REPOWER: Derisking and Accelerating the Energy Transition

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The following work done by the Terra Praxis team since 2018, summarizes analysis of the risks to the clean energy transition in the United States, United Kingdom, Germany, and Japan, and outlines the immediate risks that must be anticipated and mitigated to ensure progress toward a Net Zero future. It sets out how, by diversifying the portfolio of emissions-free technologies, aligning targets with feasibility analysis, and implementing risk-informed strategies, we can mitigate the key risks and help drive a successful transition. It identifies a REPOWER strategy that enables the repurposing of existing infrastructure to run on emissions-free energy and produce emissions-free fuel as a practical, achievable, scalable, and equitable way to reach a Net zero economy and put the world on a fast path to growth and decarbonization by 2050.

Introduction: Risks to the Energy Transition

Our actions in this decade are critical. There is a widening gap between decarbonization policy targets and the real world deployment of clean energy deployment at speed and scale.

Mainstream energy transition models, because they are derived from capacity addition models, prioritize cost optimization and overlook critical factors related to the feasibility of building massive amounts of new clean energy infrastructure, including socio-political, cultural, commercial, and financial aspects. These omissions lead to greatly overstating the potential for deployment and create a dangerous gap between the decarbonization pathways proposed and the real world of project development. This, in turn, leads to ill-informed policy targets and inadequate implementation plans.

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By studying and understanding the real risks to the clean energy transition, we can guide decision-makers to develop and implement risk-informed strategies which will increase our chances of successfully achieving Net Zero by 2050. By considering their advantages in the context of their risks, each of the zero-carbon energy technologies can contribute in a different way to achieving large-scale rapid decarbonization. This new way of modeling will enable us to reduce the likelihood of failing to decarbonize by creating a portfolio of solutions that do not all share the same risks. A renewables new build strategy complemented with a strategy that repurposes existing coal plants and other energy-intensive infrastructure with emissions-free power, heat, and steam will enable large-scale clean energy supply while hedging the risks of public opposition to renewable greenfield projects, which also require new interconnections, and extensive transmission buildout.

Land

There is a fundamental mismatch between what we consider available land for power projects in energy transition models and what is considered developable land by project developers. In these mainstream models all 'available land' is presumed to be 'developable', when in fact much of that land is not attractive or amenable to project development, and where it is, few of the projects ultimately make it to operation. As shown in **Figure 1**, the project development process begins once all practically available land is identified (i.e., site assessment). Several critical milestones – which are not currently factored into mainstream energy transition models – need to be achieved before a project is built, and each milestone has several associated risk factors. Any one of these risk factors can cause a project to fail. For jurisdictions with poor wind and solar resources that plan on decarbonizing with renewables and green hydrogen, it is important to note how much land will be needed, and how difficult it will be to secure rights to the land (or sea) and successfully develop enough capacity for economy-wide decarbonization.

For example, **Figure 2**, showing two maps, represents in colored outlines the total area that would be required for each energy resource if used to generate enough hydrogen to supply current oil consumption in the UK and Japan, respectively.

The UK is a high-income country with high energy use per capita and high population density. The area required to supply the UK's current oil consumption with hydrogen from solar would be 26,090 km^2. To produce the same amount of hydrogen instead with offshore wind would require an area of 136,120 km^2 – which would take up most of the North Sea. The pink outline shows the size of a single continuous wind farm to produce this much hydrogen. If the UK were to produce the same amount of hydrogen for liquid fuels substitution using Gigafactories or production platforms with advanced heat sources, the land area required is dramatically smaller – only 55 km^2 – illustrated by the barely visible green shape.

Japan is a particularly striking example as it is mountainous and densely populated, with very little land available for the large solar farms that would be

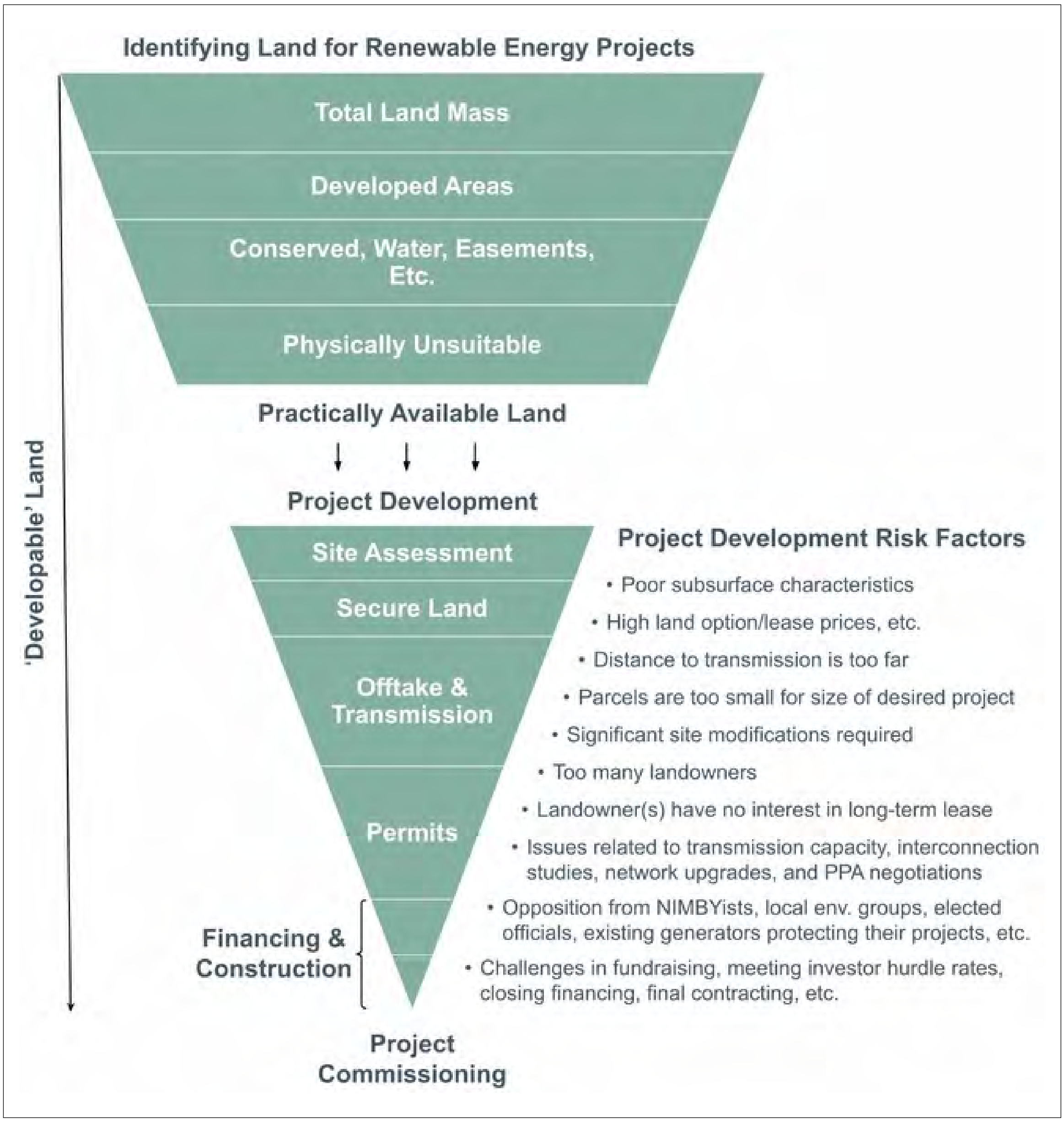

Fig. 1
Project Development Risk Factors.

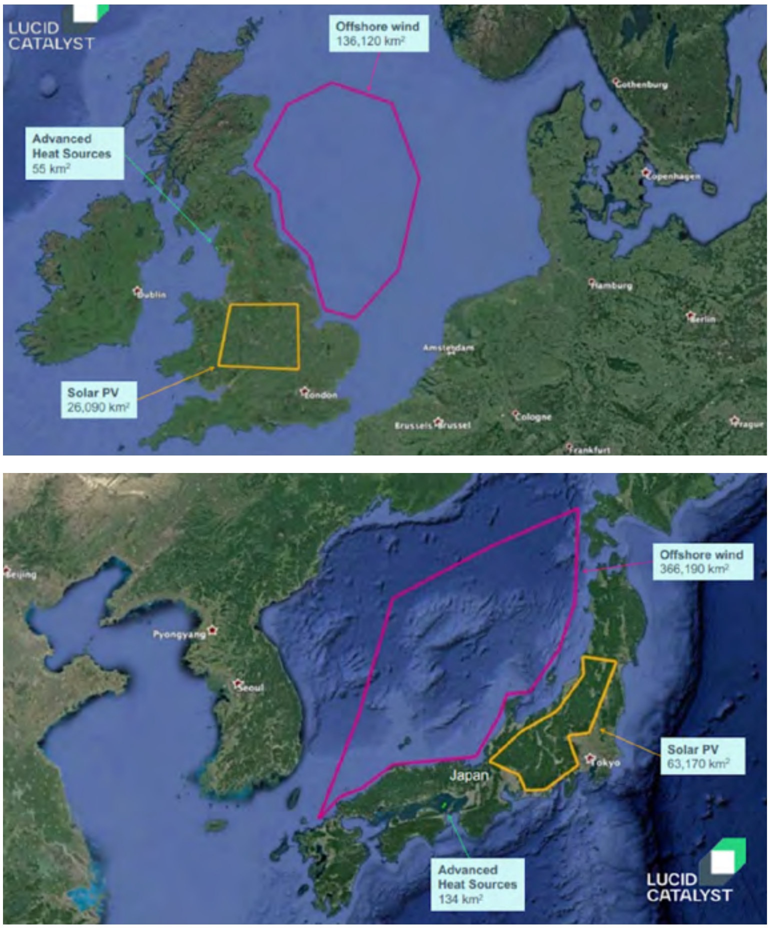

Fig. 2
Area that would be required to supply UK's (top) and Japan's (bottom) current oil consumption with hydrogen from wind, solar, or advanced heat sources.

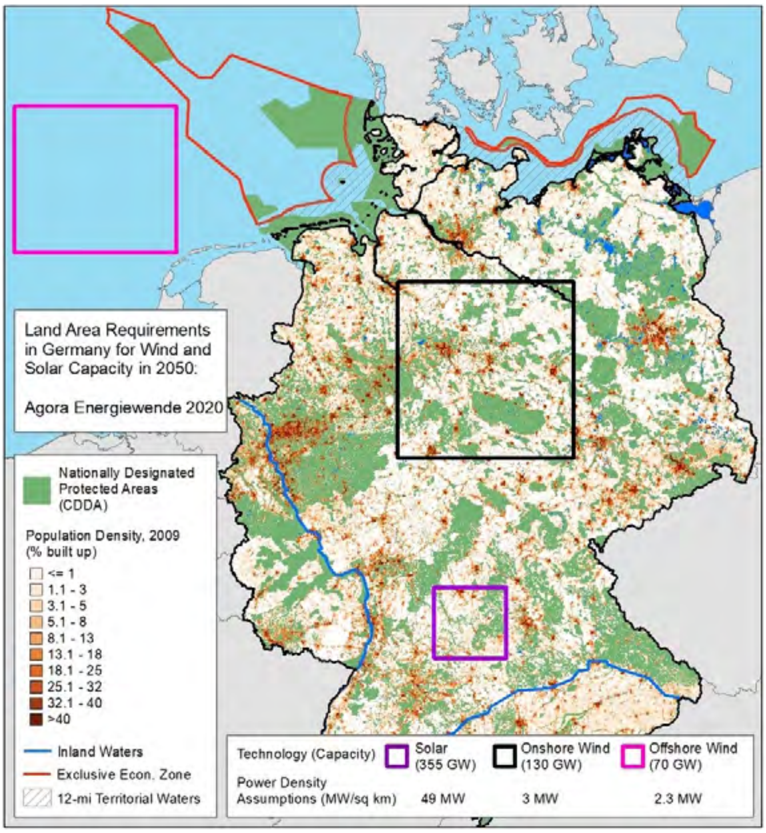

Fig. 3
Land area requirement for solar and wind power in Germany in 2050 in relation to protected areas and population density.

required for solar-generated hydrogen and similar geographic constraints facing onshore wind.

As **Figure 3** shows, the solar task is simply not viable – the area required for the 63,170 km² projects to supply the solar-generated hydrogen equivalent to Japan's current consumption of oil-based liquid fuels does not appear feasible. Japan's offshore wind resources are limited by the extent of the shallow continental shelf. Even floating offshore wind turbines must be anchored to the seabed, so water thousands of meters deep will never be suitable.

Figure 3 reflects modeling outputs from a 2020 Agora Energiewende study of land requirements in Germany for solar, onshore wind, and off shore wind, in relation to nationally designated protected areas and population density.

We do not map a projection for global comparisons, because in practice the hydrogen production locations would be in multiple locations. We have to assume that if countries are planning massive investments in clean energy that they will want – as far as possible – to control those investments. However, the numbers are striking. For example, if solar PV were to replace all global oil using hydrogen, 770,900 km² – an area similar to the size of Turkey – would have to be covered with solar panels. If offshore wind were to replace global oil with hydrogen, an even larger area of 8,380,000 km² would be required – about the size of Brazil (8,460,000 km²). If the production platforms described in this report, powered by advanced heat sources, were to do the same job – only 3,414 km² would be needed, equal to a square of 58 kilometers per side.

Transmission

Transmission fundamentally governs power project development. Without available capacity to interconnect a project, developers will not invest in development. Transmission must be built first, and due to the need to obtain approvals across multiple geographical and governmental jurisdictions, building transmission typically takes much longer than power projects.

This makes transmission development a risky endeavor. Further, because of lower capacity factors, transmission dedicated to wind and solar is substantially more expensive on a per unit energy basis: approximately twice as much will be required per TWh of wind, and approximately four times as much per TWh of grid scale solar. If enough transmission cannot be built in a timely manner (i.e., at an unprecedented rate), there simply is no practical path to delivering enough clean energy for pathways that depend on these resources.

Public Support/Opposition

Public opposition to renewable power projects is becoming better organized and more frequent. For example, **Figure 4** shows the growth of public opposition to wind energy development in Iowa over time. A growing proportion of opposition is being led by the environmental and conservation communities and others interested in protecting an area's rural character and/or viewshed. Public opposition tends to increase as more projects are deployed in a given area. It will also play a critical role in the build out of transmission as well.

Escalation of Non-Hardware Project Costs & Risks

Fortunately, solar and wind hardware costs have enjoyed a remarkable decline over the past decade. However, it is likely that non-hardware project costs and risks will escalate as more projects are developed in a given area. In addition, increased project development costs and risks must be paid with project developers' risk capital, which is more expensive and harder to raise than the low-cost capital that models assume will provide the long-term financing for projects.

Project developers typically look for factors like low land cost, large parcels in close proximity to planned or existing transmission, landowners who are willing to sign long-term land leases, good solar or wind resources, the need for few right-of-way approvals to interconnect the project, clear public support,

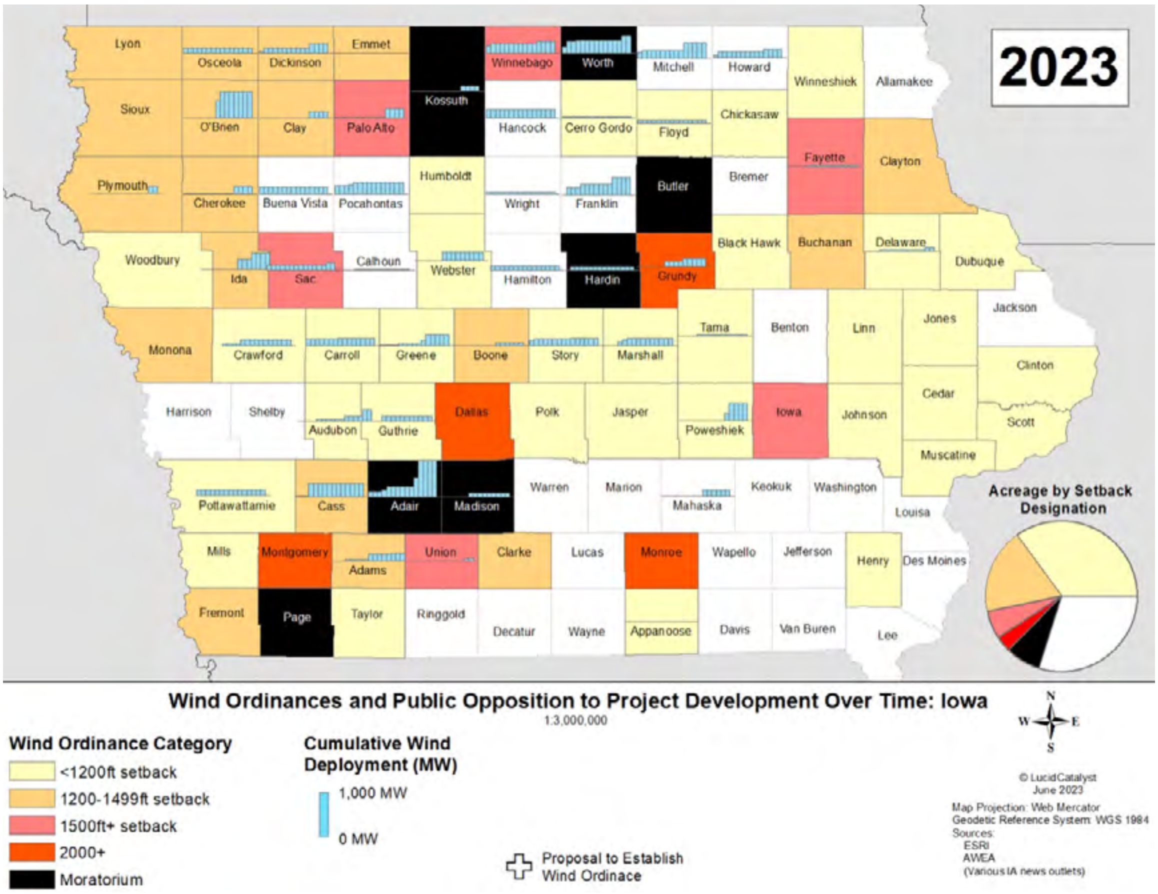

Fig. 4
Wind Ordinances, Public Opposition and Cumulative Wind Deployment in Iowa.

favorable energy market environment, etc. Nearly all these essential developer criteria get worse as more projects are deployed in an area.

As more land is converted for projects, land costs increase, projects are pushed further from transmission, project capacity factors get worse (as the good sites are taken), the public is less supportive, etc. All these conditions occur simultaneously, compounding project risk and thus cost. Energy models often show increasing deployment over time, as in a 'hockey stick' growth curve. The real factors that affect large-scale project deployment suggest that an 'S-curve' (as shown in **Figure 5**), is more likely.

Timing & Logistics

The sequencing and time-sensitivity of the massive, simultaneous infrastructure build out in every country that is required for decarbonization presents an unprecedented logistical challenge. The challenge is not only to build enough infrastructure for clean electricity generation, but to also build the infrastructure needed to electrify other sectors such as heat and transport.

Most potential projects do not make it all the way through the project development process, which means that commissioning a gigawatt of solar requires several gigawatts to reach the late-stage development. This will necessarily require more developers overall, more development capital, and more human resources dedicated to other parts of the process (e.g., permitting, interconnection studies, engineers, financiers, etc.).

2050 decarbonization targets. Advocates for these strategies point to this shortfall and say we need to redouble our efforts. But it would be prudent to consider how the current sluggish levels of deployment may actually be evidence of how difficult large-scale renewables deployment is becoming even though we are just at the beginning of the build-up needed for the energy transition. If it is difficult now, at the beginning, it is only going to get more difficult due to the best sites being taken already, lack of transmission, escalation of development risks and cost, and growing public opposition.

The magnitude of the project development challenges requires energy models that expand beyond simple cost optimization to represent and advance feasible solutions and drive policy and investment in large-scale decarbonization.

Terra Praxis is designing a system that will enable the rapid repurposing of coal plant fleets with non-emitting advanced heat sources. This will allow for the continued operation of a sizable portion of existing power plants – without emissions. Repowering coal plants leverages existing sites, infrastructure, transmission lines, industry knowledge, workforces, capital, and supply chains to accelerate the clean energy transition. It also ensures continuity for communities reliant on existing power plants for energy, jobs, tax revenue, and continued economic development.

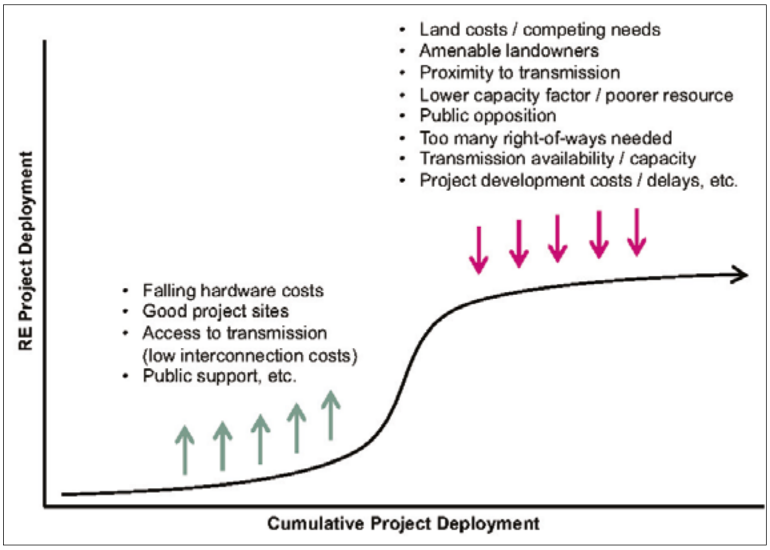

Fig. 5
The project development S-curve.

Beyond the Power Sector

Seventy-five percent of primary energy use is outside the power sector (e.g., data centers, steel, cement, aviation, marine shipping). The amount of generation capacity required to develop emissions-free substitute fuels and to decarbonize other carbon-intensive sectors of the economy will require a staggering amount of emissions-free energy.

The scale of investment required, necessary deployment rates, willingness of the public to bear these costs, and available land for development are major hurdles to the energy transition. In many locations, deployment rates for renewables are far below what is necessary to achieve renewables-intensive

Coal Power: One-Third of Global Emissions

As of 2022, the world has more than 2 terawatts (TWe) of coal-fired electric power plants, adding roughly 12 gigatonnes (Gt) of CO_2 emissions per year. These annual emissions amount to almost one-third of global total forecast net annual emissions of 38.8 gigatonnes/year. Despite international agreements reached at COP26 (The UN Climate Change Conference) in Glasgow in 2021 to "phase out" coal use, CO_2 from coal combustion hit a record high in 2022. European countries reactivated coal plants due to the worldwide energy crisis, reversing years of climate legislation intended to shut them down. Asian and African countries continue to build new coal plants to meet growing demand from increasing populations, rising standards of living, and industrialization.

Some policy makers, climate modelers, and activists incorrectly assume that countries will simply shut down their coal plants to reduce carbon emissions. But, because more than half of coal plants worldwide are less than 14 years old, it is unrealistic to expect such young assets to simply retire, especially considering growing energy demand and supply shortages. Even where there are relatively old coal plants, such as in the U.S., Canada, and Europe, closing coal plants is difficult and controversial because the loss of jobs and revenues can be devastating for communities, and utilities continue to value the reliable electricity generated. These challenges create strong political and cultural opposition to the conventional climate agenda, especially in developing countries.

Repowering Coal: A New Path

In Wyoming, the largest producer of coal in the U.S., Bill Gates's advanced reactor company, TerraPower, announced plans to build its Natrium reactor near the retiring Naughton coal plant in Kemmerer. The U.S. Department of Energy plans to invest nearly $2 billion to support the licensing, construction, and demonstration of this first-of-a-kind reactor by 2028. By locating the Natrium reactor near the retiring Naughton coal plant, TerraPower can not only take advantage of the existing energy infrastructure that is in place (such as cooling water and transmission), but also the workforce. While this project in Wyoming is a welcome step and an important signal of the demand for such solutions, we need a strategy that will enable the rapid repowering of all coal plants. To work, that strategy must be fast, cheap, minimize construction risk and enable the participation of a much broader range of suppliers and constructors.

The Opportunity: Converting Coal Power Plant Fleets to Emissions-Free Generators

Repowering existing coal plant infrastructure is the largest single carbon abatement opportunity on the planet. By replacing coal-fired boilers at existing coal plants with carbon-free small modular reactors (SMRs), also known as advanced heat sources, these power plants can generate carbon-free electricity, rather than carbon-intensive electricity. This would quickly transform coal-fired power plants from polluting liabilities facing an uncertain future, into jewels of the new clean energy system transition – an important part of the massive and pressing infrastructure buildout needed to address climate change.

This would also enable a just transition by sustaining the jobs and community tax revenues associated with existing coal plants; the larger social, economic and environmental benefits associated with continued reliable and flexible electricity generation; and the continued use of existing transmission lines – without emissions. Repowering coal fleets therefore offers a fast, large-scale, low-risk, and equitable contribution to decarbonizing the world's power generation. Converting 5,000 – 7,000 coal plant units globally between 2025 and 2050 (250 – 350 per year) will require a redesigned delivery model to achieve this rate of deployment. To be successful, the deployment model has to de-risk the construction process: the riskiest part of a project. To successfully de-risk, we must provide coal plant owners and investors with high-certainty schedules and budgets. To this end, a standardized product delivery and deployment system, with purpose-built automated tools, can achieve rapid, repeatable, and confident project assessments, delivery, and deployment.

The Global REPOWER Consortium

To achieve this vision, Terra Praxis has assembled a world-class consortium of partners, governments, regulators, academics, and industry stakeholders – to design a fast, low-cost, and repeatable project delivery model for repowering 2,400 coal plants worldwide. The global REPOWER consortium has already attracted some of the world's largest and most innovative global leaders in the critical disciplines required for success.

Repowering Coal will deliver a substantial portion of the clean electricity required to achieve Net Zero by 2050 by replacing coal-fired boilers at existing power plants with advanced heat sources, which are expected to be ready for deployment by 2028. While the companies commercializing the advanced heat sources ready their products for market, the Terra Praxis REPOWER consortium will develop standardized, pre-licensed designs supported by automated project development and design tools to enable hundreds of customers to be ready to start construction on their projects in the late 2020s. The result of this

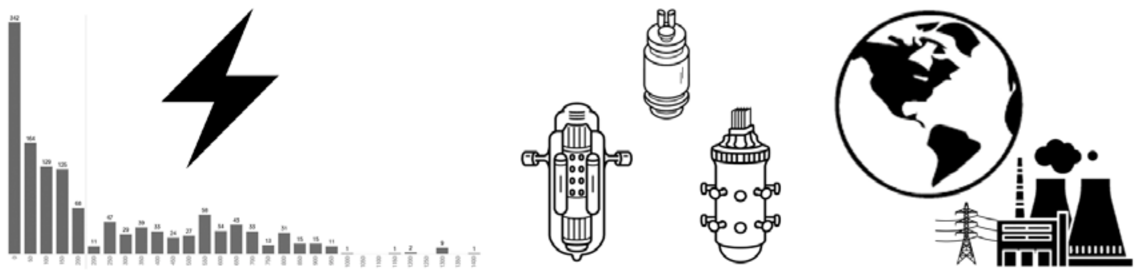

Fig. 6
Challenges to standardization of repowering systems.

repowering will be carbon-free power plants that are cheaper to operate than before, and to ensure continuity for communities reliant on these plants for energy, jobs, and continued economic development.

Design Innovations to Enable Standardization

The Terra Praxis REPOWER system is designed to be broadly applicable, because coal-fired power stations come in a wide variety of sizes and configurations. Further, there are multiple potential vendors of advanced heat sources, resulting in a wide variety of requirements for repowering **(Figure 6)**:

- Different inlet mass flow, pressure, and temperature requirements for the existing steam turbines.
- Different advanced heat source technologies as potential repowering options and their associated systems.
- Different site layouts and local requirements.

The combination of these factors would typically result in the requirement for a bespoke design for each new project, with the costs, regulatory review uncertainties, and risks to budget and schedule that will prevent most projects from moving forward. The REPOWER system embraces key design innovations to enable standardization while accommodating coal fleet diversity. These include standardized product design and supporting systems across multiple heat source vendors, a 'universal connector' heat transfer and storage system, and seismic isolation **(Figure 7)**.

Standardized Product Design

The standardized product design enables the plant to be reconfigured and expanded to accommodate different numbers of advanced heat sources while staying within its pre-approved regulatory envelope.

Standardized Supporting Systems

Standardization also addresses the differing requirements of a range of advanced heat sources, so they can be housed in the standardized building, and connected to steam generators using a standardized heat transfer system. The building-integrated reactor system can be configured to meet requirements for a variety of site layouts, energy and heat demands.

Heat Transfer and Storage System

In addition to building standardization, standardization is further leveraged by sharing the system architecture choice of delivering heat from the advanced heat source to the steam boiler using molten salt as the heat transfer fluid. These standardized design elements provide an adaptation-point, where standard components can be connected to existing plants. This system allows the new modular reactor systems to 'plug in' to existing coal plant infrastructure. This standardization and reduction in design work enables a higher volume manufacturing model for all aspects of the plant and delivers radical cost reduction. Reusing the power island and other infrastructure from the existing plant avoids those costs.

Seismic Isolation

Seismic variation usually drives the site-specific design of nuclear plants, representing a major cost driver and making standardization impossible. Redesign increases design engineering costs and requires new regulatory approval each time, increasing cost and schedule uncertainty. These dynamics are studied by Professor Andrew Whittaker at the University at Buffalo, a global expert on nuclear plant seismic isolation. His research finds that separating the reactor building from the building's foundation via seismic isolation can allow for a reusable building design. This allows the same building to be reused at multiple sites of varying seismic risk. Site-to-site seismic variation can then be addressed by these seismic isolation components.

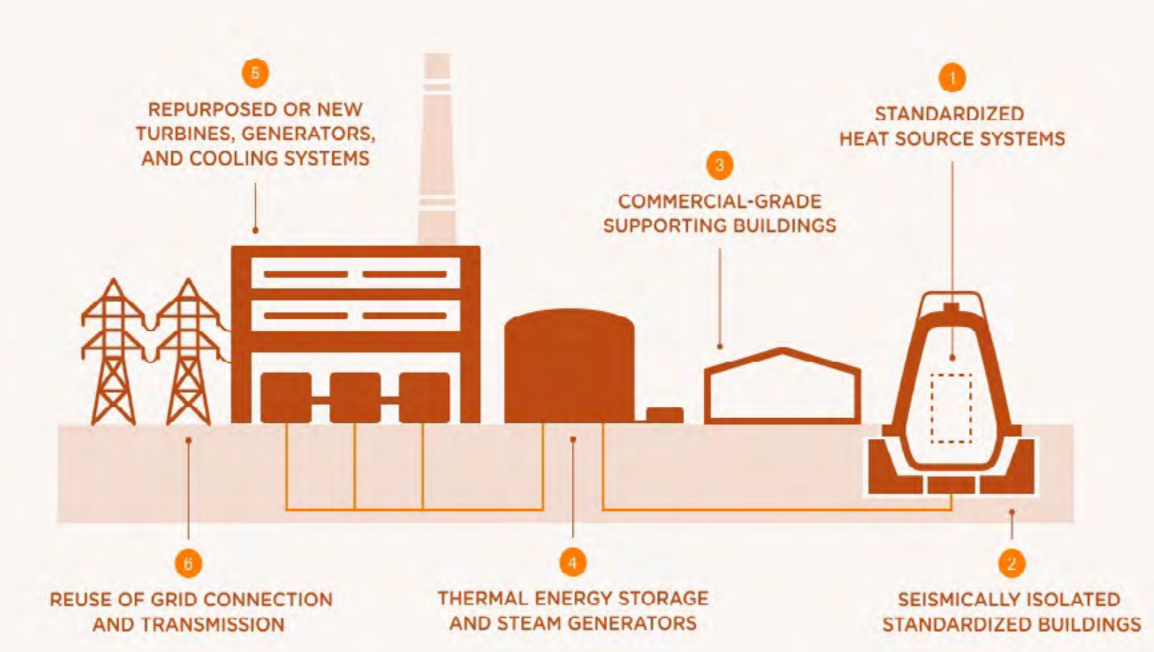

Fig. 7
REPOWER system graphic

Professor Whittaker is leading the seismic isolation system design with the goal of facilitating standardization. Whittaker's work will enable the plant to be designed for a range of seismic conditions and licensed once, allowing a rapid roll-out across a wide range of sites.

Digital Fastlanes

The sequencing and urgency of the massive, simultaneous infrastructure build-out in every country presents an unprecedented logistical challenge. Permitting and pre-development activities are outdated, bespoke, expensive, and slow; the high uncertainty around costs and schedule curtails significant investment and cannot achieve climate timescales. The REPOWER Consortium is developing digital solutions for swift and cost-effective licensing, permitting, and fleet-wide feasibility studies to lower development risk and stimulate investment. Simplified siting, licensing, and feasibility studies will enable a pipeline of hundreds of heat boxes to be ready for deployment in the 2030 timeframe.

Standardization Means Reduced Cost, Time, and Risk

The REPOWER system cost target is $2,000/kWe. This can be achieved through key design and delivery innovations. This includes: reuse of the existing power island; a standardized completed design, which eliminates hundreds of millions of dollars of design engineering each time; standardized licensing applications; a standardized product approach which radically lowers construction complexity, duration, and supervision requirements; and a manufacturing-based supply chain, enabling highly productive use of labor and multiple suppliers for all components.

The REPOWER target schedule is 5 years. By starting with a completed and licensed standardized design, a REPOWER project can be rapidly adapted to meet plant and site requirements. REPOWER customers will have access to automated design tools to eliminate years of design engineering work in a typical project. Site licensing and permitting is reduced by template-based standardized applications. Construction schedule is greatly reduced and simplified by the standardized product and delivery approach, which is designed for high quality manufacture and rapid assembly onsite.

All projects have risks, but attractive projects have low, well-defined risks, with well-understood and effective ways of managing the remaining risk. The global REPOWER consortium is focused on eliminating and reducing risks by design and using best practices from other industries.

Summary

Modeling needs to include feasibility, or else we are set up for failure. Land availability and public acceptance are only likely to get more difficult – and we need to at least triple generation and transmission capacity in the next 27 years. Resource availability in models should be based on real developable land, including physical conditions, restrictions, and other factors that drive availability for the front end of the development process. The time required to develop power projects and transmission projects needs to be accurately modeled, and the fact that investments in power project development will not start until transmission exists should be a requirement for all models.

It is highly likely that building clean power projects will become increasingly risky in the 2030s and further into the 2040s. This could lead to a situation where we have gone 'all in' on pathways that require very extensive deployment of new greenfield projects, but we are stalled long before we reach the required new clean supply. Therefore, we need energy transition strategies that support the deployment of technologies with high power density, capacity factor, and reliability, and that do not have the same constraints and risks.

In order to achieve decarbonization goals, the energy transition must leverage as much of the existing infrastructure as possible. Advanced heat sources – advanced fission, fusion, and geothermal – can be used to repower coal plant facilities and other energy- intensive infrastructure, requiring far less incremental transmission, land use, and interstate connectivity. Given the likelihood that we are living in the 'transmission constrained scenario,' we need to invest aggressively in decarbonization pathways that make optimal use of precious existing sites already connected to the grid.

The REPOWER system is a fast, low-cost, and repeatable strategy to repower hundreds of existing coal plants that would otherwise continue to burn coal, or whose closure would cause economic harm to communities. By sustaining permanent high-quality jobs for communities, repowered coal plants reduce the negative impacts on communities to help enable public and political support for a just transition. The challenge is not only to build enough clean electricity generation to power the world, but to do so quickly. Repowering is a way to accelerate and de-risk global decarbonization.

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Eric is a strategic advisor and entrepreneur with deep experience in the commercialization of new energy technologies. He has extensive project and policy experience in renewables, energy storage, oil & gas, and nuclear, with a special emphasis on advanced nuclear technologies. Eric develops commercialization and market entry strategies for advanced energy technologies such as advanced nuclear power generation, carbon capture, and zero-carbon liquid fuels. Eric was a member of the renewable energy advisory group of the National Commission on Energy Policy (NCEP), and was honored at the Obama White House as a Champion of Change in Renewable Energy.

TERRA PRAXIS

Terra Praxis is a non-profit organization that exists to de-risk the energy transition. Powered by philanthropy, Terra Praxis is innovating transformative climate change solutions for the difficult-to-decarbonize sectors of coal-for-power, industrial heat, and heavy transport. Terra Praxis shines a light on risks to the global energy transition that threaten the deployment of clean energy at speed and scale and designs and innovates scalable solutions in response to these challenges. The organization leads engagement with key stakeholders to diversify and expand the range of tools available for deep decarbonization. Kirsty Gogan and Eric Ingersoll are Founding Directors and Co-CEOs.