**DIGITAL CLIMATE SOLUTIONS INVENTORY**

| DIGITAL SOLUTION | TOOL | DESCRIPTION | SOLUTION |
|---|---|---|---|
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | To forecast fog and sea breeze conditions by collecting and organizing data sources, labeling periods during which fog and sea breeze events occurred, training the algorithms to recognize the conditions that preceded their occurrence, then testing them using new data to verify that the forecasts are accurate. | The ML techniques are to identify patterns and correlations, allowing classification of future predictors and used to estimate the uncertainty of the forecasts for solar power production. |
| Artificial Intelligence & Machine Learning | Cloud Fusion of Big Data and Multi-Physics Models | Cloud Fusion of Big Data and Multi-Physics Models using Machine Learning for Discovery, Exploration and Development of Hidden Geothermal Resources | Multiple |
| Artificial Intelligence & Machine Learning | Geothermal Anomaly | Geothermal Anomaly detection from Hyperspectral images via Deep Learning | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Develop machine learning (ML) methods to advance geothermal exploration and geothermal energy production by focusing in two areas. The first will involve ML methods to use microearthquakes (MEQs) for imaging geothermal reservoir properties and improving subsurface characterization. This work will include development of ML approaches for automated MEQ location. The second area will focus on identification of earthquake precursors and prediction of induced seismicity. The project will build on recent success in using ML to predict laboratory earthquakes. A key aspect of both focus areas will be developing open, community datasets of labeled events for future ML work. | An automated, AI-based system for locating MEQs in space, and improved scientific understanding of MEQ precursors and the linkages between stress state and associated acoustic emissions. |
| Artificial Intelligence & Machine Learning | Deep Learning for Scientific Discovery | Over 25 projects in national security, physical and computational sciences, earth and biological sciences, and energy and environment related domains. In the two years of the project, nearly 60 scientific peer reviewed papers were published. A significant focus was also on workforce development, where PNNL increased the number of deep learning knowledgeable staff by a factor of 10 in two years. | By appling deep learning across mission sciences, enabled groundbreaking discoveries and make transformational impacts to accelerate innovation and scientific discovery. |
| Artificial Intelligence & Machine Learning | Material Characterization, Prediction, and Control | This effort seeks to advance science-basd prediction and control of nuclear material processing to enable multifold acceleration in the adoption of new material systems for national security and nuclear energy. | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Downhole Sensing and Event-Driven Sensor Fusion for Depth-of-Cut Based Autonomous Fault Response and Drilling Optimization. | Multiple |
| Artificial Intelligence & Machine Learning | Data-Model Convergence (DMC) Initiative | DMC will greatly improve upon the current approach to address heterogeneous workflows among independent computing paradigms and integrate them into a converged computing capability. DMC is applying co-design to develop an integrated software stack that maps these heterogeneous workloads to conceptual designs for heterogeneous hardware architectures. Through integration of data analytics, physics models, and AI/ML, DMC will greatly reduce the amount of data needed for Deep Learning methods, while also reducing time and energy to solution. | Accelerate scientific discovery and engineering innovation through the integration of domain-aware AI/ML methods with data analytics. |
| Artificial Intelligence & Machine Learning | Few-shot learning for human-in-the-loop for large scale triage, sort, and summary | Few-shot learning is a flexible methodology that can be applied to a wide range of data types including images, audio, video, text, as well as more challenging modalities such as X-ray scans, electron microscopy, and remote sensing | Develop state of the art few-shot learning methods and systems. |
| Artificial Intelligence & Machine Learning | Assured AI: Adversarial machine learning & trustworthy and robust AI | To understand the safety and security implications of machine learning in physical, real-world environment across a variety of disparate modalities. Secondly, to characterize the risk of using machine learning in operational and mission-driven environments. | Multiple |
| Artificial Intelligence & Machine Learning | Scenario Planning Pilot – Machine Learning (ML) for Energy Systems | Scenario planning enables the development of strategies in the context of alternative futures and encourages over-the-horizon thinking. Working with directorate leadership, the pilot team selected Machine Learning (ML) for Energy Systems as the focus area or "case study" for the pilot. For a set of alternative futures, pilot participants discussed what energy systems, uses, and needs would be like and what challenges and opportunities ML/AI could address. | Multiple |
| Artificial Intelligence & Machine Learning | Energy Storage Materials Initiative (ESMI) | ESMI aspires to 1. Achieve predictive material design by establishing correlations between material structure and properties. 2. Rapid prototyping validation by linking material properties and device performance across temporal and spatial scales and 3. Bridge scales from atomistic to device for rapid new materials discovery and device performance optimization through the digital twin. | Pioneer the digital twin approach for an accelerated design of complex material systems such as batteries through physics-informed data-based models that integrate experimentation and modeling across traditionally siloed scales. |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | The underlying idea is to use Black-box approaches (Machine Learning) and White-box (Physics Based approaches) to provide complementary capabilities in addressing an applied research problem. A successful exploration would eventually trigger their adoption to other datasets in these domains and other domains within applied energy and environment domains. | Physics Informed Machine Learning for Energy and Environment Applications to maximize impact to sponsors by building a "bottom-up" capability in Machine Learning/Artificial Intelligence. |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | To develop a range of artificial intelligence and automation solutions to support geospatial data analysis, including object detection and classification in disparate modalities. These solutions will be fielded in an operational setting. | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Predictive Modeling of Subsurface Permeability for Improving Drill Targeting in Geothermal Reservoirs using Advanced Data Analytics | Multiple |
| Artificial Intelligence & Machine Learning | Network for Geothermal Drilling Optimization Supported by Deep Machine Learning and Cloud Based Data Aggregation | Develop a database of geothermal drilling information in a wide range of geologic settings through the formation of an innovative Collaboratory with geothermal operators, developers and researchers worldwide, including world-leading expertise from the oil and gas (O&G) industry. The database, accessible through internet cloud services, will be used to optimize geothermal drilling through the assimilation and analysis of well and drilling data by geothermal and O&G experts who will identify factors for given geological settings that lead to drilling success or failure. The knowledge of the human experts, in combination with artificial intelligence (AI) employing machine learning (ML) methods, will be applied to create an Expert System to automate the process of assimilating and classifying new well and drilling data with minimal human interaction. This will facilitate continuous improvement in the ability of the AI/ML algorithms to identify factors that govern drilling success. | The goal of these projects is to achieve a 50% reduction in non-productive time in geothermal drilling |
| Artificial Intelligence & Machine Learning | Play-Fairway Retrospective Analysis | Play-Fairway Retrospective Analysis with Emphasis on Developing Improved Hydrothermal Energy Assessments (USGS Mendenhall Post-Doctoral Research Project) | Multiple |

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| Artificial Intelligence & Machine Learning | Play-Fairway Retrospective Analysis | Play-Fairway Retrospective Analysis with Emphasis on Developing Improved Hydrothermal Energy Assessments (USGS Mendenhall Post-Doctoral Research Project) | Multiple |
| Artificial Intelligence & Machine Learning | Geothermal Operational Optimization with Machine Learning (GOOML) | The Geothermal Operational Optimization with Machine learning (ML) is a machine learning project focused on delivering a digital system model of geothermal operations that will result in increased plant efficiencies and electricity generation output. This will be a collaborative project lead by Upflow Ltd. partnering with NREL to develop optimization algorithms on geothermal systems using data from fields and plants operated by the U.S. partner Ormat and New Zealand-based Contact and NTGA. The resulting technology will be a tool that will predict optimal operating conditions, reduce operational uncertainty and ultimately achieve increased operational outputs to lower the levelized cost of geothermal electricity (LCOE). | A geothermal plant/reservoir system model (a "digital twin") that can be used for improved decision making in operations. An increase in capacity factor of 1 percentage point is expected to be attainable with this tool. |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Predictive Modeling of Subsurface Permeability for Improving Drill Targeting in Geothermal Reservoirs using Advanced Data Analytics | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Detecting and Characterizing Fracture Zones Using Convolutional Neural Network | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Track costal zones and increases in levy surges. | Safeguard waterside communities through research to help determine what areas will be impacted in the future by climate change due to rising sea levels. |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Develop a cyber-resilient platform with ML detection capabilities to detect cyber-attacks in microgrid environment | Provide secure microgrid environment to address climate concerns |
| Artificial Intelligence & Machine Learning | Water Cycle and Climate Extremes Modeling (WCCEM) + Dynamic Contingency Analysis Tool (DCAT) + High Performance Adaptive Deep-Reinforcement-Learning-based Real-time Emergency Control (HADREC) + Energy Storage Evaluation Tool (ESET) | Integrates algorithms searching for optimal climate forcing via deep learning-based inversion, developing ML predictive models of climate extremes and renewable (wind/solar/hydro/geothermal) generation, and machine/reinforcement learning-based grid optimization under extreme conditions. | The image deep learning-based inversion can predict climate forcing patterns responsible for the climate response for different scenarios and guidance on a strategy for acquiring the optimal forcing for negating undesired effects of climate change. The extremes modeling and prediction tool can capture the probability and return period of climate extremes in a future climate with inputs from multi-fidelity climate model simulations, and provide inputs for our energy system optimization tools to develop comprehensive grid resiliency strategies under climate extremes. |
| Artificial Intelligence & Machine Learning | Building foundation model for climate security | Develop capabilities in massive-scale self-supervised learning and joint inferences to discover new knowledge across science and security domains, including climate security. Encode multimodal knowledge representations while learning from text, images, tables, audio, and code by scaling-up and optimizing across multiple inference tasks jointly and decode knowledge representations to perform multitask describe-predict-prescribe inferences (what happened? what will happen? how to make X to happen?) without needing to be retrained on each new task or domain. | Advance scientific knowledge by advancing approaches for multimodal data fusion for the science domains including climate security and by developing AI-driven descriptive, predictive and prescriptive inference capabilities for semi-automated knowledge discovery. This system can assist climate scientists with discovering new models, new data, new treatments, new analyses, which essentially lead to new understanding. This system also enables knowledge summarization (describe), hypotheses generation (predict), and experimental design optimization (prescribe). |
| Artificial Intelligence & Machine Learning | Explainable AI (XAI) | Use explainable AI (XAI) to quantify and understand teleconnections associated with large-scale modes of variability which act as sources of precipitation predictability. Use XAI methods to quantify large-scale teleconnections in models and observations, understand modeling choices relevant to improve the representation of the sources of predictability, and quantify changes in model precipitation predictability under different climate change scenarios. Precipitation characteristics (including mean state, anomalies, and extremes) are predictable, in part, by the large-scale climate modes of variabilities. However, these teleconnections have not been fully understood and climate models do not capture the relevant processes with fidelity. | Using XAI techniques to understand the teleconnections and their linkages to local physical processes improves the precipitation predictability and provides insights into climate model development. |
| Artificial Intelligence & Machine Learning | DOE Office of Small Disadvantaged & Business Utilization (OSDBU) Customer Care AI Chatbot | Fields small business stakeholder inquiries on doing business with the Agency. Incoming queries are character-recognized by the chatbot, and are then routed to different areas of the OSDBU for initial guidance. The Customer Care team of the OSDBU has seen a material reduction in taxpayer burden through the use of the AI tool (details available upon request). | All aspects of the DOE mission that can be advanced by harnessing the innovative skills and expertise of America's small business population, including those relevant to EO 13985 and EO 14008; the more efficiently that the OSDBU through applying the AI chatbot, can guide such populations forward into effectively supporting DOE missions, the better the Nation engage domestic labor forces and capabilities to advance the American vanguard in energy science. |
| Artificial Intelligence & Machine Learning | ARIES Virtual Emulation Environment | Deploy AI algorithms for control and state estimation for autonomous urbanization for mobility and communities | Multiple |
| Artificial Intelligence & Machine Learning | Artificial Intelligence & Machine Learning | Software that includes algorithms, including AI/ML approaches. | Multiple |
| Artificial Intelligence & Machine Learning | IDAES – AI/ML Toolset | AI/ML tools especially developed to enable large scale optimization of multi-scale systems for decarbonization and carbon management. | Carbon management; hydrogen production, transport, storage, utilization; integrated energy and industrial systems |

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| Artificial Intelligence & Machine Learning | SMART | The Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART) Initiative focuses on transforming interactions within the subsurface and significantly improving efficiency and effectiveness of field-scale carbon storage and unconventional oil and gas operations. Several tools/platforms were developed in SMART: (1) Visualization platform to enable innovative, user-friendly, intuitive and attractive visualization to explore the subsurface environment and behaviors, (2) Real-time visualization packages to understand the rock properties and state of stress/pressure, (3) Real-time forecasting models for optimizing $CO_2$ storage, (4) Virtual learning platform for active $CO_2$ management, (5) Real-time visualization packages for faults and fracture networks, and (6) Real-time forecasting models for pressure management. | Carbon management and treats climate-related issues] SMART focuses on improving efficiency and effectiveness of field-scale carbon storage and unconventional oil and gas operations with the help of artificial intelligence and machine learning. |
| Artificial Intelligence & Machine Learning | Integrated Geologic and Techno-Economic Assessment of Offshore Saline Systems for Deepwater (DW) and Ultra-Deepwater (UDW) Reuse Potential | This project aims to perform case study analyses to identify optimal reservoirs and subsurface infrastructure for reuse potential, leveraging existing offshore models and tools, including NETL's Offshore Cost Model, to rapidly integrate insights from geological assessments and potential for infrastructure reuse. An integrated workflow will be developed and validated for case study locations to demonstrate how these big-data driven models can be used by regulators, industry, and researchers to identify DW and UDW co-saline storage opportunities while reducing the need for new infrastructure. | Treats climate-related issues |
| Artificial Intelligence & Machine Learning | H2 Combustion Mode Detection and Monitoring | Hydrogen offers a carbon-free alternative for fueling gas turbine engines used in power generation applications. Although turbine OEM's have demonstrated some capability for utilizing hydrogen as a fuel, operational conditions are often limited due to the onset of instabilities such as flashback and thermoacoustics. Rotating detonation offers an alternative means of combustion in gas turbine engines that is free of instabilities associated with conventional premixed and non-premixed hydrogen-air deflagration and provides a pathway to greater efficiency through pressure gain combustion. Rotating detonation combustion (RDC) consists of one or more detonation waves co- or counter-rotating within the combustor. The wave mode (number of waves and direction of travel) and wave speed constitute a performance diagnostic and potentially a means of controlling output. Traditional methods of characterizing wave mode and wave speed rely on post-processing or computationally expensive approaches. NETL has developed a methodology that integrates flame image and time series data classification through machine learning that has resulted in a real-time diagnostic and potential control. Hundreds of thousands of flame images and large quantities of transducer data were utilized to provide structured training of convolutional and deep neural networks, respectively, that can then be used as a real-time indicator of wave mode and speed without the need for time-consuming post-processing. While application to RDC is the primary objective for this diagnostic (and potential future control), similar image classification methods may be applied to conventional hydrogen combustion through deflagration to detect the onset of and control instabilities. | Carbon management and hydrogen utilization |
| Artificial Intelligence & Machine Learning | Offshore Risk Modeling (ORM) Suite | AI/ML enhanced models and tools developed to assess, predict, prevent, and support response to offshore energy (oil, gas, CCS etc) operational risks that can lead to spills, EJ/SJ impacts. Improving resiliency and reducing risks. Phase 1 https://edx.netl.doe.gov/offshore/portfolio-items/risk-modeling-suite/; Phase 2 https://edx.netl.doe.gov/offshore/research-portfolio/#phase2 | Carbon management; hydrogen production, transport, storage, utilization; integrated energy and industrial systems, EJ/SJ, resiliency |
| Blockchain | EW Zero (https://energyweb.org/case-studies/zero/) | EW Zero is a public, low-cost application built on top of the open-source Energy Web stack to help renewable energy buyers drive their carbon footprint to zero via purchases of different renewable energy products, such as impact-rich renewable energy certificates from emerging economies and power-purchase agreements. | Industrial decarbonization |
| Blockchain | Blockchain | Use blockchain technology to control energy consumption | Harness clean energy anytime |
| Blockchain | Blockchain for Optimized Security and Energy Management (BLOSEM) | A multi-lab, unified testing platform (BLOSEM) that has interoperability to support a wide variety of blockchains. This testing environment will be representative of the modern grid of the future by encompassing generation, transmission, distribution, and end user (edge) for the electric grid. | Grid modernization |
| Crowdsourcing Platform | Crowdsourcing Platform (https://network.americanmadechallenges.org/) | Fueling America's innovation engine. Members of public and private sectors provide mentoring, tools, resources, and support to accelerate the transition of ideas into real-world solutions for environmental justice and economic renewal. All Connectors are incentivized to help competitors succeed. Network members fall into one of two main categories: Connectors and Power Connectors | Multiple |
| Crowdsourcing Platform | VOLTTRON | Collects data from smart building and IoT devices | Sends to cloud for data storage, visualization, prediction and control |
| Distributed Computing for the Grid | Distributed Computing for the Grid | Develop out-of-box solution for secure home energy management system | Enable distributed energy resources such as solar panels and other to support the grid |
| Distributed Computing for the Grid | Develop physically informed emulators to improve Energy Exascale Earth System Model (E3SM) | Collect measurements from the U.S. DOE's Atmospheric Radiation Measurement user facility (ARM), satellites, and other sources, and perform a large ensemble of process model and large eddy simulations. Combining these datasets of aerosols, clouds, precipitation, and meteorology, we develop physically informed machine learning emulators to improve parameterizations for aerosol and cloud processes in E3SM. These processes include for aerosol activation, aerosol optics, and warm rain processes. | Credible climate predictions depend on accurate representation of the multi-scale physical processes governing clouds, precipitation, turbulence, convection, radiative transfer, and aerosols. Traditional process representations are typically developed based on limited data, limited knowledge, or a combination of both. By developing physically informed machine learning emulators based on data covering a wide range of regimes in the climate system, the process representations in climate models are unprecedently closer to the real-world situation, and hence improve the fidelity of the climate model. |
| Distributed Computing for the Grid | ARIES Virtual Emulation Environment (VEE) | Partnership with HPE to demonstrate edge/cloud/central | Computing as a solution to millions of controllable devices to shape, shift, and shed load to accelerate the integration of renewables. |

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| Distributed Computing for the Grid | Framework for Optimization, Quantification of Uncertainty, and Sensitivity (FOQUS) - a component of the CCSI Toolset | Runs multiple simulation suites on cloud computing (AWS) to enable large scale UQ and optimization of simulations of energy processes and carbon management technologies | Improve carbon management technologies and reduce technical risk. |
| Internet of Things | Eclipse VOLTTRON | Funded by DOE's Buildings Technology Office, this open source platform enables researchers to utilize buildings in energy efficiency applications. Eclipse VOLTTRON interfaces with buildings and devices to provide a standard interface for application developers. Applications for intelligent load control, fault detection, and other use cases have been developed by the community and are available for use. | This platform makes loads available to be controlled which might not otherwise be able to participate in energy efficiency strategies. It provides a refence platform allowing researchers to start with a full-featured open source platform to build their research or software stack. |
| Internet of Things | ARIES Virtual Emulation Environment (VEE) | Develop an emulation platform to design, operate, and analyze communities that deploy hundreds, to thousands, to millions of controllable devices across buildings, vehicles, grid, and renewables. | Determine an energy management system that doesn't just rely on storage to accelerate the deployment and integration of renewable energy. |
| Internet of Things | Distributed multi-parameter sensor suite for energy infrastructure and gas leak monitoring | A suite of distributed sensor technologies that can monitor energy infrastructure structural health (e.g., natural gas pipeline and CO2 storage wells) and methane and CO2 gas leaks along km-range long distance. (TRL 5-7) Pipeline or wellbore defects and gas leaks can be detected at an early stage or in a predictive way so that catastrophic failures and greenhouse gas (GHG) emissions can be prevented | Monitor and mitigate unintended greenhouse gas emission/leaks |
| Software & Systems | Software & Systems | For geothermal resource exploration and production optimization, e.g. "GT Cloud" and "GOOML" | Multiple |
| Software & Systems | pvlib python (https://pvlib-python.readthedocs.io/en/stable/) | Community supported tool that provides a set of functions and classes for simulating the performance of photovoltaic energy systems | Decarbonization of the electric grid by lowering the cost of accurate PV system modeling |
| Software & Systems | System Advisor Model (SAM) (https://sam.nrel.gov/) | SAM is a free and open-source techno-economic software model that facilitates decision-making for people in the renewable energy industry | Decarbonization of the electric grid by lowering the cost of accurate technical and economic modeling of renewable energy generation assets |
| Software & Systems | Solar Forecast Arbiter (https://solarforecastarbiter.org) | The Solar Forecast Arbiter is a free and open-source platform that allows transparent evaluation of solar radiation, solar power, and net-load forecasts | Decarbonization of the electric grid by lowering the cost of integrating variable solar generation in the power distribution and transmission systems |
| Software & Systems | Distribution Integration Solution Cost Options (DISCO) (https://nrel.github.io/disco/) | The DISCO tool is a free and open-source tool that can perform advanced dynamic hosting capacity analyses combined with a utility grid capacity upgrade cost evaluation module allowing for the most efficient and detailed method of determining the cheapest and most reliable interconnection option for an inverter based resource. | Supports decarbonization efforts by simplifying the interconnection evaluation process and increasing available dynamic interconnection options for developers |
| Software & Systems | WRF-Solar_V2 (https://ral.ucar.edu/solutions/products/wrf-solar-v2) | WRF-Solar is a specific configuration and augmentation of the Weather Research and Forecasting (WRF) model designed for solar energy applications such as solar radiation forecasting through clouds and other aerosols. | Decarbonization of the electric grid by more accurate forecasting of the amount of solar energy reaching the surface of the earth. |
| Software & Systems | Solar APP+ (https://solarapp.nrel.gov/) | Helps authorities having jurisdiction process solar and other DER permits | Decarbonization of the electric grid by lowering solar soft costs, including permitting challenges |
| Software & Systems | dGen (https://www.nrel.gov/analysis/dgen/) | Modeling tool simulates customer adoption of solar and DERs to help jurisdictions and authorities plan for the future | Decarbonization of the electric grid by assisting with future system planning needs |
| Software & Systems | EAGLE-I (https://eagle-i.doe.gov) | EAGLE-I™, an interactive geographic information system (GIS) that allows users to view and map the nation's energy infrastructure and obtain near real-time informational updates concerning the electric, petroleum and natural gas sectors within one visualization platform. | Mitigation of extreme weather events |
| Software & Systems | Kevala (https://kevala.com/) | For-profit platform that developers use to help site solar projects in optimal grid locations | Decarbonization of the electric grid by lowering soft costs, including system siting |
| Software & Systems | Aurora (https://www.aurorasolar.com/) | For-profit industry-leading too for rooftop solar design and sales | Decarbonization of the electric grid by lowering soft costs, including system design and sales |
| Software & Systems | Synthetic dIstribution Network Generator (SING) | The software is a standalone python module that creates synthetic distribution models for OpenDSS using GIS datasets. SING uses Bokeh platform and the simple to use dashboard which allows users to build rich synthetic distribution models down to individual loads. The supported dashboard allows users to tweak a handful of parameters that inform the machine learning \ heuristic methods employed to build the network. | Municipal and other "district level" decarbonization though improved solar project design |
| Software & Systems | Software & Systems | Develop out-of-box solution for secure home energy management system | Enable distributed energy resources such as solar panels and other to support the grid |

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| Software & Systems | Lawrence Berkley National Laboratory uses digital tools and platforms they developed to support the Office of Environmental Management (EM) sites in development of the Vulnerability Assessment and Resilience Plans (VARPs) | The data analytics framework for evaluating the climate resilience assessment at the EM sites includes (1) the automated ingestion of climate datasets at multiple sites through the cloud data storage and API, (2) the quantification of relevant climate metrics and features, and (3) cross-analysis of hazards and various site infrastructure. In addition, implementing machine learning and AI capabilities, including unsupervised learning for grouping similar sites and for identifying anomaly sites as well as supervised learning for identifying key climate drivers at each site. Development of an open-source python package: (https://pypi.org/project/climate-resilience/). Additional details of their work can be found in Zexuan Xu, Erica Siirila-Woodburn, Haruko Wainwright, Kenneth Hurst Williams, Satyarth Praveen and Efthymios Nikolopoulos, "Development of Climate Resilience Assessment Toolkits for Nuclear Waste Sites – 22455", WM2022 Conference, March 6 – 10, 2022, Phoenix, Arizona. | The framework will enable more automated/streamlined updates of the climate assessments as new model results and datasets arrive for updating VARP every four years, as well as the complete transparency and documentation of the workflow from the datasets to the results and visualization. |
| Software & Systems | Energy Exascale Earth System (E3SM) is an Earth System Model developed by/for the U.S. Department of Energy. The model supports both traditional climate-scale (dx=100km) and storm-scale (dx=3km) resolutions. Use large eddy simulations (LES, dx=20m). | Perform E3SM and LES simulations with perturbed forcings (e.g., perturbing the surface temperature, aerosol emissions, greenhouse gas concentrations) to investigate how the climate and weather systems respond at different spatial and temporal scales. Analyze the changes in mean climate state and variability of Earth's energy budget, water cycle (e.g., precipitation, storm frequency and intensity, etc.), and biogeochemical cycle. While the climate-scale E3SM includes the full multi-scale physics and can be used to inform large-scale, remote, and long-term environmental changes, the storm-resolving E3SM and LES can be used to understand small-scale, local, and short-term features. | These models are used to provide predictions of the climate system in transition, improving our understanding and guiding mitigation and adaptation strategies. |
| Software & Systems | Building Benchmark Datasets (BBD) Portal (https://bbd.labworks.org/) | The BBD portal was established by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Building Technologies Office. BBD provides secure, timely, easy, and open access to several high-resolution building systems datasets that have broad applicability to address highest-impact use cases that support decarbonization. The portal was developed as part of the DOE funded Benchmark Datasets Project. The portal uses data tools that provides the ability to collect, store, curate, catalog, preserve and disseminate building datasets. | Improving the energy performance and reducing the emissions from buildings across the U.S. is a critical part of the path toward reaching energy and climate goals. Building from Lord Kelvin's truism, "if you can't measure it, you can't improve it," understanding the built environment, accounting for the critical assets and tracking their energy performance, is fundamental to reaching performance goals for energy or carbon. In an ideal world, building scientists would have ready access to datasets that include every attribute relevant to building performance and occupant comfort at high spatial and temporal fidelity for any building of interest. The dearth of research-grade datasets from real buildings is a stubborn barrier that has always limited our analysis capabilities, in large part because broad-scale instrumentation efforts are so resource-intensive. The BBD data portal and its associated data tools represent a fundamental enabler by providing a unique resource that can help researchers, industry and other stakeholders develop data driven models, optimization and control algorithms to serve a variety of decarbonization related use cases such as design of demand management technologies, model development for benchmarking energy performance, models for developing predictive controls, occupancy prediction, automated fault detection and diagnosis, calibration of building energy models, co-optimizing indoor environment quality and energy, cyber-security of building operations, and identification and prevention of energy mismanagement. |
| Software & Systems | Risk Analysis Framework for Tropical Cyclones (RAFT) | RAFT quantifies the risk of tropical cyclones (TC) by evaluating shifts in future TC tracks and estimating realistic intensities using AI/ML to generate synthetic tracks to identify probabilities under future climate conditions. RAFT realistically represent TC tracks, along-track intensities and rainfall. | TC or hurricanes are the deadliest and costliest natural disasters in the U.S. RAFT allows the quantification of the amount of storm surge and inland flooding that will occur and then climate translators derive risks and impacts to human systems (I.e. electric power disruption). RAFT can also be applied to climate model output to determine the impact of climate change on TC characteristics and environment, and consequently the risk associated with them in the future to support infrastructure design criteria. |
| Software & Systems | Global Change Analysis Model (GCAM) (https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model) | GCAM has been developed at Pacific Northwest National Laboratory for over 30 years and is now a freely available community model and documented online. GCAM is a market equilibrium model with a global scope and operates from 1990 to 2100 in five-year time steps. It can be used to examine, for example, how changes in population, income, or technology cost might alter crop production, energy demand, and water withdrawals, or how changes in one region's demand for energy affect energy, water, and land in other regions. | The team at JGCRI is comprised of economists, engineers, energy experts, forest ecologists, agricultural scientists, and climate system scientists who develop the model and apply it to a range of science and policy questions. The team works closely with Earth system and ecosystem modelers to integrate the human decision components of GCAM into their analyses. GCAM has been used by the IPCC and the White House to develop pathways for decarbonization of the U.S. to meet sustainability goals. |
| Software & Systems | Integrated Multisector Multiscale Modeling (IM3) (https://im3.pnnl.gov/modeling) | IM3 is a group of software tools integrated to serve as open-source data, models, and tools to ensure the reproducibility of data and facilitate collaboration. IM3 is used to study the evolution, vulnerability, and resilience of interacting human and natural systems and landscapes from local to continental scales, including their responses to the compounding effects of long-term influences and short-term shocks. | IM3 is providing utilities and agencies with an understanding of the implications of uncertainty in data, observations, models, and model coupling approaches for projections of human-natural system dynamics to build additional understanding of future climate risks to the grid and to infrastructure. |
| Software & Systems | Software & Systems | Developing dashboards and models to understand Energy Justice which intersects with Climate Justice. | Dashboards and models help frame issues of equity and help users understand associated data. One example that is publicly available is the Energy Justice Dashboard which visualizes DOE investments. This can be coupled with areas designated as "Disadvantaged Communities" per Executive Order 14008. https://www.energy.gov/diversity/energy-justice-dashboard-beta |
| Software & Systems | DOE Sustainability Dashboard | Reporting of various sustainability metrics associated with the operation of the organization, including accounting of GHG impact. | Multiple |
| Software & Systems | Software & Systems | Serves as part of the analysis toward developing and implementing climate solutions | Multiple (e.g. Deployment of technologies to reduce carbon emissions, etc.) |
| Software and Systems | ARIES Virtual Emulation Environment (VEE) | Control orchestration to meet the energy needs of the end users that are sourced green. | Multiple |
| Software and Systems | Institute for the Design of Advanced Energy Systems Integrated Platform (IDAES) | Open-source modeling, simulation, and optimization computational platform for optimizing the multi-scale design and operations of integrated industrial and energy systems to enable decarbonization and carbon management while also quantifying and reducing technical risk. | Carbon management; includes direct air capture (DAC), Carbon Capture Utilization and Storage (CCUS), and industrial carbon capture and storage applications; hybrid integrated energy systems; hydrogen production, storage, transport, and use; industrial decarbonization; carbon dioxide removal technologies. |
| Software and Systems | Carbon Capture Simulation Initiative (CCSI) | Provides a comprehensive, integrated suite of scientifically validated models, with uncertainty quantification, optimization, risk analysis and decision-making capabilities with a focus on technical risk reduction and maximizing learning from pilot scale projects. | Carbon management |
| Software and Systems | Wafer Scale Engine Field Equation Application Programming Interface (WFA) | NETL collaborates with Cerebras to leverage Cerebras' advanced computing technology, Wafer Scale Engine (WSE), and NETL's expertise in computational fluid dynamics. NETL developed an application programming interface (API) to solve field equations on WSE. Initial results showed that the WFA achieved a 200x speed enhancement, and the greenhouse gas emission and energy consumption are also lower than running on NETL's supercomputer. Shifting 1% of the workload on NETL's supercomputer to WSE can reduce 160 MT of $CO_2$ emission per year. The significant reduction in computational energy consumption and greenhouse gas emission can help achieve President Biden's net zero mission targets. | Advanced computing technology with carbon emission and power consumption reduction |

| DIGITAL SOLUTION | TOOL | DESCRIPTION | SOLUTION |
|---|---|---|---|
| Software and Systems | Aspen Plus and Aspen Plus Dynamics | Modeling and simulation software tools for calculating steady-state and transient emissions from energy and chemical process systems. | Carbon management; includes direct air capture (DAC), Carbon Capture Utilization and Storage (CCUS) applications, and industrial carbon capture and storage applications. |
| Software and Systems | PROMOD | Electricity market analysis and emissions analysis | Emissions analysis. |
| Software and Systems | CO2U LCA Guidance Toolkit Version 2.0 | Lifecycle Analysis Carbon Use and Reuse | Quantifies climate change |
| Software and Systems | WaterTAP | Open-source modeling, simulation, and optimization software platform to evaluate water technology cost, energy, environmental, and resiliency tradeoffs across different water sources, sectors, and scales. | Monitors climate-related issues |
| Software and Systems | SimCS | Variability and uncertainty are essential factors when quantifying carbon footprints, costs, well leakage, and other climate impacts. SimCS is a Microsoft Excel Add-In to estimate uncertainties and analyze risks with Monte Carlo and Latin Hypercube simulation. It is designed to be directly used in Excel without installation. With SimCS, users can estimate outcomes given any situation and understand their likelihoods. It is a tool that can be generalized to use in virtually all Excel-based risk quantification. | Carbon footprint and cost quantification] SimCS has been used in estimating the uncertainties in the life cycle analysis and the variabilities in the carbon storage project costs. |
| Software and Systems | MATLAB/Simulink | Software for simulation and control of system operations to reduce emissions. | Emissions reduction |
| Software and Systems | National Risk Assessment Partnership (NRAP) | Carbon capture, utilization and storage (CCUS) is recognized as a key technology to reduce anthropogenic greenhouse gas emissions. The U.S. DOE's National Risk Assessment Partnership (NRAP) focuses on developing and demonstrating science-based methods, computational tools, workflows, and protocols to quantitatively assess and manage environmental risks at geologic carbon storage sites. The toolsets include: (1) Open-IAM focuses on risk management and containment assurance, (2) DREAM 2.0 for leakage monitoring design and optimization, (3) Passive Seismic Monitoring Tool (PSMT) for optimal design of microseismic monitoring network using surface or borehole geophones, (4) State of Stress Analysis Tool (SOSAT) embodies a Bayesian approach to quantify the certainty with which both the current state of stress, and how the state of stress will evolve as a result of subsurface fluid injection, (5) The Short-term Seismic Forecasting (STSF) tool uses site-specific catalogs of measured seismicity to forecast future event frequency over the short term, (6) RiskCat is an adaptation of conventional Probabilistic Seismic Risk Analysis (PSRA) method developed for application in estimation of risk of structural damage from naturally-occurring earthquakes. | Quantifies climate changes, monitors emissions, treats climate-related issues |
| Software and Systems | Advanced Infrastructure Integrity Model (AIIM) | The AIIM applies big data, advanced computing, machine learning, and spatial modelling techniques to evaluate and forecast infrastructure integrity, identify potential hazards, and quantify risk of failure. AIIM improves upon current assessments by utilizing scientific, data-driven models that account for the infrastructure design, past incidents, geohazards, environmental loading (including meteorological and oceanographic data), and infrastructure operational history. Ultimately, providing insights that improve upon the current the state of knowledge and help prevent infrastructure failures and their impacts upon surrounding communities and the environment. | Treats climate-related issues |
| Software and Systems | Climatological and Instantaneous Isolation and Attraction Model (CIIAM) | CIIAM applies mathematical theories of dynamical systems and metocean data — including real-time ocean current patterns — to determine where oil and other particles in the ocean (e.g., debris, hazardous waste, plankton, etc.) are likely to be attracted or repulsed. CIAM offers a novel and efficient way to summarize big ocean current and wind data to determine the ultimate destination of ocean particles. | Quantifies climate changes; Treats climate-related issues |
| Software and Systems | Ocean Geohazards Analysis (OGA) | The OGA is a flexible, smart tool designed for offshore hazard analysis and visualization to support risk assessments, change detection, and hazard reduction. The OGA provides modules for assessing the risk potential for a range of hazards, including mudslides, turbidity flows, wind events, wave events, current events, earthquakes, hurricanes, and spills, to forecast and identify areas more susceptible to metocean and seafloor hazards. OGA data and tool outputs can also provide insights into climate change related to the marine ecosystem. | Quantifies climate changes; Treats climate-related issues |
| Software and Systems | Blowout and Spill Occurrence Model (BLOSOM) | BLOSOM is a comprehensive modeling suite for blowout and spill events that addresses jet/plume behavior, high pressures, gas and hydrate dynamics, droplet-size distributions, and subsurface plume formation to provide a greater understanding of how hydrocarbon leaks are transported throughout offshore systems. | Treats climate-related issues |
| Software and Systems | Variable Grid Model (VGM) | The VGM leverages geographic information system (GIS) capabilities to simultaneously visualize and quantify spatial data trends and underlying data uncertainty, allowing stakeholders to better evaluate resources, assess potential impacts, understand trends, calculate project feasibility, identify knowledge gaps and more. | Foundational Solution to improve visualization and communication of uncertainty underpinning data and/or analyses, many of which are common data formats/types used in climate modeling |
| Software and Systems | Signatures of Kicks to Inform Drilling, Operations, and Safety | The objective of this effort is to develop a numerical surrogate of an acoustic sensor as found on LWD tools based on fundamental physics modeling. If this proves viable, the tool can be used to create a database of simulated signals over conditions beyond those available in the lab. Such data serves as a testbed for early kick detection algorithm development. | Controls and optimizes system operations; and treats climate-related issues. |
| Software and Systems | Enabling Technologies to Manage Hydrogen Storage | Develop modeling tools for the transport of pure and blended hydrogen/methane gases in porous media, supported by experimental measurements, to predict prospective storage resource for hydrogen across the U.S., assess storage efficiency and provide capabilities for operators to apply at their sites. Develop advanced sensor technologies for real-time monitoring of microbial conversion in pure and blended hydrogen/methane gases ($H_2$ depletion), gas composition, and geochemical monitoring (e.g. pH) in the $H_2$ storage wells and for assessing and monitoring of well integrity, tracking $H_2$ migration, gas leaks, and structural health of cement, casing, and other well components. | Monitors emissions; Treats climate-related issues |
| Software and Systems | Well Surveillance Tool | This task will develop a well integrity tool that allows an operator to combine wellbore completion, maintenance, and monitoring data with advanced data analytics. The tool will aid in prioritizing wells for wellhead surveillance, integrity surveys, and workovers based on key risk indicators. The tool will allow operators to build a database of digitized completion diagrams, maintenance and workover records, casing pressure and other monitoring data, and well characterization logs. Using advanced data analytics methods, the tool will provide a priority ranking of wells for wellhead surveys, integrity logging, and maintenance. | Monitors emissions; Controls and optimizes system operations to reduce emissions; Treats climate-related issues |

| DIGITAL SOLUTION | TOOL | DESCRIPTION | SOLUTION |
|---|---|---|---|
| Software and Systems | DisCO2ver – a common operating platform for the next generation of CO2 systems | This next-generation ecosystem would provide a common operating platform environment hosting data and cutting-edge tools and models needed to innovate technologies and enable safe, affordable, and environmentally responsible carbon storage (CS), hosting a planning dashboard, large subsurface dataset visualization, sub-basin resource assessment layers, with potential to collaborate on hosting tools for pipeline route planning and SimCCS (in collaboration with Carbon Solutions LLC). The ecosystem will leverage the ML/NLP tool SmartSearch to find and query additional carbon storage variables through an integrated search process, enabling users to use "smart" search capabilities to fill in data gaps. | Treats climate related issues |
| Software and Systems | Basin Scale Risk Assessment | Supporting rapid gigatonne-scale GCS deployment by assessing basin-scale risks from many concurrent operations. The deployment of GCS at Gigaton scale and at a rate to be an effective climate change mitigation strategy will require rapid development of many commercial-scale injection and storage projects within the same sedimentary basins. There is critical knowledge gap on how multiple GCS projects will affect basin-scale geomechanics and hydrology. The NRAP team will assess the risks and evaluate effectiveness of different deployment scenarios to assess leakage and induced seismicity risk for GCS sites. This work will leverage the tools and methods developed previously for characterization, risk quantification, monitoring design, and decision support at the site scale, and those tools/methods will be modified as needed to appropriately quantify risk evolution/risk management for many concurrently operating projects. If assessed risks are shown to be concerning for rapid, large scale deployment scenarios, subsequent (out year) studies could consider risk management scenarios and establish the technical basis for de-risking large-scale GCS deployment. These studies will help to reduce the uncertainty associated with risks of basin-scale GCS deployment and to develop best-practices for multi-project risk management and support high-level decision making about carbon management. | Carbon management |
| Software and Systems | MFix and Optimization Toolset | NETL's simulation-based engineering tools (MFiX, Optimization Toolset, etc.) will be used for design and optimization of novel pyrolysis and gasification reactor designs supporting the Office of Fossil Energy and Carbon Management (FECM) mission. Novel oxygen-blown, pilot-scale pyrolysis and gasification reactor designs will be evaluated for use in carbon-negative H2 production. Simulation-based design and optimization will study both fluidized bed and moving bed reactor configurations operating with mixed feedstocks including biomass, MSW, and waste plastics. | Reduce carbon emissions, carbon-negative H2 |
| Software and Systems | Carbon Storage Planning Dashboard | A carbon storage (CS) dashboard facilitates rapid exploration of data in support of carbon storage resource and feasibility assessments and planning efforts. The platform offers the ability to rapidly interrogate a range of social and environmental justice related data, with information related to CS resource potential, sources, and existing infrastructure to meet growing demand for CS planning support. Offer critical information for decision support, including information and insights to aid with the development of new technologies, effective planning to meet current and future demands, adapt to changing technology landscapes, aid in the development of new materials, evaluate potential environmental and/or community level risks or hazards, monitor progress and evaluate success of projects, and much more. | Carbon management |
| Software and Systems | Cerebras Wafer-scale Engine | The Wafer Scale Engine technology can be leveraged for high performance computing that is both faster and at a fraction of the power consumption than traditional supercomputers. The significant reduction in computational energy consumption and greenhouse gas emission can further support a net zero mission. | Green computing |
| Software and Systems | Offshore Saline Carbon Storage Calculator | The Offshore CO2 Saline Storage Calculator is a data-driven tool that applies the adapted DOE CO2 Methodology to calculate all potential distributions of offshore storage efficiency and resource potential at multiple spatial scales for saline formations. The tailored methodology include accounting for changing CO2 density with the overlying water column and sediment differences in unlithified, porous, and permeable offshore saline formations. (https://edx.netl.doe.gov/dataset/offshore-co2-saline-storage-calculator) | Carbon storage assessment and risk analysis model/tool |