

CLIMATE SOLUTION PROFILE / REPOWERING THE GLOBAL COAL FLEET BY 2050

MARCH 2022

THE CHALLENGE

As of 2022, the world has more than 2 terawatts (TWe) of coal-fired electric power plants, adding roughly 12 gigatonnes of CO₂ emissions per year (Figure 1).¹ These annual emissions amount to almost one-third of global total forecast net annual emissions of 38.8 gigatonnes/year.²

Some policy makers, climate modelers and activists assume that countries will simply shut down their coal plants to reduce carbon emissions. However, 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 in countries with relatively old coal plants, such as 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.

For example, Wyoming is the largest producer of coal in the U.S. Roughly 80% of the state's electricity production comes from coal-fired power plants that have been steadily declining in terms of their output, but also closing down, since the mid-2000s.

In 2019, PacifiCorp, Wyoming's largest utility, announced it would reduce its coal fleet by two-thirds by 2030; local economists project that this will lead to a loss of approximately 1,600 coal jobs over the next decade. In addition to job losses,

these closures will directly impact the communities around these plants; they will lose millions in state and local tax revenues that help pay for public schools and infrastructure projects.³

Further, existing coal-fired power plants potentially offer enormous value by virtue of their grid connections, cooling water access, real estate holdings, experienced site personnel, and established role in ensuring system reliability. In Wyoming, Bill Gates's advanced reactor company, TerraPower, recently announced plans to build its Sodium 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 Sodium 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.

Achieving Net Zero carbon emissions over the next 28 years will require a massive, simultaneous, and international infrastructure buildout. It is an unprecedented logistical challenge because it needs to happen so quickly.

THE OPPORTUNITY

Repowering existing coal plant infrastructure is the largest single carbon abatement opportunity on the planet and could greatly accelerate the clean energy transition. 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.

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.

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 2030 and 2050 (250 – 350 per year) will require a redesigned delivery model to meet 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, purpose-built automated tools can achieve rapid, repeatable, and confident project assessments. By establishing planning confidence, modern automated tools can facilitate initiation and completion of repowering projects.

The Repowering Coal consortium

To achieve this vision, TerraPraxis, a non-profit organization focused on action for climate and prosperity, has assembled a world-class consortium of partners including Bryden Wood, Microsoft, Massachusetts Institute of Technology (MIT), and University at Buffalo, along with a consortium of global utilities—to launch the Repowering Coal initiative (Figure 2).

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 TerraPraxis Repowering Coal initiative will ready 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.

Figure 1. Global Coal Plant Tracker Map

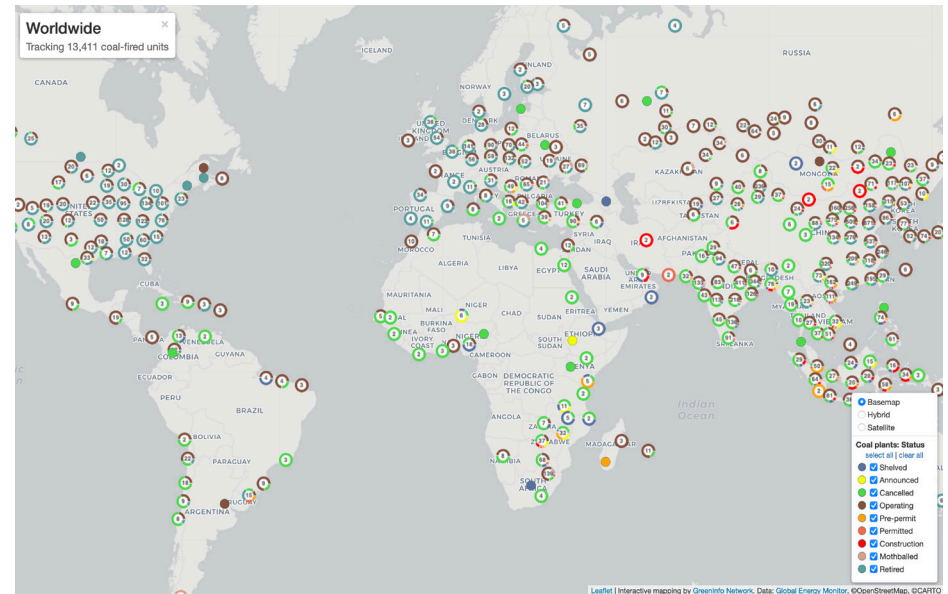
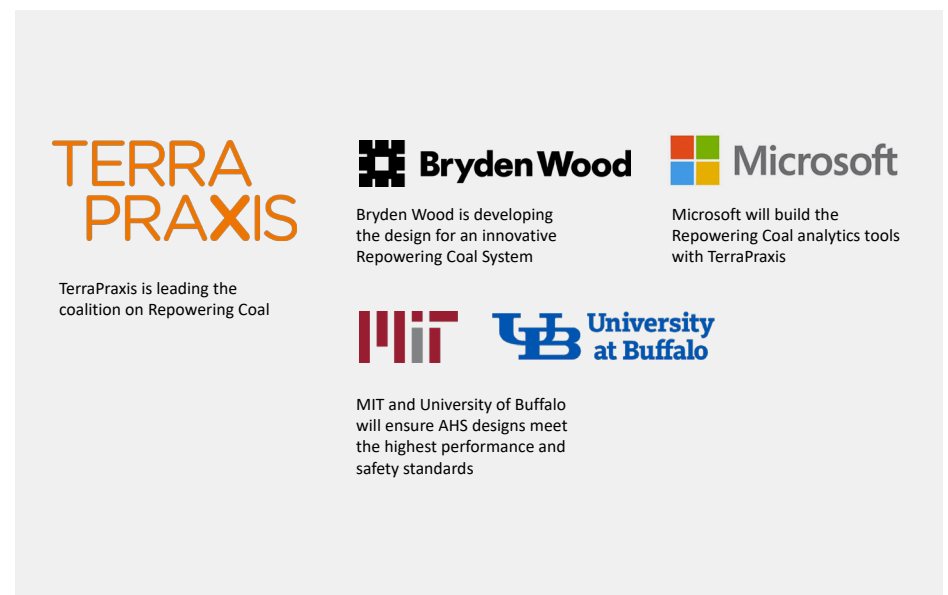


Figure 2. Global consortium of partners



TerraPraxis has engaged Bryden Wood, a global design and engineering firm, to create a new design and construction solution, a key part of the digital platform that will make this possible at the necessary scale and speed.

The result of this 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.

The challenge to standardization

The TerraPraxis Repowering Coal 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 3):

- 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.

DESIGN INNOVATIONS TO ENABLE STANDARDIZATION

The Repowering Coal system embraces key design innovations to enable standardization while accommodating coal fleet diversity. These include seismic isolation, 'kit-of-parts'-based design, standardization of supporting systems across multiple heat source vendors, and a 'universal connector' heat transfer and storage system (Figure 4).

Figure 3. The challenge to standardization

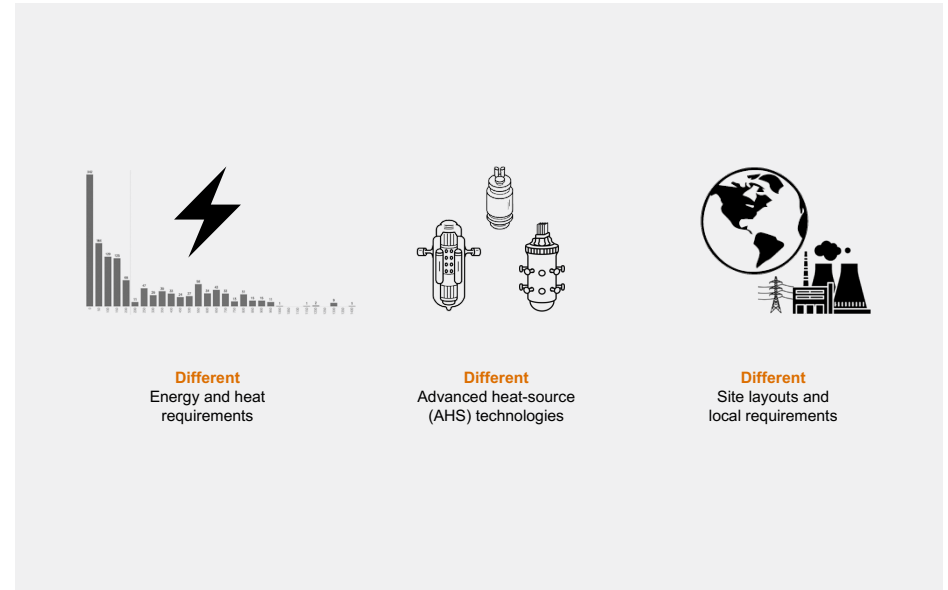
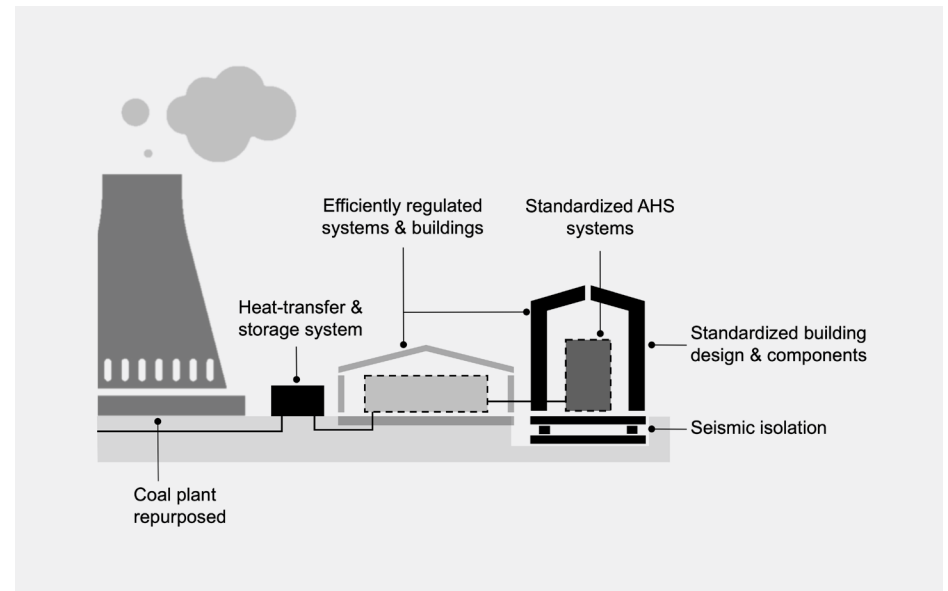


Figure 4. Design innovations to enable standardization



Seismic isolation

Seismic variation usually drives the site-specific design of nuclear plants, representing a major cost driver and making standardization impossible.⁴ 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.⁵ 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. 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 (Figure 5).

'Kit-of-parts'-based design

The 'kit-of-parts'-based 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 (Figure 6).

Figure 5. Seismic isolation to enable standardization

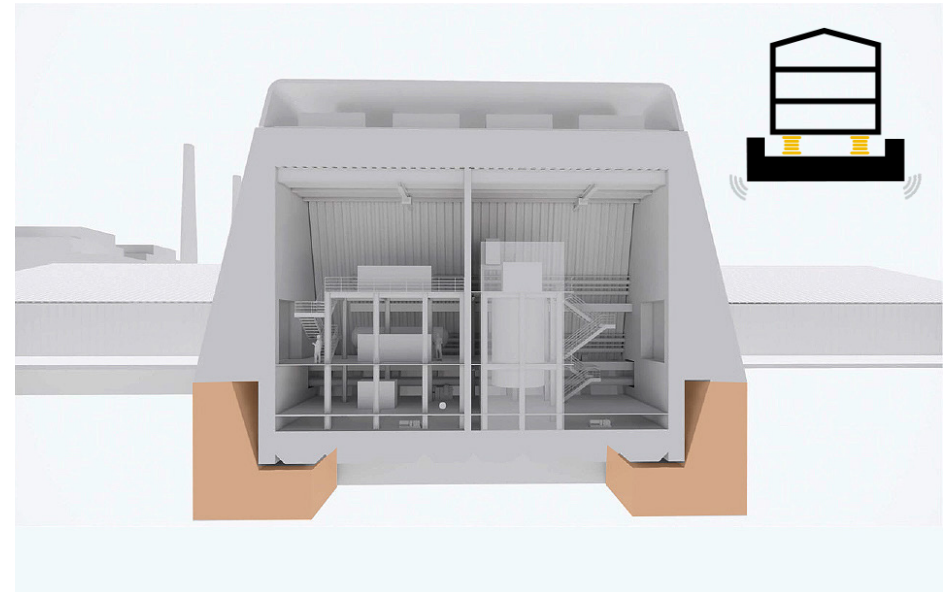


Figure 6. Building system can be reconfigured and expanded to accommodate different types and numbers of advanced heat sources

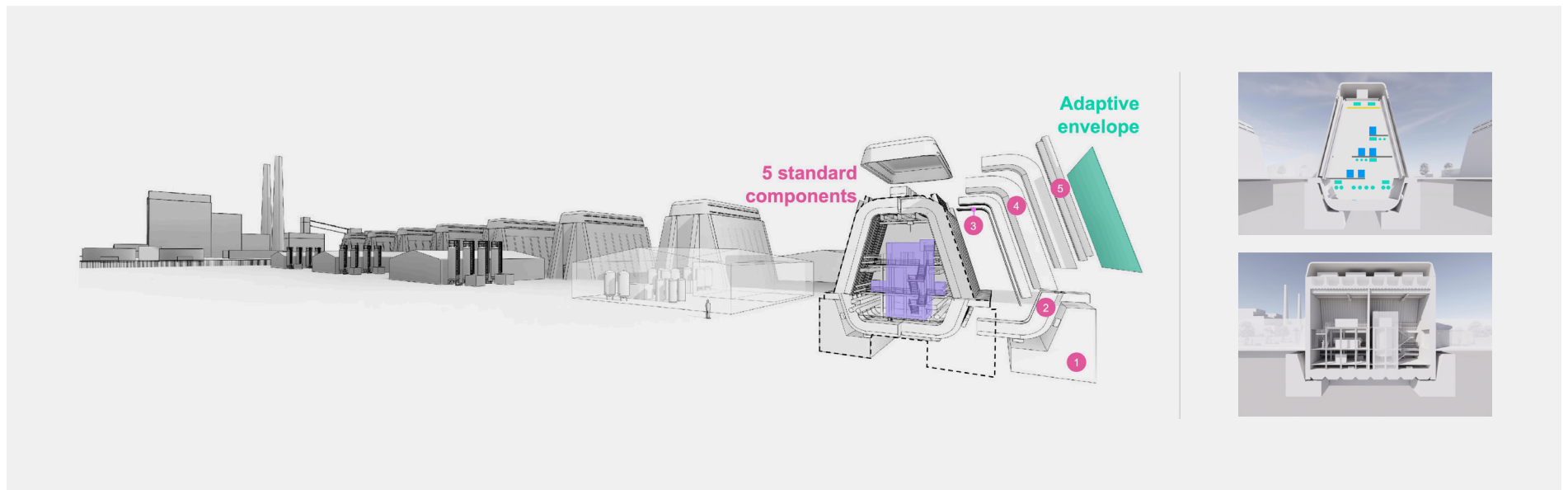


Figure 7. Standardization for a range of advanced heat sources requirements

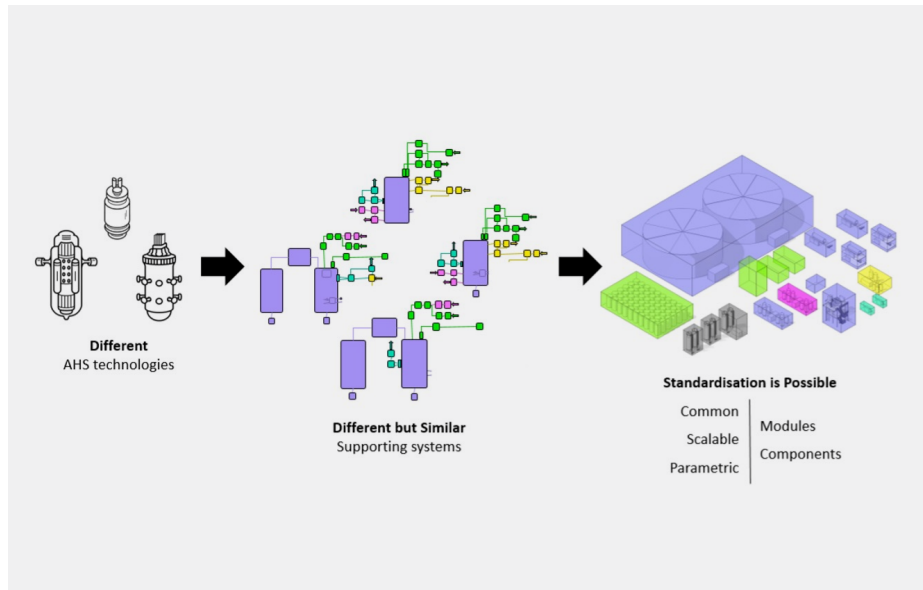
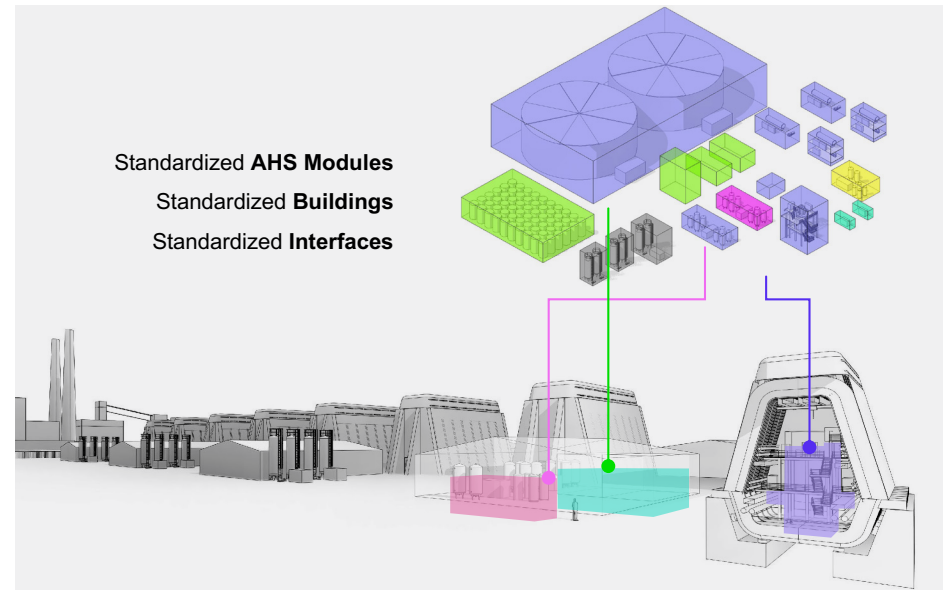


Figure 8. Standardized building system



Standardization of supporting systems

Standardization also addresses the differing requirements of a range of advanced heat sources (Figure 7), 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 (Figure 8).

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 AHS 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; which would otherwise drive site-specific redesign.

Shown in Figure 9 are the storage tanks which are part of a standardized but customizable heat transfer and storage system. 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. Figure 17 shows a site-level view of a repowered plant, and shows an example placement of the heat storage tanks and reactor buildings.

Figure 9. Customizable heat transfer and storage system



A NEW DIGITAL PLATFORM

In addition to innovative building system design strategies, the Repowering Coal consortium is creating new purpose driven digital tools and data exchange infrastructure for the building system to standardize and optimize the following:

- Procurement, investment, and regulatory approval.
- Building and engineering systems.
- Design, manufacture, assembly, and operation.
- Interactions between supply chain organizations increasing collaboration.

Microsoft and TerraPraxis have been working together creating Azure tools to enable automated analysis of the U.S. (and ultimately global) coal fleet for retrofit. Microsoft will build the analytics tools with TerraPraxis, and help undertake strategic partnerships with Repowering Coal consortium stakeholders.⁶

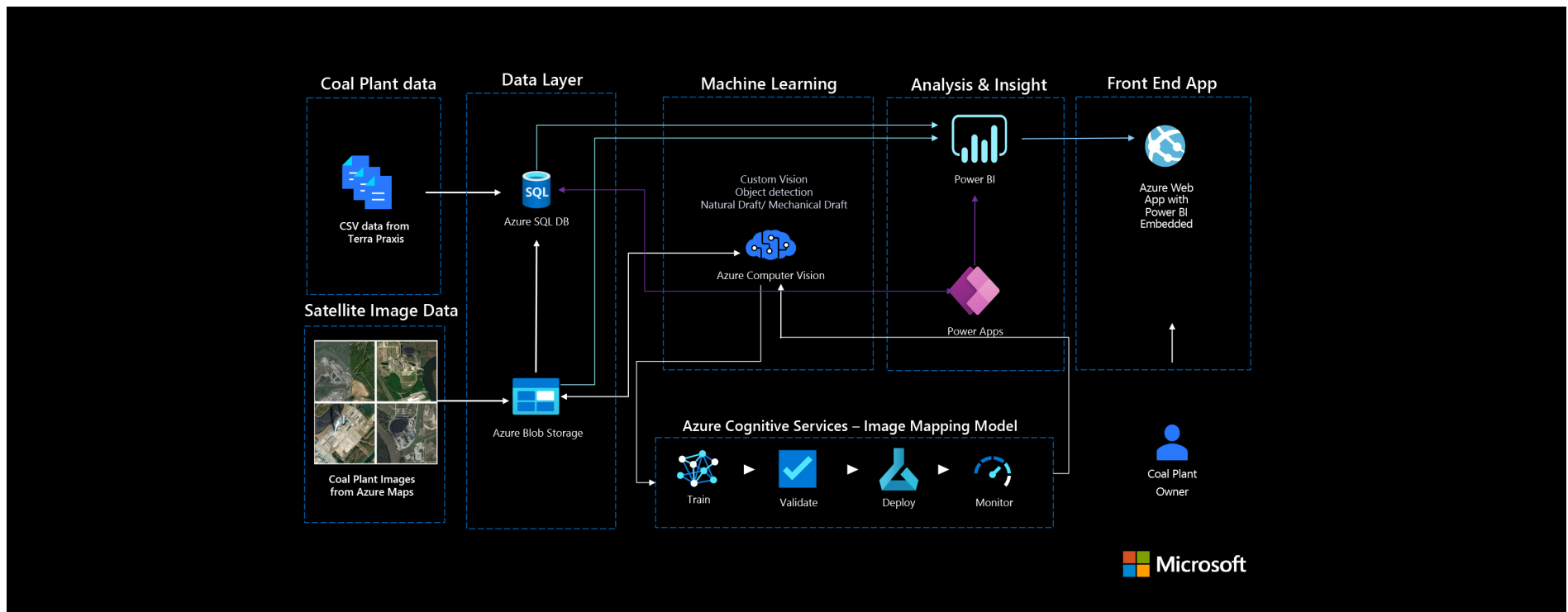
The goal of the analytics tools is to quickly assess repowering design options for a large number of coal power plants. For each of many plants, the tools integrate: plant thermal assessment, steam unit configuration, site assessment, and heat source options; while reusing the existing balance of plant, such as turbines, switchyards, transmission infrastructure, buildings and roads.

A further goal is for the tools to capture and communicate developing design knowledge, allowing all parties to communicate results and status in real time across all projects.

Algorithmic design tools are being created by Bryden Wood to:

- Assess coal plant viability for boiler replacement.
- Create initial concepts using a design configurator in just days.
- Produce detailed design outputs for manufacturing.

Figure 10. Repowering Coal solution architecture and tools integrate myriad services implemented by Microsoft Azure Cloud Computing Services



The design process incorporates an ongoing process for establishing and enhancing a catalog of vetted, mass-produced standard components. Components may be proposed by existing or new manufacturers. Where appropriate, plant elements may be assembled on-site by non-nuclear specialists.

Together, the tools will create a completely open digital platform to which all stakeholders may be granted access and will be able to contribute. For the first time in the nuclear energy sector, there will be a seat at the design table for everyone; from plant owners to regulators, suppliers, AMR vendors, customers, communities, investors and assemblers. Role-based access control will allow for sophisticated configuration and control of data security. Now, for the first time, it will be possible to connect everyone involved in a project through a digital platform and give them access to all the information about their project and create a mechanism for capturing their input at every step of the design and development process.

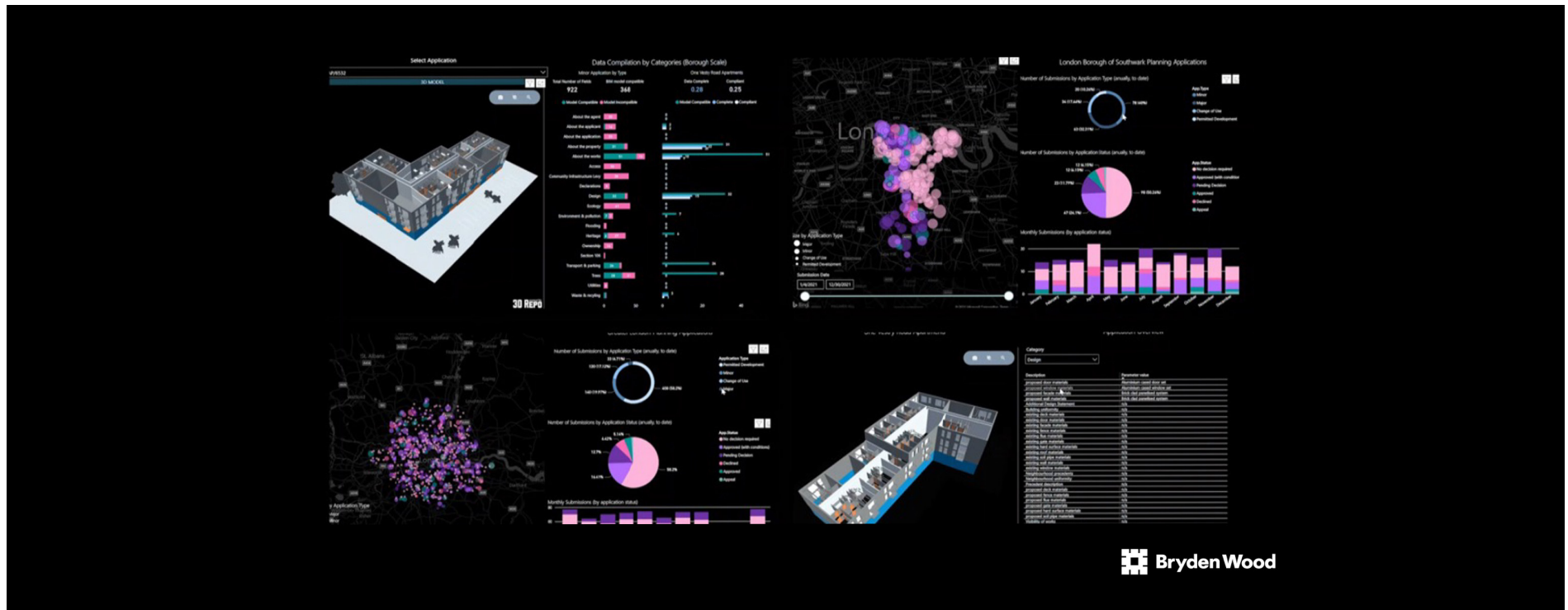
Similar automated site assessment and design tools have been designed and tested by Bryden Wood in other highly complex, highly regulated sectors, such

as pharmaceuticals, highways and data centers (Figure 11). These will be greatly enabled by software engineering and tools development, as well as by the financial model that will enable coal plant owners to evaluate the benefits and value creation opportunities from repowering.

This means that instead of having to spend hundreds of millions of dollars—and potentially years—evaluating the prospects for a single site (making it unlikely to happen at all), the evaluation of a site for repowering will be extremely fast, low-cost, and repeatable. The goal is to have hundreds of sites being assessed by the end of 2022.

The end-product will enable coal plant owners to begin pre-development analysis for their fleets using these tools to evaluate the financial, social and environmental benefits of repowering with a high level of certainty with respect to requirements for budgeting, scheduling, licensing and site development. This, in turn, could make existing coal plants into attractive assets, making it easier for owners and investors to build, maintain and operate them as new clean energy plants across a broad range of markets.

Figure 11. Automated assessment and design tool



Path to market

To be successful, we need more than a good product. We must address barriers to fast, low-cost and scalable repowering, such as untenable pre-development, project delivery, licensing and supply chain costs and risks. All the key stakeholders associated with a repowering project (Figure 13) ought to be at the design table to enable new interactions that leverage the value of the digital tools and the repeatability of the design, in order to overcome these challenges.

Figure 14 shows the range of tools being developed to radically improve the costs, risk profile and timescales for each stakeholder type that will transform project design, licensing, development, and delivery.

As discussed above, the tools will leverage research from consortium members on seismic isolation systems, as well as automated design and project development tools that have been built and demonstrated in other complex, highly regulated industries.

Figure 15 shows how the tools will support customers throughout the project development and delivery process, starting with automated site assessment and design tools, followed by project definition using the automated configurator.

Site-specific design is also greatly accelerated by the ‘kit of parts’ components designed for manufacture and assembly, which include standardized information

Figure 13. Key stakeholders interacting throughout the repowering process

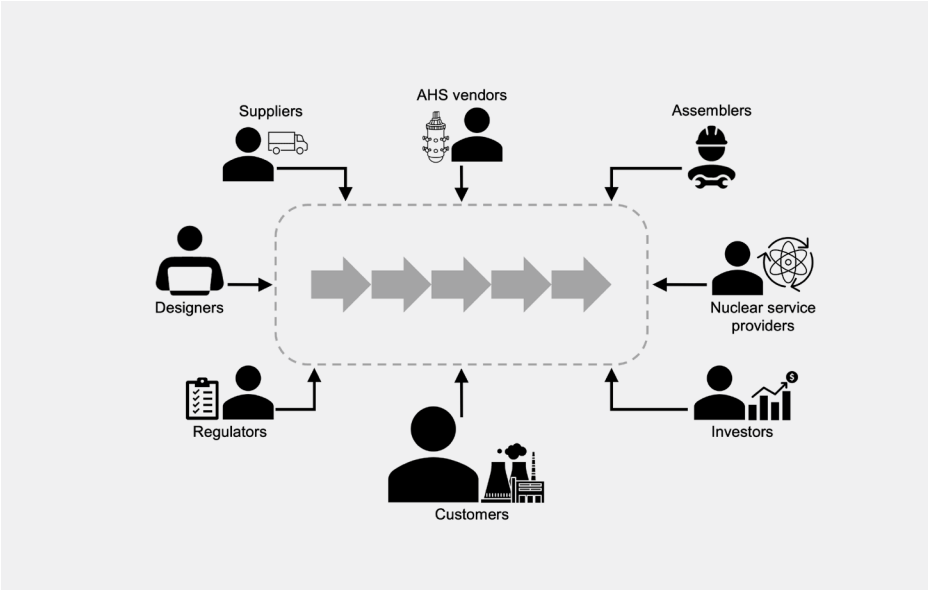


Figure 14. Range of cloud-based tools designed for each stakeholder to interact during the repowering process)

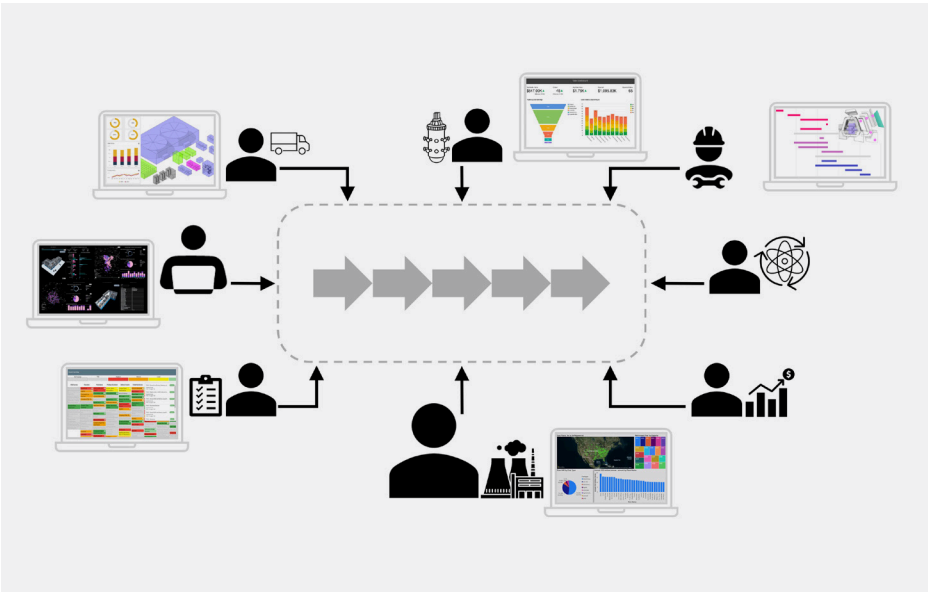
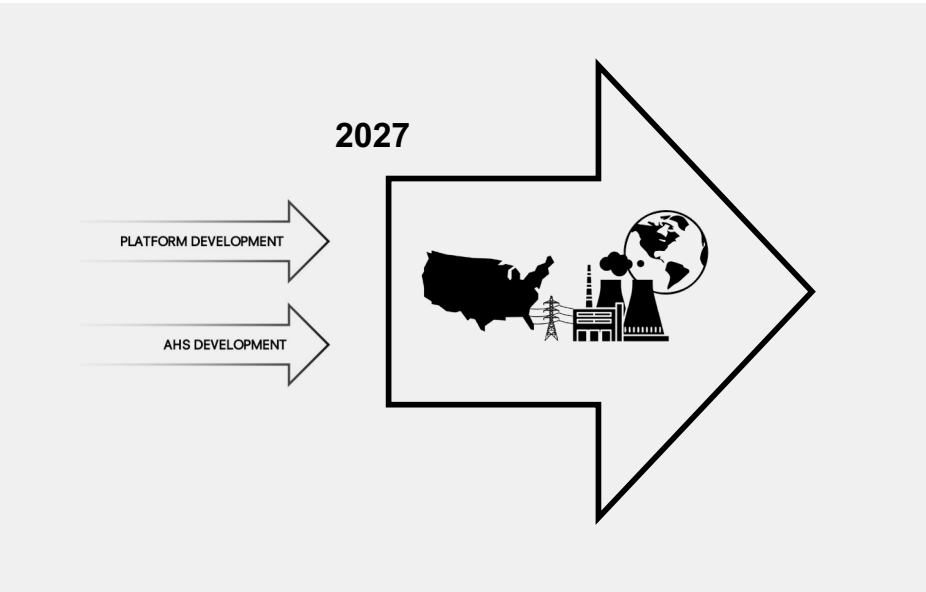


Figure 12. Priming the market for mass deployment



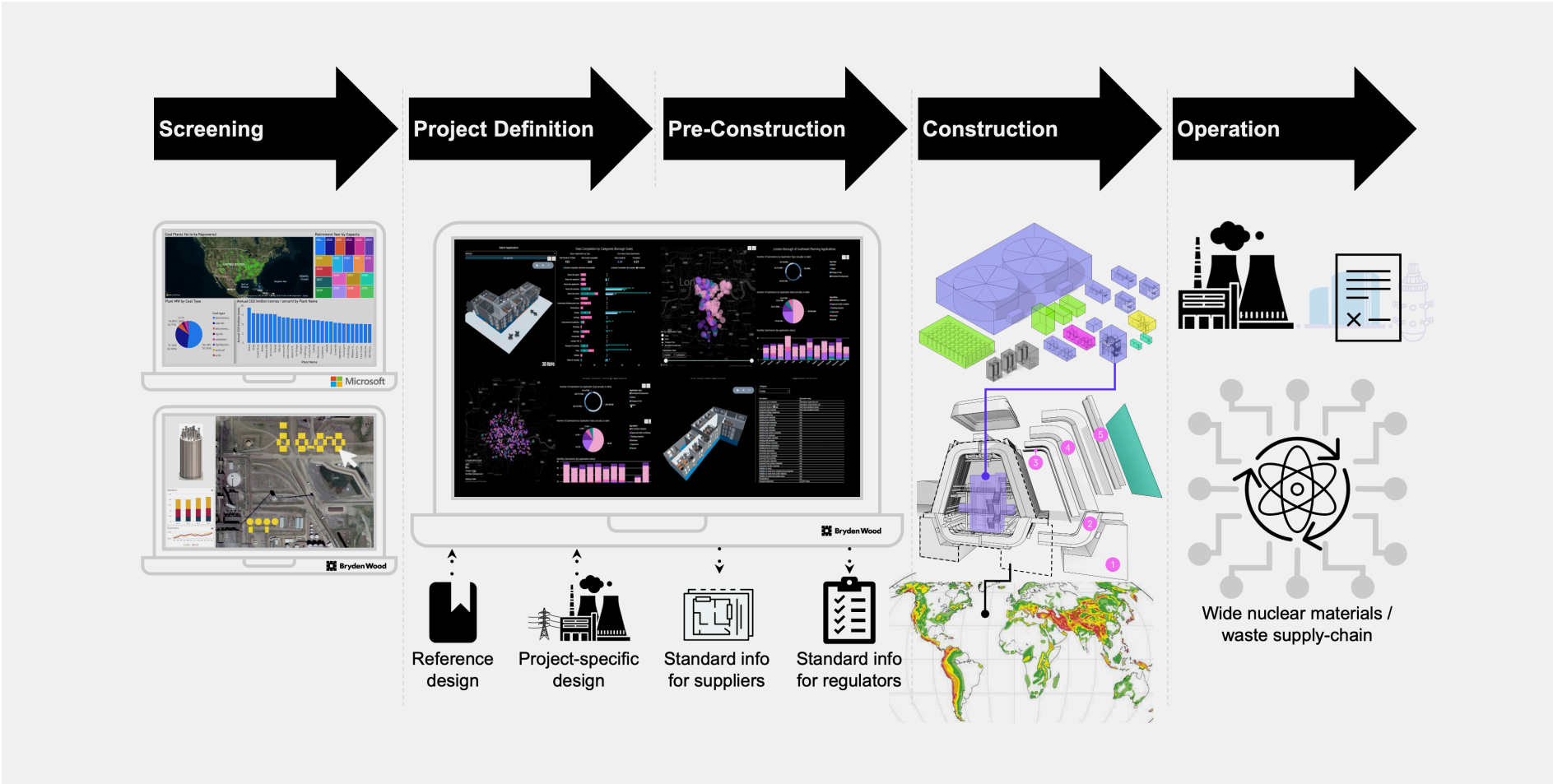
for suppliers, constructors and operators. Regulators can interact with the platform to receive licensing information provided through existing templates and online tools for verification and certifications.

As discussed, standardization is enabled by design innovations, including seismic isolation and heat transfer and storage systems, standardized components, and automated design tools. This will enable accelerated licensing for large markets and low-cost, low-risk investment decisions by investors, coal plant owners, and supply chain.

Even the uncertainty around which advanced heat source to choose is mitigated by the option to choose much later in the process, when these technologies will be further advanced in their commercialization pathways. The target timeline for the development of the core platform of interactions is shown in Figure 16.

Figure 12 illustrates the parallel development of these market-enabling tools alongside the demonstration and commercialization of a range of advanced heat sources. While not all of the advanced heat source developers will be successful in commercializing their product, some will and when they are, these tools will enable mass deployment for maximum climate benefit.

Figure 15. Tools support stakeholder interactions through project delivery



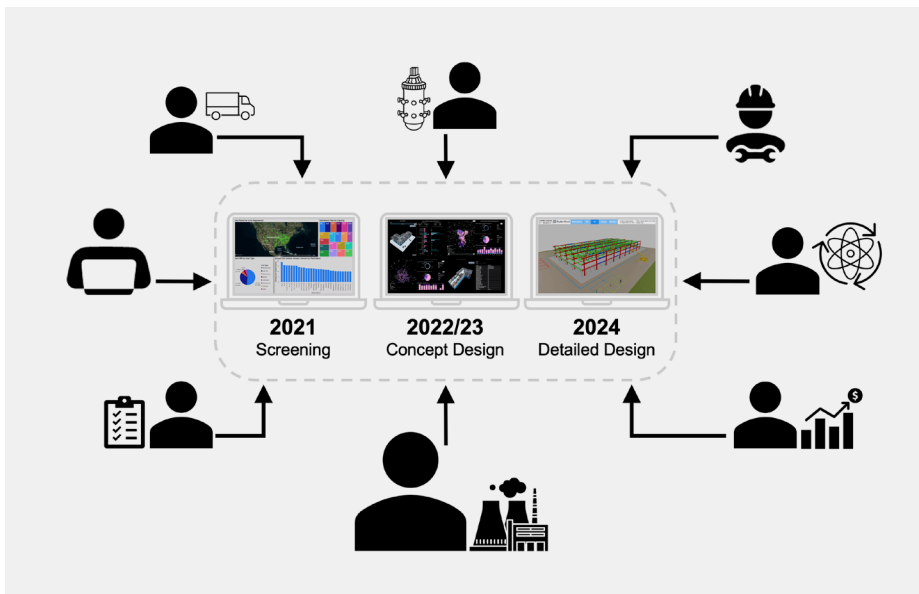
The customers for this product are current and prospective coal plant owners. Our customer advisory group includes Southern Company and the Tennessee Valley Authority (TVA), which together represent 45GW of operating or recently shuttered coal plants in the U.S. Based on strong interest from other utilities, TerraPraxis expects the customer group to be reviewing hundreds of sites globally by the end of 2024.

Product development timeline

The tools will ultimately integrate full preliminary designs, cost estimations and detailed construction schedules, and reflect preliminary inputs from regulators. The team plans to complete the financial site assessment and automated design tool by 2024, which will coincide with the development and testing of a digital licensing process using dozens of real sites and simulated projects. These tools are specifically designed to inform investment decisions (Figure 15).

Starting in 2025, the team will further develop the tool in order to fully automate detailed plant design, integrate project management functionality, and establish supply chain integration interfaces. At that point, the platform will reflect thousands of hours of direct engagement with regulators to develop ‘pre-approved’ design work and a mechanism for digital licensing (Figure 16).

Figure 16. Timeline for product development



Regulatory engagement

The building system is designed to reduce regulatory scope by firstly separating the power island from the heat island via thermal energy storage. This delinks the heat island regulatory safety case from the power island, enabling the continued use of the coal plant balance of plant.

Secondly, advanced heat sources are designed with passive safety systems. This reduces complexity and means that all safety-related systems can be combined in one reactor building. The relatively small reactor building, assembled from pre-fabricated components, therefore becomes the only safety-related building. As part of their initial license review, the regulator will have already reviewed this exact configuration and its associated building designs.

Earning regulatory approval for the standard design elements and achieving rapid, reliably repeatable design automation is fundamental to Repowering Coal, and is applied to licensing also.

The tools will enable a paradigm shift and transformative reduction in cost and time required for regulatory engagement, documentation, approvals and oversight.

The team is already working closely with regulators to define—and design for—requirements for product-based licensing as well as to test and iterate design principles based on regulators’ feedback.

“First, I would like to applaud Kirsty Gogan and Eric Ingersoll on their work around flexible nuclear applications, including heating, hydrogen, and repowering coal plants, with small modular reactors. This kind of ingenuity serves as a reminder: regulators must always be ready for whatever comes our way...we need to know and understand what’s coming.”

Rumina Velshi, President and CEO of the Canadian Nuclear Safety Commission

Intellectual property

Microsoft will assist TerraPraxis in developing the hosted cloud services infrastructure and this will be hosted by TerraPraxis on Microsoft Azure (Figure 14). The tools are designed to expand and support multiway data exchange among all supply chain participants. Data exchange will enable electronic modes of construction management and project delivery.

CONCLUSION

In summary, this paper describes 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.

- Our partners at Bryden Wood are designing a standardized building system, designed for manufacture and assembly, incorporating seismic isolation to eliminate the need for site redesign.
- The building system will be configurable to accommodate a range of advanced heat sources, sites, and power plant requirements.
- The heat transfer and storage system being designed by MIT acts as a versatile USB-style 'plug and play' system for a range of existing power plants.
- The new digital infrastructure being built with Microsoft and hosted on Microsoft Azure will enable all key stakeholders, including regulators, suppliers, and customers, to have a seat at the design table for the first time in the nuclear energy sector.

Repurposing the majority of existing coal plant sites and infrastructure, including transmission, and maintaining the workforce employed today, dramatically reduces the investments and effort otherwise required to site, plan, build, and connect new infrastructure. (Figure 17 shows a rendering of a repowered 1,200MWe plant.)

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 while building the infrastructure required to decarbonize end-use sectors such as heat, industry, and transport.

Repowering is a way to accelerate and de-risk global decarbonization, while also supporting an affordable clean energy provision on existing sites utilizing existing transmission. This provides an opportunity to reduce the overall scale of investment required to enable the clean energy transition.

Time is short. We invite all parties with a genuine interest in pragmatic and global-scale solutions for tackling the climate crisis to join us in Repowering Coal. You can find out more at terrapraxis.org

Figure 17. Repowering case study: two-steam-unit, 1,200MWe plant



ENDNOTES

- 1 [Global Coal Plant Tracker, Global Energy Monitor, February 2022.](#)
- 2 [TerraPraxis 2022 analysis of IPCC 2021 AR6 data.](#)
- 3 [Office of Nuclear Energy, Next-Gen Nuclear Plant and Jobs Are Coming to Wyoming, November 16, 2021.](#)
- 4 [MIT Future of Nuclear \(2018\).](#)
- 5 [Parsi, Sai Sharath, Lal, Kaivalya M., Kosbab, Benjamin D., Ingersoll, Eric D., Shirvan, Koroush, & Whittaker, Andrew S. Seismic isolation: A pathway to standardized advanced nuclear reactors. *Nuclear Engineering and Design*. Volume 387, February 2022.](#)
- 6 [Microsoft at CERAWeek: Accelerating digital transformation for a sustainable energy future, by Darryl Willis, Microsoft Corporate Vice President, Worldwide Energy Industry, published March 3, 2022.](#)

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