #startups/ NPV [Million #shutdown **Participation** Capacity Capacity USD] of DFC [in kg/s] [in MW] PJM-W\_\$150 Electricity 15.2 777.7 102.4 84/83 Both electricity and 86.7 777.7 102.4 95/94 argon NYISO\_\$100 -36.4 176 23.2 Electricity 114/113 Both electricity and 777.7 102.4 26.9 114/113 argon INDIANA\_2022 -53.5 176 Electricity 0/0

176

23.2

**Conclusion:** Co-production of power and argon reduces the number of startup and shutdowns, improves the economics, and affects the optimal size of the system. For INDIANA\_2022, operation is not profitable without co-production. \*Cohen and Durvasulu (2021): NREL Price Series Developed for the ARPA-E FLECCS Program. PJM\_\$150, and NYSIO\_\$100 are projected price signals for the year 2035. INDIANA 2022 corresponds to the historical price signal for the MISO market.

-42.9



Both electricity and

argon



92/92



		Witho	ut Co-pro	ductio	on Res	sults	
	LMP Signal*	Storage Status	NPV [Million USD]	DFC Capacity [in MW]	ASU Capacity [in kg/s]	LOx Tank Capacity [in tonne]	# #s
or	CASIO_\$100	Without Storage	10.7	777.7	102.4	-	
		Storage	9.4	777.7	99.5	11610.2	
	CASIO_\$150	Without Storage	-8.2	777.7	102.4	-	
		Storage	-3.3	777.7	81.6	69386.9	
	NYISO_\$150	Without Storage	-36.3	176	23.2	-	
		Storage	-24.2	777.7	44.4	230919.4	
	and improves	the econor	duces the numbe nics for certain Ll al size of the ASL	MP signal	s. In NYS	•	
		Optima	al Operatio	on of t	the Sy	vstem	
	200 - (150 - 100 - 0 - 0 - 0 - 0 -	200	400 600 8 time (hr)	00 1000	1000 1200		a a a a a Asu_asu_asu_asu_asu_asu_asu_asu_asu_asu_a
	200 (150 100 50 0 0				1200		00 00 00 Power_to_grid
	200 - (4 150 - 100 - 4 50 -		time (hr)	TIMAN			20000 00000 80000
		200	400 600 8 time (hr)		1200		60000
	With LOx Storage, NYISO_\$150						
		Remarks					
		<ul> <li>The analysis is presented for the direct fired supercritical CO<sub>2</sub> power cyc</li> </ul>					
	<ul> <li>however, this can be used for any co-production system with storage.</li> <li>Interface makes it fairly easy to incorporate uncertainty in model parameters as the projected price signal</li> </ul>						
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21/21 37/37 63/62 27/28 of the ASU

#startups **#shutdowr** of ASU 34/34 17/17