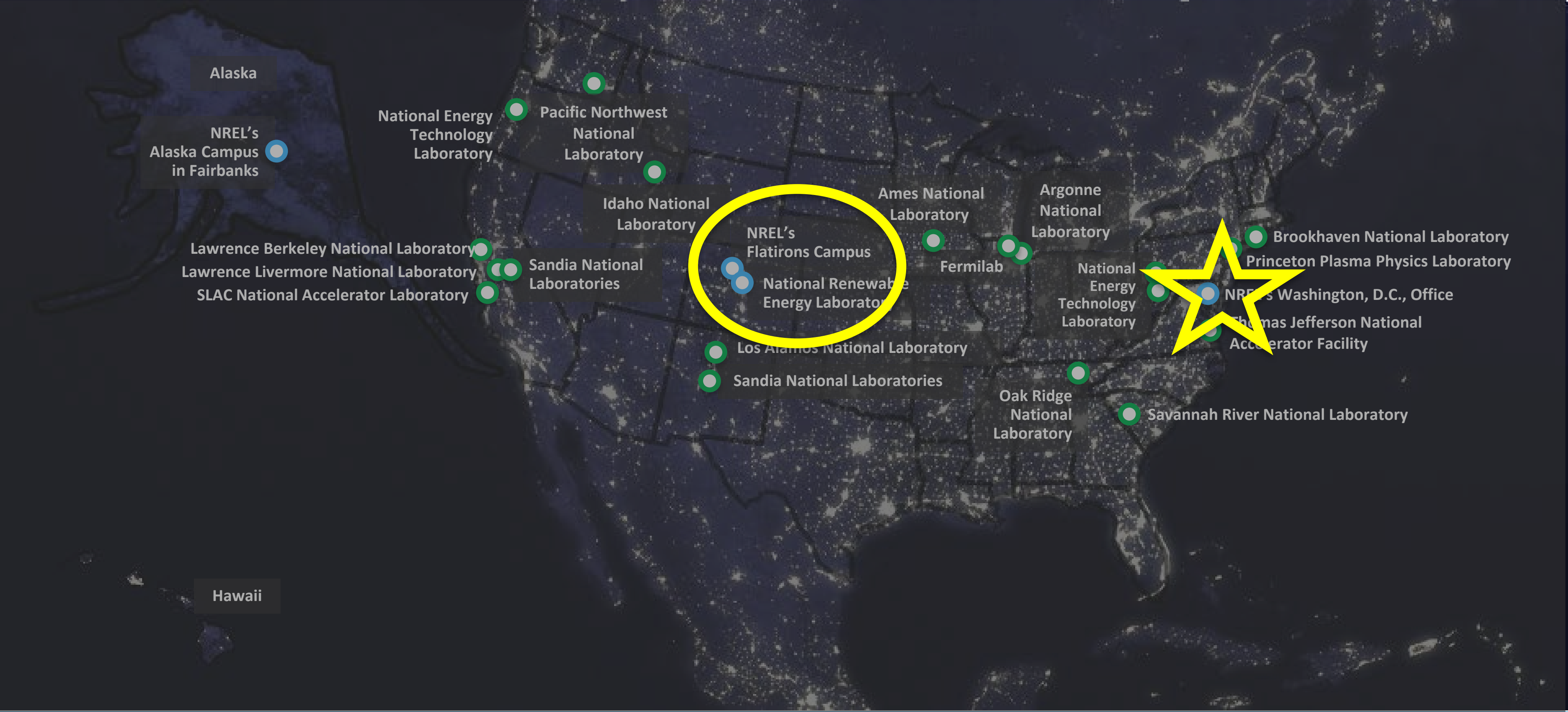
Reviewing Flexibility in Industrial Electrification: U.S. Green Ammonia and Steel Industries

Liz Wachs

April 23, 2023

Virtual



Coast to Coast

The **17** national laboratories have served as the leading institutions for scientific innovation in the United States for more than 90 years.

NREL: Transforming Energy Together

NREL at a Glance

3,862 Workforce, including:

- 2,863 regular/limited term
- 528 contingent workers
- 221 postdoctoral researchers
- 140 graduate student interns
- 110 undergraduate student interns

—as of 3/28/2024

World-class research expertise in:

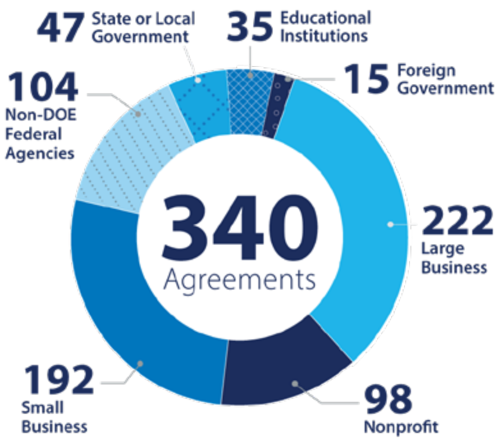
- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

Partnerships with:

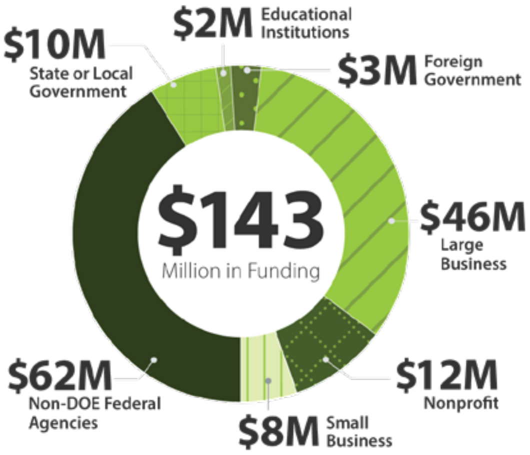
- Industry
- Academia
- Government

4 Campuses operate as living laboratories

More Than 1,100 Active Partnerships in FY 2023



Agreements by Business Type



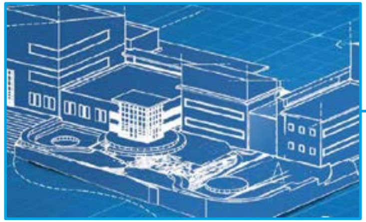
Funding by Business Type

NREL Brings Distinct Capabilities

Foundational Science	Accelerated Technology Scale-Up	Systems	Markets

Bench-scale- discovery → Scaling R&D and Process Engineering → R&D with Industry Partners

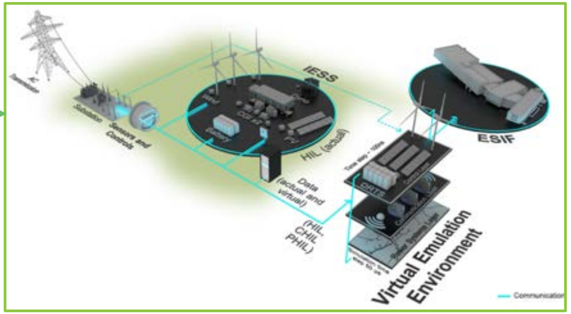
Solar Energy Research Facility
Science and Technology Facility
Field Test Laboratory Building



Energy Materials and Processing at Scale (Completion 2025)

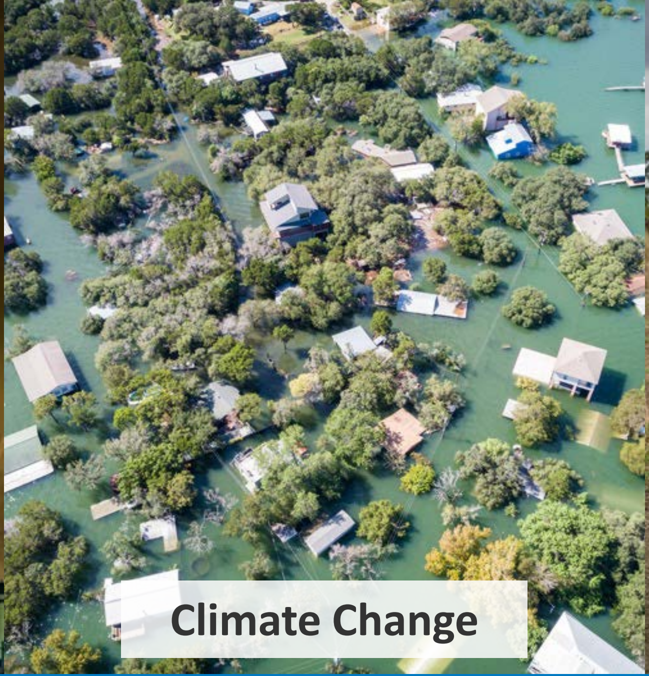
Energy Systems Integration Facility

- Carbon-free H2
- Products from electrochemical processes and CO2
- Advanced Batteries
- PV, Wind, Water Power, Geothermal
- New Buildings and Industrial Materials, Manufacturing and Systems
- Grid and security tech



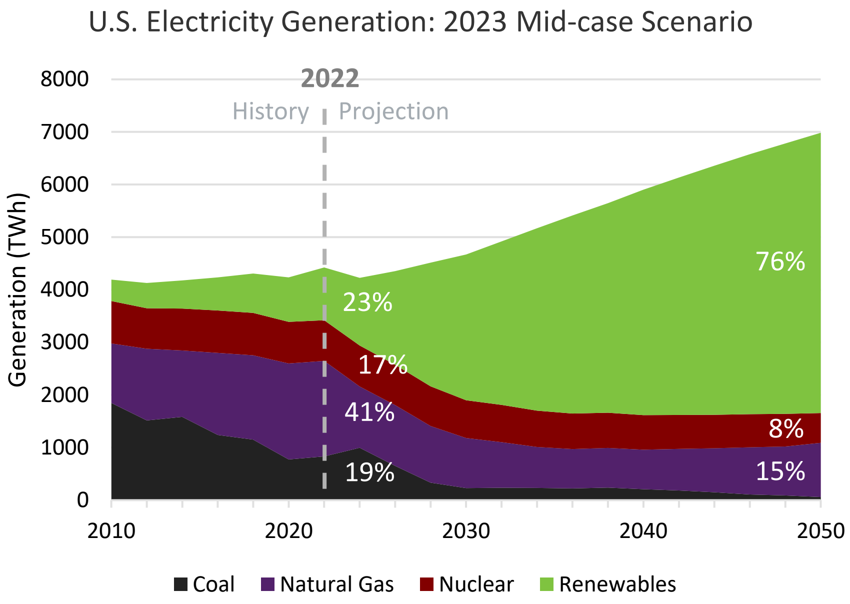
Advanced Research on Integrated Energy Systems

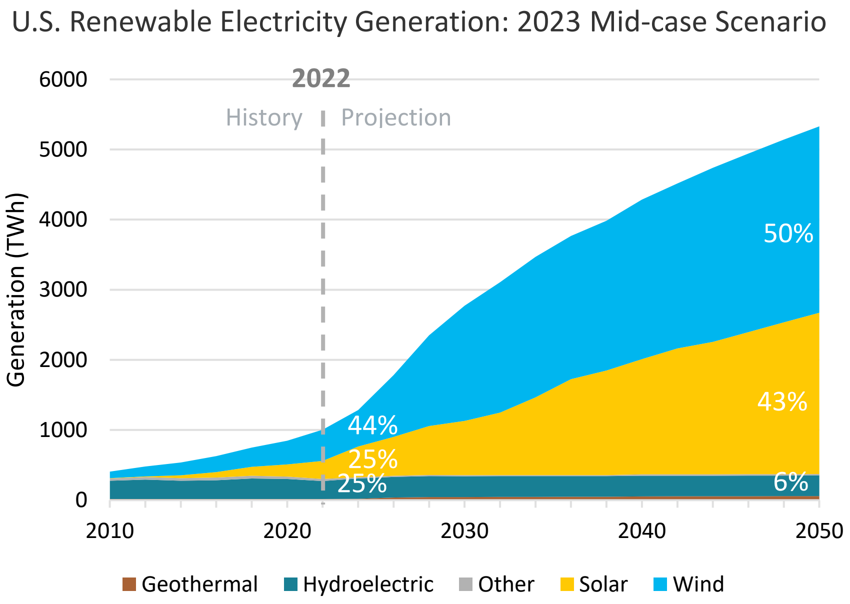
High-Performance Computing, Simulation, and Visualization



The Triple Planetary Crisis

The **triple planetary crisis** refers to the three main issues that humanity currently faces, reinforcing one another and driving further damage. Each must be resolved for us to have a viable future on this planet.





Renewables could generate 76% of U.S. electricity by 2050

- NREL's 2023 Standard Scenarios estimates half of renewable electricity generation in 2050 will come from wind, with 43% coming from solar.

Flexible Loads in Context

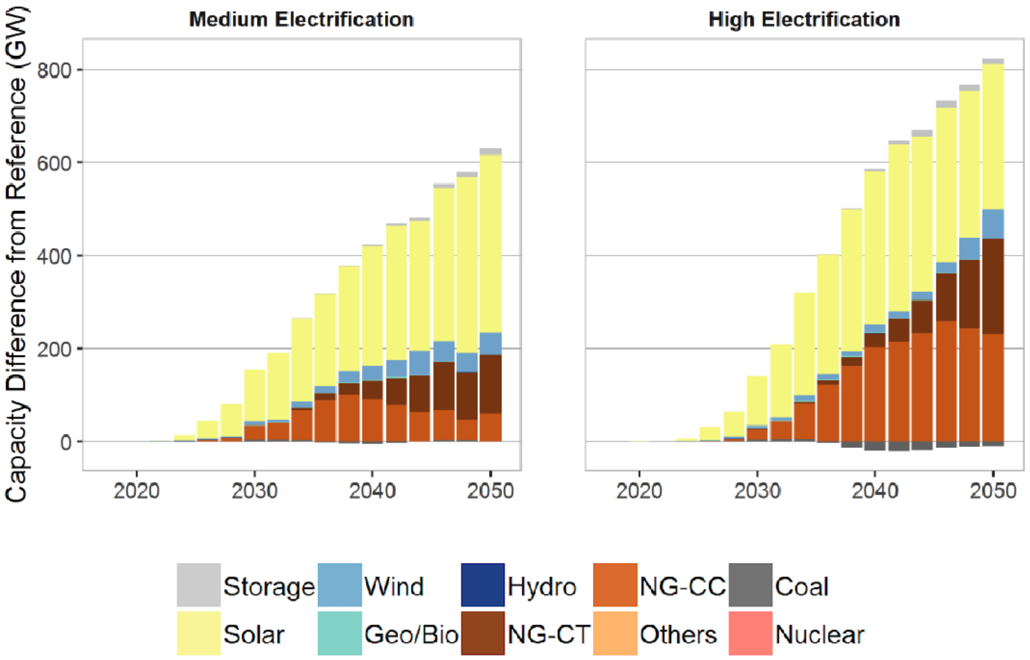
- Variability in power supply changes grid characteristics (FERC, 2021)
  - Reserves & flexibility more important

Photos by Werner Slocum / NREL

Flexible Loads in Context

- Electrification requires more generation capacity
  - Demand response frequently cheapest option

The combination of renewable energy transition and electrification makes flexible demand especially beneficial… but where is it and how can it be deployed?



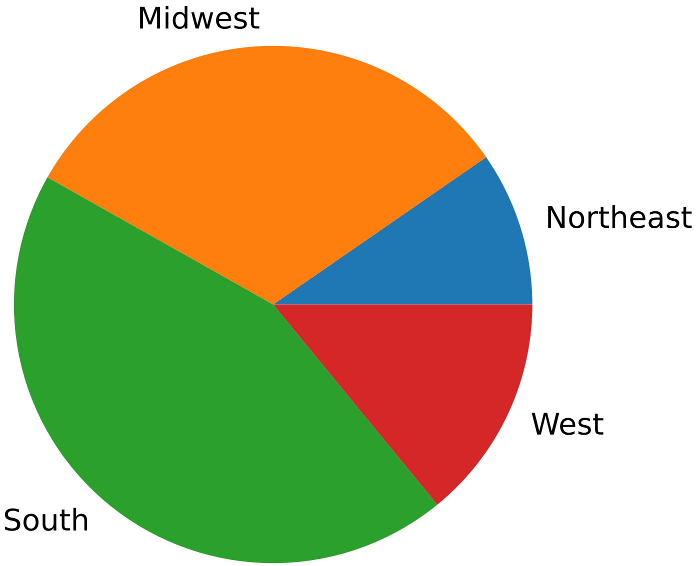
Murphy et al. 2021. Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States.

US >1,200 GW capacity Feb 2022

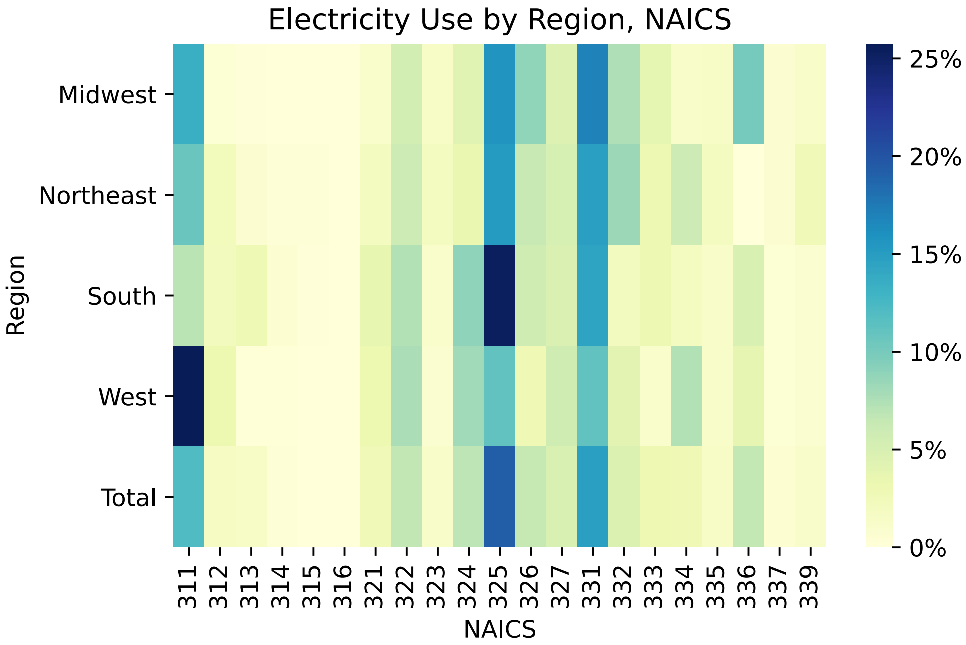
Electricity Use by Industry

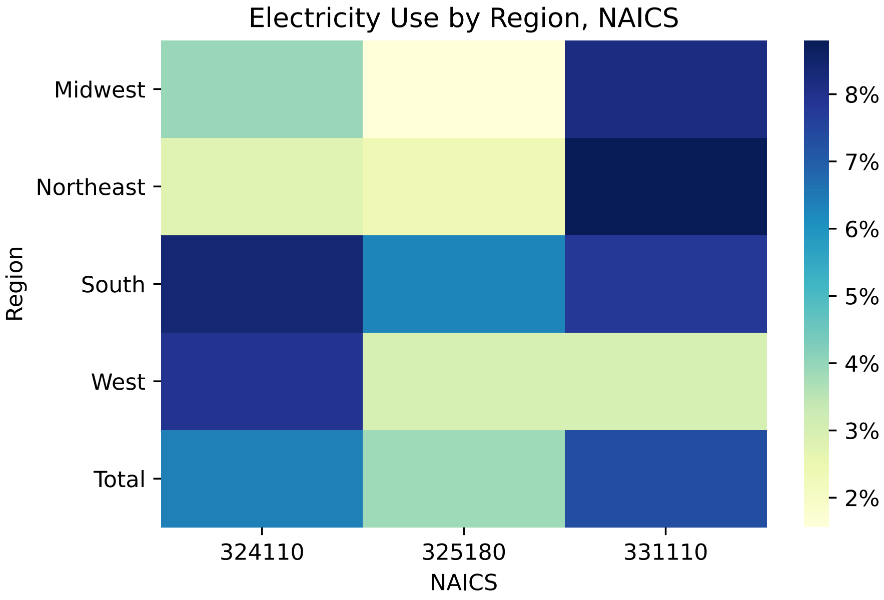
- 26% of US electricity retail sales in 2021
- Average load: 100x residential; 16x larger than commercial
- ~70% current demand response

Total manufacturing net electricity by region, MECS 2018



2018 Electricity Use by Industry, by Region

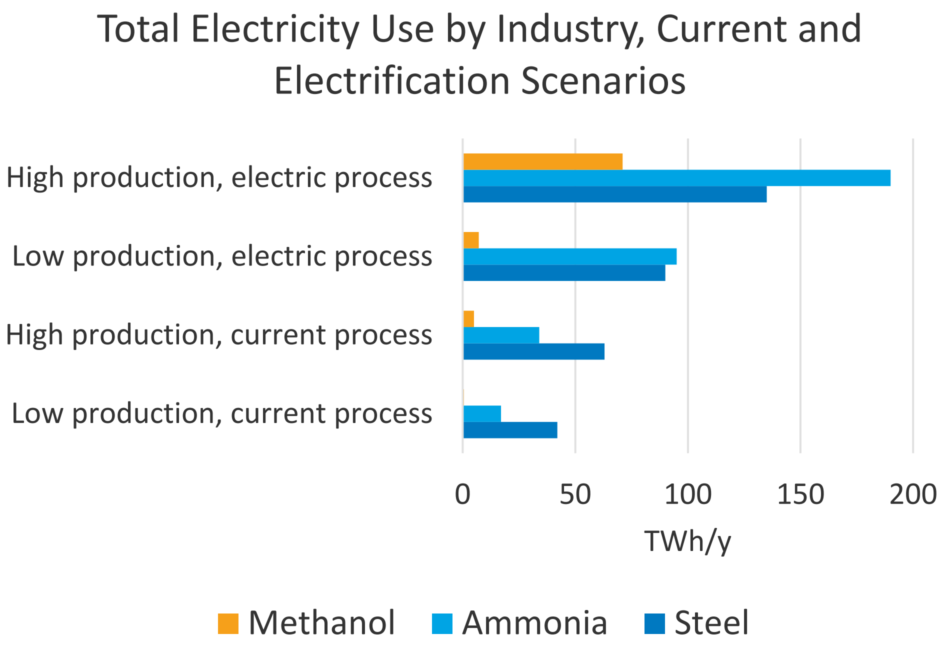




Fairly uniform with some exceptions; very few 6-digit NAICS codes exceed 5% of the total in any region

Electrification of Manufacturing

Electrification pathways increase industrial electricity demand & change use patterns



Ammonia production based on electrolytic hydrogen could overtake steel as largest manufacturing electricity user at current capacity levels

Flexible Demand and Decarbonization

How flexible demand can aid decarbonization **immediately**
…and **longer term**…

- Increasing utilization of low carbon resources
- Decreasing deployment of high carbon resources
- Cost reduction by deferring new investment in capacity, storage and transmission

Flexibility Descriptions

"any customer load that need not be on or totally served at all times" –Siosanshi

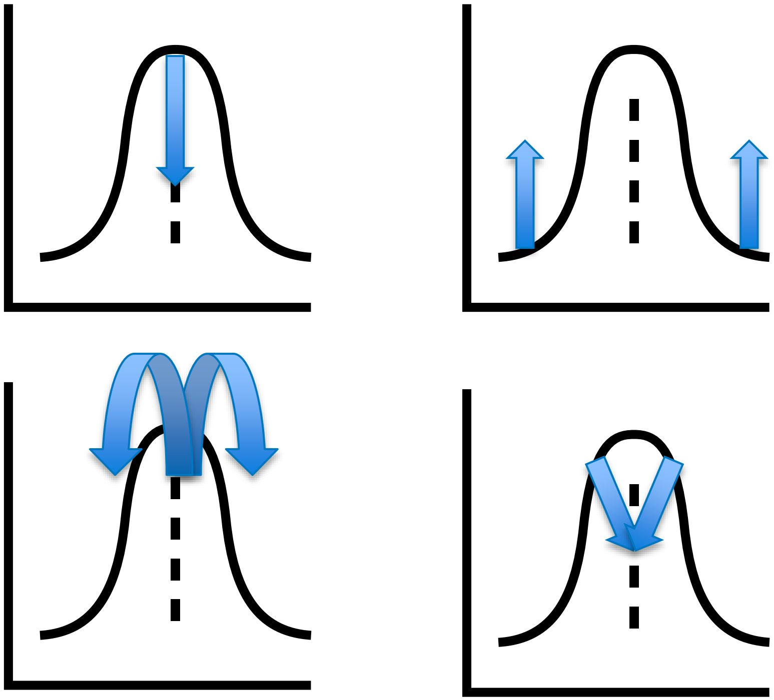
"the potential for reconfiguring the temporal organization of social life and the energy demands that follow" –Blue et al.

Flexibility Definitions

1) **Energy systems: flexibility as a property of a system**;
    1) how much total system supply and demand can be modified
    2) measured in MW
    3) Underlying assumption: baseline, which is 'imagined.'
2) **Operations: storage or DSM assessed for flexibility they can supply for the grid;**
    1) Measured in MW
    2) assumptions:
        1) demand patterns are constant over time,
        2) assumed (but unknowable) values for present storage and flexibility,
        3) framing operational changes as discrete actions thus ignoring links to societal organization.
3) **Commodification: flexibility defined to be bought or sold;**
    1) valued in $
    2) assumption: can hold other features related to social life constant.

What is Demand-Side Load Flexibility?

System



Operations/DSM

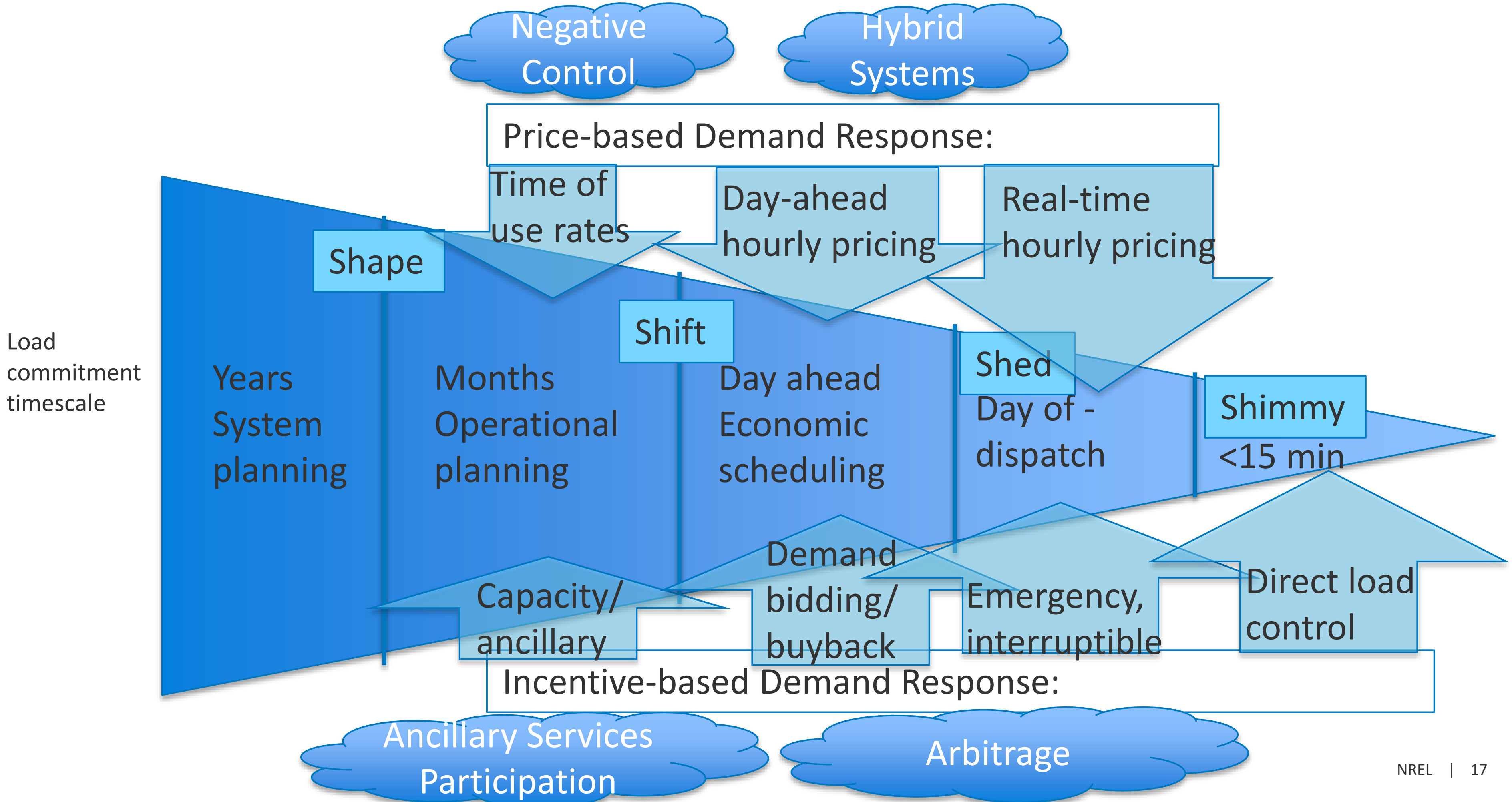
- Energy storage systems
- Co-generation/hybrid systems
- Load shedding
- Load shifting
- Energy efficiency
- Waste heat recovery

Commodification

- Interruptible rates
- Direct load control
- Time of Use/Real-time Rates
- Ancillary services markets
- Arbitrage

Low-cost, efficient, fast, provided by industry

Demand Response



Design Characteristics

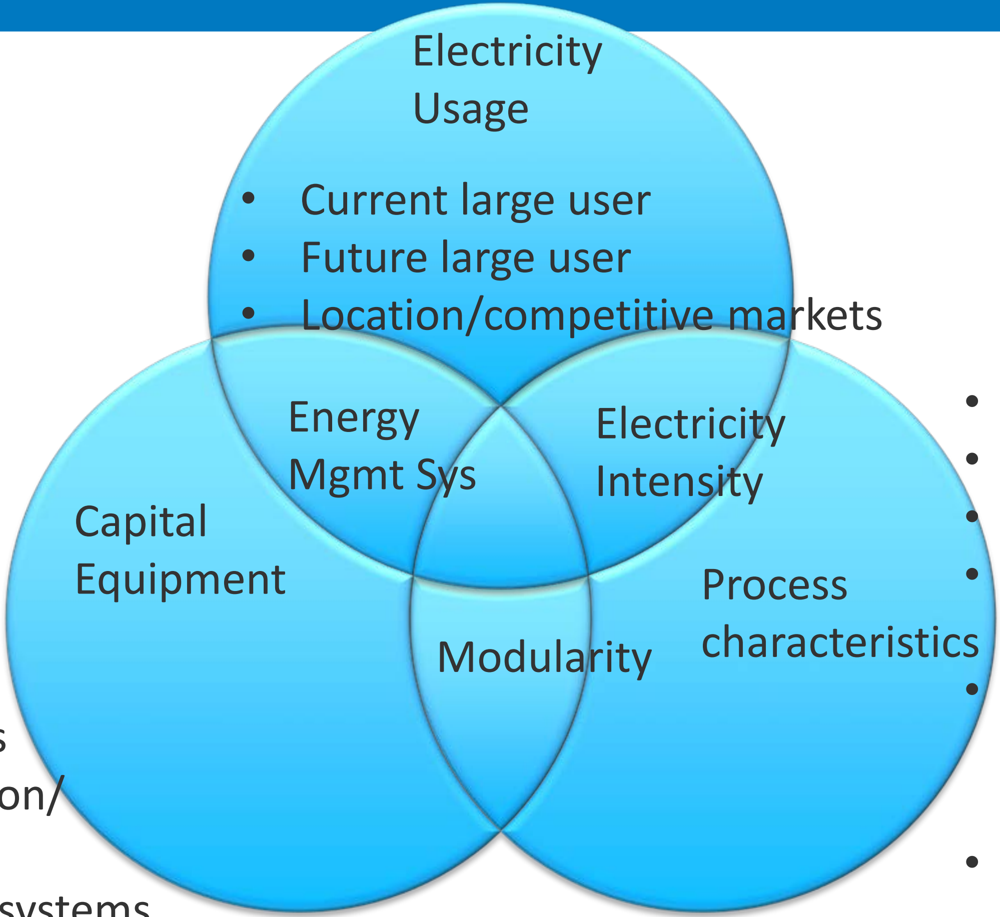
Input Flexibility
- Equipment designed or selected for capability of dynamic operation
- Oversized equipment that can adapt to range of loads
- Buffering (batteries, storage tanks)

Output Flexibility
- Product and pathway diversification
- Recipe/production scheme diversification

Throughput Flexibility
- Oversized equipment for peak flow rates
- Parallelization of production lines
- Scheduling

Paraphrasing Luo et al. 2022

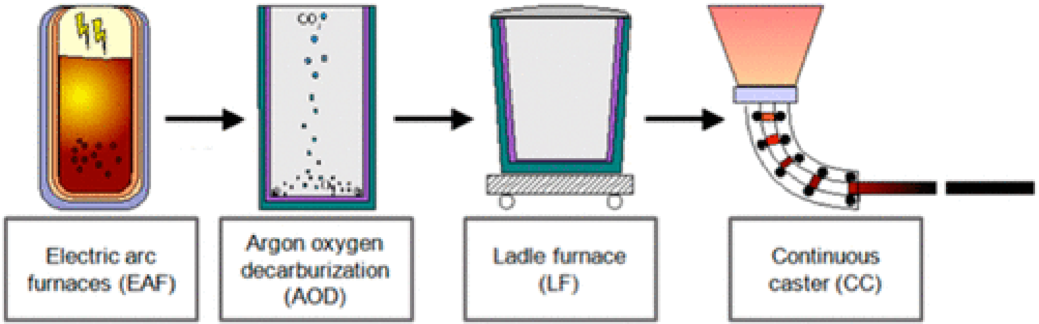
Characteristics

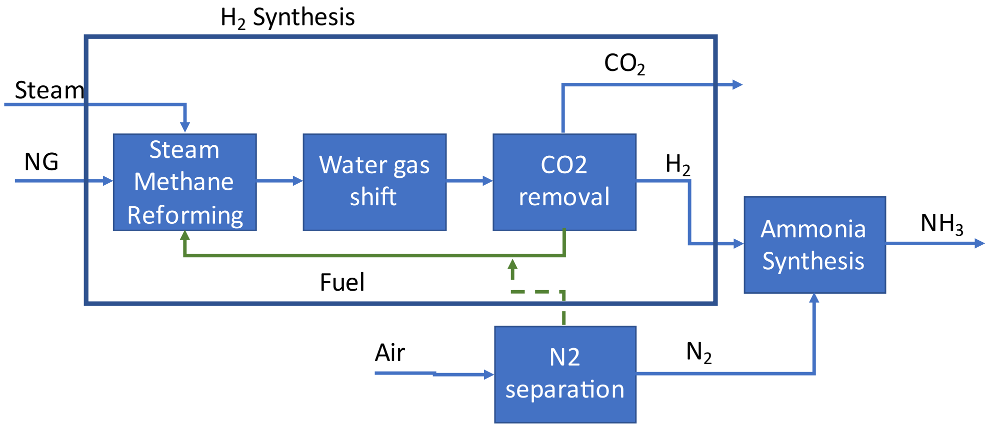


- Low capacity utilization
- Storage capacity
- Overcapacity can be cheaply built
  - Control systems
  - Onsite generation/ cogeneration
  - Hybrid heating systems

- Dynamic operation
- low ramp time
- Modularity
- Heterogeneous operations
- Public good/electricity dependent/emerging technologies
- Movement to process innovation

Case Studies: Steel and Green Ammonia





- **Electric Arc Furnaces:** largest industrial electricity user today
- **Green Ammonia:** potential large future user of electricity, power-to-X

Framework: Technological Innovation Systems

Dimension	Category
Actors	• Companies, institutes of learning, government, NGOs, other stakeholders
Institutions	• Hard: laws and regulations • Soft: Customs, norms, routines
Interactions	• Networks • Between individuals
Infrastructure	• Physical • Knowledge • Financial

Functions
F1: Entrepreneurship
F2: Knowledge development
F3: Knowledge diffusion
F4: Guidance of the search
F5: Market formation
F6: Resources Available
F7: Creation of legitimacy
F8: Positive Externalities

(Hekkert et al. 2007; Bergek et al. 2008; Markard and Truffer 2008)

A structural-functional approach to detect barriers and opportunities for innovation

Interviews

- 20 interviews with 22 stakeholders
  - Semi-structured
- 4 categories: markets, industry, steel, green ammonia
- Grid operators, industry associations, universities, regulatory, consulting, start-ups, utilities
- Engineers, managers, professors, consultants, economists, vice presidents, directors, presidents, researchers, CEOs

Conversations with stakeholders throughout value chain

Characteristics of Inflexible Load TIS

Load Flexibility

Inflexible Load TIS **Flexible Load TIS**

Actors: Chemical companies, refineries

Interactions: Failure to find compensation agreement

Institutions

Hard: EHS, demand charges; fixed rates; DR opt-out

Soft: continuous operation, standard operating procedures, focus on yield maximization, stakeholder opposition to ‘double payment’, lack of knowledge/instruction on dynamic operations

Infrastructure

Physical: Process health and safety issues if interrupted; thermal chemical process; lack of smart sensors, meters, storage

Knowledge: Highly optimized continuous/steady; ISO infrastructure

Financial: Large capex, low specific electricity consumption

industry and market dimensions can both complicate industrial flexibility

Characteristics of Flexible Load TIS

Load Flexibility

Inflexible Load TIS **Flexible Load TIS**

Actors: Cryptocurrency mining, data warehouses, aggregators

Interactions: Industry and electricity provider, either directly or through 3rd party intermediary

Institutions

Hard: Regulations that allow energy, capacity and ancillary payments for DR; access to wholesale pricing

Soft: Opportunistic behavior in seeking profits; nontraditional business models

Infrastructure

Physical: sensors, smart meters, storage available, overcapacity, parallel processes, hybrid environment, multipurpose plants, modularity

Knowledge: dynamic operation possible, scheduling algorithms

Financial: Electricity major portion of total costs (low capex; opex dominated by power), investment support for alternative processes, market support for public good aspect of product

Technological solutions can facilitate flexibility; most relevant for cost structure dominated by opex; requires communication between actors

TIS - Market

F1: Entrepreneurship	
F2: Knowledge development	
F3: Knowledge diffusion	
F4: Guidance of the search	
F5: Market formation	
F6: Resources Available	
F7: Creation of legitimacy, organization	
F8: Development of Positive Externalities	

Hurdles: Lack of profit, not focus of R&D, market operators agnostic to resource type, operational difficulties and resistance

TIS – Flexible Steel

F1: Entrepreneurship
F2: Knowledge development
F3: Knowledge diffusion
F4: Guidance of the search
F5: Market formation
F6: Resources Available
F7: Legitimacy, organization
F8: Positive Externalities

One of largest contributors to DR; Hurdles: not focus of R&D, lack of connection between resource type, scope 2 emissions goals and flexibility; possibility of catastrophic freezing

TIS – Flexible Green Ammonia

F1: Entrepreneurship	
F2: Knowledge development	
F3: Knowledge diffusion	
F4: Guidance of the search	
F5: Market formation	
F6: Resources Available	
F7: Creation of legitimacy, organization	
F8: Development of Positive Externalities	

Strong interest and movement here not yet aided by regulations, certifications; flexibility link with VRE, not always with power grid

Trends

Markets	Green Ammonia
• Stable/declining industry DR participation *except* cryptocurrency, data centers. • longer downtimes when called • more calls to emergency resources	• Significant increase in interest • Interest from utilities • Speaking invitations, attendance • Funding, conversations

‘We do have people on curtailable rates, the contract says if the grid is getting overloaded we've got to shut you down, that actually happened last year and they were very angry about it. It's not like a sophisticated operation, based on the day ahead, they'll call you up’
–Interviewee 19, Markets

NREL Image

Stable industrial DR; momentum building in green ammonia sector

Interesting Remarks

‘I looked at electric intensive industries, what's their history. A very interesting one was looking at history of aluminum. It goes where the price of electricity is cheap. Used to be in Ohio valley, don't see many now. Pacific NW, not now. Cheap hydropower in Canada. Bitcoin mining is following the same model. And data centers are following similar type of thing, electricity is their major input. Google has massive server farm, because they get cheap power.’
-Interviewee #6, Markets

‘We do not have real time pricing with industrial customers we have contracts with customers because they want stability, we pass along the fuel charge.’
-Interviewee #19, Markets

Interesting Remarks

‘The issue of forecasting we determined is an important issue, how should the RTO forecast that there will be a level of flexibility coming in and how does one do that. Forecasting load flexibility in the short term is a challenge, my own opinion, the forecasting both the utility and ISO level is so behind the times, driven by econometrics, weather, which are all appropriate but they don't go beyond that, don't go with what's behind that, any forecasting is going to require more precision or going into the bottom up, which utilities and RTOs aren't going to be willing to do .’
-Interviewee 6, Markets

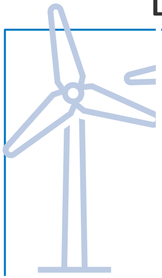
Interesting Remarks

‘We started to talk about for us there's more benefit in having load that's willing to just react based on the price instead of being demand response.’
-Interviewee #2, Markets

‘Manufacturing facilities are in business to produce products, so their key financial strategy isn't to get rebates from the power company but these types of ideas need to be explored, some of these utilities already have some involved mathematical models and can look at these scenarios. The utilities understand what kind of load facilities are drawing, but they don't understand the operations within those facilities, where the flexibility is, where you get into situations where you cause safety or environmental risks’
–Interviewee #18, Steel

Decarbonization Pathways for Ammonia

Distributed green ammonia

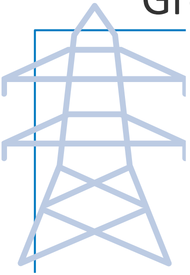


- New producers
- New locations
- Limited grid connection

Blue ammonia

- Existing producers
- Existing locations and similar infrastructure
- Demand response possible

Green ammonia for power plants



- Existing producers?
- Existing locations and similar infrastructure?
- Retrofit of existing power plants
- Peaking plants running on green fuels

Green ammonia from purchased H_2

- Large-scale, centralized production… by whom?
- Locations close to hydrogen hubs
- Grid flexibility from hydrogen hubs rather than ammonia

Producers/actors
Infrastructure/location
Flexibility

Different pathways have diverse flexibility outcomes; might not add to grid load, flexibility need

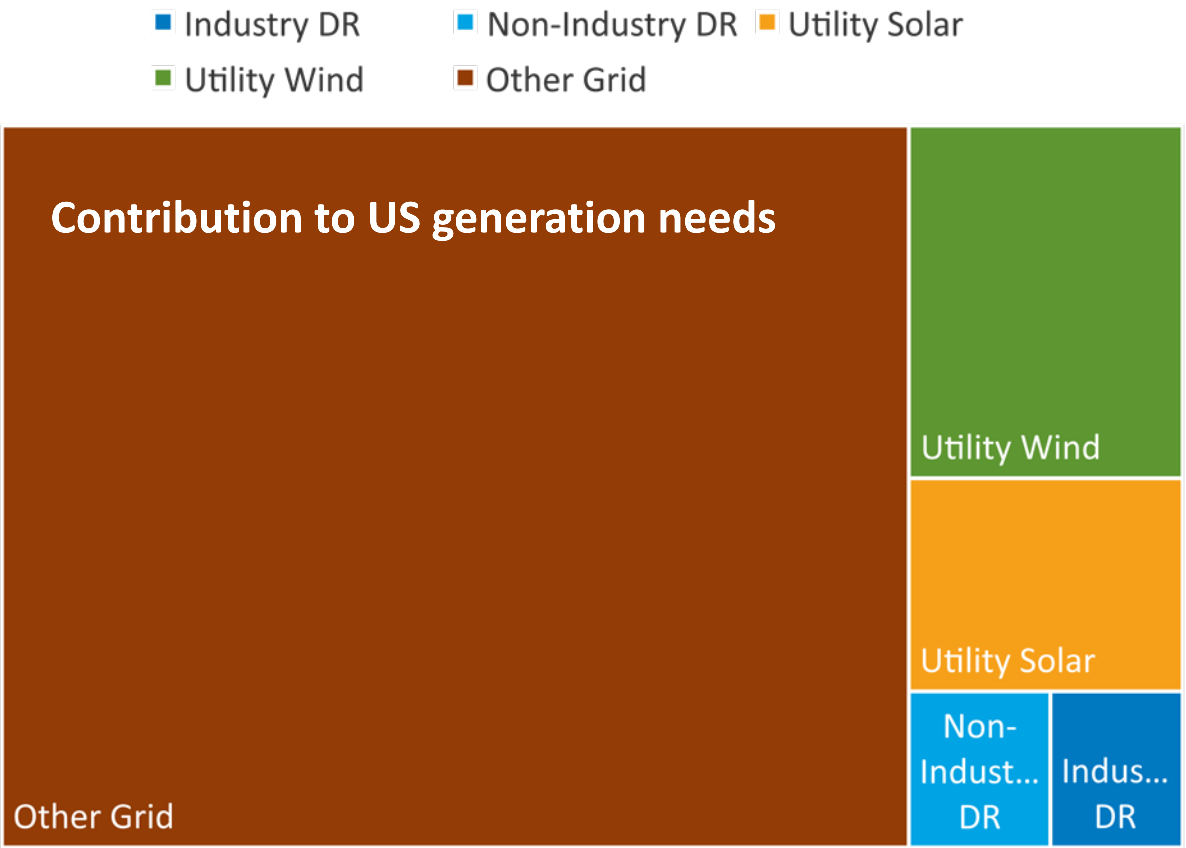
Possible Targets: Industrial Flexibility Transition

- Additional industrial load flexibility **target** in MW
- Additional **investment** in load flexibility
- **Markets and products** for flexibility created
- **Sensors and met**ers in system
- **Location** – make sure flexibility is distributed evenly
- Increase load flexibility in **# of companies**
- Increase **# planned projects** with flexibility
- Support of **innovation and R&D around industrial DSM**
- Increased access to IT for flexibility

Adapted from Heffron et al. 2020

Flexibility Transition - Conclusions

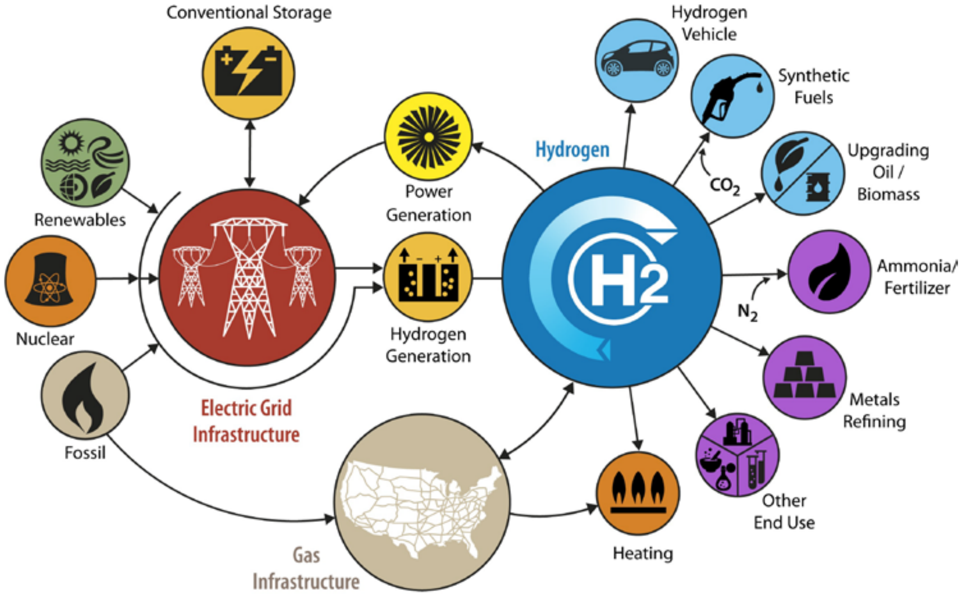
- US flexibility transition not just beginning…
- Most via interruptible programs
  - Not flexibility justice/2-sided market
- Regulatory frameworks do not target industry
  - Agnostic resource type
  - ***No one's focus***
- ***Transition motivated by sustainability***
  - ***But no direct linkage between flexibility/ghg***



We did not find a TIS functioning around flexible industrial loads

Green Ammonia - Conclusions

- Electrolytic H_2 to ammonia – 'power to X'
  - Large scale production challenging
    - Smaller scale production is new paradigm…
      - for flexibility, practices, infrastructure, institutions
      - grid connection?
    - Grid factor for CO_2 must be low
  - Integration to the grid → demand for capacity, flexibility in DR
  - Changing production locations
  - Changing producers



Different practices and paradigms for flexibility

Graphic by Al Hicks / NREL

TIS - Conclusions

No TIS seen functioning around flexible industry loads

- Except green ammonia case study

Context important

- Clarity lacking on designs
- Tapestry of regulations – context-specific strategies
- Communication necessary

Flexibility commodification now based on $ alone

- Higher flexibility need/transition tied to ESG
- No explicit tie to resource mixture
- Cannot help facilities meet scope 2 emissions goals

Electrification and power-to-X change practices

- New paradigms for flexibility

Thank You

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