# Decarbonization through process electrification: An industrial perspective on challenges across technologies and scales

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Shell's net carbon intensity

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Shell's operating plan, outlook and budgets are forecasted for a ten-year period and are updated every year. They reflect the current economic environment and what we can reasonably expect to see over the next ten years. Accordingly, they reflect our Scope 1, Scope 2 and Net Carbon Intensity (NCI) targets over the next ten years. However, Shell's operating plans cannot reflect our 2050 net-zero emissions target, as this target is currently outside our planning period. In the future, as society moves towards net-zero emissions, we expect Shell's operating plans to reflect this movement. However, if society is not net zero in 2050, as of today, there would be significant risk that Shell may not meet this target.

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This presentation may contain certain forward-looking non-GAAP measures such as cash capital expenditure and divestments. We are unable to provide a reconciliation of these forward-looking non-GAAP measures to the most comparable GAAP financial measures because certain information needed to reconcile those non-GAAP measures to the most comparable GAAP financial measures is dependent on future events some of which are outside the control of Shell, such as oil and gas prices, interest rates and exchange rates. Moreover, estimating such GAAP measures with the required precision necessary to provide a meaningful reconciliation is extremely difficult and could not be accomplished without unreasonable effort. Non-GAAP measures in respect of future periods which cannot be reconciled to the most comparable GAAP financial measure are calculated in a manner which is consistent with the accounting policies applied in Shell plc's consolidated financial statements.

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# Outline

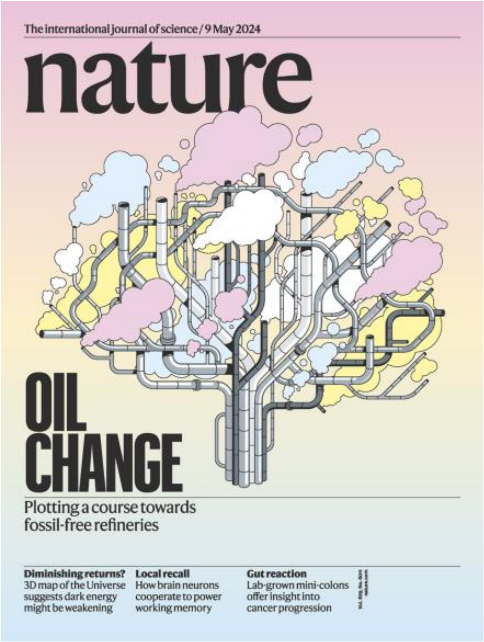
- Motivation and roles of direct and indirect electrification in industrial decarbonization
- Characteristics of electrical loads across scales & challenges each present
- Case studies that highlight specific challenges associated with electrifying unit operations and utilities
- Research challenges and priorities for the process systems engineering community

# Some things change, while others remain the same

My view on evolution of process systems engineering in the era of decarbonization

- What is changing
  - **F:** Feedstocks, Fuels, & Flexibility
  - **I:** Intricacies & Interconnection
  - **P:** Pace, Parameters, Processes & Products

- What is not changing
  - **S:** Systems, Scales, Synthesis, Simulation, & Safety
  - **E:** Economics & Efficiency

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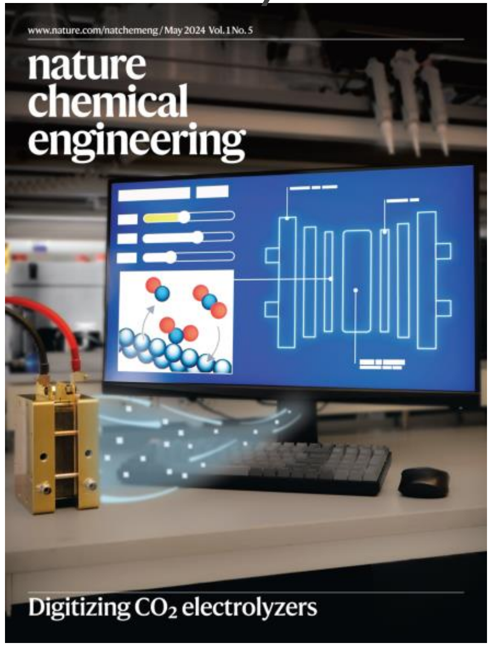


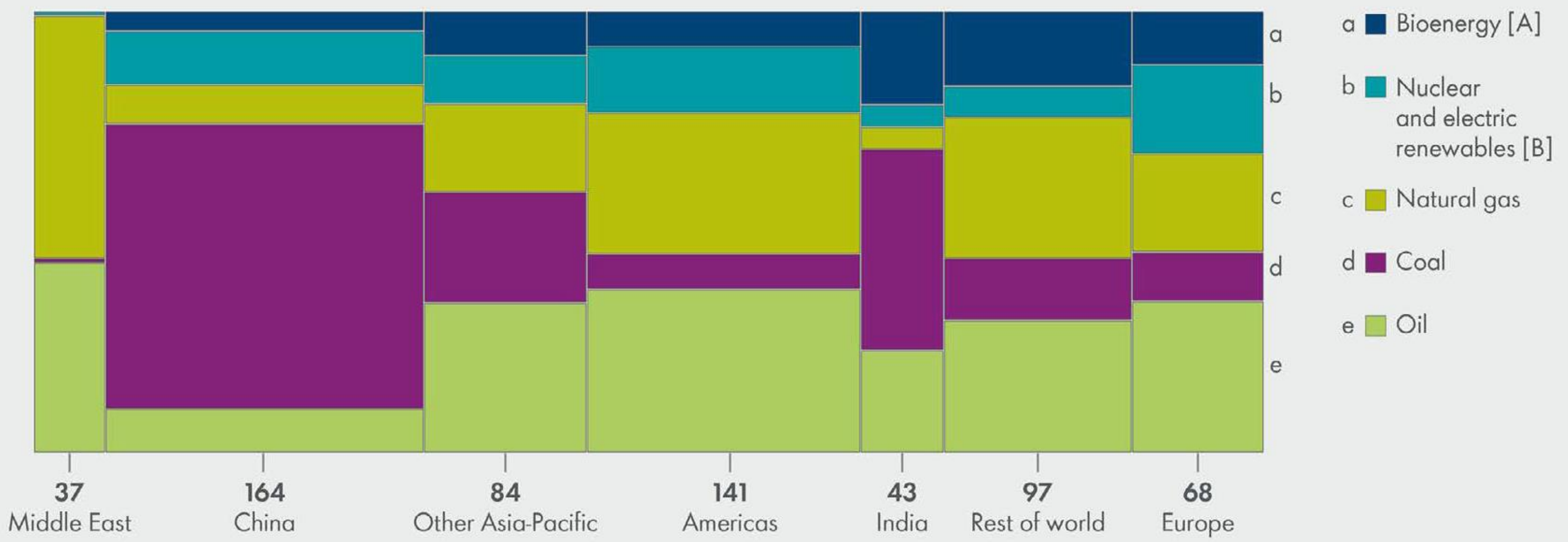



Volume 629 Issue 8011, 9 May 2024 (nature.com); Volume 1 Issue 5, May 2024 (nature.com)

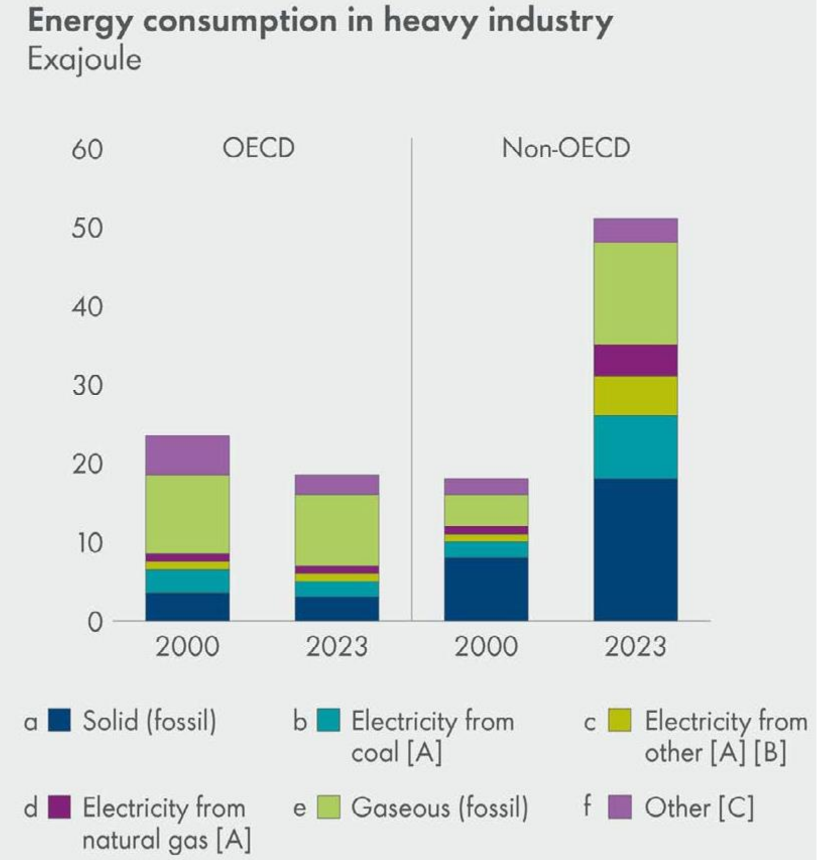
# Moving from today to tomorrow

# Regional & sector energy uses preclude a "one size fits all" solution

Need for solutions that fit existing & future assets, through a transition

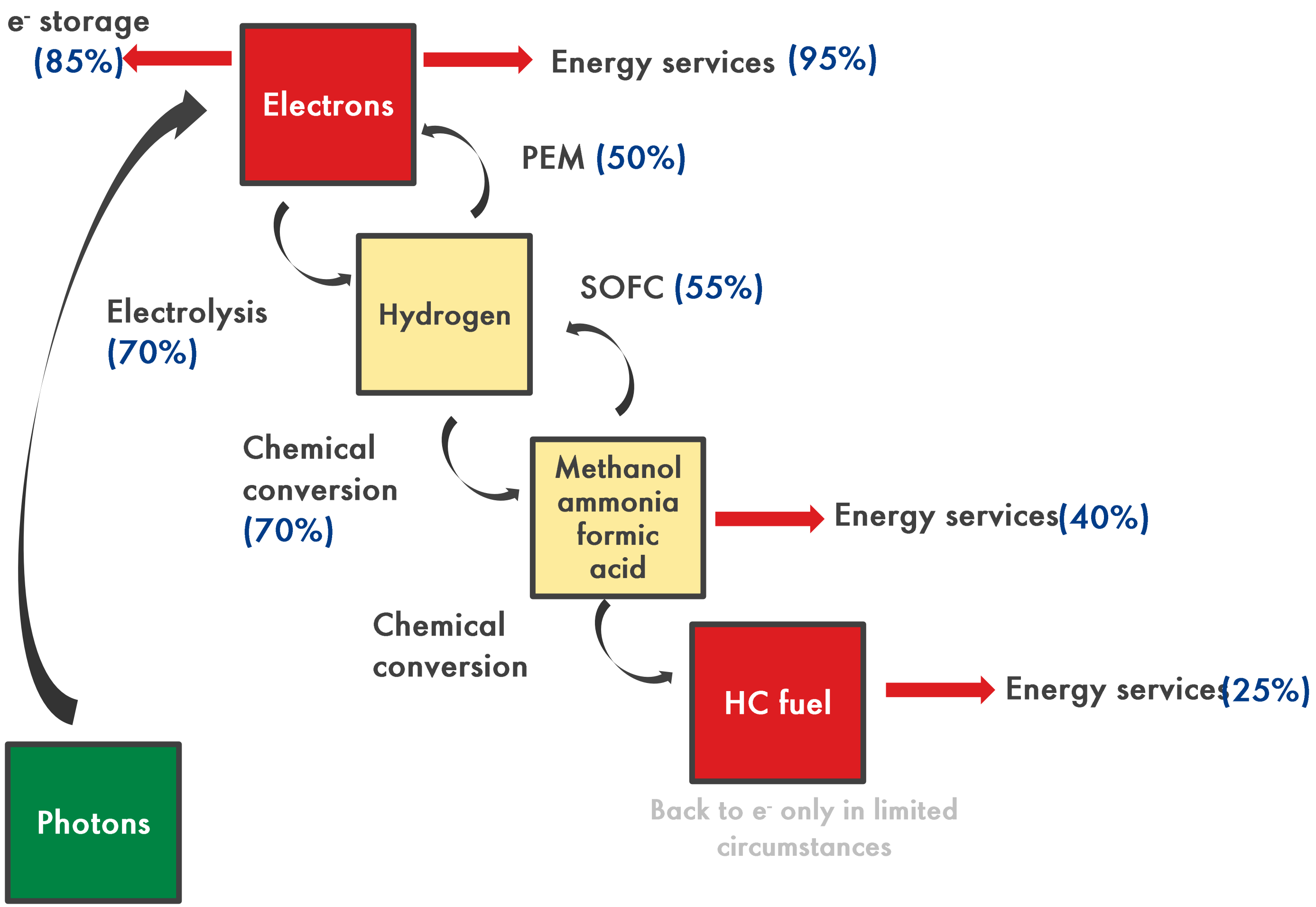



[A] Bioenergy includes traditional and modern uses of biomass in solid, liquid or gaseous form.
[B] Electric renewables include hydroelectricity, solar and wind.
Source: Shell analysis of IEA Extended Energy Balances (2023).




[A] Includes heat.
[B] Consists of nuclear, renewables and oil.
[C] Includes liquid fossil fuels and bioenergy.
Source: Shell analysis of IEA's Extended Energy Balances (2023).

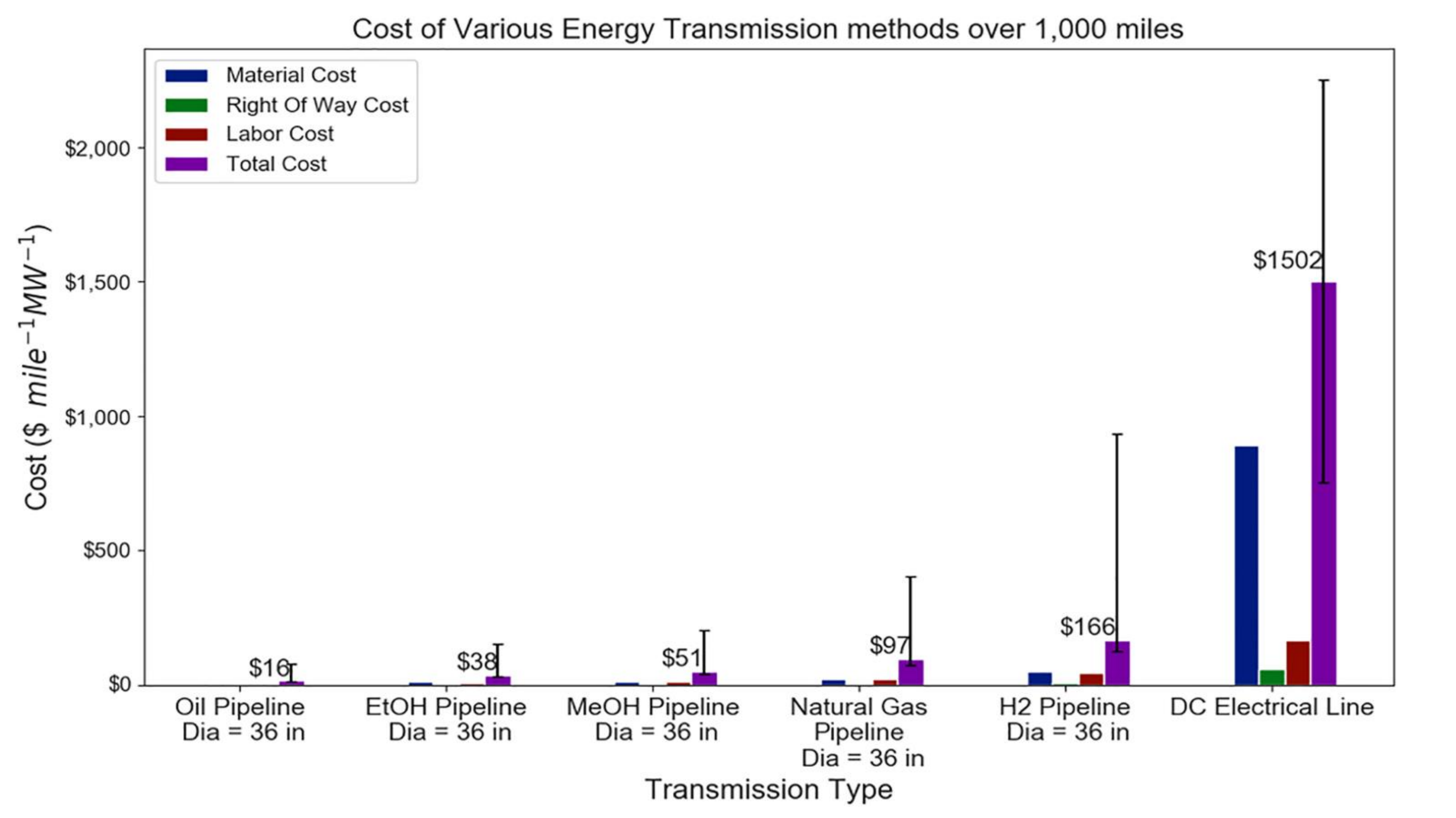
# Electricity as a new paradigm




***The lower the conversion process efficiencies for each step, the more advantaged "electric-only" pathways are on a primary energy basis***

# Chemical bonds make energy transport & storage more straightforward over long distances

This becomes a key tradeoff with efficiency



# Electricity in the industrial sector

Historically limited to processes at intersection of low-cost power, critical products & practical driving forces

- 1870s — Copper
- 1888 — Aluminum
- 1892 — Chlor Alkali
- 1902 — Air separation

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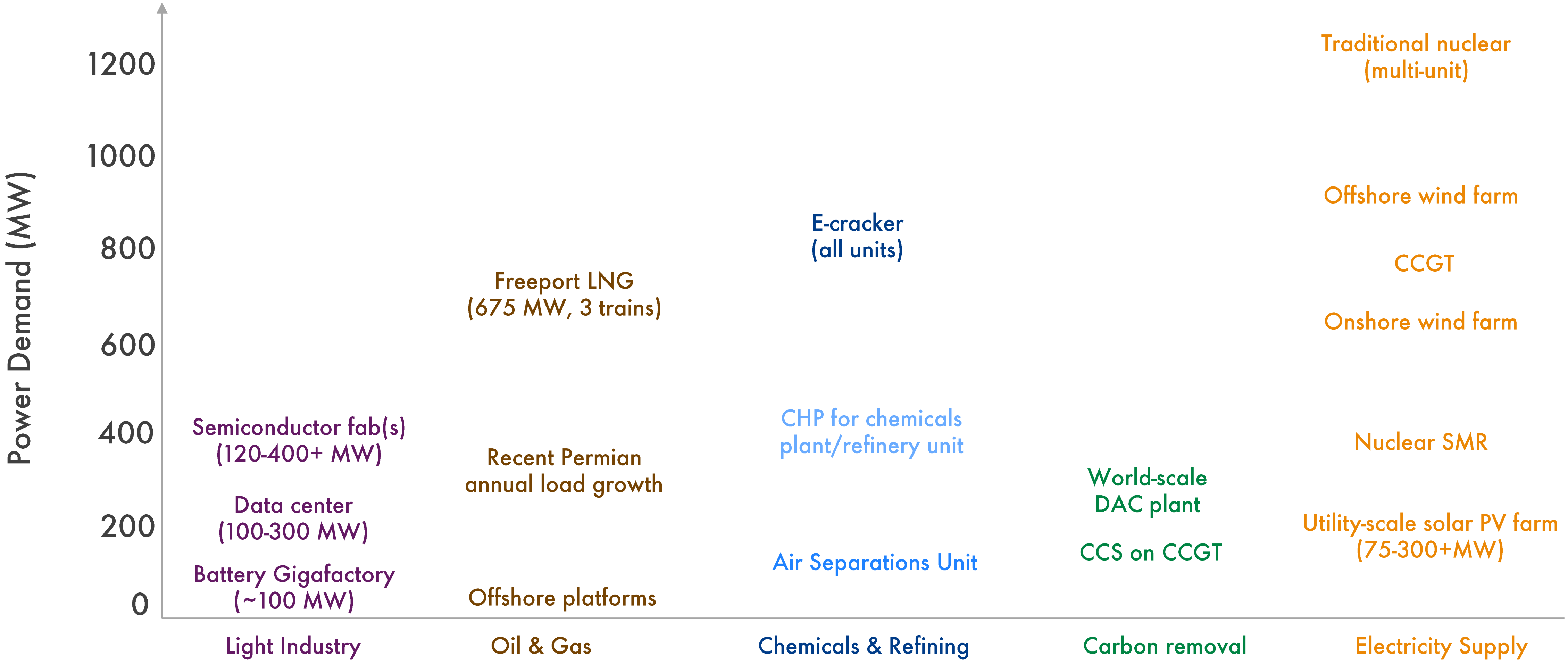
- Hydrogen
- Base Chemicals
- Specialty Chemicals

***What will this require?***

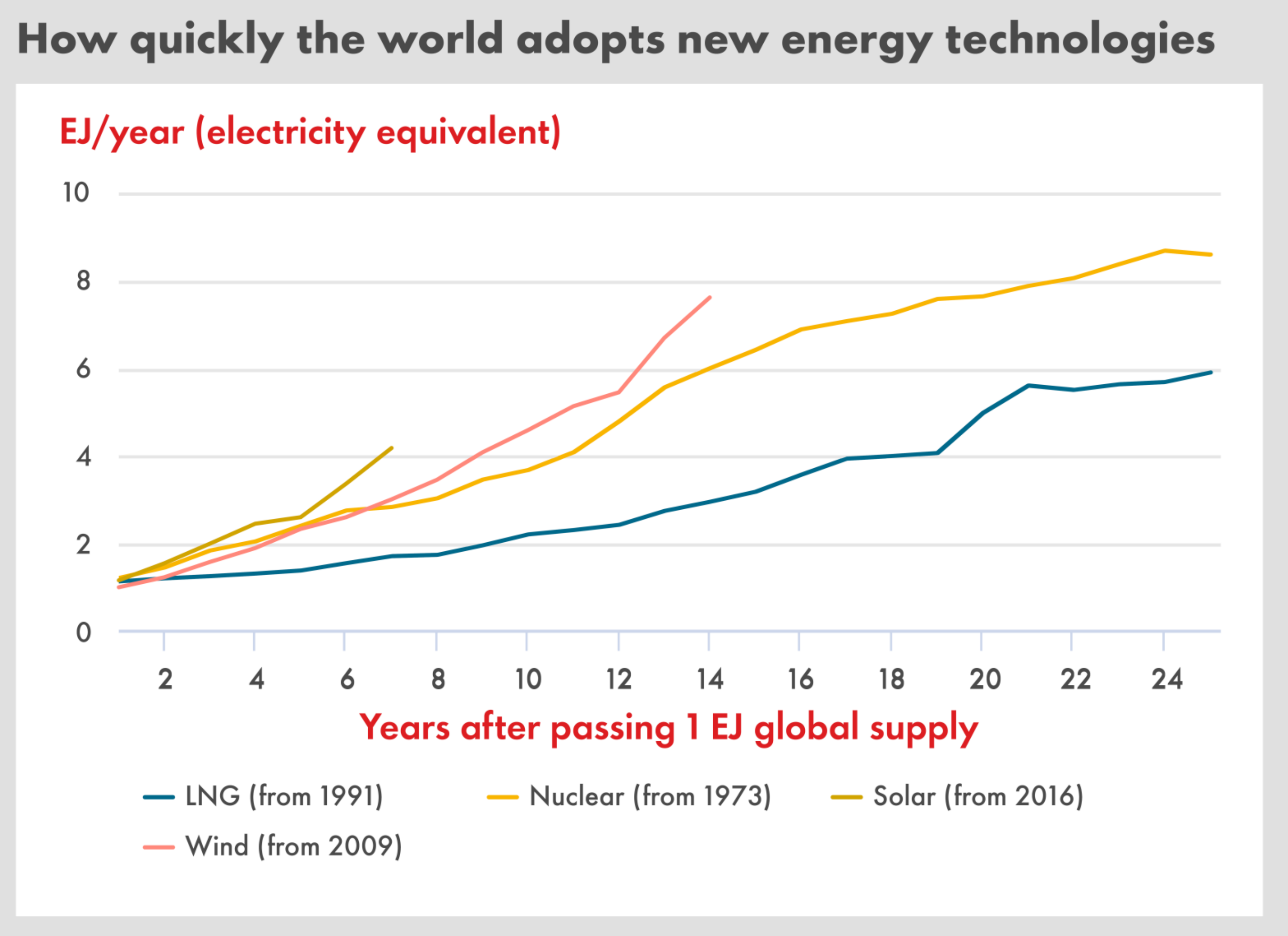
# Electrical loads & supply across scales

# Emerging electrical loads >100 MW




Source: U.S. Oil Drillers Are Going Electric—if They Can Get the Electricity – WSJ; Enverus Intelligence, 8 April 2024, “Electrifying the Permian”; S&P Global, 2023, https://doi.org/10.15530/urtec-2023-3859345; https://stand.earth/wp-content/uploads/2024/02/Clean-Clicks-or-Dirty-Chips-Feb-2024_230224.pdf; This key chemical is super dirty to make. Can an... | Canary Media; Power blocks in natural gas-fired combined-cycle plants are getting bigger - U.S. Energy Information Administration (EIA)

# Scaling energy technologies has historically taken time



# Thinking about electrified processes

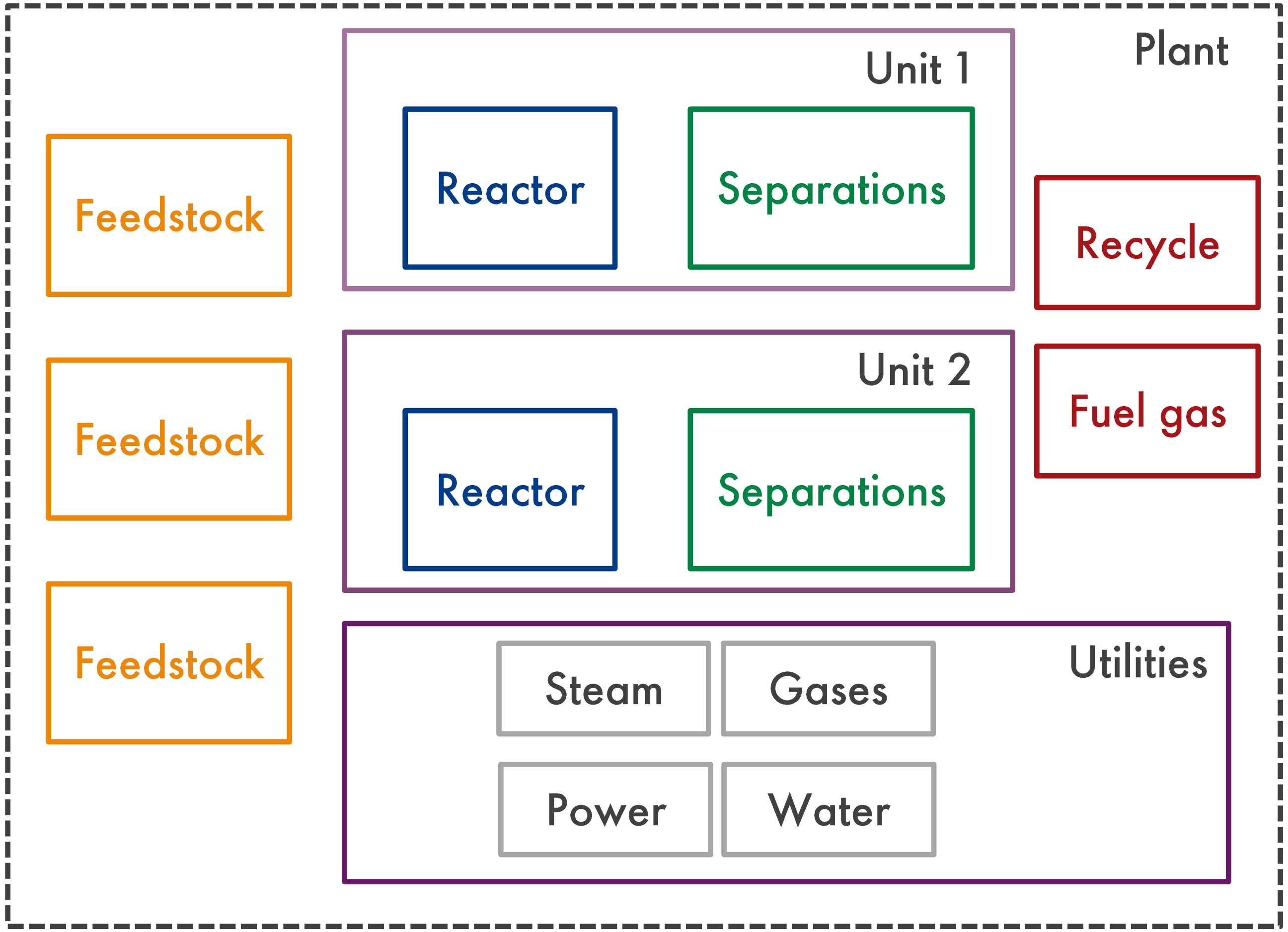
# Electrification of Utilities, Unit Operations, and Process Lineups

## Tradeoff between scale, complexity, timing, and decarbonization potential

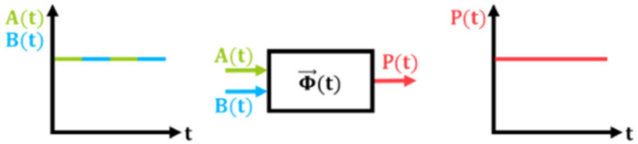
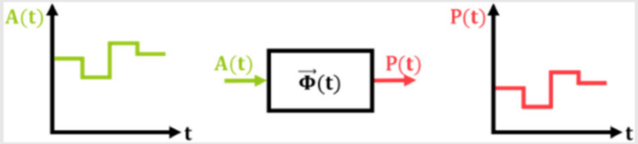
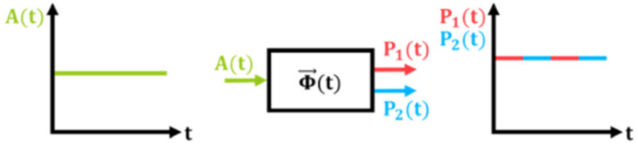
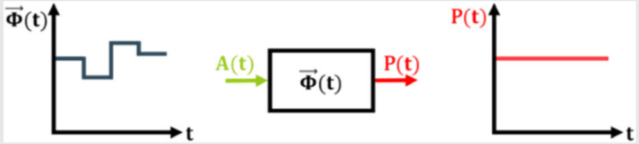
- Exogenous vs. endogenous emissions
- Endothermic vs. exothermic units
- Feasibility of other decarbonization levers

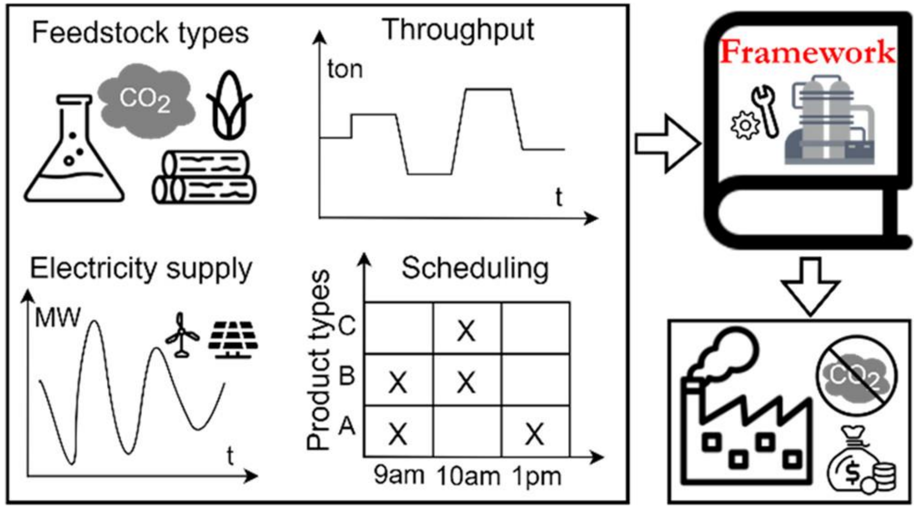
- Known operational envelopes vs. emerging process technologies

- Replicability
- Scalability
- Speed of deployment



# While flexibility has been part of chemical processes, electrification adds a new dimension

| Dimension of flexibility | Flexibility parameter | Impact on apparatus or process |
|---|---|---|
| Feedstock flexibility<br>The ability to handle changing feedstock without violating product specification or capacity. | $x_{in,\ i}$ |  |
| Capacity flexibility<br>The ability to handle changing feed quantities, more specific feed flow rates, without violating product specification. | $F_{in}$ |  |
| Product flexibility<br>The ability to produce changing products or product qualities within certain specifications and capacity boundaries. | $x_{out,\ i}$ |  |
| Operational flexibility<br>The ability to handle changes regarding input or operational parameters without compromising feedstock, capacity or product specifications. | $F_{in}$, $x_{in,\ i}$, $T_{in}$, $p_{in}$, $T_{sys}$, $p_{sys}$, $x_{sys,\ i}$, $n_{sys}$ |  |

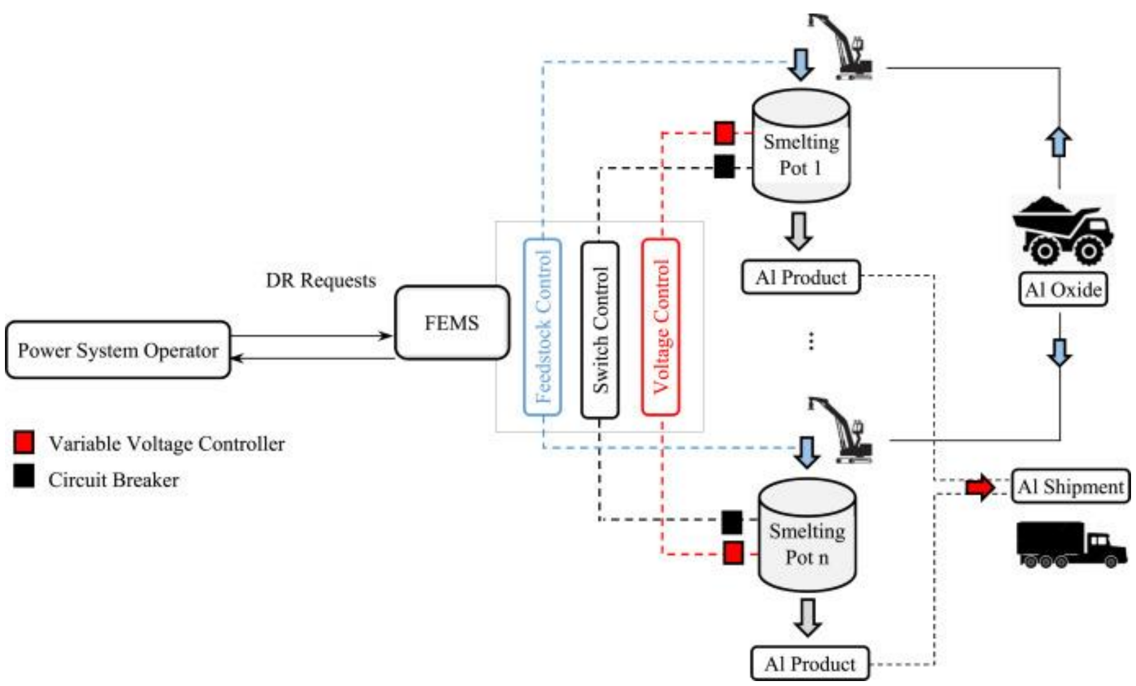



Product demand

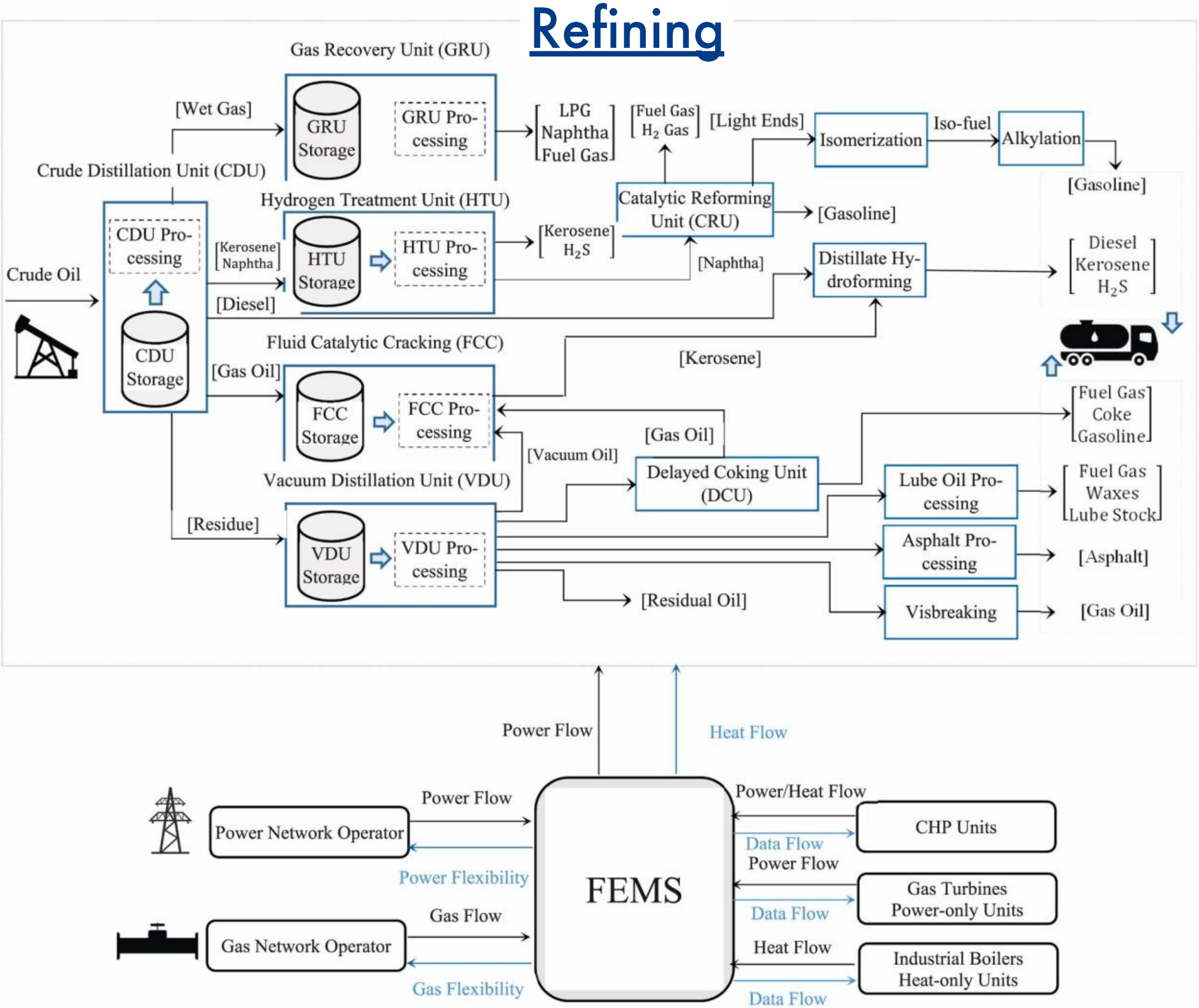
Product storage

# Constituents of industrial flexibility range in number & size

## Aluminum




## Refining






Demand-side management in industrial sector: A review of heavy industries – ScienceDirect;
FEMS = Factory Energy Management System

# Shell electrification examples

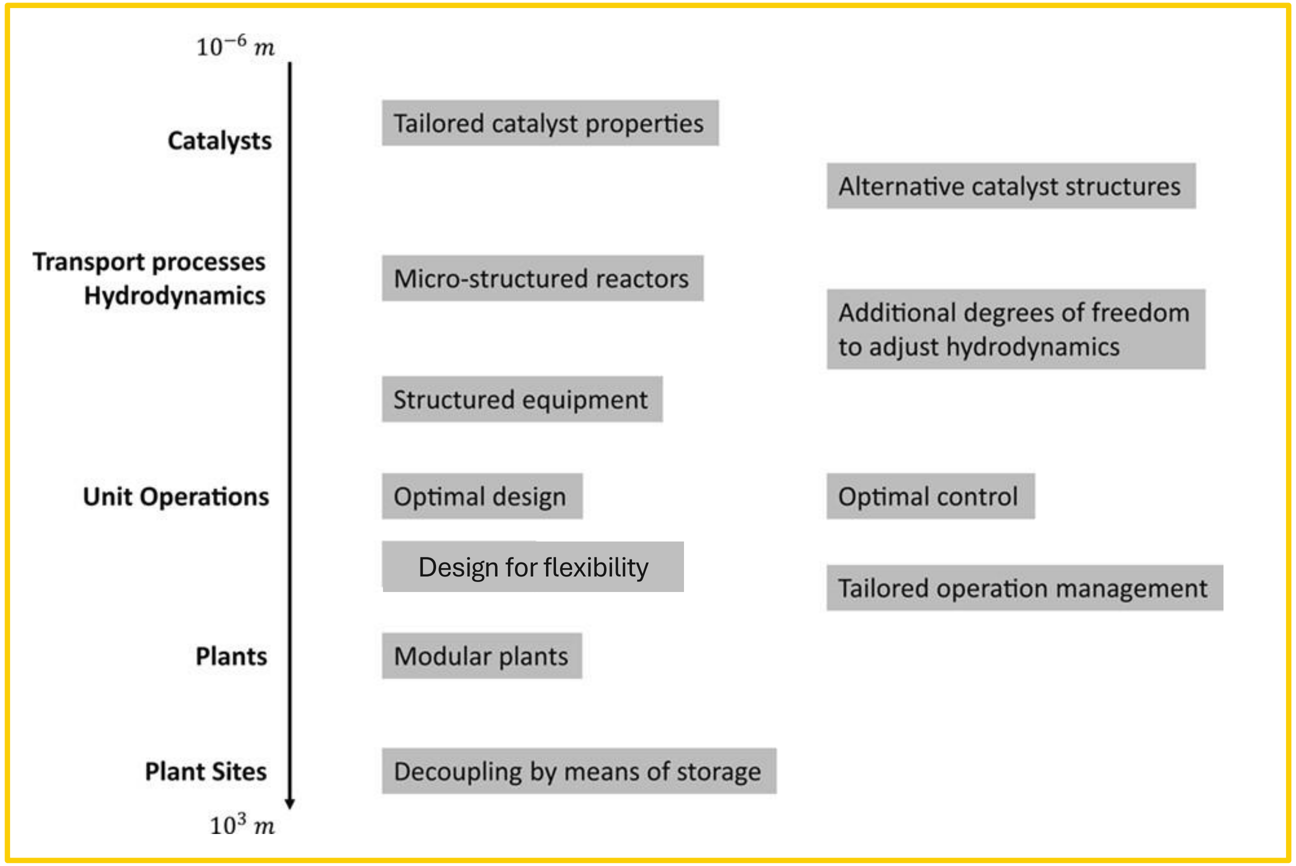
- Technology for a net-zero energy future | Shell Global
  - Shell and Dow start up e-cracking furnace experimental unit | Shell Global
  - Hydrogen | Shell Global
  - shell-energy-transition-strategy-2024.pdf

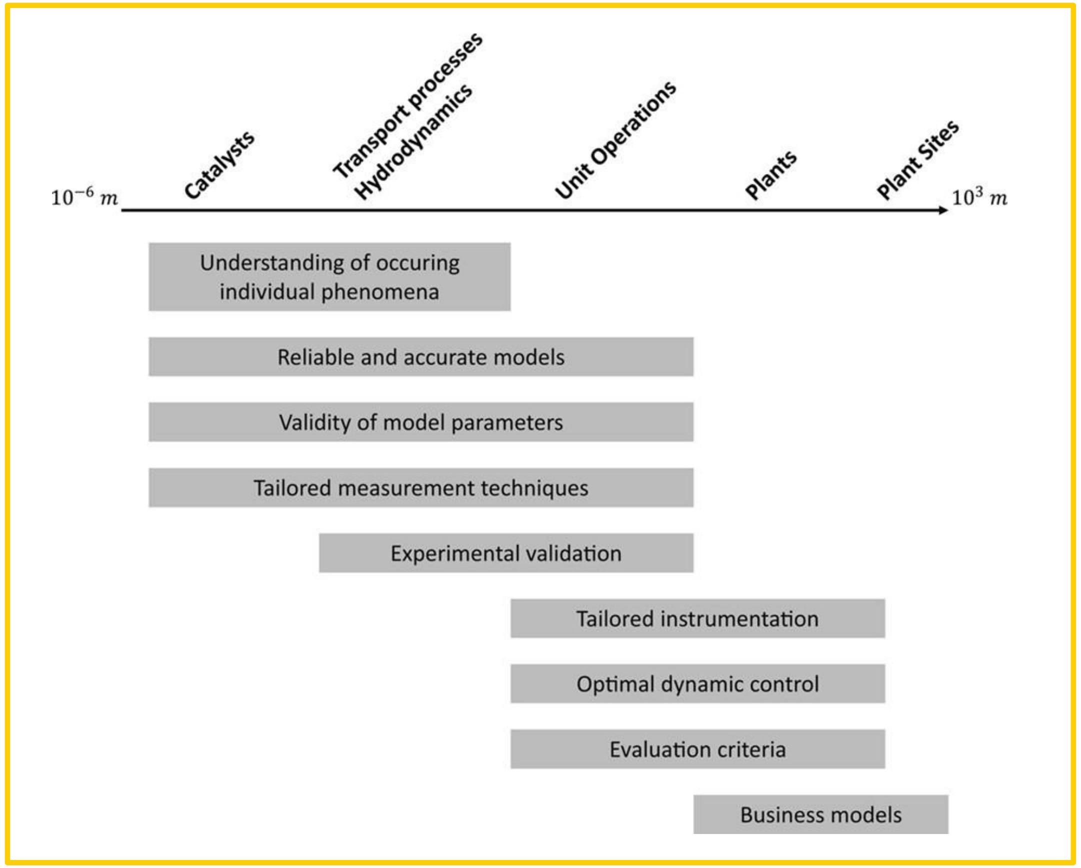
# What will it take to scale?

# Challenges & Priorities

# Challenge #1: RD&D is happening at every scale in parallel for new processes

Rapid learning, digitalization critical to incorporate and build on results

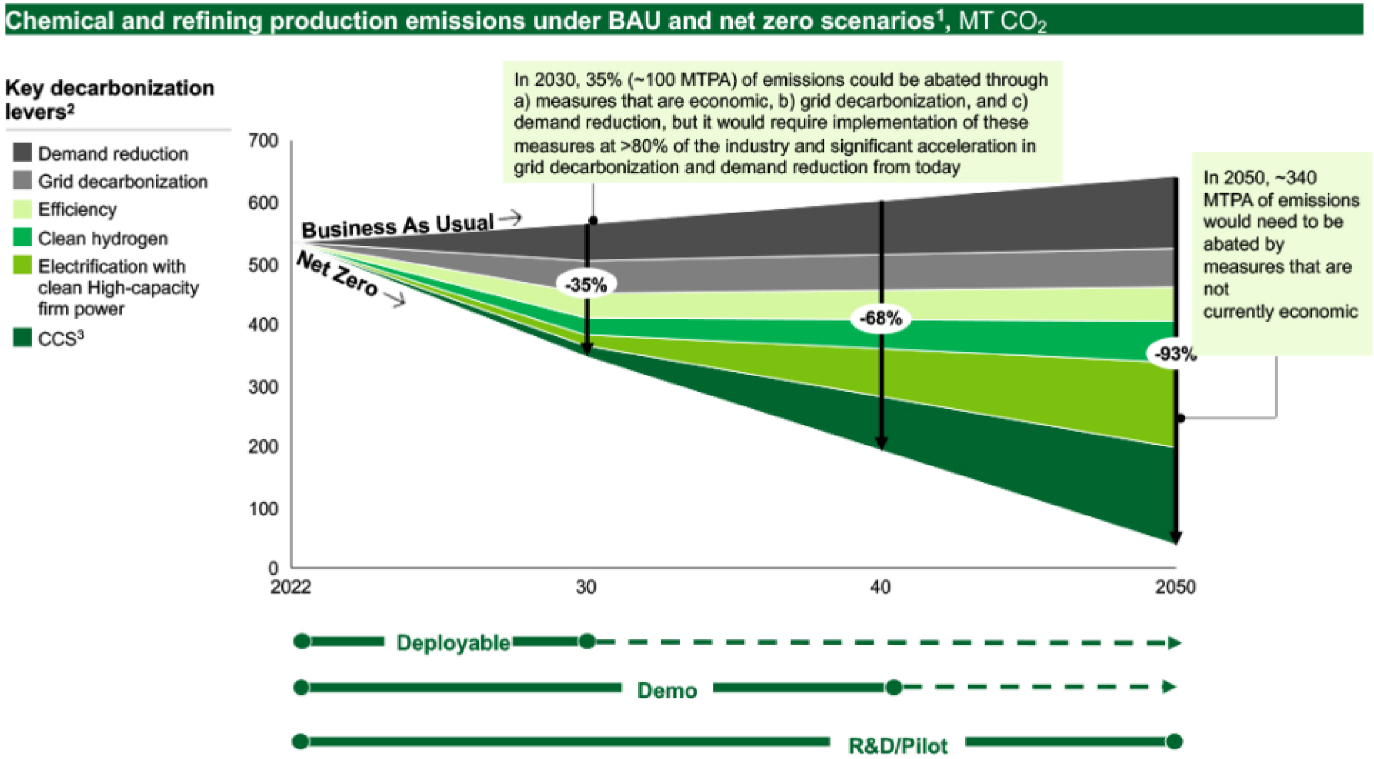


# Challenge #2: Diversity of processes and technologies requires attention in many areas

- Early "wins" are at the <= 100 MW levels
- Larger processes require more $$, which leads to more de-risking (& more time until deployment)

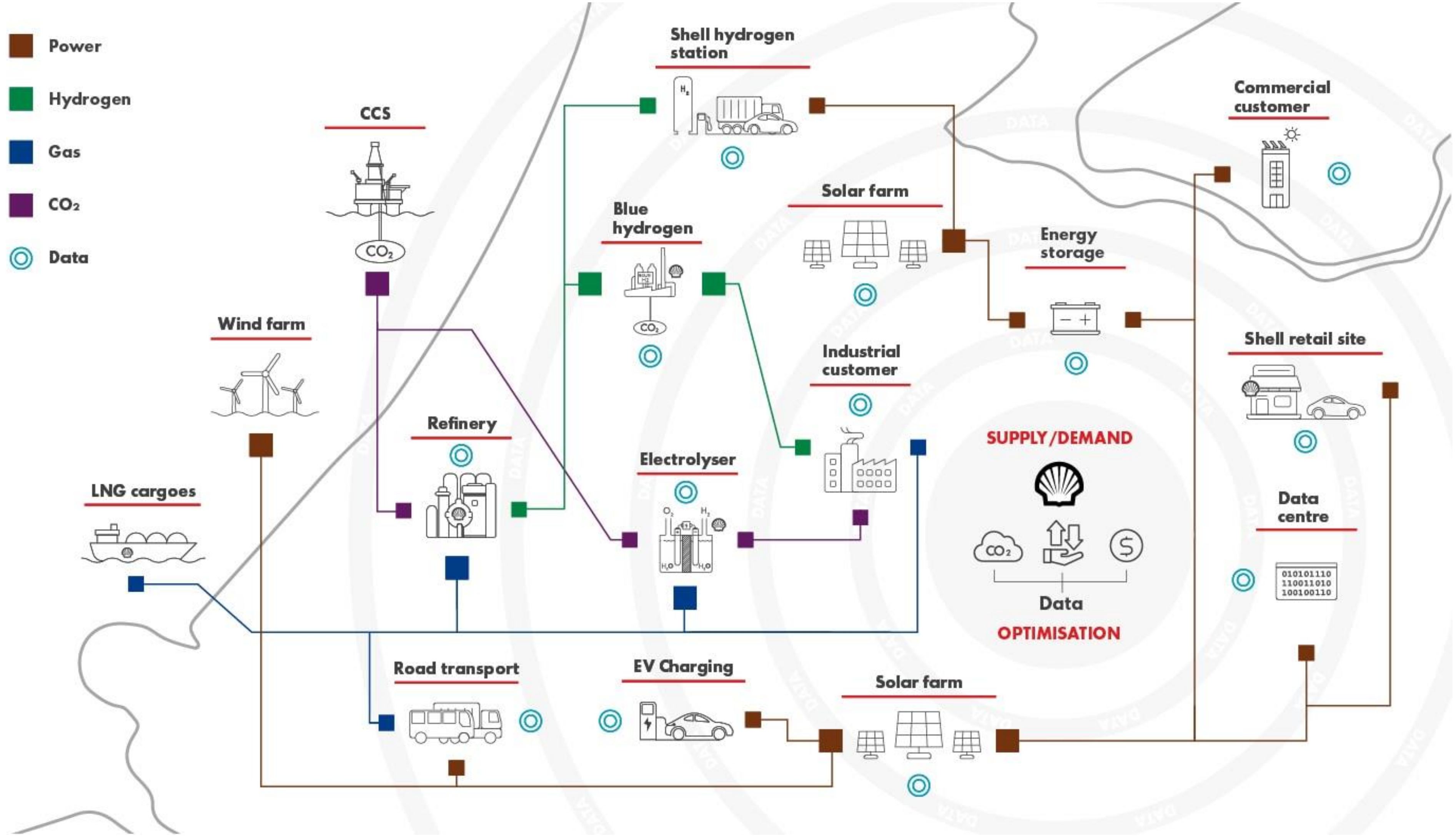
⇒ **Decision support is key**




1. Deployable bio-processes that reduce lifecycle emissions of chemicals and refining products are not considered in the pathway to net zero
2. Technologies considered in pathway are in the deployable and demo categories. Pathways may be updated with different developed technologies in future
3. Only CCS is considered in the net zero pathway, refer to Carbon Management Liftoff report for discussion of carbon utilization technologies

Source: EIA data for energy-related emissions, EPA national recycling strategy, White House – The Long-Term Strategy of the United States – Pathways to Net-Zero Greenhouse Gas Emissions by 2050

# Challenge #3:  Connections are becoming increasingly complex



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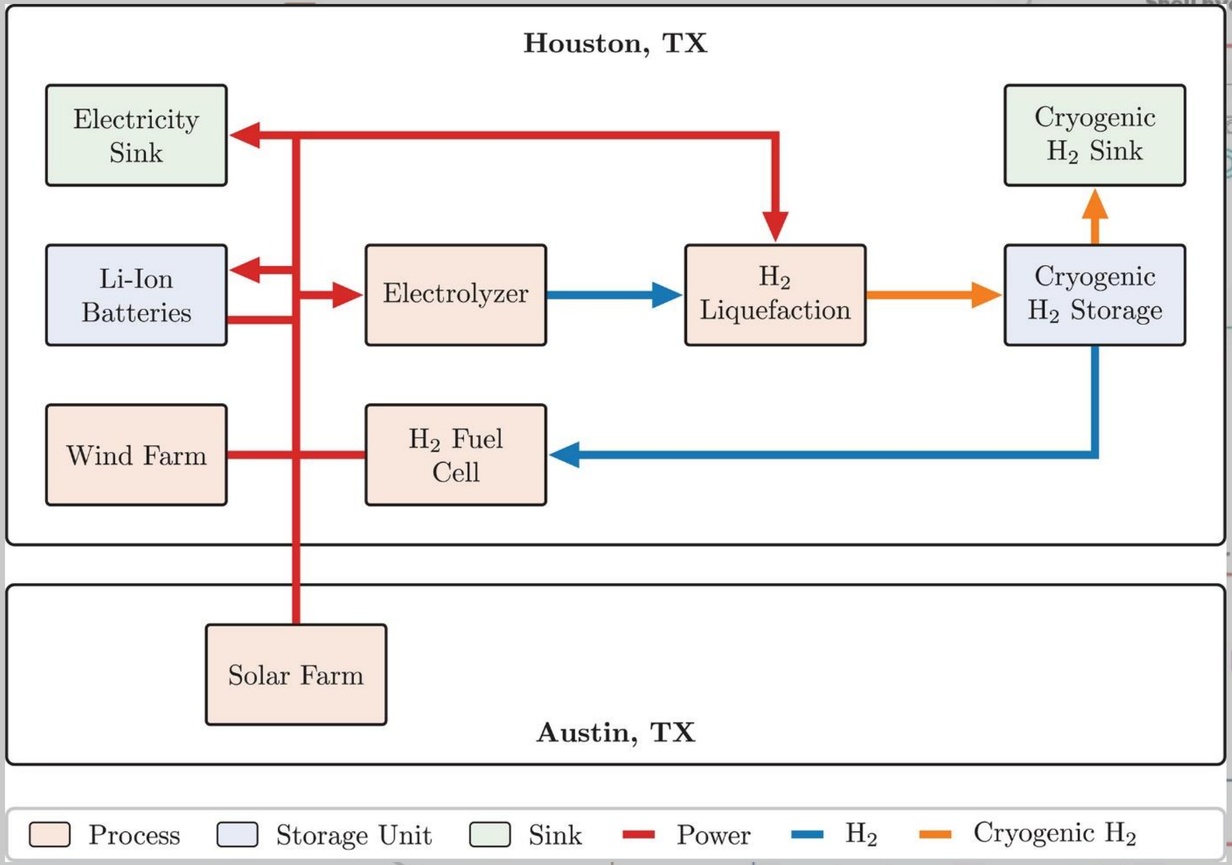
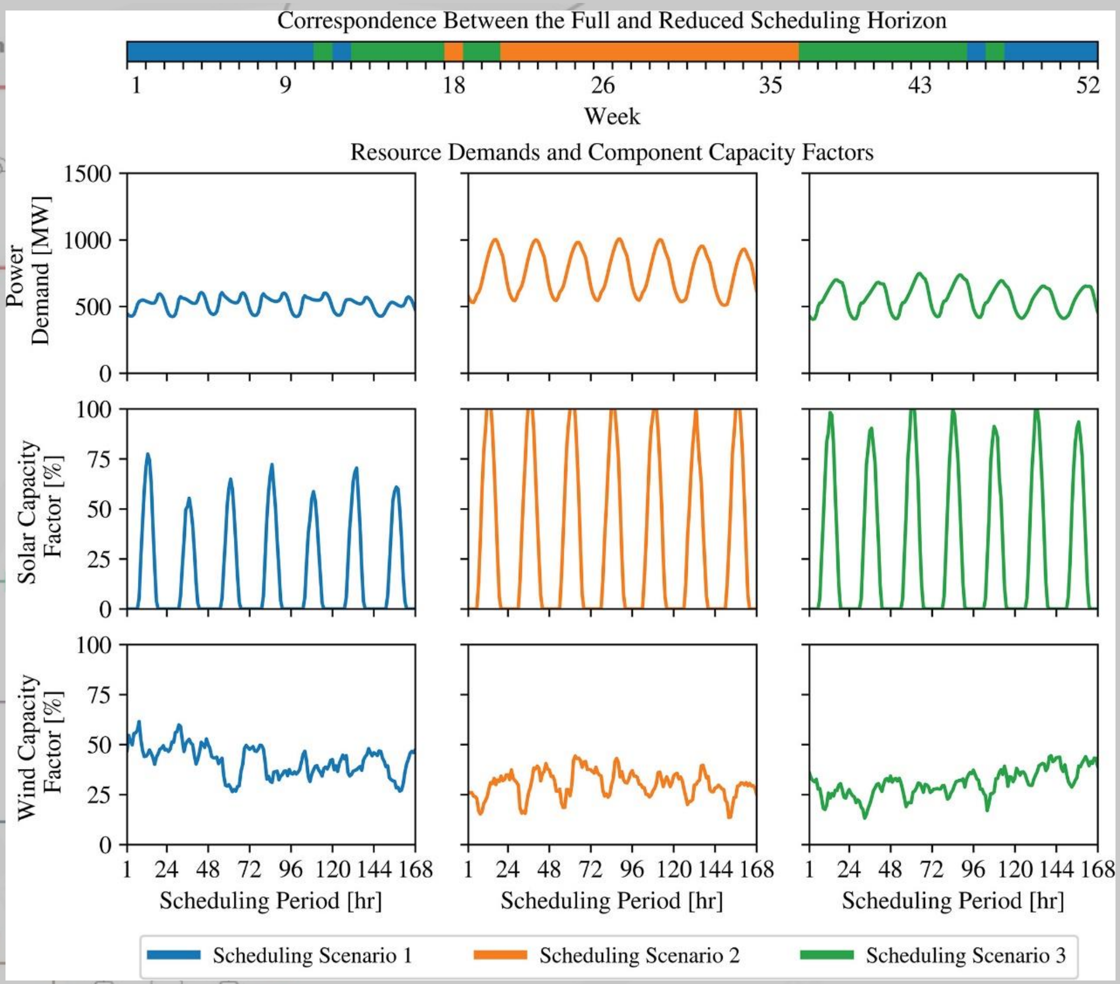
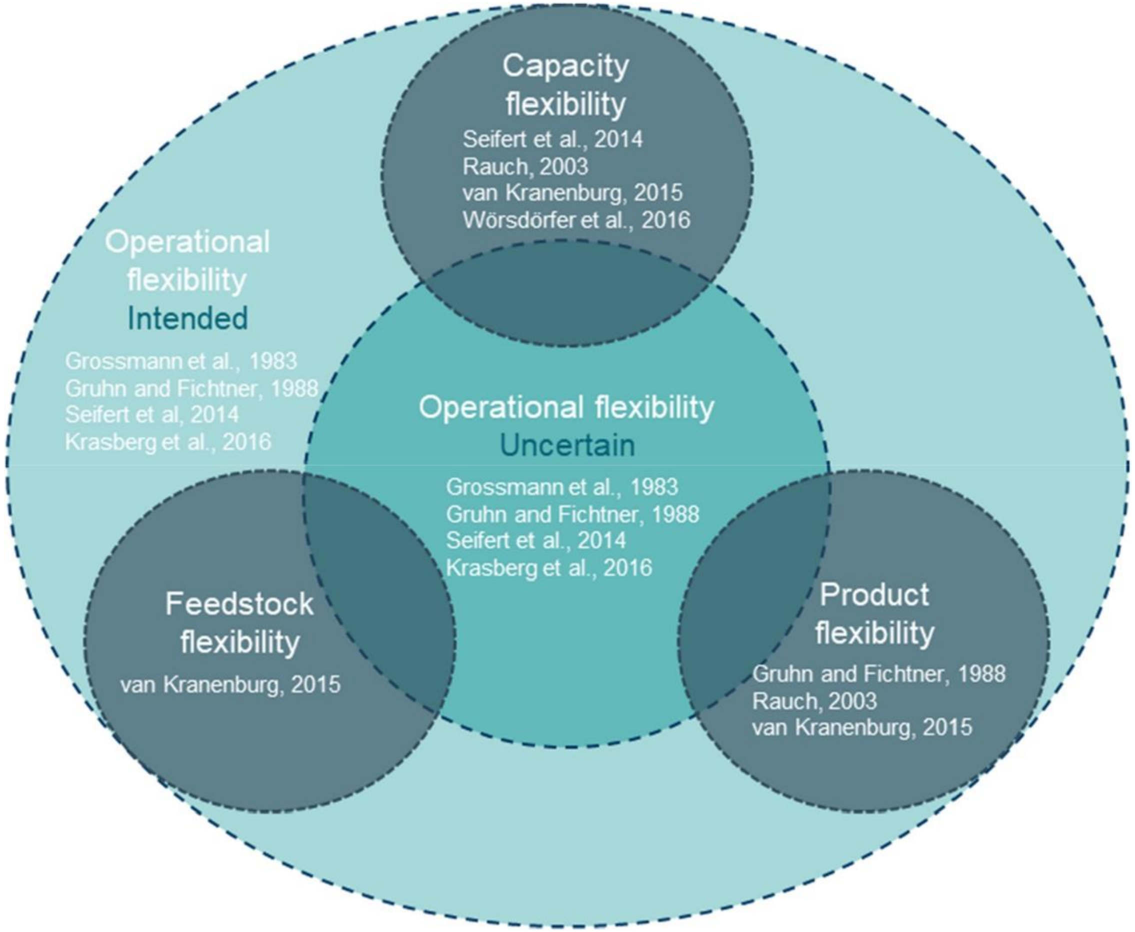


# Challenge #4: Cost and quality are joined by additional objectives & constraints

- GHG intensity
- Broader LCA: water, air quality
- Societal: resilience, environmental justice
- Fixed vs. dynamic values of key attributes

- Flexibility needed to help accommodate these - consistent definition or protocols for characterization needed






Challenges and Opportunities to Enhance Flexibility in Design and Operation of Chemical Processes - Riese - 2020 - Chemie Ingenieur Technik - Wiley Online Library; A systematic approach to define flexibility in chemical engineering - Bruns - 2020 - Journal of Advanced Manufacturing and Processing - Wiley Online Library; Development of a Conceptual Framework for Evaluating the Flexibility of Future Chemical Processes | Industrial & Engineering Chemistry Research (acs.org)

# Final thoughts

- Electrification is an increasingly attractive decarbonization lever for the industrial sector.
- Larger loads are complex, requiring additional de-risking and decision support for investment.
- Identification **& validation** of additional benefits is a key opportunity for new technologies
- Illustrating a path of transformation can be very powerful: how do we use and create tools to help?

- **F:** Feedstocks, Fuels, & Flexibility
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- **S:** Systems, Scales, Synthesis, Simulation, & Safety
- **E:** Economics & Efficiency

# Acknowledgments

FIPSE-6 organizing committee

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