From ambition to reality

Weaving the threads of net-zero delivery

Worley
energy | chemicals | resources

Princeton E-ffiliates Partnership
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Foreword introduction

Chris Ashton
Chief Executive Officer

Worley

We are pleased to be a Princeton E-ffiliates partner and contribute to the development of breakthrough thinking which supports delivering a more sustainable world for us all.

This paper weaves together Worley's extensive practical experience in delivering major infrastructure projects with the detailed modeling, analysis and mapping undertaken by Princeton's Andlinger Center for Energy and the Environment.

We believe the global climate response demands imagination. We must imagine a transformed way of living which sustains the environment and human lifestyles. We must imagine the many technologies, techniques and resources we can bring to bear. We must imagine the ways all this can be done within our social expectations.

A complex interplay of factors will be required to achieve net zero. Ambition, targets, agreements and technology development are all necessary, but alone they are not enough to achieve our mid-century targets.

The urgent imperative is for governments and industry to shift focus to the practical challenge of delivering a previously unimagined pace and scale of infrastructure development and engineered solutions.

This paper illuminates the significant delivery challenges we face and outlines the key shifts needed to transform project delivery to enable the necessary changes. It builds on the influential Net-Zero America study by Princeton University, and is of direct relevance to government policy-makers, industry leaders, investors and broader society.

Humanity has risen to monumental challenges before and, working together, we can do it again. This paper shows us how we might begin to turn our net-zero ambitions into reality.

Prof. Lynn Loo
Director,
Andlinger Center for Energy and the Environment

Princeton University

The Net-Zero America study that Princeton and the Andlinger Center for Energy and the Environment published frames the necessary actions for the United States to reach net-zero, and provides a starting point for how the rest of the world can do so too.

It's the first study that provides the sectoral granularity and the spatial resolution needed to inform decision making in the policy and business sectors at a local level. The researchers developed custom algorithms to site and map the tens of thousands of low-carbon energy and infrastructure assets to show just what the net-zero transition could look like 'on the ground,' and finds multiple pathways to net-zero that are technically feasible using technologies available today. The research also shows that the cost of energy services as a share of GDP remains similar to historic levels, meaning the transition is relatively affordable.

The study draws attention to the extraordinary scale and pace of the net-zero challenge, and highlights the role of companies like Worley in executing the projects needed to navigate the energy transition. That's why Princeton's E-ffiliates partnerships program exists – to connect the business, government, and non-profit communities with researchers.

I am excited by the uptake and media attention that Net-Zero America has received, and also how industry and governments have turned to it for guidance. I am hopeful that this collaboration can help bring about a clean energy transition that ultimately has a net-positive economic outcome, and supports the planet and those who inhabit it.

About the authors

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Clare is the Group Sustainability Lead for Worley and is passionate about the decarbonization of the energy, chemical and resources industries. As the Group Sustainability Lead, she stewards Worley to meet the commitments made in our Climate Change Position Statement, embedding sustainability in the way we operate our business and deliver services to our customers.

Clare has a PhD in Chemical Engineering, specifically relating to the adaptation of low-carbon technologies.

She has over two decades of project and engineering management tenure and is a skillful leader of large technical teams. Her experience spans all phases of project development from concept development through to detailed design, construction and operation.

Clare also has considerable experience working in government organizations, specifically Cooperative Research Centres (CRCs).

Clare has delivered major energy infrastructure projects in Europe, South Africa and Australia.

She is a former director of the Australian Institute of Energy and currently sits on the advisory panel for Net-Zero Australia.

Chris Greig is the Theodora D. and William H. Walton III Senior Research Scientist at Princeton University's Andlinger Center for Energy and the Environment. He has a PhD in Chemical Engineering, is a fellow of the Australian Academy of Technology and Engineering (ATSE) and holds an adjunct appointment at the University of Queensland.

His ten-year academic career follows almost three decades of international experience in the private sector, firstly as a company founder, and then senior executive and non-executive director roles in major engineering and resources companies. These include CEO of ZeroGen (one of the early pioneer CCS ventures), Deputy Chair of Gladstone Ports Corp and Non-Executive Director of two ASX listed engineering firms.

At Princeton, Chris spearheads the Rapid Switch Initiative at the Andlinger Center and is an Affiliated Faculty member of Princeton's High Meadows Environmental Institute. His research combines, engineering, business and social sciences to explore the challenges of rapid decarbonization for different regions and sectors. He co-led Princeton's ground-breaking Net-Zero America (2020) study which describes five net-zero emissions pathways for the United States at an unprecedented level of detail. Chris is also leading Princeton's efforts on similar collaborative studies with universities in Australia, Asia and South America.

Paul Ebert is the Group Director Energy Transition for Worley and a Specialist Advisor for their subsidiary Advisian. A mechanical engineer, Paul completed a PhD in wind turbine aerodynamics and his career has followed the rise of renewable energy, broadening to include other technologies, enablers and issues that make up the fuller energy transition spectrum.

Paul has always focused on connecting the innovative to the traditional. As examples, he has specialist expertise in the integration of renewables into hybrid systems and was part of a small team which launched Worley's low-carbon hydrogen business, focused on the hard-to-abate industries. While principally a technologist, he has worked in over 30 countries in roles providing advice in relation to policy, markets and strategy, and with responsibility for capital project development, delivery and operation.

For Worley, Paul's role directs the energy transition thematic within and external to the business, including working with strategic customers and partners in responding to the scale and pace challenge of decarbonization.

Paul is the former Chair of the Australian Renewable Energy Agency Advisory Panel and sits on several other governance and advisory panels, including for Net-Zero Australia, the Australian National University and CSIRO.

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CHAPTER 1 Sizing up the challenge ahead

Chapter 1: Sizing up the challenge ahead

If we develop energy infrastructure the way we always have, we won't get to net zero by 2050. We might not even get halfway.

To reach our target we need to dramatically accelerate the pace and scale of how we work. Everyone involved in creating infrastructure needs to rethink their approach – from governments and investors, to construction companies and engineers.

The challenge to decarbonize is upon us, and net zero by 2050 is the aspiration. Across the world, governments have shown their commitment by becoming parties to the Paris Agreement. China, the US, the UK, Japan, France and Sweden – the full list tops 100 countries according to the United Nations – now have net zero in their sights. And some are writing laws to make it happen.

To achieve this ambition, our energy systems need to be transformed. We'll need vast amounts of new infrastructure: from grids and wind farms, to nuclear power plants and facilities for sequestering carbon. And all these projects take years – or decades. Which is time we don't have.

To decarbonize the world and meet the mid-century net-zero challenge we need to reinvent the way we deliver energy infrastructure.

Translating the pathways to reality

Worley and Princeton University's Andlinger Center for Energy and the Environment are working to examine what it will take to deliver net zero.

Princeton published a study called Net-Zero America at the end of last year. It lays out five pathways to a low-carbon future for the United States of America – the world's largest economy – at a level of detail no other study has reached.

None of the pathways are projections of the future, or the only way to reach net zero. They're all plausible visions of the path forward, which can guide policymakers and investors in navigating the challenge ahead.

All five of Princeton's pathways are technically feasible and affordable. But they demand infrastructure to be built at a speed we've never attempted before.

We've used this work, focusing on supply-side infrastructure, to explore five key shifts in thinking needed to deliver a net-zero transition:

1. **Broadening how value is defined.**
2. **Keep our technology options open.**
3. **Design one, build many.**
4. **Communicate and collaborate.**
5. **Enable and monitor digitally.**

This paper will help you understand the scale of the task, and then take you through each of these five shifts. The combination of all five is how we can go about making net zero happen.

> ***"To decarbonize the world and meet the net-zero challenge there is only one choice around infrastructure. We need to entirely reinvent the way we deliver it.***

We'll take the US as our case study

Everything we discuss here can be applied globally. Our recommendations will work best if every country takes action (and collaborates across borders). The US will be an important part of the transition and is a good case study to begin with. It has great potential and great challenge. It's an innovating giant, but it's also the second biggest emitter of greenhouse gases in the world.

For both the US and the world, the journey to net zero will be a difficult one. There's no single solution or company that can get us there alone. This is a vast, complicated task made up of many different threads. We need to untangle these threads – each technology option, each element of project delivery – and weave them together in a way that makes sense, and that leads us boldly towards the future. The solution will be a tapestry that many people have a hand in making, made up of thousands of different threads.

Everything we do has prepared us for what's coming

The **Andlinger Center for Energy and the Environment** at Princeton is a world-leader in exploring sustainable energy solutions. Our mission is to research and develop technologies that transform the world's energy and deliver us to a secure, sustainable future.

Worley takes large-scale energy projects from idea to reality. We design them, deliver them and run the infrastructure they create. Projects are complicated. There are competing priorities, multifaceted technologies, global supply chains, complex logistics, contract constraints and rigid schedules. Managing all of this is what we do.

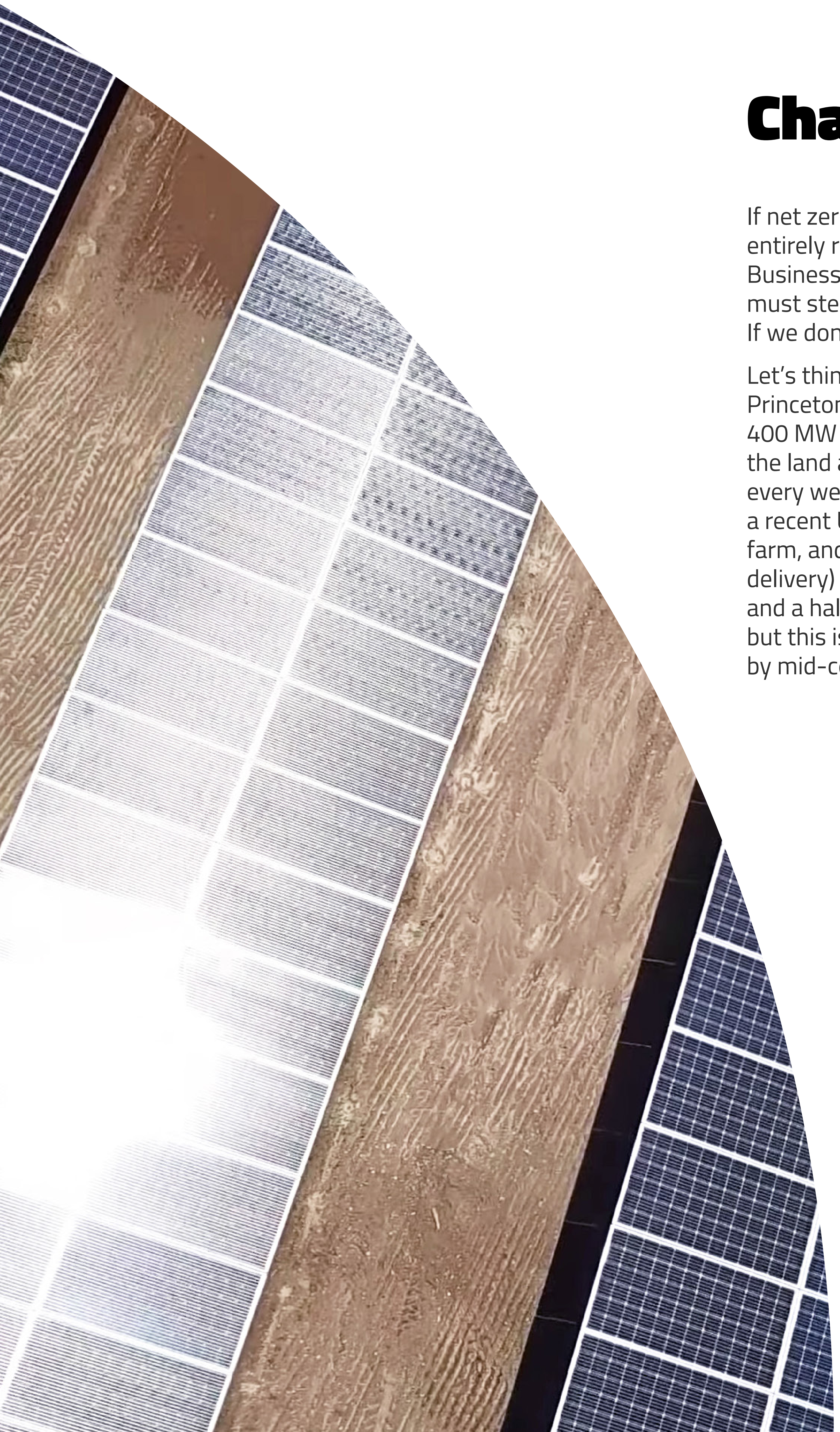
Together, we are well-placed to explore the challenge ahead. To the Andlinger Center and Worley, net zero is not a pipedream, or a lofty ambition. It's a mission. Or more accurately, a program of projects with clear and well defined objectives.

And, like any project, we need to approach it with open-minded research into future options, and meticulous planning that will deliver it successfully.

> *"To the Andlinger Center and Worley, net zero is not a pipedream, or a lofty ambition. It's a mission.*

CHAPTER

2 From years to weeks



Chapter 2: From years to weeks

If net zero is to become a reality we need to entirely reimagine how we approach big projects. Businesses and governments across the world must step up how they engage, design and build. If we don't, we will fail.

Let's think about the US. In a middle-of-the-road Princeton scenario, the US would need to build two 400 MW solar PV power stations – each roughly the land area of 130 Tokyo Olympic stadiums – every week, for the next 30 years. We're aware of a recent US project (half the size of one such solar farm, and considered an exemplar of solar project delivery) that took approximately three and a half years. Solar projects are quick to build, but this is still too long if we are to achieve net zero by mid-century.

"The US would need to build two 400 MW solar PV power stations – each roughly the land area of 130 Tokyo Olympic stadiums – every week, for the next 30 years.

The light blue line in *Figure 1* is the indicative extent of decarbonization in the US if we carry on delivering projects as we are and with no net-zero policies.

The red line is what happens if net-zero policies are applied but we follow a traditional approach to infrastructure delivery. It shows that, even with environmentally supportive policies, the US might only achieve a 50% reduction in emissions by mid-century. If we widen this prediction to the whole world, we would fall dismally short of meeting the Paris Agreement objective of limiting warming to 1.5°C. And we wouldn't avoid the worst effects of global warming.

The dark blue line, however, illustrates what needs to happen to meet net zero by 2050 in the US. It's only by revolutionizing how we develop and build infrastructure that low-carbon energy will be sufficiently available by the time we get to 2030, 2040 and 2050.

Achieving net zero requires changing both policies and delivery practices

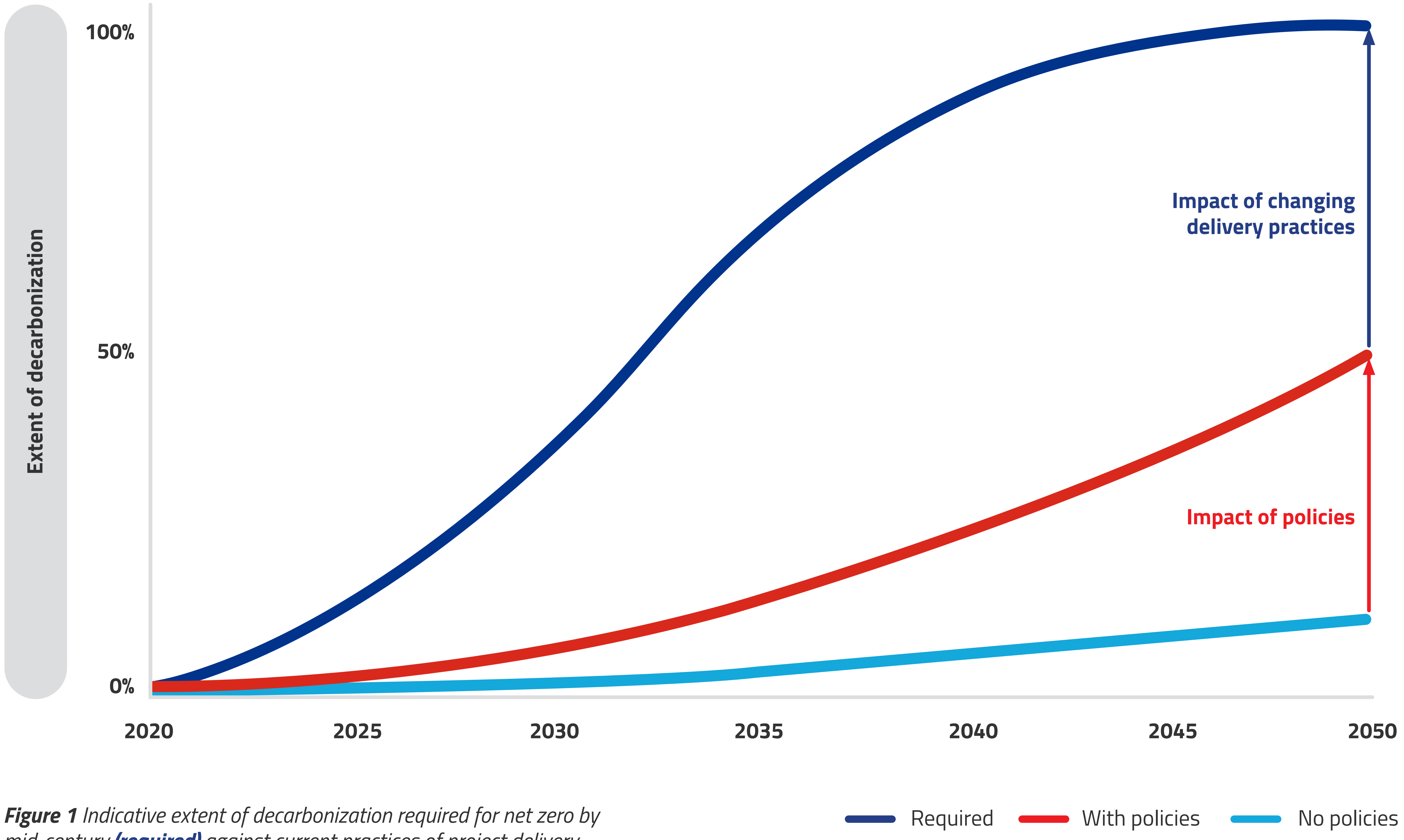


Figure 1 *Indicative extent of decarbonization required for net zero by mid-century* ***(required)*** *against current practices of project delivery* ***(with policies)*** *and without any policies* ***(no policies)****.*

Based on authors' analysis. Illustrative only.

Princeton's pathways towards change

	Pillars of decarbonization
01	End-use energy efficiency and electrification
02	Clean electricity: wind, solar generation, transmission, firm power
03	Bioenergy and other zero-carbon fuels and feedstocks
04	CO_2 capture, utilization, and storage
05	Reduced non-CO_2 emissions
06	Enhanced land sinks

Pathways	Mix of decarbonization pillars utilized in pathway
E+	Max electrification
E-	Less electrification
E- B+	Less electrification. High biomass
E+ RE-	Max electrification Constrained renewables
E+ RE+	Max electrification 100% renewables

Pathways of focus

Figure 2 *Net-Zero America (pillars of decarbonization and pathways)*

> ***"All the pathways show fossil fuels tapering off by between 70% and 100%. Coal doesn't feature beyond 2030.***

Princeton have mapped out the possible pathways for the US in detail (*Figure 2*). On the left are the fundamental pillars of decarbonization: the methods we could use to reduce carbon levels in the atmosphere. On the right are Princeton's five resulting pathways. Each uses a different blend of the pillars – electrification, renewables, biomass, nuclear and gas coupled with carbon capture and storage (CCS) – to meet the US's energy needs. All the pathways show fossil fuels tapering off by between 70% and 100%. Coal doesn't feature beyond 2030.

We'll concentrate on the 4th and 5th pathways. Both lean on more aggressive end-use electrification.

- The 4th is the constrained renewables pathway. In this scenario, the US maintains its 2020 build rate (the fastest in history) for wind and solar – year on year, for the next 30 years. While this in itself is challenging, the scenario also relies on unprecedented build rates of CO_2 capture and storage and nuclear power to make up for the lower renewable capacity.
- The 5th is the 100% renewables pathway. This one switches to 100% renewable energy by 2050. That means building at a much higher rates than have been achieved before. This pathway dispenses with fossil fuels entirely by 2050. And it assumes no CO_2 storage or new nuclear plants at all.

To enact any of the pathways, we need to build infrastructure significantly faster than we ever have before.

Figure 3 shows how much extra capacity we'd need to install every year from each technology, for each of these two scenarios.

Every pathway demands big changes

To enact any of the pathways, we need to build infrastructure significantly faster than we ever have before.

Even under the constrained renewables pathway, we'd need to install 20,000 MW of solar power each year. The biggest solar photovoltaic project in the US is 580 MW, so 35 of these would need to be built every year. And, in this scenario, we need to build new nuclear and CCS projects at unprecedented rates, too.

The picture's similar when we consider transmission corridors. The largest one at the moment is in China and stands at 12 GW. In the 100% renewables pathway, the US will need dozens of similar or larger transmission corridors – that are both high voltage and long distance – to be built each year.

Right now, it takes years to even start

Currently, a large-scale energy project takes anywhere from a few years to decades to go from concept to first operation, depending on complexity, economics and location. Obtaining the land and satisfying the regulations to build – critical for the project to begin – can take many years. For nuclear infrastructure and CCS, timelines are even longer.

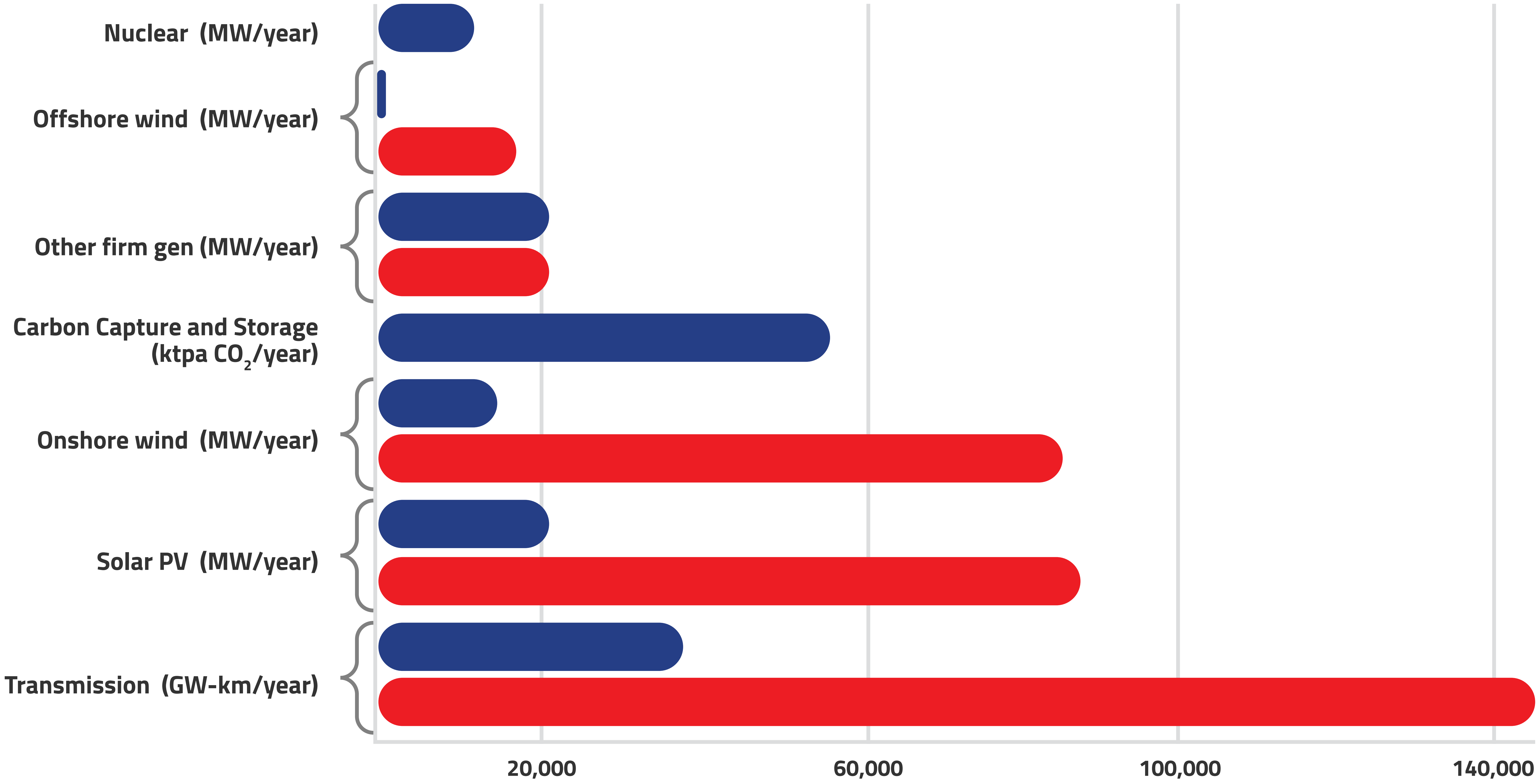


Figure 3 *Net-Zero America (required average annual capacity increase in the constrained and 100% renewables pathways)*

We need to rapidly ramp up construction

The graphs in *Figure 4* highlight how much more infrastructure must be built. On the left of each graph is the amount of infrastructure we need for the constrained renewables pathway. On the right are the requirements for the 100% renewables pathway. The solid and dotted black lines running across show the highest five-year build rates ever achieved for the US and the world. It's easy to see how much faster we need to go.

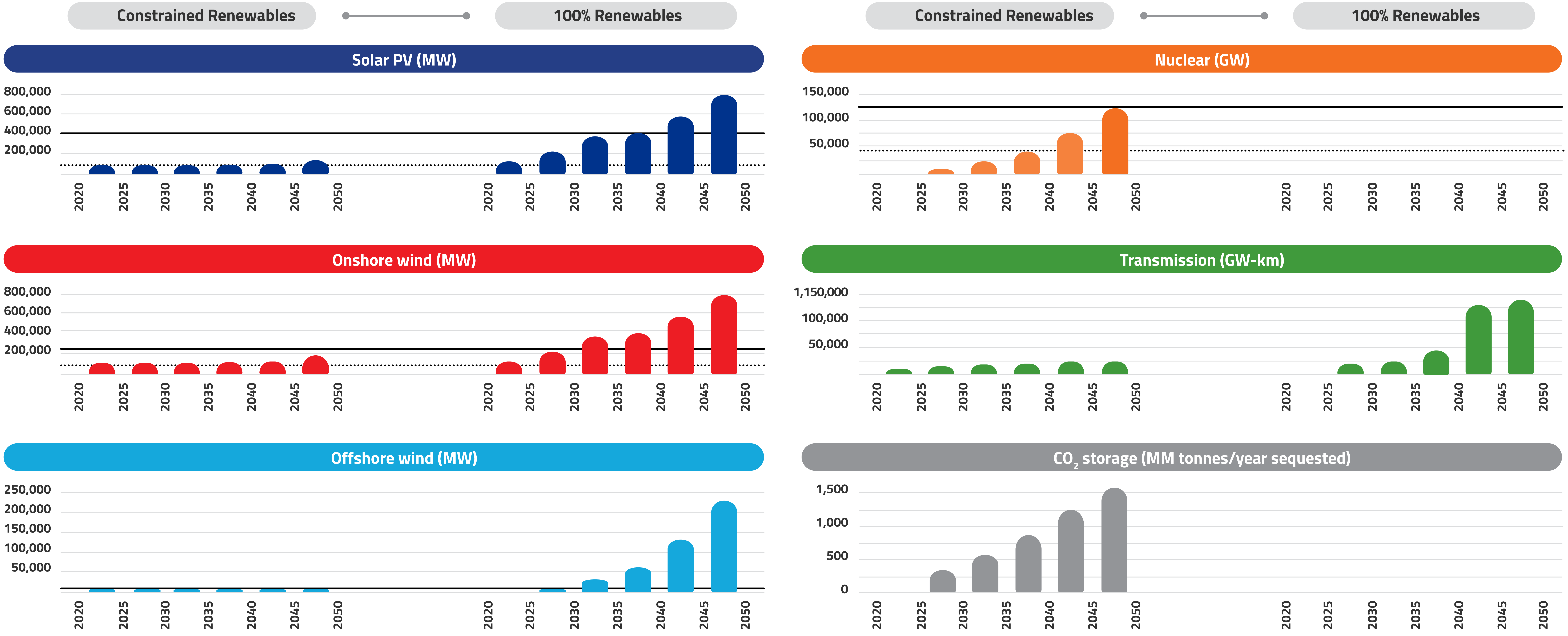


Figure 4 *Net-Zero America (5-year build rates in the constrained renewables and 100% renewables pathways)*

Global 5 year max capacity added
US 5 year max capacity added

All new nuclear and CCS facilities need to be in planning stages by 2030 if they're to be operational by 2050.

Projects need to move faster

The data in *Figure 5* shows high, average and low estimates for how long it will take to build each net-zero technology if we use a traditional development path. The grey columns on the right-hand side tell us how many of each project need to be carried out by 2030, 2040 and 2050, for both the constrained and 100% renewables scenarios.

We need to shift our approach and expectations

All of this shows that it won't be enough to incrementally improve traditional infrastructure delivery processes: we need to change the processes themselves.

Businesses and governments need to find solutions to address every area of the process. Unless timelines are dramatically compressed and projects are kicked off sooner, we will fail.

All new nuclear and CCS facilities need to be in planning stages by 2030 if they're to be operational by 2050. For more flexible timelines, creative solutions can shorten the process.

We could develop large-scale renewable energy hubs in parallel. We could repurpose and repower existing sites where possible, retrofitting eligible power plants and industrial facilities with CCS solutions. And multiple projects could share pipelines and storage hubs.

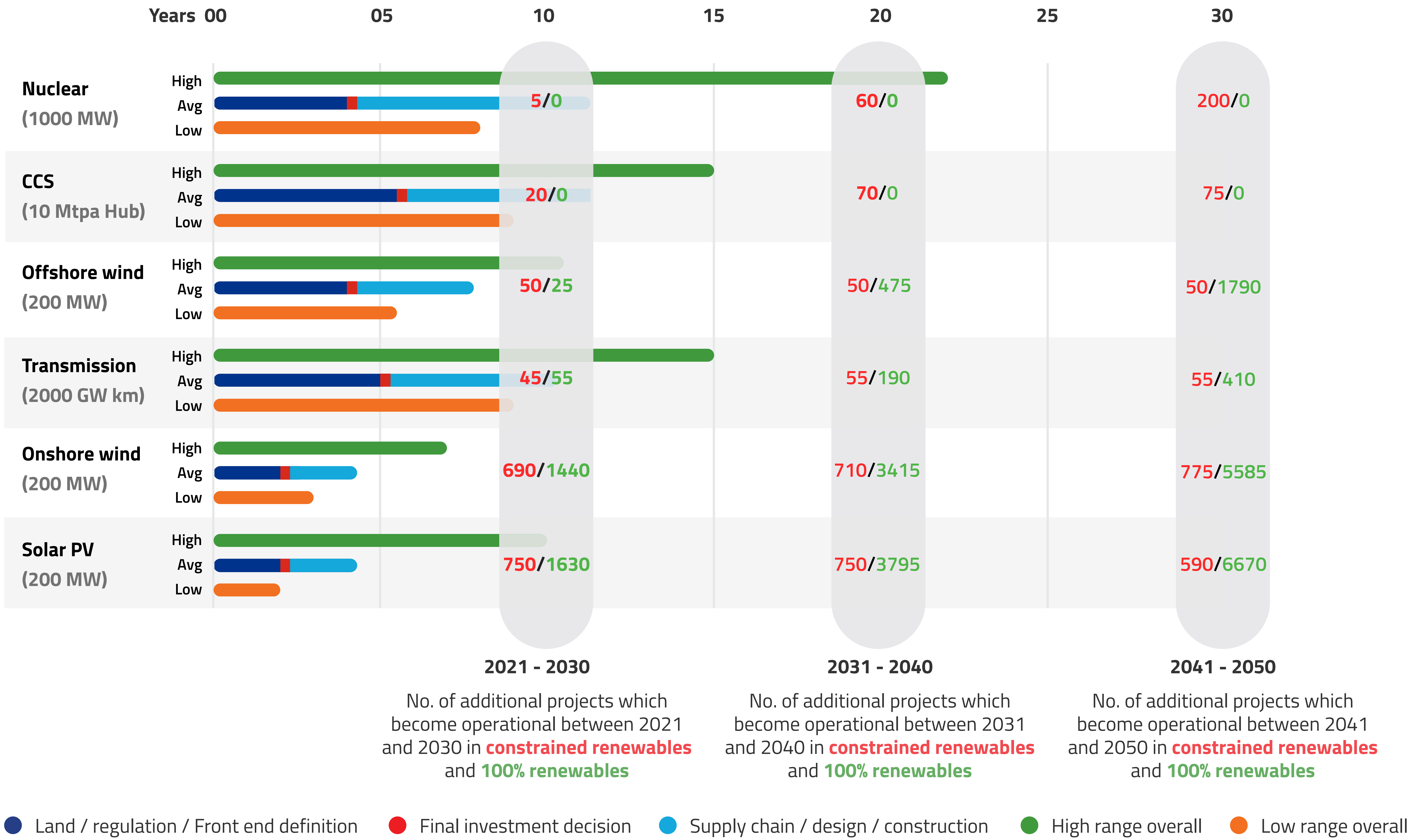


***Figure 5** Notional project timescale for low-carbon energy and transmission technologies. The value under each technology shown defines a notional 'project'.*

When the stakes are high, we can speed up

In 1998, 4.7 million people in Victoria, Australia were left without natural gas after an explosion at the Longford Gas Plant. All of a sudden, a pre-existing plan to build another gas plant in the state became urgent. The government appointed a developer who wasn't afraid to shift their approach, and accelerate delivery. They didn't follow linear timelines for engineering design and procurement. Instead, they let schedules progress simultaneously and made parties communicate from the start. They engaged the entire supply chain throughout, shortening the time it took to get critical equipment and materials in place. With BAU, the project would have taken three years. They did it in six months.

Challenge can make great things possible

The challenge is enormous. Countries the world over need to lower their net carbon emissions to zero – in a way that aligns with the UN's Sustainable Development Goals and is fair for everyone. But this is an opportunity, too. The transition gives us a chance to make sure energy is affordable globally, and available to more of the world's population.

Princeton's analysis shows that Net-Zero America is affordable and that energy prices need not be higher than they have been in the past, as a percentage of GDP. And there'll be huge employment benefits, with the transformation predicted to grow the energy workforce in all scenarios and by as much as 300% by 2050 in the 100% renewables scenario.

> ***"The transition gives us a chance to make sure energy is affordable globally, and available to more of the world's population.***

CHAPTER 3 A new way of thinking

Chapter 3: A new way of thinking

We're proposing **five key shifts** in how to think about and approach projects. These five shifts don't need to be sequential but will collectively help consideration of how to identify, develop, design and construct infrastructure through a new lens. A lens which focuses on and prioritizes achievement of net-zero.

- **Broadening how value is defined.** We need to consider whether projects deliver social and environmental value, not just financial value. The value of projects – money, jobs, clean environments – should be shared amongst all stakeholders.
- **Keep our technology options open.** We need to install low-carbon technology that's available already and keep investing in future technology. We must keep an open mind when it comes to developing technologies. Even if some are favored over others in particular regions, we need to make sure we allocate time and resources to a wide range of them, as we don't yet know which will be most effective.
- **Design one, build many.** Standardize equipment, plans and techniques. We need to create certainty in the supply chain that one design will be built repeatedly. This will dramatically shorten planning and lead time. Government policy and underwriting can play a key role here, mandating that this happens, and giving suppliers the confidence to build supply chains in advance.
- **Communicate and collaborate.** Governments, industry and communities sharing information openly will build trust. Governments will set the mission objectives, and keep communities' needs at the center of their policy and regulatory changes. Industry – which has a major role in delivering these changes – must work with both, to make sure everyone embraces the final outcome.
- **Enable and monitor digitally.** Digital platforms can be used to streamline design and delivery and optimize operations. Using digital technology, we can visualize the impact of a project, and track its performance once it's up and running. This will encourage public scrutiny and, consequently, public trust.

By weaving all these threads together, we will change thinking and achieve the shifts in practices required to make net zero a reality.

By broadening what we view as valuable, and monitoring projects digitally and transparently, both stakeholders and communities are more likely to support and trust the transition.

Sharing information and using designs which can become blueprints for multiple builds will save everyone time and money. It'll mean teams on different continents aren't spending years solving the same problem (or a problem that's already been solved). And new low-carbon technology will potentially provide future breakthroughs.

Figure 6 is a visualization of how shifting our mindset and approach in these five ways will bridge the gap between where we are and where we need to be.

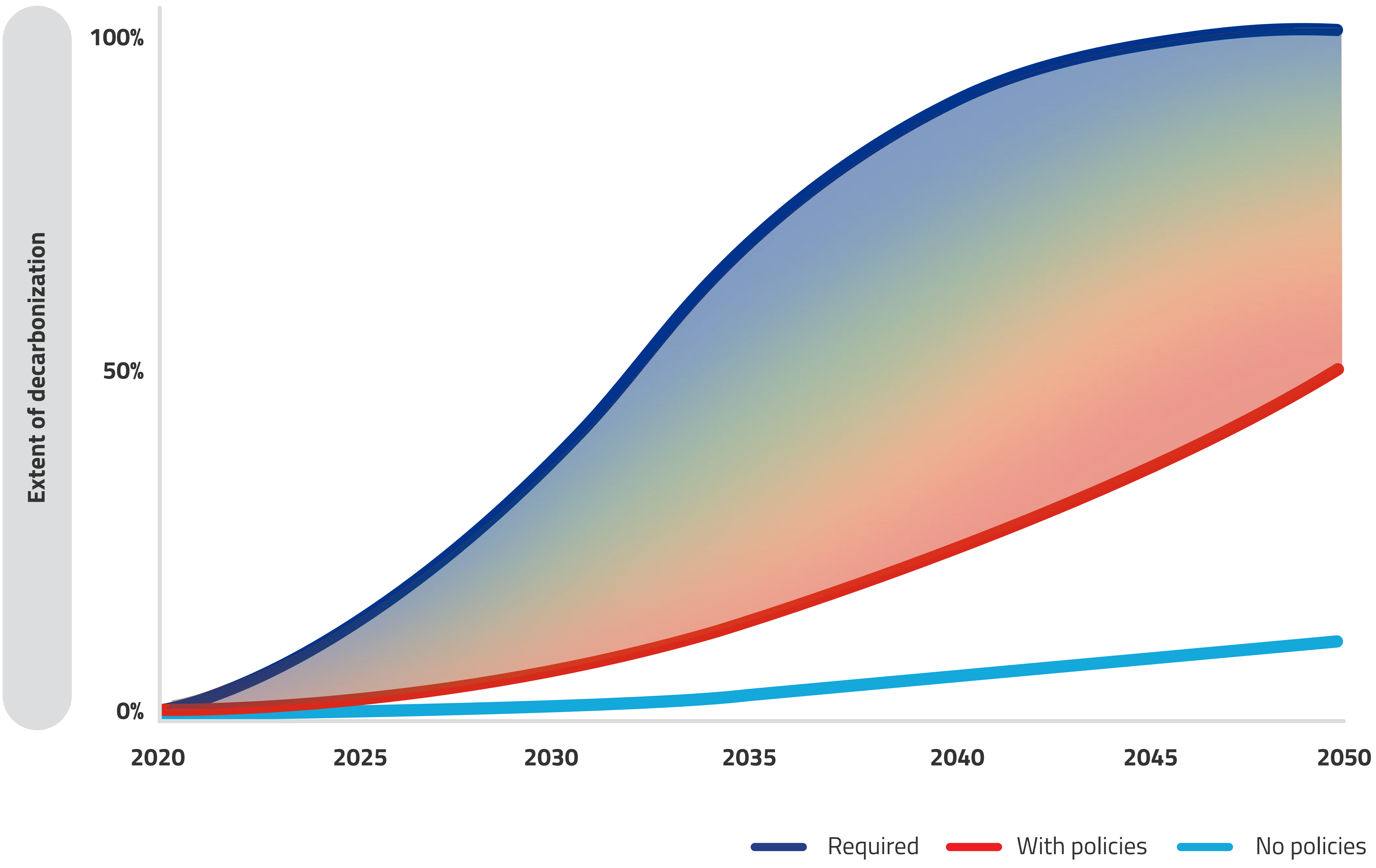


Figure 6 *Accelerating the extent of decarbonization through a new paradigm based on Figure 1*

"By weaving all these threads together, we will change thinking and achieve the shifts in practices required to make net zero a reality.

CHAPTER 4

The five shifts, in-depth

In this chapter, we'll examine in detail each of our **five shifts in thinking.** Each one reframes how we currently view projects and pushes our approach forward. They force us to consider all the different threads in supply-side energy, untangling them from their current formation, and braiding them into a coherent pathway towards net zero. The next chapter explains how we can put all five shifts in place. How we can make sure they're successful. And why they're so important to get right, starting now.

Chapter 4: The five shifts, in-depth

Broadening value

Shift from "economic" to "social-economic-environmental"

Shift 1 – Broadening how value is defined

We need to make it more attractive to invest in low-carbon energy than high-carbon energy. Getting to net zero will need significant investment. If we're going to find the capital to make it happen, investors need to feel motivated to commit and confident that environmental and social values will be preserved. It's going to mean expanding how society considers and shares value.

To broaden what value means, we need to:

- **Strengthen human capacity.** This means making the energy sector a more attractive employer. But also training people from the industries impacted by the transition in the roles needed to deliver and operate the net-zero solutions. Upstream oil and gas workers could transfer their skills to CCS. Offshore oil rig designers and constructors, to offshore wind turbines. Oil refinery workers, to biofuels and hydrogen production plants. The current energy workforce will be a huge asset and we need to make use of their valuable experience in design and construction.
- **Invest with foresight.** We need to earmark land we'll need in the future. This includes corridors of land for pipelines and grid infrastructure. Sites for terminals and ports. We need to identify and set aside zero-carbon energy hubs, zoned for large-scale development. We need to do this early, to make sure we're able to access them. This way delays can be minimized once projects start and reduce disruption to communities.
- **Increase system redundancy.** It's important that communities have reliable energy services during and after the transition. We need to strengthen resiliency in electrical infrastructure, assure grid reliability and protect against cyber attacks. This helps build confidence in these supplies and makes sure these critical services stay reliable.
- **Nurture people's trust.** We need to involve people who'll be impacted by the infrastructure or transition in the process. We can encourage communities to engage with projects and empower their participation in the change. We must work responsibly: consulting with broad stakeholders in transition planning, including project siting and zoning, and by using community ownership models.
- **Accelerate approval and regulatory processes.** This needs to be transparent, so that people keep trusting in governance processes. We need to ensure that the rigor and quality of the regulatory processes stay high, as the pace and complexity of projects increase.

Governments can usher in this change

Governments have an important role to play. They can create certainty in and for the clean-energy sector. They can underwrite investments; underpin clean-energy markets; set low-carbon targets to motivate the private sector; and provide companies with a safety net through their policies.

Value needs to encompass more

When it comes to value, the main focus right now is economic. For net zero, this won't work: projects need to deliver social and environmental value if communities are going to accept them. So, if a site seems expensive but will bring environmental value, we need to widen our view of what we deem to be worth paying for.

We also need to be willing to make trade-offs

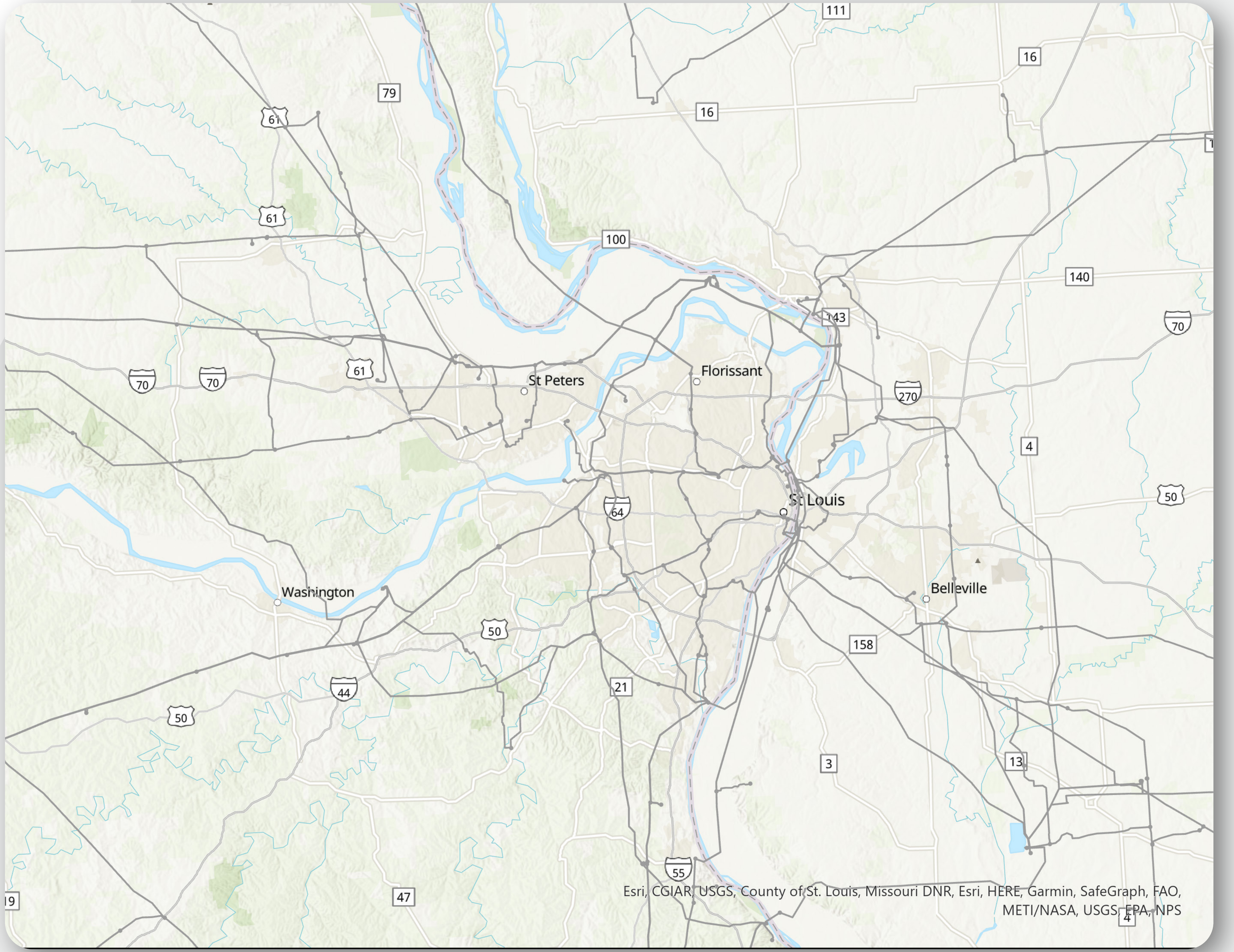
The transition brings great opportunity across the engineering, manufacturing and construction sectors, but it will interrupt other businesses. It will also dramatically affect landscapes, seascapes and communities. We need to engage sensitively with communities to understand what they value; communicate positive and negative project outcomes; and reach a mutually acceptable solution. Otherwise, projects will stall and the transition may fail.

All scenarios see significant impacts on communities and natural environments. The implications range from the visual amenity of pipelines and to the injection of CO_2 into underground aquifers and management of nuclear waste. Even renewables have impacts.

Figure 7 is a map of St Louis in Missouri. It shows just how far communities and landscapes may be affected. The city limits are overlaid with blue and maroon shading, to indicate the spatial extent of wind and solar farms across most pathways.

It's clear governments and companies could face resistance to these projects from local landowners and neighboring communities. But, if they can carry out the transition so that people understand and experience the benefits, there is a stronger chance of building and maintaining the support needed.

Different communities will make decisions based on their own perceptions of the risks and rewards, and these may change over time. We don't know yet which pathway – or combination of pathways – will be the most acceptable, and therefore the most feasible to achieve net-zero emissions. This is why we need to keep all these threads of change running through everything we do. Sitting more comfortably with risk and the unknown, and not allowing either to bottleneck plans, will be crucial.



Existing substations and transmission > 115 kV

New wind and solar PV in 2050 (all pathways)

New 230 kV spur lines and bulk transmission > 230 kV in 2050 (all pathways)

Figure 7 *Net-Zero America (new wind farms, solar farms and transmission networks required for St Louis, Missouri for all of Princeton's high electrification pathways)*

Map courtesy of Dr. Andrew Pascale, Net-Zero America study team member

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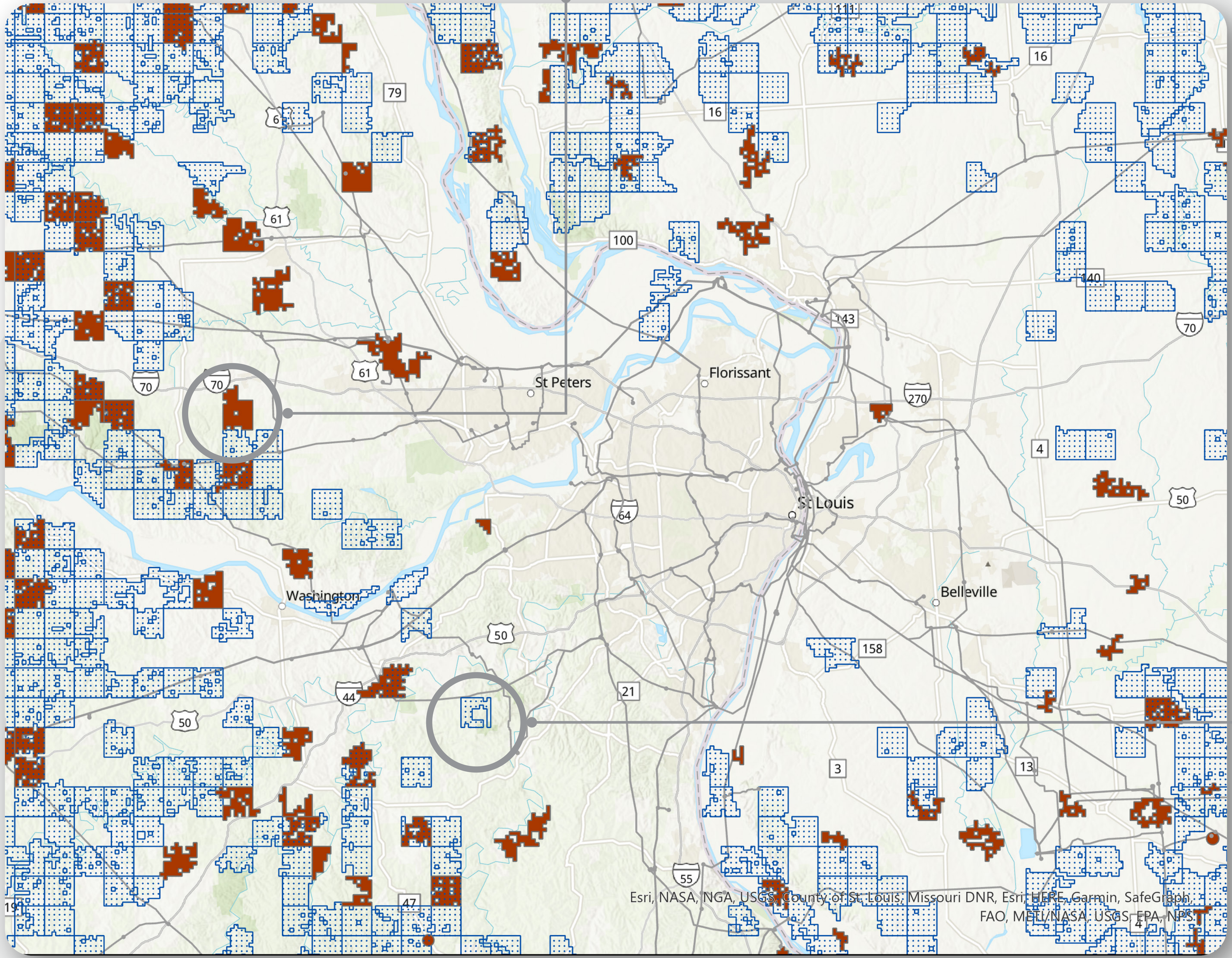
500 MW solar facility (generic future facility)



80 MW wind facility (generic future facility)*

Existing substations and transmission > 115 kV

New wind and solar PV in 2050 (all pathways)

New 230 kV spur lines and bulk transmission > 230 kV in 2050 (all pathways)

Figure 7 *Net-Zero America (new wind farms, solar farms and transmission networks required for St Louis, Missouri for all of Princeton's high electrification pathways)*

**Image courtesy APA Group*

We also need to be willing to make trade-offs

The transition brings great opportunity across the engineering, manufacturing and construction sectors, but it will interrupt other businesses. It will also dramatically affect landscapes, seascapes and communities. We need to engage sensitively with communities to understand what they value; communicate positive and negative project outcomes; and reach a mutually acceptable solution. Otherwise, projects will stall and the transition may fail.

All scenarios see significant impacts on communities and natural environments. The implications range from the visual amenity of pipelines and to the injection of CO_2 into underground aquifers and management of nuclear waste. Even renewables have impacts.

Figure 7 is a map of St Louis in Missouri. It shows just how far communities and landscapes may be affected. The city limits are overlaid with blue and maroon shading, to indicate the spatial extent of wind and solar farms across most pathways.

It's clear governments and companies could face resistance to these projects from local landowners and neighboring communities. But, if they can carry out the transition so that people understand and experience the benefits, there is a stronger chance of building and maintaining the support needed.

Different communities will make decisions based on their own perceptions of the risks and rewards, and these may change over time. We don't know yet which pathway – or combination of pathways – will be the most acceptable, and therefore the most feasible to achieve net-zero emissions. This is why we need to keep all these threads of change running through everything we do. Sitting more comfortably with risk and the unknown, and not allowing either to bottleneck plans, will be crucial.

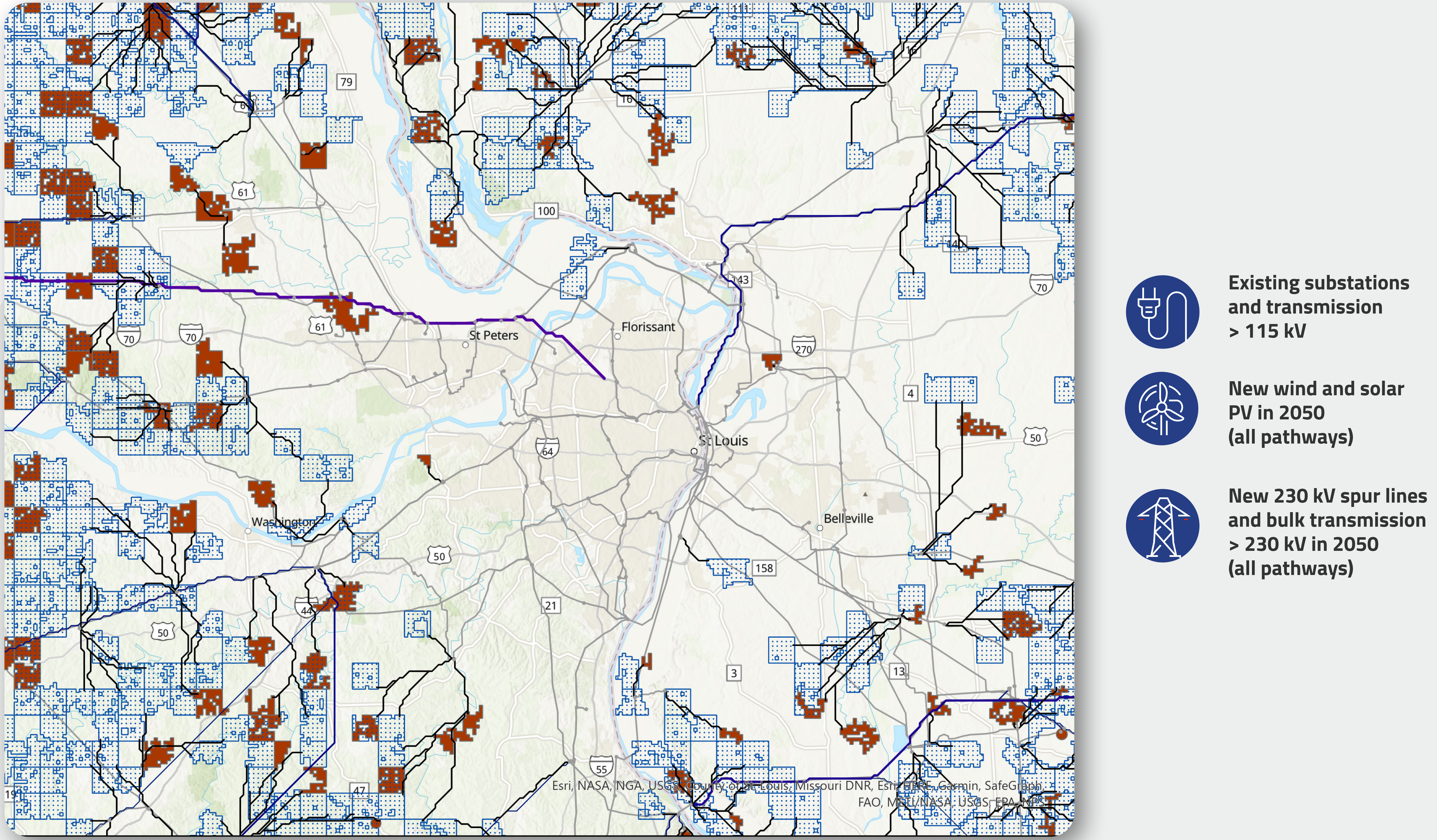


Figure 7 *Net-Zero America (new wind farms, solar farms and transmission networks required for St Louis, Missouri for all of Princeton's high electrification pathways)*

Enabling options

Address uncertainty through development of all technologies

Shift 2 – Develop all possible low-carbon technology options

The final net-zero tapestry will be made up of threads we're already using – current technology and processes that work well – and threads we've not even discovered yet. We need to research a wide range of decarbonization technologies, spreading our effort and investment evenly. This way, we give ourselves the best chance of finding future solutions. We need a pipeline of innovation: some of the technologies may not work out, but others could be key in years to come.

New technology will be ready in stages

The technologies that will make decarbonization possible are in various stages of development. The Technology Readiness Level framework (TRL) allows us to see how ready they all are at any given point. Combining this with commercial readiness levels (CRL) will be a good way to track development progress, so that we know when we'll be able to put these technologies into action.

In *Figure 8*, we've taken the TRL / CRL framework, and overlaid it onto Princeton's six pillars of decarbonization to see when it's likely these technologies will be ready. It shows we can start the transition now, with the low-carbon technologies that are ready – such as wind and solar – while investing in those still emerging, like hydrogen and DAC.

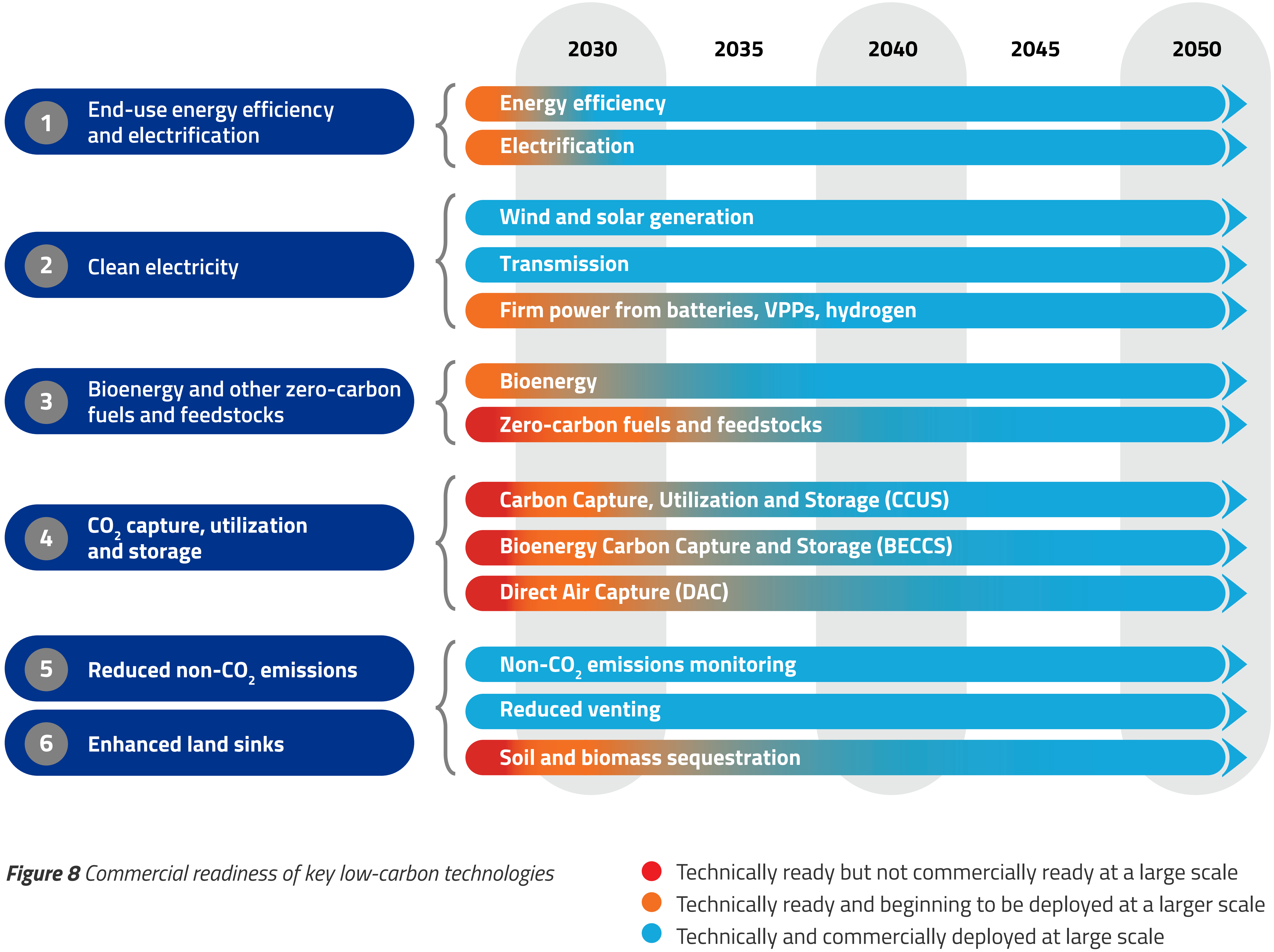


Figure 8 *Commercial readiness of key low-carbon technologies*

From early stages to flight-proven

It took just eight years from John F. Kennedy committing to landing a man on the moon, to Neil Armstrong walking across its surface. Not only was this wild ambition achieved swiftly, but it brought with it a new, quicker way of getting new technology into circulation. In the 1970s, NASA developed TRL as a result of the moon landing. Today, it's used all over the world. Combined with CRL, it gives us a framework to move new technologies from early stages to being flight-proven.

"

One technology alone won't get us to net zero. The solution is going to be a tapestry of different approaches.

Keeping an open mind

One technology alone won't get us to net zero. The solution is going to be a tapestry of different approaches, working within resource, geographic, market, and enviro-socio-political constraints. And all technologies will have their own challenges.

Some technologies require a lot of land

Some clean electricity infrastructure (such as wind, solar and transmission) can have a significant effect on landscapes and visual amenity. This could pose problems for communities. Bioenergy has a similar issue. Some biomass crops will be competing for space and water with food crops. Similarly for CCS, CO_2 transport systems will need significant pipeline infrastructure.

Decentralized energy solutions present opportunity

For example, the millions of small solar systems across the world can occupy people's rooftops and be part of the solution. Using this previously unutilized resource means these solar panels don't have to go through lengthy planning processes. Instead, their limitations lie in their decentralized nature, potential market distortion, the impact on grids, the security of the system, and how controllable they are.

Green hydrogen offers promise but faces challenges

It's currently more expensive than higher-emissions options; it needs large volumes of water; and transporting it can be complicated. That said, it could be transformative in industries where decarbonizing isn't straightforward. For example, the steel industry turns iron ore into steel using coking coal, which can be replaced with hydrogen. Similarly, hydrogen fuel cells may offer advantages over electrification for heavy-duty transport.

For some, it's a problem of carbon storage

Natural gas has an important ongoing role to play, particularly when coupled with CCS for blue hydrogen and clean firm power. In addition, BECCS, and DAC, offer negative emissions solutions. But all these need solutions for the long-term storage of CO_2.

The solution will be a combination

Each of the low-carbon technologies come with their benefits and challenges. We need to take a portfolio approach to net zero so that we use multiple technologies to lower emissions. And so that we cause the least possible disruption to communities as we do it.

From bespoke to modular

In WW2, a desperate need for more ships ignited an emergency shipbuilding program in the US. They switched from using bespoke measurements for each ship, to standardized components. The modular ships could be built by workers who were new to the industry – taught only to perform one small task in the process, over and over again.

This process became so efficient that the program average for the complete build of a ship went from approximately 240 days to around 40 days.

The program built nearly 6,000 ships in 5 years.

Standardization

Replicate designs and build in parallel

Shift 3 – Design one, build many

We must move to a system where we standardize as many aspects of a project's design as possible, and then replicate that design many times.

Currently, most builds are bespoke. Each time, a design must be drawn up and put through a lengthy approval process. Each time, we go back to square one. Each time, we waste time.

We must also develop projects in parallel. The execution of large programs of projects will streamline all steps in the development sequence.

So, if we use a successful design as a blueprint – to be cloned again and again – running programs of builds in parallel, we can dramatically increase how much gets built, and how quickly.

This approach will:

- **Save time.** We'll cut down engineering effort and regulatory approvals. We'll have multiple projects being built at once, with shared project teams. Fabrication and construction can be carried out in parallel on different worksites, using local workforces.
- **Optimize resources.** We'll use highly skilled subject matter experts for the front-end design phase of the project. But we can use local teams for the construction and operational phases. This will spread work around the globe, rather than concentrating it in a few spots and reduce the risk of skill shortages. And we can use the transition to distribute job opportunities more evenly across countries.
- **Speed up the supply chain.** By introducing common equipment standards across all countries, equipment and parts will be quicker to make, transport and install. This will also let us set up local supply chains.

Identical plants, in China and South America

A recent example is a chemical plant which was built in China with a duplicate being built in South America. The design of the Chinese plant was passed over to the team in South America when the engineering was 90% complete, where it was then adjusted to allow for location conditions.

The original Chinese design took 16 months to develop, whereas the design for the South American plant took just six months to adapt. To achieve further time and cost savings, all of the structural steel, piping and manual valves were jointly purchased for both projects from Chinese suppliers. The electrical and instrumentation equipment was sourced in South America for the cloned plant to meet local code requirements.

Readying the supply chain

If we're cloning designs, and their components can be bought off-the-shelf (rather than being bespoke), we'll cut down lead times.

We need to bring the global supply chain players, and their logistics partners, into the process early on. This way, they can contribute to the design and identify the solutions that already exist, are already being manufactured, and will be easiest to scale up.

There's a big barrier for suppliers, though.

Will their orders go ahead? And how quickly? To solve this, governments could underwrite developments to build confidence in the pipeline of future projects.

Sourcing enough raw materials

One hurdle to overcome will be how to source enough raw materials. Lots of projects using the same parts and equipment will cause demand for raw materials to skyrocket.

A recent report by the International Energy Agency (IEA) reveals that demand for raw materials could grow to six times what it is today.[1] There may be shortages of key metals and minerals, which limits supply and inflates costs.

The critical minerals supply has several vulnerabilities. Because the minerals are concentrated in a handful of countries, there may be a supply constraint due to geopolitical tensions. Growing scrutiny of Environmental, Social and Governance (ESG) issues could endanger raw material sources, particularly in areas where water is scarce, or human rights are threatened. Changing climates and extreme weather events could also make sourcing more difficult. And all of this could limit access to high quality, cost effective minerals.

We can meet these challenges in several ways. One is by extracting minerals from complex lower-grade ore bodies, in a fast and sustainable way. And another is by establishing circular economies, where we take pre-used and surplus industrial materials and recycle them.

We need to get these innovations and practices up and running for key materials this decade.

[1] IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Developing in parallel

Right now, the series of decisions involved in a project looks like *Figure 9.*

The stages before the final investment decision – the first three phases of the diagram – usually take years and are done project by project. It's an inefficient process, both in terms of time and resources.

Identify

- Concept and pre-feasibility studies
- Awareness of stakeholder sentiment and regulatory environment

Evaluate

- Feasibility studies
- Assessment of markets
- Begin engagement with stakeholders and regulator
- Begin Environmental and Social Impact Assessment

Define

- Front End Engineering and Design (FEED)
- Market defined and assured
- Stakeholder strategies and regulatory approvals in place

Final Investment Decision

- Capital is committed

Design

- Detailed engineering issued for construction
- Procure equipment and materials
- Continue stakeholder and regulation engagement

Build

- Construction in place
- Continue stakeholder and regulation engagement

Commission and handover

- System completion
- Ready for start up
- Continue stakeholder and regulation engagement

Asset management

- Maintenance and operations
- Continue stakeholder and regulation engagement

Figure 9 *Typical project decision sequence*

The alternative is to run programs of projects, shown in *Figure 10*, using the same development teams in parallel.

At the top of *Figure 10*, five notional offshore wind projects are being developed in a traditional, linear way. Starting dates rely on the availability of key people in the teams, and how long it takes to procure items. Currently projects, at best, follow a phased development approach.

By contrast, the lower half shows a scenario where equipment is standardized and resources are shared across multiple projects. Much less time has to be spent on the project before it gets funding. We avoid bespoke engineering, and agencies can grant approval to multiple projects at once.

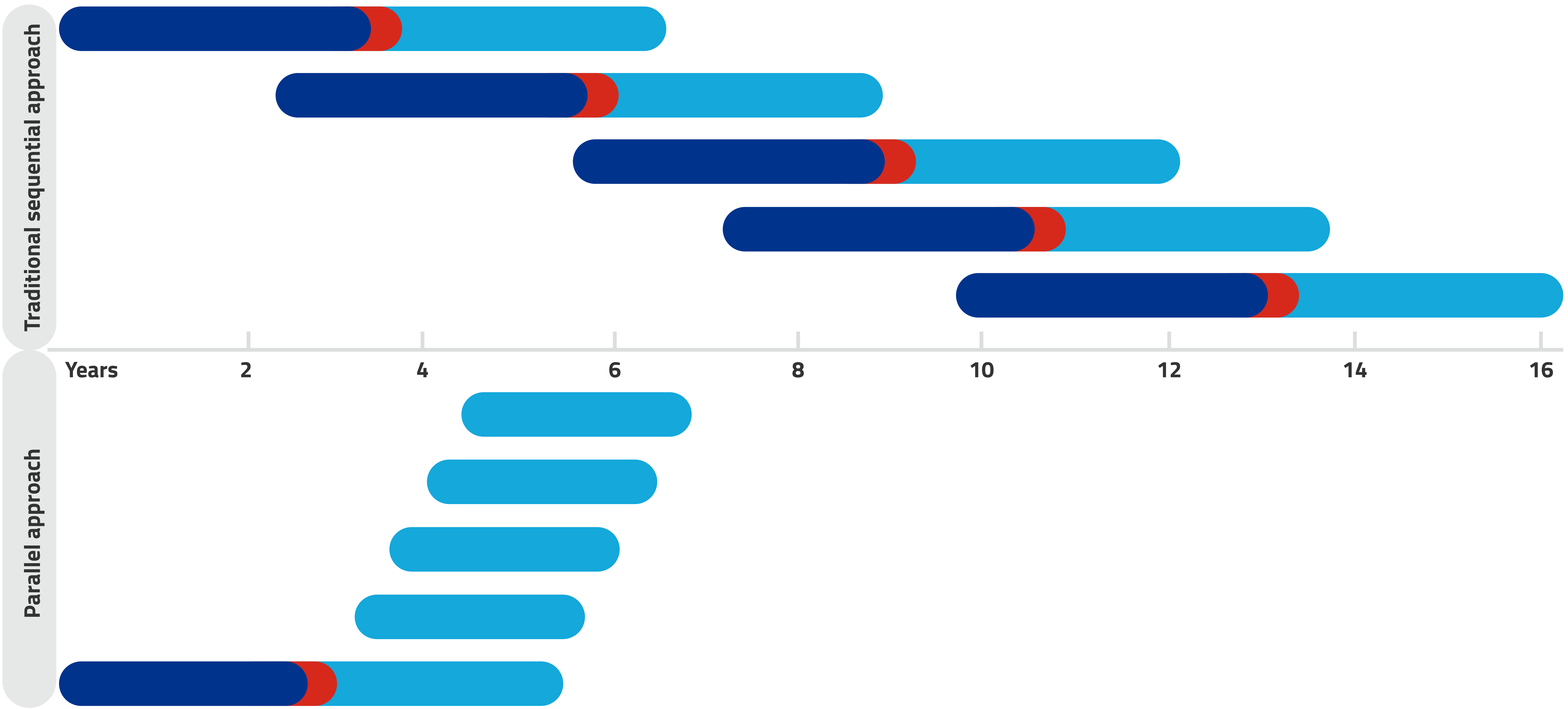
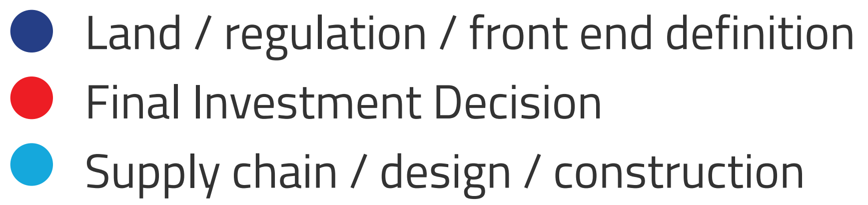


Figure 10 *Sequential versus parallel approaches to building five notional offshore wind farms*



Creating partnerships

Governments set the objectives and partnerships form

Shift 4 – Communicate and collaborate

Net zero is an endeavor that will reach every corner of the world – so we need global communication and collaboration. It'll make the transition more efficient and spread the best solutions far and wide. For this to work, we need mutual respect, trust, clarity, and well-defined roles and expectations.

Working with the enemy

At the height of the Cold War, the unlikeliest collaboration achieved something astonishing. The US and the Soviet Union worked together to eradicate smallpox. Despite a tight budget and the tension between them, they came together to donate 75 million vaccine doses to the world. They tracked outbreaks of the disease with a network of informants, and worked quickly to contain them with vaccinated 'rings' forming around infected communities. This strategy to break the chain of infection was then applied successfully in Nigeria, West Africa, India, and then the rest of the world. Together, they wiped out smallpox in 14 years.

Expect governments to lead from the front

The rules will dictate the change. Governments need to set ambitions, define goals and enact legislation that creates the market forces to drive the desired low-carbon behaviors. They can incentivize this in various ways: access to capital markets, entry to carbon markets, and tax breaks.

This is already underway.

The UK recently banned diesel and petrol car sales from 2030. This is driving electric-vehicle manufacturing and supply chains. The EU banned single-use plastics from 2021. Consequently, Coca-Cola Europe announced 100% of their bottles would be based on recycled plastic. The EU voted to phase out palm oil in biodiesel by 2030, to reduce the loss of animals and plant species from rainforests. Now companies are finding alternatives.

Norway provides a compelling case study of the impact of legislative change.

The government introduced a carbon tax in 1991, to encourage research into low-carbon solutions. Later, they established the Technology Centre Mongstad. The country responded.

Norway became the first country to geologically sequester CO_2 – at the Sleipner gas field in the North Sea. They were also the first to do it from an LNG facility, when they built the Snøhvit CCS facility. Ten years after the tax was introduced, carbon emissions had dropped by 14%.

Today, Norway continues to lead innovation. They're at the center of the Northern Lights project, where CO_2 will be captured onshore from industrial sites across Europe and transported, injected and permanently stored 2,600m below the North Sea seabed.

Policies influence emissions. This should be an exciting prospect for governments, and many have already made commitments around net-zero. And not just for the environmental outcomes, but also to drive more sustainable growth and future-proof their economies.

Share information

Countries need to work together. As do companies.

All need to play to succeed, rather than play to win. We must start sharing. Ideas. Patents. Processes. Designs. We need to see open-book contracts with transparent, auditable margins.

We need everyone who's capable of pushing towards net zero – governments, vendors, contractors and communities – to do so. They need to form coalitions, who feel empowered to hit targets and deliver value. Value in financial terms. In job creation. And in clean environments.

And we need to share what we learn on each project, even with competitors. Yes, that means businesses might lose some competitive advantage. But where one company might win two bids in 20 years – hording knowledge – three companies that work together can win 20 bids between them over the same time.

And, as we've seen, there's plenty of net-zero transition work to go around.

We've seen this style of working is possible. The COVID-19 vaccine development was revolutionary. Never have so many experts in so many countries focused on a single topic with such urgency.

Scientists communicated across borders. Governments underwrote research and facilities. The discussion of who would get academic credit was abandoned. Instead, they made studies available to read before they were published. Researchers shared viral genome sequences digitally. And sharing data made it possible to find the solution so fast.

It wasn't perfect, but it shows what humanity can achieve when our collective backs are against the wall.

Work together

We'll be collaborating, rather than competing.

It'll reduce the hours we all need to work to get a design from concept to completion. And it'll increase how much gets built.

To do this right, we'll need to learn from where things go wrong, and share this through a collaborative platform. We can feed back on how to better manage risk, and how to put sufficient change management processes in place. Everyone in the value chain should contribute to the platform, so we can iron out any – and all – problems.

For example, if a low-emissions project stalls because of grid-connection requirements, this can be fed back. The right changes can be made. And a cloned project won't run into the same hurdle.

Have a master plan

Governments will require master plans that split the decarbonization task into technologies or specific objectives.

These plans need to set out national targets and contemplate key aspects of the transition, while retaining flexibility to build in new technologies that are invented along the way.

These plans must include a feedback loop with key communities to ensure shared value.

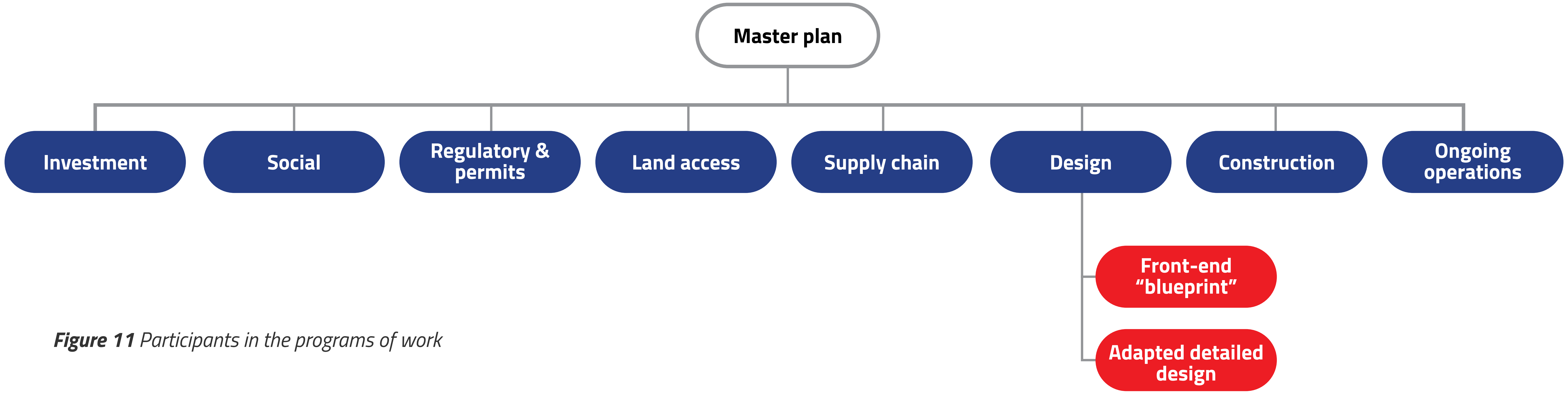


Figure 11 *Participants in the programs of work*

The digital accelerant

Digital platforms create the trust to move forward

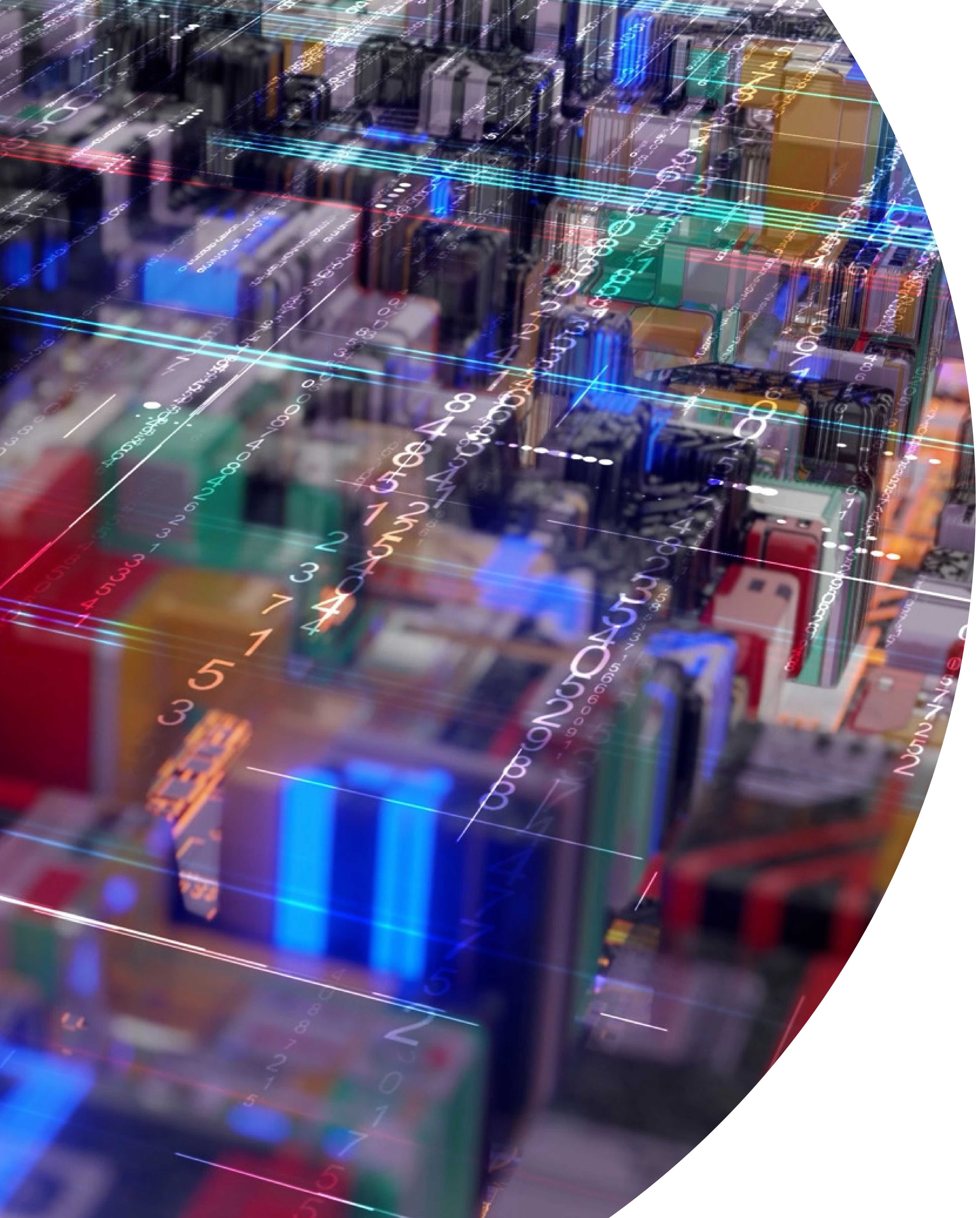
Shift 5 – Enable and monitor digitally

Digital technology will make the net-zero transition more efficient. Once projects are up and running, we'll digitally monitor them to make sure they're performing optimally, and to work out if we can make any improvements to the next set of projects being built. There's also an opportunity to use data to build people's faith in net-zero infrastructure.

Digitization is already driving outcomes in energy systems that weren't possible a decade ago. There's the side that people see: light appearing when you flick the switch, for example. But an entire digital process is at play too – in this case, keeping the electricity supply stable, monitoring and controlling safety systems, and trading in electricity commodities. There's so much that flies under the radar, from the digitization of engineering designs, to the forecasting of risk within markets.

If people can log into a digital platform and see real-time data that depicts the direct effects of the net-zero transition, their trust in the process will grow. They'll understand why landscapes are changing around them. And they'll know it's for something that will ultimately benefit them. Data will also play a key role in convincing stakeholders to commit to financing infrastructure.

Figure 12 *3D modeling of new equipment*



An unseen revolution

One way that digitization is quietly revolutionizing energy is by balancing supply and demand.

People across the world have started generating their own renewable energy, by putting solar panels on their roofs.

In isolation this isn't an issue, but when there are millions operating independently it can create problems for electricity grids. Technology can now digitally aggregate these within Virtual Power Plants (VPPs). This allows the solar panels to operate as a single virtual entity or trade between each other in a manner which builds value for owners, while keeping the network more stable.

Digitization also lets us site and design wind farms and solar power stations without needing to be onsite.

Technology can simulate what the finished power plant will look like – from any angle – and virtually fly you through even the most complex of project circumstances. It can describe the asset to communities and regulators, and estimate the plant's output before it's even built. Then, after the build, technology can track measurements and performance through remote sensors and make automatic adjustments to keep plants at optimal performance, and everyone involved safe.

Conquering complexity

As energy systems get more complicated, digitization will be the only way to make sure they're most effective.

Blockchain, for example, allows an immutable transaction process – one that cannot be undone, faked or changed. This will be key to forging and retaining trust in data, and ultimately net-zero outcomes. Consider a molecule of green hydrogen. Blockchain can help guarantee that this comes from a zero-emissions source. Already we're seeing people start to use this technology to track green credentials and commodities such as low-carbon aluminum.

Digital enablement is already streamlining the engineering process of how we design and deliver large infrastructure. It's also making how we source, select and procure items more efficient. When digitization is operating, Internet of Things (IoT) sensors measure discrete asset performance, while industrial operations centers track and control asset portfolios, making the trade of commodities into markets smoother.

Artificial intelligence and machine learning then have a large part to play. They'll combine to make operational and commercial models evolve, becoming more efficient and more effective. It's already routine to forecast future outputs of wind and solar plants, to enhance the matching of supply and demand in electricity markets. Artificial intelligence will evolve these trades, making them more effective.

And digital solutions like this mean we can imagine huge future possibilities. A world where gas and electricity markets are connected via renewable energy and hydrogen, for example.

Enabling a transparent value chain

Digital monitoring is key for building people's trust in what we're doing. It lets us make processes visible. And if people can see how things are working and the impact they're having, they'll believe in their value. We'll be able to show that projects are meeting their targets. How much carbon they've sequestered. How many jobs they've created.

But building trust is only the end point of what a digital platform could do. Governments and regulators will be able to pull levers and tweak processes, because they'll have immediate access to real-time information. We should be able to digitize the entire project-decision sequence.

Regulatory approval will be easier and faster. And stakeholders will be able to use the platform to engage with projects more fully.

To achieve all this, we need a Net-Zero Enablement Platform (*Figure 13*). Building on Princeton's six decarbonization pillars, it has three distinct levels:

1. **Data platform.** This tracks the projects being built, and then how they perform. It collects and aggregates data on an open, standardized information-sharing model, and verifies performance using blockchain.
2. **Market intelligence platform.** This is where decisions are made, by operators and government entities, about how to optimize portfolios based on demand profiles, policies and market signals.
3. **Reporting platform.** This makes sure different stakeholders can work together and trust each other.

It's going to work best if everyone participating in the network gives input. They'll need to agree on accreditation, compliance and regulation, as well as the roles of government, industry and communities.

But the platform should be overseen by an autonomous, or semi-autonomous, government body – a net-zero regulator. They would make sure everyone's complying and using it properly. They'd also have access to the data that the platform is collecting, to scrutinize it and make it publicly available.

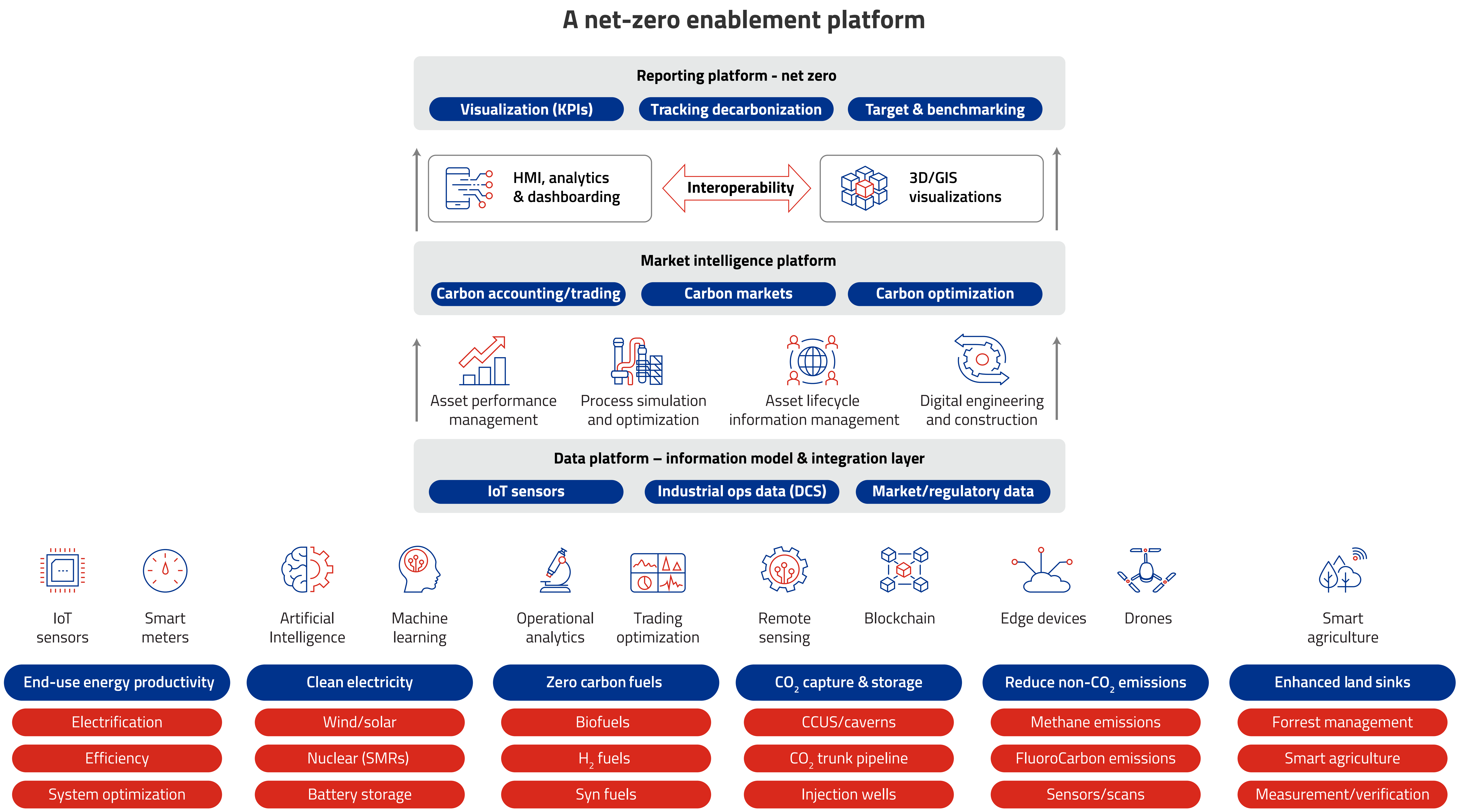


Figure 13 *An example of a net-zero enablement platform*

CHAPTER 5 Necessity breeds innovation

Chapter 5: Necessity breeds innovation

These five key shifts combine to reframe our mindset and approach.

They are some of the threads we can use to weave the net-zero tapestry into reality. As are technologies we already know; technologies on the horizon; and the hundreds of coalitions and millions of individuals who will be a part of making this transition happen. All these threads must be woven in too. And shifting our thinking – in line with our five recommendations – will keep us aligned in our endeavor.

These five shifts are the sorts of changes we need to make to arrive at net zero in thirty years.

Of course, everything we've said sits within a bigger picture. *Figure 14* shows how our piece (in the dark blue box) fits into the overall jigsaw.

We need to get the precursors right. How we source raw materials. The policies governments put in place. The supporting infrastructure and demand side will both need huge investments in their own right if they're going to adjust. And we need to consider the sustainability elements as we go. How we pave the way for a low-carbon future can't impact on food, health, safety, or any other necessities for us to thrive on the planet.

There's much to be done across the board. And it's clear we need to think of the whole ecosystem as we progress. But it's also clear that supply-side infrastructure is at the heart of net zero.

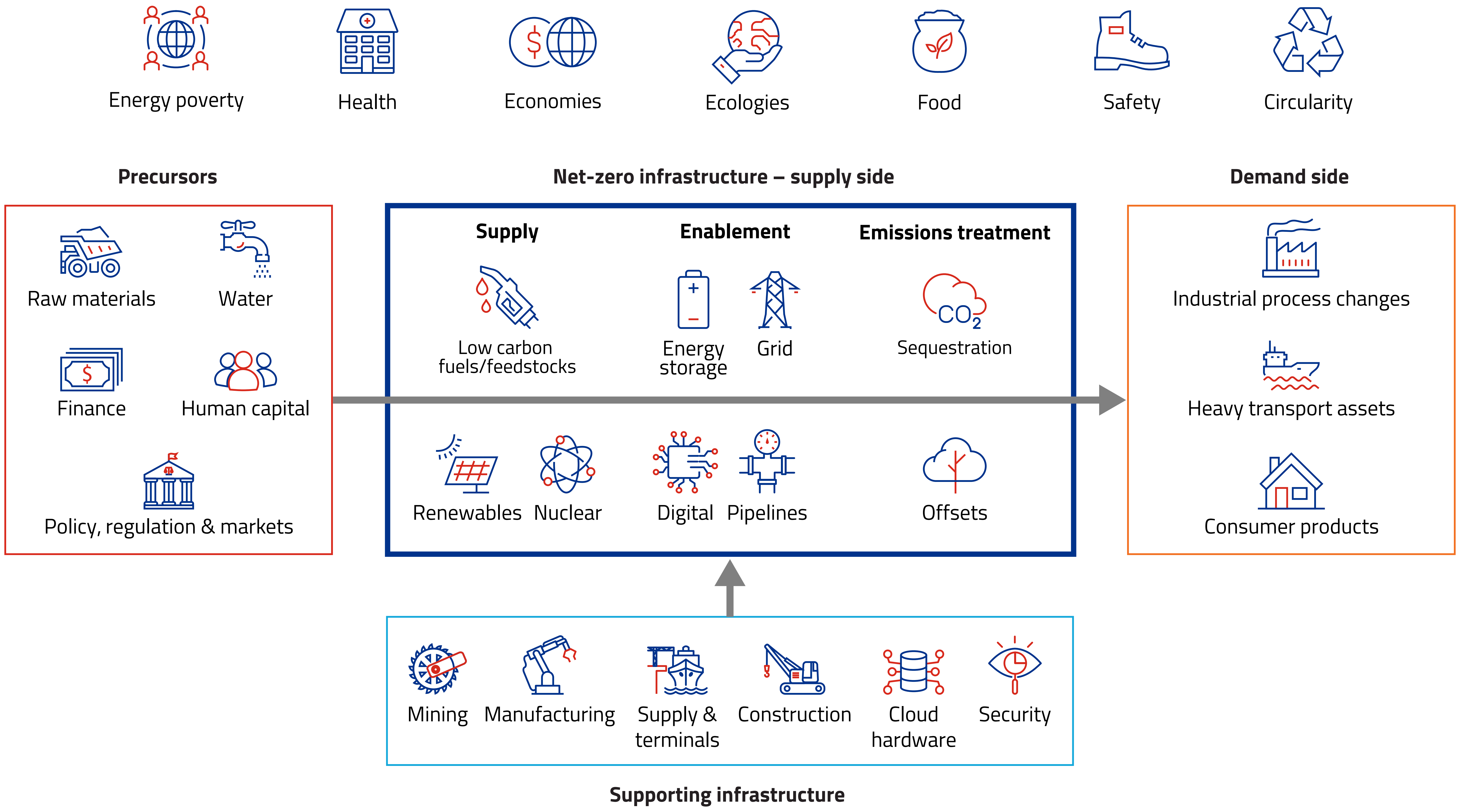


Figure 14 *A part of the bigger decarbonization picture*

“Our need will be the real creator”
– Plato.

If you think back to thirty years ago, either in your own life, or in history, you’ll realize just how quickly time goes by.

The invention of the Hubble telescope, Nelson Mandela’s release from prison, the fall of the Berlin Wall. In the grand scale of the human race, these are all very recent events.

Because thirty years isn’t long.

Net zero doesn’t need to happen in some distant future. It needs to happen in most of our lifetimes.

Princeton’s Net-Zero America makes clear how we can meet this need, on the ground. Whichever pathway – or blend of pathways – we follow, the level of change will test us. We need to break all our own records if we’re to prevail.

But we’ve witnessed the kind of extreme effort needed. Very recently. Our response to COVID-19 tells us it can be done. It seemed impossible. There was no precedent for working that cohesively or quickly. And yet we overhauled norms and created a new way of working.

Energy is the fuel that the world needs to run. It is the sustenance that powers so many accomplishments and activities across the globe.

And finding a way to weave all the different threads we’ve discussed together – each with a part to play in creating a world where energy is clean – is now our most pressing challenge.

We need to come together, to work intelligently with the solutions we have and foster innovative new ones too.

And all of it needs to start now.

Acronyms

BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon dioxide
CRL	Commercial Readiness Levels
DAC	Direct Air Capture
ESG	Environmental, Social and Governance
EU	European Union
FID	Final Investment Decision
GDP	Gross Domestic Product
GIS	Geographic Information Mapping
GW	Gigawatt
H_2	Hydrogen
HMI	Human-Machine Interface
IEA	International Energy Agency
IoT	Internet of Things
KPIs	Key Performance Indicators
Kt	Kiloton
kV	Kilovolt
LNG	Liquefied Natural Gas
MW	Megawatt
PV	Photovoltaic
SMRs	Small Modular Reactors
TRL	Technology Readiness Level
UK	United Kingdom
UN	United Nations
US	United States
VPPs	Virtual Power Plants
WW2	World War Two

Worley
energy | chemicals | resources

Princeton E-ffiliates Partnership
eFFILIATES
energy ▪ environment ▪ engagement