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

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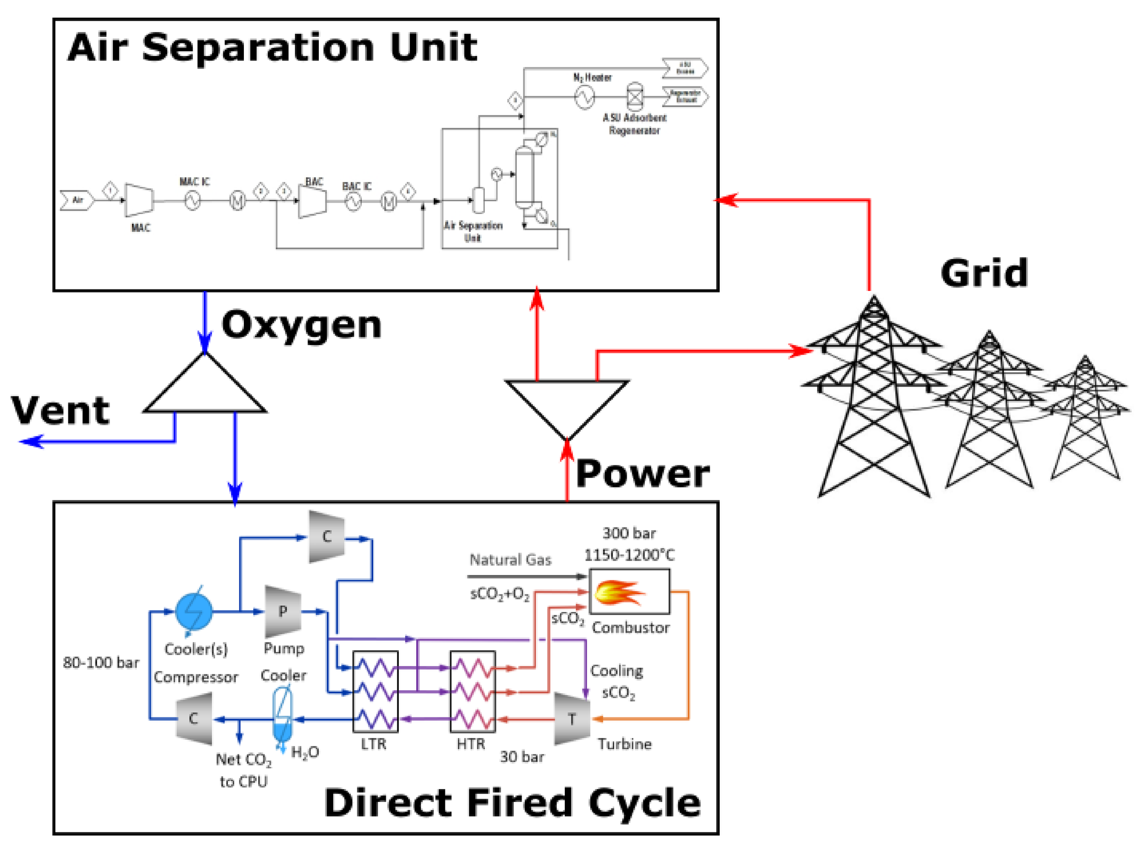
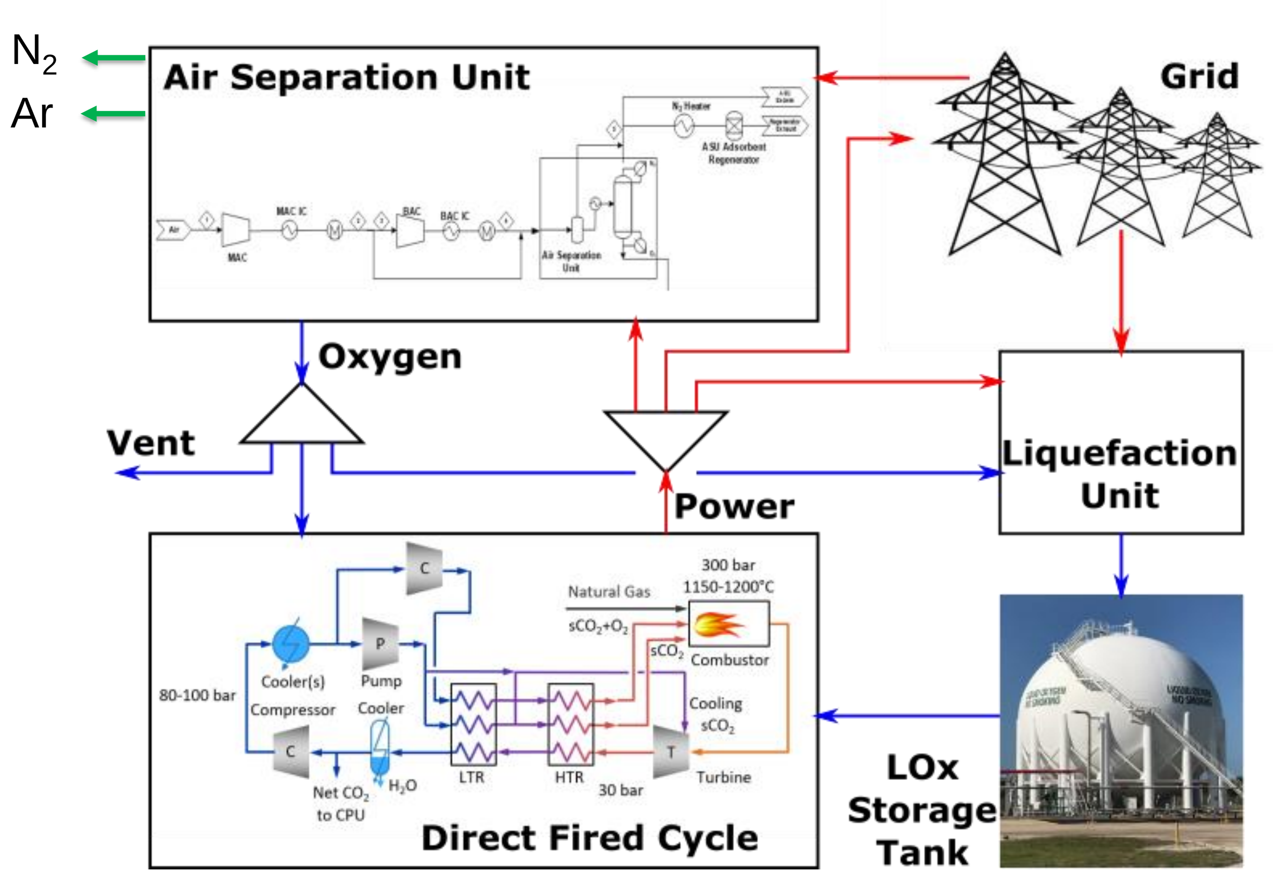
## Motivation

- 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 $CO_2$ 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

## Key Questions

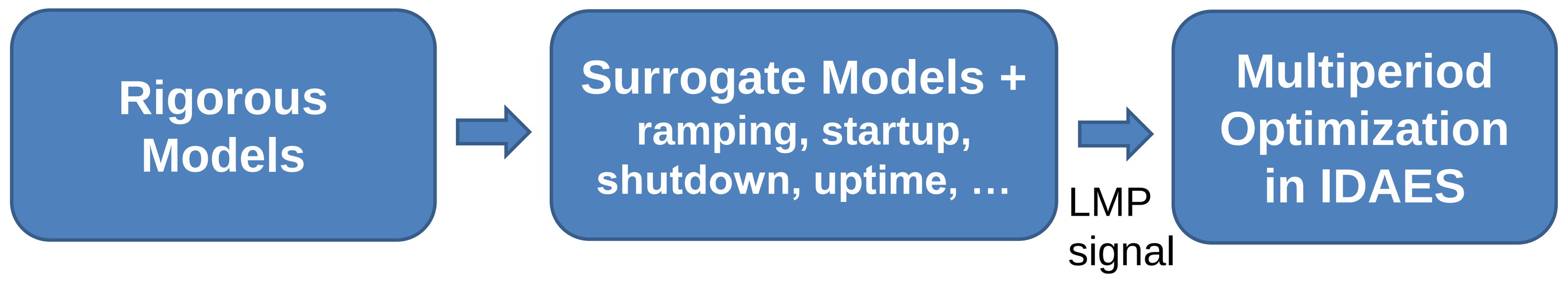
- Is the system profitable without co-production? If not, does the addition of new revenue streams from co-production improve profitability?
- Does liquid oxygen storage improve flexibility and justify the capital expenditure for a liquefaction unit and tank?
- Does either help in reducing the frequency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

## Technical Challenges and Solution Approach

**Challenges:**

- High intra-day and inter-day variability in the locational marginal price (LMP) requires a dynamic operation and frequent startups and shutdowns
- Startup/shutdown procedures, which take place over the span of a few hours, are 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 IDAES**




## Co-production Without Storage Results

| LMP Signal* | Market Participation | NPV [Million USD] | DFC Capacity [in MW] | ASU Capacity [in kg/s] | #startups/ #shutdown of DFC | #startups/ #shutdown of ASU |
|---|---|---|---|---|---|---|
| PJM-W_$150 | Electricity | 15.2 | 777.7 | 102.4 | 84/83 | 40/39 |
| | Both electricity and argon | 86.7 | 777.7 | 102.4 | 95/94 | 0/0 |
| NYISO_$100 | Electricity | -36.4 | 176 | 23.2 | 114/113 | 60/59 |
| | Both electricity and argon | 26.9 | 777.7 | 102.4 | 114/113 | 0/0 |
| INDIANA_2022 | Electricity | -53.5 | 176 | 0 | 0/0 | 0/0 |
| | Both electricity and argon | -42.9 | 176 | 23.2 | 92/92 | 0/0 |

**Conclusion:** Co-production of power and argon reduces the number of startups and shutdowns, improves the economics, and affects the optimal size of the system. For INDIANA_2022, operation is not profitable without co-production.

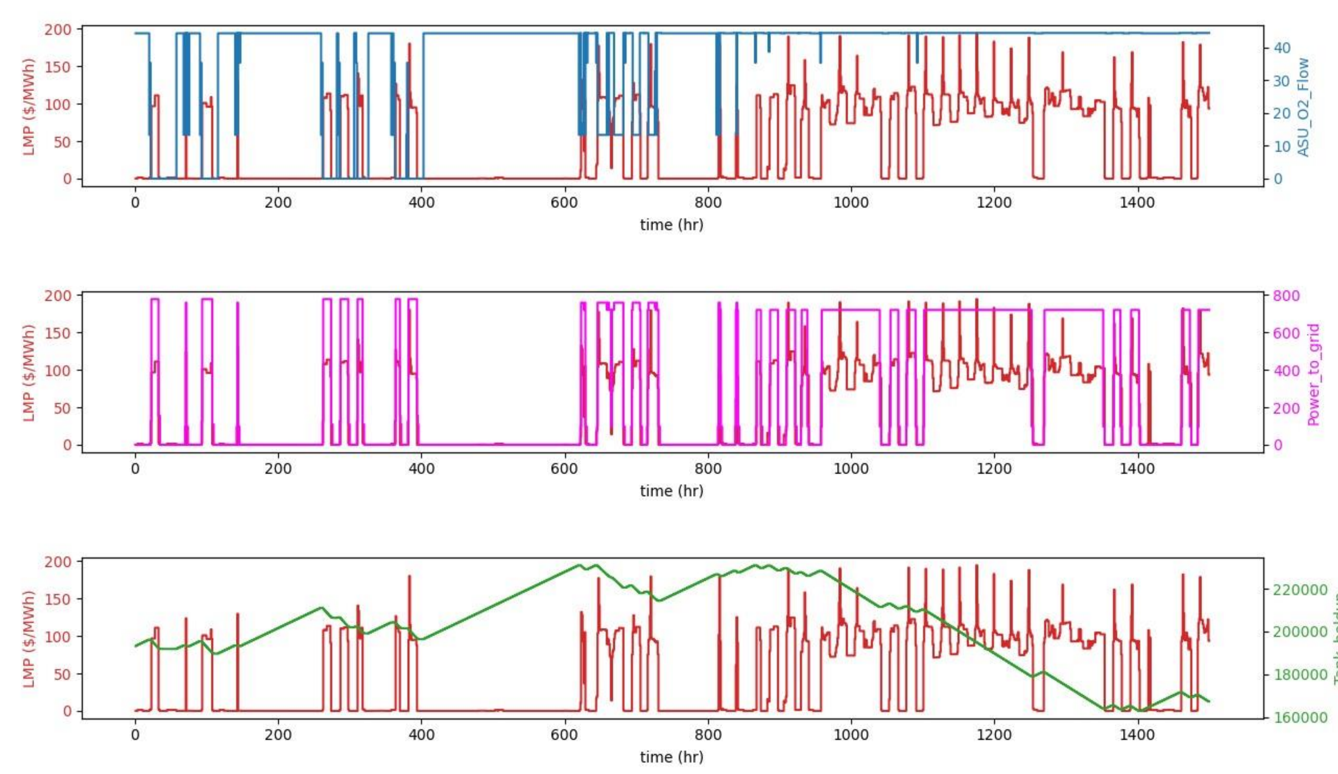
*Cohen and Durvasulu (2021): NREL Price Series Developed for the ARPA-E FLECCS Program.
PJM_$150, and NYISO_$100 are projected price signals for the year 2035.
INDIANA_2022 corresponds to the historical price signal for the MISO market.

## Without Co-production Results

| LMP Signal* | Storage Status | NPV [Million USD] | DFC Capacity [in MW] | ASU Capacity [in kg/s] | LOx Tank Capacity [in tonne] | #startups/ #shutdown of ASU |
|---|---|---|---|---|---|---|
| CASIO_$100 | Without Storage | 10.7 | 777.7 | 102.4 | - | 34/34 |
| | Storage | 9.4 | 777.7 | 99.5 | 11610.2 | 17/17 |
| CASIO_$150 | Without Storage | -8.2 | 777.7 | 102.4 | - | 21/21 |
| | Storage | -3.3 | 777.7 | 81.6 | 69386.9 | 37/37 |
| NYISO_$150 | Without Storage | -36.3 | 176 | 23.2 | - | 63/62 |
| | Storage | -24.2 | 777.7 | 44.4 | 230919.4 | 27/28 |

**Conclusion:** Storage reduces the number of shutdowns and startups of the ASU and improves the economics for certain LMP signals. In NYISO_$150 case, the storage affects the optimal size of the ASU and DFC

## Optimal Operation of the System



**With LOx Storage, NYISO_$150**

## Remarks

- The analysis is presented for the direct fired supercritical $CO_2$ power cycle, however, this can be used for any co-production system with storage.
- Interface makes it fairly easy to incorporate uncertainty in model parameters, such as the projected price signal

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