21 April 2023

The transition will not be televised

Part 2 – Opportunities in storing and transforming clean electricity

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Executive summary

- The Inflation Reduction Act is stimulating a wave of new clean technology investment in the US. The potential has never been greater for technologies that store and transform surplus electricity to disrupt traditional energy value chains.
- Decarbonization targets, energy security concerns and falling technology costs are fundamental drivers for a rapid expansion of domestic clean energy. But despite favorable economics, a further evolution in the US regulatory landscape will be needed for renewables to expand at their highest potential.
- While end-use electrification, storage and hydrogen will all see rapid growth, the market share for each in the future energy system is far from settled. In this paper we explore the role for emerging electricity 'midstream' technologies in a cleaner, more efficient energy system.

Introduction

In Part 1 of this series, we considered the prospects for wind and solar as upstream sources of primary energy supply. Overall, we saw compelling economics driving sustained double-digit growth rates for new renewable power installations, in the US and globally. But to realize their potential, renewables need to be paired with complementary technologies. Here, we describe how electricity storage and 'power-to-x' (P2X) help fill the intermittency gap of wind and solar generation and enable the clean electrification of buildings, industry and transportation.

The gains from electrification

The global impetus to achieve net-zero emissions is accelerating investment in renewable energies. Other low-carbon technologies, including advanced geothermal and small modular nuclear power, are also advancing. GE Hitachi, for example, signed a contract for North America's first grid-scale small modular reactor earlier this year.[1] Even fusion, a long-heralded game-changer, got a shot of adrenaline when the National Ignition Facility in California achieved a fusion reaction that produced more energy than it took to achieve it.[2]

But while it's clear that our future energy grid will run on low-carbon electricity, there's more confusion than consensus about how to establish a stable, balanced system. Downstream from electricity production, a range of 'midstream' technologies will play an important role in storing, transforming and delivering clean power to end users.

The first priority for scaling low-carbon electricity should be expanding and interconnecting electricity grids. Progress there has been slow. Currently, it takes around 10 years to complete new transmission lines in the US.[3] Federal permitting reform would help, but to rapidly decarbonize the system new routes to market will need to develop.

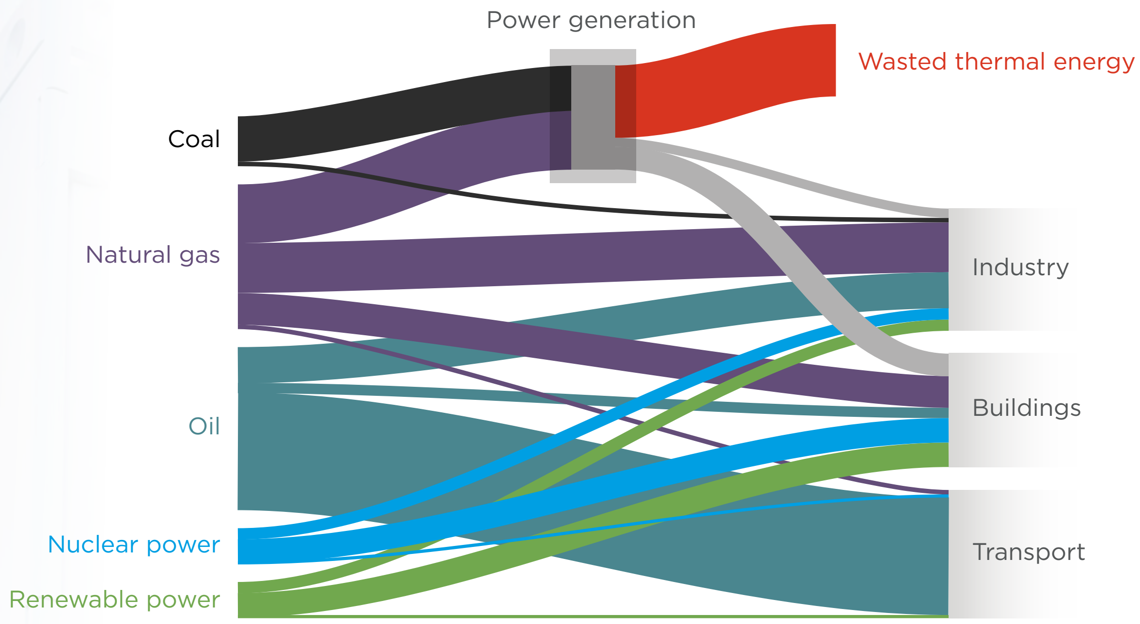
It's well known that a transition away from fossil fuels in the electric power sector will reduce carbon emissions and improve air quality. Less appreciated are the productivity benefits from making the switch from hydrocarbons to renewables. As illustrated in Figure 1 below, two-thirds of the primary energy used for US electricity production is currently wasted due to thermal losses associated with combustion. Even super-critical coal and combined cycle natural gas fail to turn about half of the potential energy in fossil fuels into electricity. The shift to an energy system based primarily on renewable power is an opportunity to not just reduce costs, but also minimize waste and vastly improve system efficiency.

1 General Electric, 27 January 2023: GE Hitachi Signs Contract for the First North American Small Modular Reactor
2 Clery, D., 13 December 2022: With historic explosion, a long sought fusion breakthrough, *Science*
3 National Academies of Sciences, Engineering, and Medicine, 2021: Accelerating Decarbonization of the U.S. Energy System

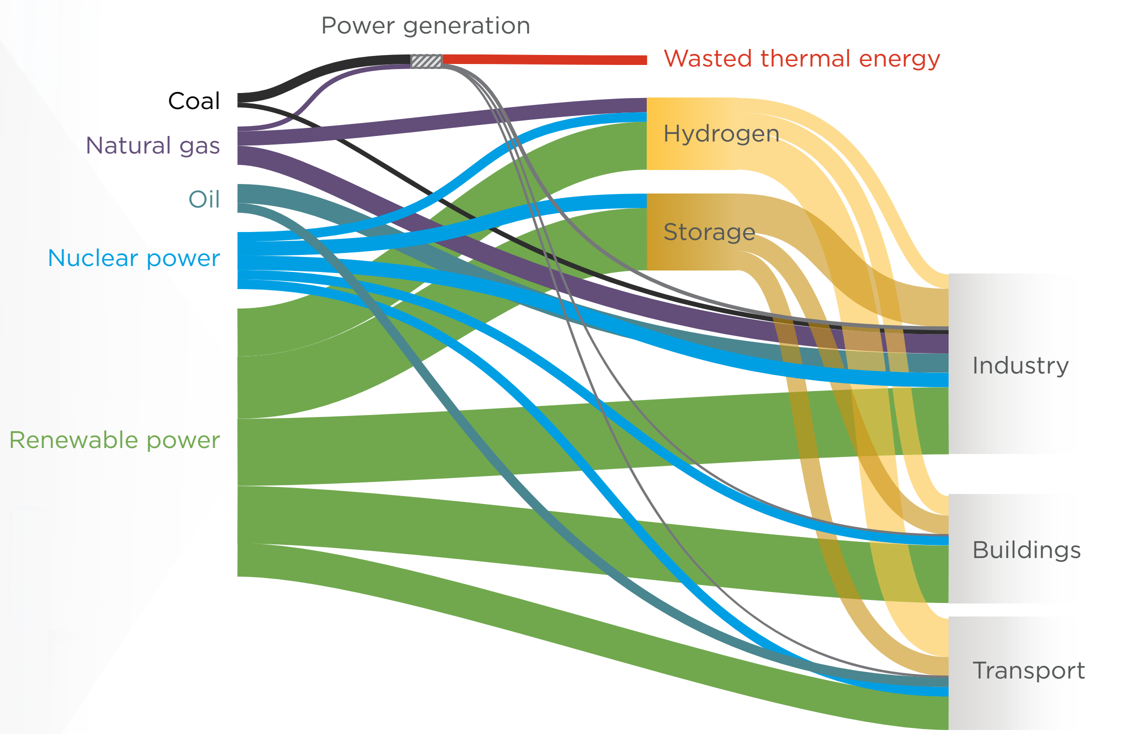
Figure 1: More clean energy, less waste

How renewables, storage and transformation can combine for greater efficiency

US energy system flows in 2021



Potential US energy system flows in 2050



Source: Impax graphic based on 2021 data from the Lawrence Livermore National Laboratory (2022) and 2050 estimates from the IEA (2022). The 2050 data is for illustrative purposes only. Energy system flows have been simplified.

The technologies described in this paper aim to overcome two key challenges in building a renewable energy economy.

- The first is that renewable power generation is intermittent. Even with more intelligent grids and demand side management, electricity storage will be needed across the country to match cheap renewable power supply with real-time patterns of energy consumption.
- The second challenge arises from technical obstacles to electrifying processes like steelmaking and cement manufacturing. Transforming surplus renewable power into hydrogen opens new pathways for lowering the carbon intensity in those industries.

And while there's no avoiding the fact that electricity storage and transformation add to system costs, the Inflation Reduction Act (IRA) has made American clean tech much more attractive to multinational companies and investors.

Fundamental drivers are accelerating the transition

The scale and simplicity of incentives contained in the IRA have prompted other major economies to develop their own stimulus programs to avoid losing competitive positioning in clean energy supply chains. As the European Union and other trade partners craft their responses, concerns have been raised about a green subsidy race that could result in a 'boom and bust' market if more difficult economic conditions force national governments to scale back their support. While that is a possibility, we see three fundamental drivers ensuring positive market conditions in the years ahead.

1. Decarbonization targets

Governments and companies are finally grappling with how to turn their climate pledges into reality. Experience tells us there's no silver bullet. There are, however, several promising routes to deep decarbonization.

Electrification offers some of the lowest-hanging fruit in reducing greenhouse gas (GHG) emissions. That's why many US states are accelerating plans for cleaning up the power sector – in the case of Minnesota, by mandating that utilities provide 100% clean electricity by 2040. In California, new homes up to three stories high must now install solar panels.[4] The benefits for homeowners should be lower utility bills.

Though the move to clean electricity is relatively easy at a residential level, cleaning up an entire system is another matter altogether. Solutions there will require new approaches, prompting states to adopt a flurry of new initiatives, including:[5]

- New incentives for dispatchable clean power in states like Maryland
- Targeted support for microgrids and backup power, as in Colorado and New Jersey
- Legislation to establish new industrial hubs for hydrogen, for example in Illinois and Texas

4 California Energy Commission, 2023
5 National Conference of State Legislatures, 5 December 2022: New Support for Energy Projects and Transition to Low-Carbon Power

Initiatives like these are both gathering pace and becoming more common as states compete for the new jobs and inward investment stimulated by the IRA.

2. Energy security and price stability

Russia's invasion of Ukraine in 2022 exposed the economic vulnerabilities of fossil fuel dependence. The war in Ukraine is reshaping energy commodity trade flows globally and has introduced new sources of market uncertainty, including expected production by national oil companies (NOCs). Geopolitical instability has brought with it a new sense of urgency to the low-carbon transition. Governments increasingly recognize that cost stabilization and energy security are a double dividend from moving to renewables.

Despite the stunning drop in natural gas and coal prices in Q1 2023, the economics of new wind and solar power generation remain superior. While a warmer-than-average winter and economic growth concerns have taken some sting out of energy prices, we see little prospect for a return to the pricing regime seen during the past decade. China's re-opening from COVID-19, rising international trade in liquified natural gas (LNG), OPEC production cuts and uncertainty about interest rates all point towards both continued volatility and structurally higher fossil fuel prices going forward.

We see major economies increasing their commitment to domestic clean power as a tool for meeting energy security objectives and improving price stability. America is no exception.

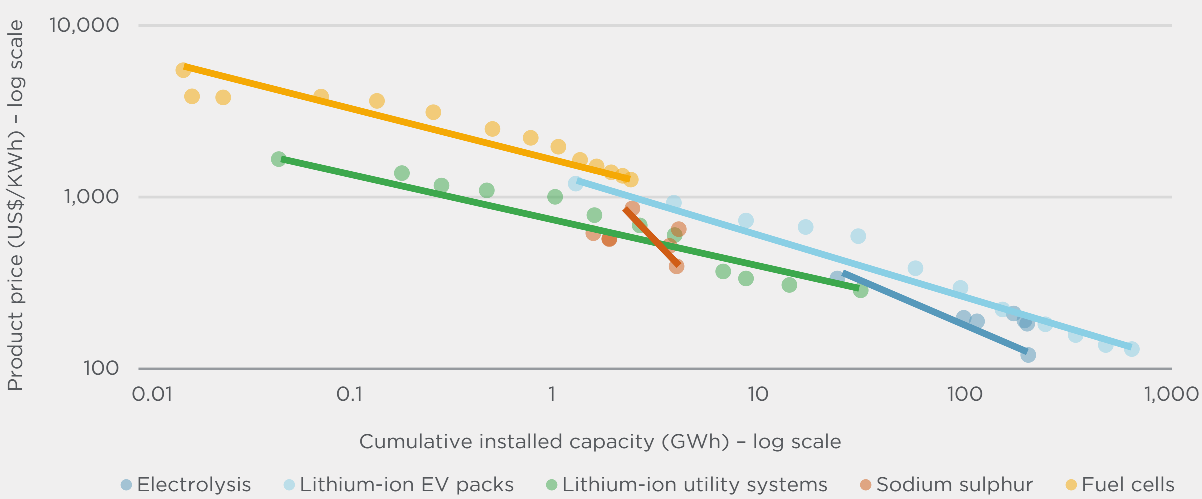
3. Falling technology costs

Most electricity storage and transformation technologies are not new. Indeed, some companies around today had their initial public offerings more than two decades ago. Clean tech has suffered at least two boom and bust cycles – the first around the 'dot.com' craze of the late 1990s and the second associated with the Great Financial Crisis that unfolded in 2008. This time should be different.

Before, unproven technologies were seeking to gain their first commercial footholds. Today, proven technologies are making a march towards lower costs. As shown in Figure 2 below, the costs of electricity storage technologies have fallen rapidly as installed capacity multiplied, replicating the cost gains seen in solar and wind.

Figure 2: The experience curve for storage technologies

Costs of electricity storage fall exponentially as technologies are rolled out



Source: Schmidt, O., & Staffell, I. Monetizing Energy Storage - A toolkit to assess future cost and value. Oxford University Press. Forthcoming. Analysis as of December 2022

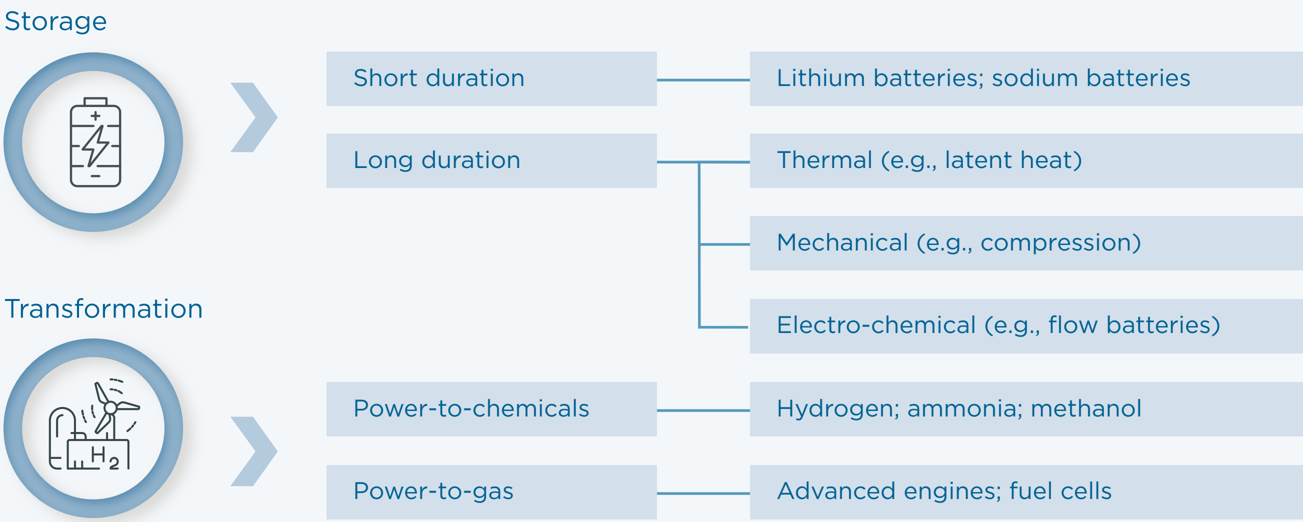
The IRA is accelerating these long-term trends: there is nearly US$17 billion for investments in grid projects that include energy storage, and over US$6 billion in support for the US battery supply chain.[6] The Infrastructure Investment and Jobs Act (IIJA) meanwhile contains US$505 million for demonstration projects in stationary energy storage as well as US$9.5 billion in funding for green hydrogen. As a result, nearly US$100 billion of advanced battery manufacturing investment commitments have now been made in the US.[7]

'Midstream' technologies positioning for take-off

Favorable economics, dependable supply chains, sufficient customers, supporting infrastructure and technical replicability are key determinants of technology tipping points. Several technologies in the clean electricity midstream are on the cusp.

While the trade-offs associated with competing energy technology pathways are complex, there is one simple conclusion: a net-zero future is going to require vastly more clean electricity. As summarized in Figure 3, we describe in this section the ways in which electricity can be stored and transformed to enable an efficient low-carbon energy system.

Figure 3: A summary of emerging 'midstream' storage and transformation technologies



6 Energy Storage Association, December 2021: Infrastructure Investment and Jobs Act Boosts US Supply-Side Investments in Energy Storage

7 Energy Storage News, 26 January 2023: US battery supply chain investments reach US$92 billion since Biden took office.

Energy storage

For renewable power to make the US energy system more efficient, there need to be sufficient incentives to store intermittent electricity production. That means payments to companies whose assets can soak up excess supply and release it when demand is peaking. Storing electricity within a single day is generally described as short duration, while storage over multiple days (or even months) is referred to as long duration. According to the US Energy Information Administration, the installed capacity of all forms of electricity storage is set to triple over the next three years.

Short duration

Lithium-ion (Li-ion) batteries are the dominant technology for shifting power within a single day. Their cost superiority has been made possible by the rise of consumer electronics and, more recently, electric vehicles (EVs). Those battery packs now trade for about one-tenth of prices just 15 years ago.[8]

And while there are ongoing efforts to further improve Li-ion technology, it is far from the only solution. Emerging alternatives include sodium-ion (Na-ion), lithium-air (Li-air) and multivalent ion batteries. The US Department of Energy's (DoE) roadmap has lithium-based batteries vying with other battery chemistries (including sodium sulfur, advanced lead-acid, and zinc) for roles in an expanding market.[9]

Long duration

Lithium-ion batteries are not well suited to long duration storage. The need for electricity storage at larger scale and longer duration has brought forward a multiplicity of approaches:

- **Electrochemical**

  Despite their lower energy density, redox flow batteries – characterized by circulating electrolytes and selective membranes – boast higher operational safety, longer asset lives and greater scalability. Challenges must be overcome for both vanadium and zinc-bromide redox flow batteries to be deployed at scale. These include expensive chemical inputs and membrane design.

- **Mechanical**

  For almost a century, pumped hydroelectricity energy storage has played a valuable role in meeting variable energy demand. When there is surplus electricity on the grid, water is pumped uphill to then be released through turbines whenever needed. New projects face environmental and geographical hurdles, though, and many suitable locations have already been taken. There are many designs for alternative forms of mechanical storage, employing compressed air, gravity weight and flywheel systems, that are seeking to establish commercial footholds.

- **Thermal**

  Storage can also be accomplished by heating or cooling a liquid or solid medium. Energy is discharged by reversing the process. Many thermal storage technologies have been demonstrated, including those using molten metals. A lingering challenge remains how to convert heat back into electricity in a cost-effective way.

It has been estimated that with the right market structures, energy storage could grow 20-fold over the course of this decade, reaching as much as 10% of total US electricity generation by 2030.[10] Excitement is running especially high for hydrogen, which has the potential to play a unique double act. The universe's most abundant and least dense element can be employed for both storage and as the building block for green fuels and chemicals, as discussed below.

8 Office of Energy Efficiency and Renewable Energy, 4 October 2021: DOE Estimates That Electric Vehicle Battery Pack Costs in 2021 are 87% Lower than in 2008
9 US Department of Energy, July 2020: Energy Storage Grand Challenge Draft Roadmap
10 Singer, B., et al., 15 August 2022: Energy Reliability: How the US is faring through May; maintain bullish view on battery storage and hydrogen

Energy transformation: P2X

Our focus in this section is on processes that transform clean electricity into synthetic fuels and industrial feedstocks, often referred to as power-to-x (P2X).[11]

All P2X transformation pathways start with turning clean electricity into hydrogen. There are three primary methods: alkaline water electrolysis, polymer electrolyte membrane (PEM) electrolysis and solid oxide electrolysis (SOE). Though the first two are well proven, high-temperature SOE cells have captured imaginations by presenting greater throughput efficiency. All show some promise in reaching commercially competitive price points, with the stimulus from the IRA and IIJA hastening progress.

When powered by renewable energy, electrolysis produces ‘green’ hydrogen, which can be stored, combusted or converted back into electricity. Hydrogen can also be used to make compounds like methanol and ammonia. Today, industrial hydrogen is usually ‘grey’ hydrogen (generated from steam reformation of natural gas, for example). It could be produced in the future as ‘blue’ hydrogen (using a fossil fuel feedstock, but with capture of the CO_2). The greatest growth potential, however, is for green hydrogen.

According to the International Energy Agency (IEA), the global installed capacity of electrolyzers will need to grow 6,000 to 8,000-fold by 2050 to generate the volume of green hydrogen needed to meet goals of the Paris Agreement.[12]

It has been projected that P2X could reduce global GHG emissions by more than 20% by addressing emissions from hard-to-abate industries (including steelmaking, cement and shipping) and driving zero-carbon energy further into electricity production and heating.[13]

In aggregate, P2X technologies have the potential to create markets worth hundreds of billions of dollars by 2030.

But will homes and businesses be best served by hydrogen-based fuels and feedstocks, or the direct use of electricity? Put another way, should we be changing the plumbing, the faucet, or a bit of both?

While net cost to the consumer remains the over-riding factor, the overall size and shape of the P2X market will also hinge on non-economic constraints. Chief among these is permitting. An inefficient system for consenting new clean energy infrastructure in the US presents a barrier to further growth of the centralized electric power system. According to a recent US Department of Energy study, the US will likely need 47,000 GW-miles of new high-voltage transmission by 2035, a 57% increase compared to today.[14] Should the slow pace of expanding this system continue, distributed generation (i.e., smaller projects set within lower voltage distribution networks) and hydrogen present next-best alternatives.

11 P2X has also been used to describe increasing use of electricity in existing applications (e.g., home heating & electric vehicles). In this paper, we are primarily concerned with P2X pathways involving the transformation of electricity into a different energy carrier. Electrification of end use demand will be explored in Part 3.
12 IEA, 2021: Net Zero by 2050
13 Israel, H., et al, September 2020: The Special 1 – Hydrogen primer, BofA Global Research
14 US Department of Energy, February 2023: National Transmission Needs Study – Draft for Public Comment

Power-to-chemicals

The most compelling case for converting renewable power into green hydrogen can be found today in the chemicals industry. The IRA will significantly accelerate progress towards making green hydrogen cheaper than grey hydrogen.[15] US demand for hydrogen is already 10 million metric tons per year, derived almost entirely from fossil fuels.[16] Approximately one-third is used to produce ammonia – a compound of nitrogen and hydrogen that's a key input to the creation of industrial-scale fertilizers. Using green hydrogen to produce ammonia as a fuel is starting to attract attention by the shipping industry, which is responsible for approximately 3% of global GHG emissions.[17] The American Bureau of Shipping recently granted early-stage approval for certain kinds of ammonia powered ships and fueling infrastructure.[18]

Power-to-gas

Green hydrogen can be blended with other gases (like methane), combusted in advanced engines and boilers, or stored and converted back into electricity when it's needed most. Given that around half of US homes currently use natural gas for heating and hot water, there has been increasing debate about the role for mixing green hydrogen in existing natural gas networks. The obvious appeal is that hydrogen doesn't produce CO_2 when combusted or converted back to electricity (for example, in a fuel cell). Technical studies, however, are pointing towards a need for dedicated pipes for hydrogen blending above 20%. Indeed, a recent meta-study concluded that the inadaptability of legacy infrastructure will put a brake on plans for using pure hydrogen in home heating.[19] Electric-powered heat pumps, which act like fridges in reverse, offer a cheaper and more direct route to meeting consumers' needs, without fossil fuels.

15 Zhou, Y., 3 January 2023: Can the Inflation Reduction Act Unlock a Green Hydrogen Economy? International Council on Clean Transportation
16 National Renewable Energy Laboratory, 2020: Study Shows Abundant Opportunities for Hydrogen in a Future Integrated Energy System
17 Tullo, A.H., 8 March, 2021: Is ammonia the fuel of the future? Chemical & Engineering News
18 Crownhart, C., 31 August 2022: How ammonia could help clean up global shipping, *MIT Technology Review*,
19 Rosenow, J., 27 September 2022: Is heating homes with hydrogen all but a pipe dream? An evidence review, *Joule*

Summary

Many midstream storage and P2X technologies will be vying for supremacy in new energy value chains. Eventual winners will be those that respond to the fundamental drivers of decarbonization objectives, energy security concerns and price competition.

Clean power will be the backbone of a clean energy future. And while the need for complementary storage and transformation technologies is clear, not every type of battery will work, nor will every potential application of hydrogen prove profitable. Which technologies end up playing leading roles downstream from clean electricity production is a trillion-dollar question facing investors today.

Coming next
Part 3

In Part 3 of this series, we'll explore how residential, commercial and industrial customers are adapting to the push for clean electricity in 'downstream' segments. To harness the potential for reduced costs and lower environmental impact, regulators will need to respond to a new world in which energy can be produced, managed and consumed at a local scale. The shift from hydrocarbons to renewable power calls for new approaches to physical and financial aggregation. We'll look at the companies making a difference by changing the way they trade and consume energy.

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20LDNH_04/23

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