CHARTING A COURSE TOWARDS A NET ZERO ECONOMY: HOW DO ENERGY LEADERS VIEW THE ENERGY TRANSITION?

PennState

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Introduction

Energy and related industries are major sources of economic value-added and social well-being. They face unique challenges related to a changing geophysical, economic, political, and legal context. How industry responds to this changing context, even in the current absence of formal U.S. climate policy, impacts the cost and reliability of energy supplies and the overall economy and human welfare. It is also a potential source of technological and organizational innovation. The U.S. energy sector is in the midst of a large-scale transition in technology, policy and consumer demand that is being driven by concerns about the climate impacts of energy production and use, as well as other environmental concerns and the need to harden energy systems against major disruptions.

In April of 2022, Penn State's College of Earth and Mineral Sciences; Center for Energy Law and Policy; and Center for Climate Risk Management jointly hosted a one-day roundtable discussion around the process of energy transition, bringing together leaders of major energy companies, non-profits, government and academia, representing diverse interests including oil and gas; electric utilities; transportation and renewable energy development and academic researchers.[1]

The goal of the roundtable was to have an honest and open discussion, devoid of politics, around what a net zero carbon energy system looks like in the United States, what steps industry leaders believe need to be taken to get us to such an end state by 2050 (or sooner), and how to navigate the energy transition process amidst multiple potential disruptions. The roundtable discussion was held under Chatham House Rules, so we avoid mentioning individual participants by name or attributing any particular viewpoint to a specific participant.

We chose to anchor our discussions around an end-state of a net zero carbon energy economy by 2050 because such an end-state is aspirational but also viewed as necessary

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View report online: https://celp.psu.edu/energyroundtable.pdf

[1]Organizations represented at the discussion, not including Penn State, were Alfred P. Sloan Foundation, American Electric Power, DTE Energy, Energy Futures Initiative, Pennsylvania Department of Community and Economic Development, Shell USA, U.S. Department of Energy, U.S. Federal Aviation Administration, and Xcel Energy.

For the purposes of the roundtable discussion and this report, "net zero carbon" can be taken to include other major classes of greenhouse gases, including methane. We felt that the term "net zero carbon" was less cumbersome than "net zero carbon equivalent" or a similar term.

to mitigate against some of the most severe impacts of climate change globally. This anchor also allowed us to focus discussions on process instead of the end state itself, even as energy leaders clearly have different ideas for what such an end state will actually look like.

Our discussions were wide-ranging and suggested elements of the energy transition where there is broad agreement among a diverse segment of the energy industry. These included the need for a broad technological portfolio that recognizes the limits of electrification, a substantial ramp-up in carbon capture and sequestration, as well as marked improvements in carbon accounting. Our participants found less agreement, however, in some areas critical for policy creation and implementation including the best spatial scale for solutions and what exactly we mean when we talk about a "net zero carbon" energy system. Our discussions also highlighted the critical role of leadership in both the private and public sectors, particularly in the absence of a national climate policy.

The Penn State Energy and Climate Roundtable took place before the passage of the Inflation Reduction Act, which provides a large number of incentives for low-carbon energy technology deployment. The predecessor proposal to the Inflation Reduction Act, known as Build Back Better, was raised by multiple participants as an example of the kind of public-sector leadership that participants believed could unleash clean energy capital in the United States. While some of the needs identified at the Penn State Energy and Climate Roundtable are reflected in elements of the Inflation Reduction Act, many are not. A major take-away from the Roundtable is that mobilizing capital is certainly necessary, but is not itself sufficient to achieve ambitious goals around decarbonizing energy systems in the United States. Leadership is still needed in the private, public and non-profit sectors (including education) to ensure that decarbonization is pursued in ways that are broadly beneficial and make measurable progress towards low-carbon energy goals.

This report captures the discussion points raised by our roundtable participants around these themes of agreement and disagreement. Since the report synthesizes these discussions without attribution, there are some conflicting thoughts reflecting different participant positions. There are also ideas in the report that may seem incorrect or unfamiliar. Since the report captures a diversity of ideas that emerged from multiple parallel discussions, this is unavoidable but also provides a broader picture of a day of rich discussions.

We conclude the report with some thoughts on needed next steps to support the successful implementation of a net zero carbon energy vision, based on the roundtable discussions. Our focus here is on initiatives that would not only be ambitious, but areas ripe for partnership between industry, the public sector and universities. Our roundtable discussion of the role of universities in supporting implementation appropriately covered the traditional areas of technological innovation and workforce development. It also focused on leveraging the unique role of universities as convenors and communicators.

This report focuses on four broad themes that emerged throughout the Penn State Energy and Climate Roundtable:

- The regional and sector-specific context for net zero carbon energy transition;
- Critical actions needed for a successful energy transition;
- Specific opportunities in technology, policy and industrial innovation;
- How universities can contribute to a successful energy transition.

Purpose of this Synthesis Report

The Penn State Energy and Climate Roundtable afforded a unique view into how leaders from across the energy space view the

process of energy transition and the needed steps to achieve a net zero carbon energy economy. It also supported conversations between leaders in segments of the energy economy that have traditionally been very separate (including major oil and gas companies, electric utilities, transportation regulators) but will likely need greater convergence if successful zero-carbon energy transition is going to be achieved.

The purpose of this report is to capture big ideas and themes that emerged from our discussion. These ideas, themes and views are presented without attribution or quotation. The outcomes and ideas presented here reflect several different viewpoints from several different discussion sessions. These viewpoints did not always agree and were not always consistent with one another. This report is not intended to be a consensus statement or a conclusive summary of any kind. It is meant to synthesize wide-ranging areas of discussion with the intent of raising needs for research, education, policy and multi-sector collaboration.

Regional and Sector-Specific Context for Net zero Carbon Energy Transition

There was broad recognition among Roundtable participants that a net zero carbon 2050 energy system will need to involve a wide array of technologies and systems. The challenge of system integration was repeatedly raised as a major element of successful transition, where experimentation and rapid innovation are going to be badly needed. While electrification can go a long way, the electrification process itself is an intermediate goal and one on which the ultimate success of a net zero carbon energy system depends. If deliberately planned and designed, a zero-carbon electricity system could be used to reduce carbon emissions from other sectors through direct or indirect electrification (conversion from fuels to electricity directly or the use of electricity to make low-carbon fuels – green hydrogen via electrolysis is one such example but there may be others).

Even a highly electrified energy system would need a broad array of technologies on the power grid to support net zero carbon electricity production including some legacy technologies and fuels such as natural gas (including carbon capture to achieve the net zero carbon goal). There was a high degree of skepticism that a power grid consisting largely of wind, solar and hydroelectric power would perform at a socially acceptable level of cost and reliability, even as battery technology becomes cheaper and the grid is made smarter and more flexible. Current energy storage technologies have one or

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more drawbacks: they are geographically limited (pumped storage hydro is an example); rely on materials and supply chains that are difficult to scale up in a globally secure fashion (including but not limited to critical minerals); and are not well suited for the environmental management challenges that come from depending on the weather for fuel to supply the power grid (the long duration energy storage challenge).

The broad technology mix needed to achieve a highly electrified and net zero carbon power grid involves more than just the rapid deployment of wind, solar and energy storage (plus other location-specific technologies like hydroelectric and geothermal). Getting the electricity system to a point of net zero carbon emissions without threats to reliability will need to involve technologies such as nuclear energy and carbon capture and storage. Our Roundtable participants generally agreed on this point, although there were different voices around how critical each technology was to a net zero energy future. Some believed that a bigger role for one or both of nuclear energy and carbon capture and storage would facilitate a smoother energy transition. Others made a stronger argument that a net zero energy transition simply would not be successful without a much larger role for nuclear energy and carbon capture, and that these technologies would need to be deployed at an exceptionally large scale.

Both nuclear energy and carbon capture and storage have economic, regulatory and social challenges. Industry, regulators and consumers will need to accept the deployment of these options at scale because of their benefits in supporting a net zero carbon energy system. One aspect of such acceptance raised at the Roundtable was the continuation or creation of "safe harbor" policies that shift risk away from consumers and from industry. The Price Anderson Act, under which the U.S. federal government serves as the backstop insurer for commercial nuclear power plants, is one important example of an existing safe harbor policy.

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There are both challenges and opportunities in thinking about sector specific needs. Net zero carbon power and broad electrification represent opportunities for utilities, but even with technological innovation, this is likely to only go so far. The decarbonization needs of some sectors (much of residential and commercial building energy, for example, along with ground transportation) can be closely tied to electrification. Other industries will need technology solutions that are less likely to leverage a zero-carbon power grid. For example, aviation will probably continue to rely on liquid fuels. Heavy industry such as petrochemicals, steel, cement and aluminum needs both highly reliable energy and high temperatures or pressures for its processes.

Successful net zero carbon energy transition was also viewed as needing to recognize and adapt to different regional contexts.

Appalachia, for example, is very different from the U.S. Southwest or the Gulf Coast. These differences arise in the nature of zero-carbon energy options as well as the industrial context in which a net zero carbon energy system would be deployed. Appalachia does not have the same level of renewable resource (either wind or solar) as does the Southwest or other regions, but has both plentiful hydrocarbon resources and potential for carbon sequestration. The nature of the industrial base also highlights region-specific challenges in getting to a fully net zero carbon energy system. Appalachia and the U.S. Gulf Coast, for example, with its focus on industries such as steel and chemicals, faces greater challenges in industrial electrification and therefore greater need for net-zero-carbon fuels.

Technology transitions will need to be built around these regional differences. If approached correctly by business and policy leaders, our participants believed that these regional differences could be advantageous rather than inhibiting. Policy initiatives and business strategies centered on a national approach might not be as adaptable to regional or local conditions where local energy supply and demands can be more closely considered. A national policy strategy for zero-carbon energy was believed to be beneficial if it could be enacted – a difficult task even in less difficult political environments. Examples of successful regional zero-carbon energy strategies in which our participants have been involved have been built around a shared sense of opportunity and benefit (not to mention trust) which may be more easily achieved at a regional level.

Critical Actions for Successful Energy Transition

Some critical decisions that Roundtable participants identified to support a net zero carbon energy system by 2050 are not surprising. There is a clear and well-understood need for widespread technology deployment at multiple scales, for example:

- Building and transportation energy efficiency needs to be improved;
- Zero carbon electricity supply through renewables or facilitated by carbon capture needs a significant ramp-up along with supporting infrastructure;
- Urban transportation options need to be substantially overhauled.

Technological innovation and development are always important, but our Roundtable participants believed that, by and large, technology that exists today could facilitate a substantial level of energy sector decarbonization. Rather, the focus should be on policy and implementation of existing solutions at scale, on a timely basis, and in a way that supports widespread and equitable benefits. This is especially true for areas where household energy cost burdens are high or basic access to energy services is limited. To be sure, some innovation is needed (such as in aviation fuels and long duration batteries) but there is neither a business nor a policy case to

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be made for waiting for a technological magic bullet.

When asked to consider examples of specific decision points that helped achieve success in a 2050 net zero energy economy, our Roundtable participants believed that regulatory and policy innovations were the most crucial steps to take. There was a widely shared feeling that the energy industry is a bit stuck. There is money ready for deployment in multiple areas, but within the bounds of business decision-making that are going to drive private capital, the current investment environment is clouded by uncertainty and high regulatory or compliance costs. Some of these costs are driven by uncertainty over future climate policy at both state and federal levels and the feeling of policy impermanence in a volatile political environment. The many clean energy provisions of the Inflation Reduction Act address these concerns to some extent, but not completely. Other costs are driven by the structure of current regulatory environments, and the variability in regulatory environment from location to location. For example, how rates are set and costs recovered through rates allowed by a utility commission may seriously impact innovation in local areas. There may need to be ways to pilot innovative programs not currently allowed by the existing regulatory structures. Creating circumstances under which regulators can allow industry to take risks represents another potential safe harbor to support net zero carbon energy choices. Allowing companies to experiment and fail, as long as failure happens quickly enough to not be burdensome on customers, was a regulatory goal expressed at the Roundtable discussion.

Wellhead high pressure Hartmann Valves GmbH CC https://commons.wikimedia.org/wiki/File:Wellhead_Bohrlochkopf.JPG

More generally, the Roundtable discussion suggested some different areas of tension that need to be resolved to create an environment for successful energy transition.

What Does Net Zero Mean?

At the beginning of the Roundtable (and in some of the breakout sessions) we grappled with the very basic question of what we mean by a "net zero carbon" energy system. This could mean net zero carbon emissions (don't add to the existing stock of greenhouse gases in the atmosphere) or it could mean net zero climate forcing (as discussed at the Roundtable, this refers to net zero radiative forcing – the net change in energy entering and leaving the earth's atmosphere). This is an important distinction for decision-making. Achieving a goal of net zero carbon emissions will involve some portfolio of zero

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carbon energy technologies, carbon capture and sequestration and a robust offset/credit market. Achieving a goal of net zero climate forcing is more complex and would involve the deployment of multiple technologies to remove carbon from the atmosphere or engage in other geoengineering strategies to deliberately change atmospheric or terrestrial systems to reduce climate forcing.

Business and Regulators are Waiting for Each Other to Lead

Our Roundtable participants pointed towards multiple legal, regulatory, and policy barriers that they felt inhibited them from innovating and taking risks on zero carbon energy technology development and adoption. The electricity sector, where decarbonization is a crucial first step in a larger transition process and where innovation could pay substantial future societal dividends, has been operating under a century-old regulatory framework that awkwardly divides responsibilities between federal and state oversight (the Federal Power Act) and a state level regulatory environment that does not reward risk taking (public utility commissions). In other areas, such as carbon sequestration, there are clear incentives but the regulatory framework is incomplete on multiple levels. A lack of leadership in regulatory reform is hampering the mobilization of private capital in ways that could achieve very rapid decarbonization using existing technologies and support the development of new solutions. Industrial policy is not popular in the United States, but some Roundtable participants expressed feelings that it should seriously be considered as a feasible way to closely align social goals with business incentives.

At the same time, other pressures that might spur quicker action from the private sector are missing or are not being applied. Roundtable participants described spending substantial amounts of time addressing shareholder concerns around Environmental and Social Governance (ESG). But they also reported very little movement of money out of companies whose responses to shareholder ESG concerns were not satisfactory. Some of our Roundtable participants felt that this pressure was coming – within the next few years for some companies – and that once money begins to move, then energy industry leaders will have stronger incentives to take action. In the absence of a strong climate or industrial policy to push decarbonization, continued shareholder concern could be a driver. The extent to which shareholder concern alone could push voluntary decarbonization

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Marcellus drilling site; Credit: Patricia Craig

decisions by industry remains an open question.

Our Roundtable discussion suggested an environment where there was no clear-cut leadership, either on the business, investor or regulatory sides. Without this leadership, cutting through the various layers impeding technological, economic and regulatory risk-taking and change will be substantially difficult. Such leadership, our discussion suggested, does not need to be one-sided. Comprehensive planning around energy goals and their implications for climate can be highly successful if approached as a collaborative effort among the private and public sectors. Universities can also play an important role as convenors and facilitators in collaborative multi-stakeholder energy planning.

Regional and Federal Scale of Solutions

The scale needed for solutions to achieve a net zero carbon energy system by 2050 was a substantial focus of discussion at the Roundtable. We did not find uniform agreement about the ideal scale on which changes need to be made and technology deployed.

Some leading energy firms naturally operate at a regional or sub-national scale. Others, recognizing sclerosis in national political systems, are building strategies around regional engagement. In many ways a regional approach to achieving net zero energy by 2050 is sensible and perhaps preferable. Action is easier on a sub-national scale since it is easier to identify shared interests and opportunities. Our Roundtable participants shared success stories of regional cooperation to promote zero carbon electricity, such as a power transmission planning initiative in the upper Midwest. A broad recognition that regions have specific resource and technology advantages suggests that a collection of regional initiatives may be more successful and entail lower costs than a uniform federal approach to net zero carbon energy transition.

Some of our participants wondered if the U.S. even needed a national climate policy to begin with. While regions have their own particular challenges and advantages that might suggest the advantage of highly regional solutions, climate change is still a national and global security issue that to some extent requires a national response.

Our discussion of regional approaches, however, came back to some basic economic and organizational tensions. Region-specific challenges and resources also lend themselves to identifying shared opportunities and goals that can catalyze regional action in a way that national action cannot be as easily catalyzed. There are thus organizational and political reasons to think about formulating region-specific strategies for getting to a net zero energy economy by 2050. Economically, however, some regions where action is possible may be too small geographically to minimize the economic costs of energy transition, thus placing larger burdens on consumers. The scale over which solutions make sense from an engineering or economic context may not make sense or may be harder to achieve through organizational cooperation.

Multiple studies discussed by the participants have shown how integration of wind and solar power over very large geographic areas can both lower decarbonization costs and improve electric reliability. Over a space as large as the eastern or western U.S., it is almost always windy or sunny somewhere, thus offering the opportunity for balancing supply and demand. But these optimal cost regions may not be amenable to coordinated decision-making and depend on more robust transmission. Western U.S. states and utilities have been discussing regional grid coordination for over two decades without substantial progress, because there has not been a shared economic interest; however, this conversation is starting to take place. An initiative in the Midcontinent Independent System Operator (MISO) for regional coordination worked well when the MISO footprint was made up of a smaller number of states. However, a recent initiative to coordinate transmission planning for wind energy was challenged when the MISO footprint expanded to include south-central states that did not want to bear the costs of northern transmission projects.

Regional organizations themselves can be challenging because they have no natural jurisdiction the way that federal or state actors do. Regional cooperation in the power grid has been achieved in many areas of the U.S. with encouragement from the Federal Energy Regulatory Commission (FERC), but FERC has been hesitant to require regional cooperation or dictate the form that it takes. The infrastructure bill contains substantial funding to establish regional hydrogen hubs, but there is no model for regional cooperation or regulation of these hubs. Interstate Compacts, such as those used in the joint governance of some water resources, are a potential model but have not been tested.

If You Can't Measure It, You Can't Manage It

There was wide agreement that the goal of a zero carbon energy system (producing energy with zero emissions) is fundamentally

How we measure emissions affects the decisions we need to make to manage those emissions. Industrial emissions can be measured on several different levels:

- Scope 1 emissions represent direct emissions from a company, from equipment owned and operated by that company.
- Scope 2 emissions reflect emissions from commodities, products or services purchased by a company but not directly produced by that company.
- Scope 3 emissions go higher up the supply chain than Scope 2 emissions to encompass material purchases by companies and can also reflect embodied emissions as well as emissions associated with travel.
- Scope 4 emissions are a more recent development; these encompass avoided emissions from a business decision. If a remote worker produces less carbon using electricity at home than driving to an office, those emissions savings would be counted under Scope 4 emissions.

different than the goal of a net zero carbon energy system (carbon contributions are either captured to avoid atmospheric buildup or are offset with carbon removals elsewhere). The 2050 energy system visions coming out of the Roundtable discussions largely reflected a net zero carbon energy system rather than an energy system that produced no gross carbon emissions. This means adoption of carbon capture and storage, but also a wider role for offsets and carbon credit trading within well-defined and credible decarbonization targets. These mechanisms will only be meaningful if there is a way to measure and track its emissions and its emissions offsets in an honest way.

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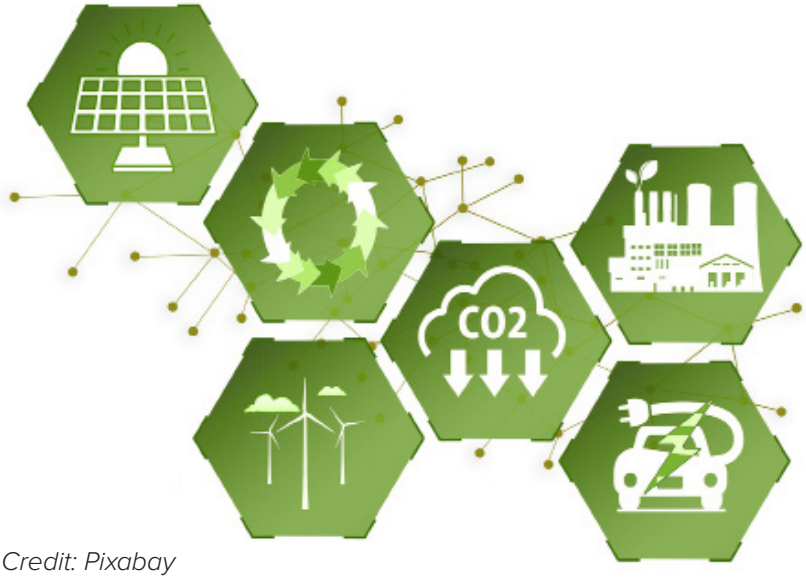
Energy firms are trying to track Scope 1 and Scope 2 emissions, in part to facilitate compliance with new carbon reporting requirements from the Securities and Exchange Commission (as well as reporting requirements in Europe, for those companies with international operations). These requirements were perceived as in need of improvement, but a start. Serious carbon accounting will need to incorporate Scope 3 emissions as well, and potentially even Scope 4 emissions. Neither businesses nor regulators know how to do this with a level of accuracy that would be widely acceptable. Carbon accounting remains an area where substantial innovation is necessary for implementation, both in the business world and also for carbon labeling or other forms of consumer information.

Specific Opportunities in Technology, Policy, and Industrial Innovation

The Roundtable participants believed that enough technology exists now to move substantially towards a net zero carbon energy economy. Some areas of the U.S. energy economy, like the power grid, could be largely decarbonized earlier based on existing technology. There are several economic, regulatory and institutional challenges, but a lot of technology exists and could be deployed at scale. There were some specific technology and policy areas that our participants highlighted as being a critical part of achieving a net zero energy economy by 2050. We mention some of these here to highlight specific needs and opportunities for innovation identified by leaders in the energy, government and non-profit sectors.

- Carbon capture and storage: The ability to reliably capture a high proportion of carbon emissions from industrial sources and securely dispose of (or re-use) the carbon would very likely need to play a substantial role in regions with existing natural gas industries. Some of our Roundtable participants observed that the scale and speed at which carbon capture and storage would need to ramp up was exceptionally daunting. Carbon capture and storage as an industry is highly immature – the regulatory framework for drilling wells is highly variable (even with Class 6 well

standards), and the industry exists in a legal limbo on multiple levels. There are no standards or best practices for a carbon storage industry in the U.S. Just as other industries have test facilities that are used to develop standards and practices, there is an urgent need for test facilities to demonstrate the ability to store large volumes of carbon in subsurface formation. This is a huge collaborative opportunity for research, industry and government. In some regions like Appalachia, mature carbon capture and storage will be the major constraint to creating a mature hydrogen market.



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- Hydrogen: The time for hydrogen may finally have arrived, as a solution to decarbonize some sectors of heavy industry, transportation and electric power generation given the need for fuels that can support high temperature and high pressure processes. The successful deployment of hydrogen at scale, however, would need to be coupled with other technical and regulatory innovations. Carbon capture and storage is likely to be needed to support net zero hydrogen production from natural gas; some of our participants were skeptical that so-called "green hydrogen" (produced via electrolysis and entirely renewable power generation) would be economically viable in all regions of the U.S. even as cost come down and the industry matures. Others felt there are few viable alternatives at this stage that make sense. Likely many industrial and commercial processes that use fossil fuels would need to be modified to use hydrogen but it is not clear whether using the electricity or hydrogen gas makes better operational sense. A regulatory environment to support the production and distribution of hydrogen (including industrial standards for equipment and end-uses to ensure safe operations and minimize leakage) also needs to be developed.

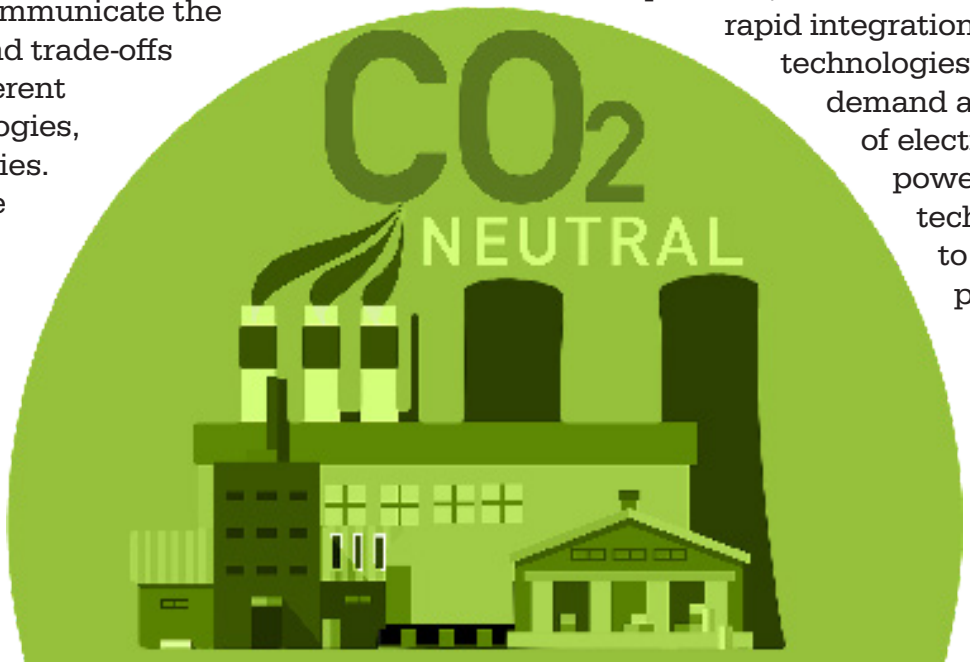
The U.S. may never be self-sufficient in certain materials but low-cost ways to recover these minerals from consumer and industrial wastes are probably under-valued and need to be developed.

- Minerals and materials: Global supply chains for many critical technological materials are highly concentrated and existing supply sources carry geopolitical risks. The U.S. may never be self-sufficient in certain materials but low-cost ways to recover these minerals from consumer and industrial wastes are probably under-valued and need to be developed.
- Addressing cost allocation: Legacy energy infrastructure will be needed for many years, even with the most rapid energy transition possible. As more economic actors move towards new energy sources and systems (such as through electrification) the costs of maintaining legacy infrastructure will become

concentrated in a much smaller number of sectors and actors. These actors will be the most expensive or complex industries to move to alternative fuels (such as aviation) or industries who use hydrocarbon commodities as feedstock (petrochemicals, for example). This brings risk of exacerbating price volatility for those legacy commodities but also economic uncertainty for industries dependent on those commodities. There may be an opportunity to repurpose legacy energy infrastructure to meet new demands, such as repurposing pipelines or pipeline corridors for the movement of hydrogen or captured carbon dioxide.

How Universities can Contribute to Successful Energy Transition

Leaders from all sectors of the energy industry, non-profits and government believe that universities have a special role in society as a source of highly trusted and highly impartial expertise. This gives universities a particularly valuable role to play as convenors, bringing different parties together on commercially neutral platforms (including discussions such as this Roundtable itself). While public trust in all institutions is challenged at the present time, universities were viewed as having a special skill and role to play in helping to communicate the complexities and trade-offs involved in different energy technologies, choices or policies. Our Roundtable participants felt that too much public discourse around low-carbon energy revolves around discussions of binary choices. This kind of discourse was widely viewed to be counterproductive.



Such a role for universities as "boundary spanning" organizations (able to effectively engage with different constituencies that are at times in opposition to one another) was widely viewed by our Roundtable participants as vital but not trivial. Industry has substantial technical knowledge to deploy net zero technologies effectively, and has the capital to do it successfully. But that success will take trust, and partnerships that can support trusted voices are likely to be needed. The Roundtable participants raised that this might be a new model for the kinds of extension or outreach services that some universities have operated for many years.

The traditional role of universities as engines for new knowledge and innovation was also viewed as strongly needed. Some of this discussion focused on the kind of technological innovation for which universities have long been known. Our Roundtable participants also focused substantially on policy or mechanism design innovation that can address some of the major institutional challenges to net zero carbon energy transition. Some examples suggested by our Roundtable participants included:

- Electricity market designs that can promote, rather than thwart, the rapid integration of new technologies (on both the demand and supply side of electricity) into the power grid. Many technologies to support power grid decarbonization operate on fundamentally different economic models than legacy technologies, and market

designs need to reflect these new economic models.

- Development and analysis of standards that can allow for robust and granular carbon accounting. The space of carbon accounting was characterized by a need for enhanced international standards and analyses that can compare existing standards on a neutral playing field. Building on decades of research in life cycle assessment, our Roundtable participants also noted a need for developing new methods and data tools to quantify Scope 2 through Scope 4 emissions in particular.
- Technological innovation should be driven and informed by the economic and political environment in which these technologies will be deployed. Batteries and clean fuels, for example, will need to be designed to be economically competitive and not just better-performing or more efficient in an economic sense. Materials will need to be employed that do not add to global supply chain pressures around critical minerals and other raw materials. These values should be embedded into the process of engineering design from the beginning.
- The Roundtable structure itself represented a kind of scenario-based thinking exercise. We started with the question of how the U.S. gets to net zero carbon energy within a few decades, and unpacked some of the critical decisions and uncertainties that would need to be confronted. These kinds of exercises will need to happen on larger scales and could be informed by sophisticated system and market analysis. Bringing these sophisticated analytical tools to scenario-based strategic planning and decision-making would represent a substantial advance in how concrete decisions around energy transition are made.
- The energy workers of today and tomorrow will need to be trained, and the basic energy knowledge of society as a whole will need to be lifted. Universities can help to raise society-wide awareness of personal energy use and how that is directly linked to carbon emissions. Our Roundtable participants further discussed ways in which labor supply was a current constraint impeding the rapid deployment of multiple zero carbon technologies at multiple scales. The labor needs for a net zero carbon energy system will be immense, even as industry finds ways to be more productive. New programs will need to be created and existing programs will need to be revamped and expanded to meet these new needs. Next-generation energy education and workforce training represents excellent opportunities for universities to partner with industry and government.

Conclusion: Initiatives for Successful Energy Transition

Convening the Penn State Energy and Climate Roundtable was one of a number of steps towards addressing social and industrial needs around the transition to lower-carbon energy systems. Hearing the perspectives of energy industry leaders is vital to informing our own research and educational initiatives, and for helping us understand where partnerships are likely to be particularly beneficial.

The Roundtable discussions pointed towards a clear need for major initiatives to support the successful implementation of a net zero carbon energy system. These initiatives will need to involve broad partnerships, and require leadership and engagement from both the private and public sectors. We conclude with an outline of these initiatives, meant to identify needs and points of departure for additional discussion.

The establishment of ***Regional Centers of Energy Innovation*** can support the development and implementation of net zero carbon energy systems on a regional basis. Such a regional approach increases the likelihood of identifying shared opportunities. Ensuring that regional centers are highly networked with one another will allow for the

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transfer of innovative practices.

Finding ways to ***Pilot New Solutions*** in an environment supporting rapid implementation and low regulatory risk (perhaps in association with regional innovation centers) would support the experimentation that is needed to quickly identify successful technologies and practices.

Research and development around ***Carbon Accounting Standards*** is needed to improve the way that industry tracks and reports the net carbon intensity of its activities. A transparent set of standards is also of value to investors making determinations about firm or industry carbon footprints; insurers or other actors who need to evaluate climate risks; and for individuals to understand the carbon implications of their own decisions.

Expansion of Universities as ***Convenors and Communicators*** takes advantage of universities' positions as neutral parties and the connections that many have with local constituencies. Part of this role is to continue to engage with diverse segments of the energy industry. Discussions such as the Penn State Energy and Climate Roundtable can support specific initiatives to move the U.S. towards a net zero carbon energy system, as well as to continuously revisit how industry, government and other stakeholders are viewing the process of energy transition.

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PennState College of Earth and Mineral Sciences