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Small Money Agile Research and Technology Transitions (SMARTT)

November 2024

Cynthia A Powell

U.S. DEPARTMENT OF ENERGY

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Abstract

The Energy and Environment Directorate's (EED's) applied energy mission aligns with the larger DOE mission to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions. This Small Money Agile Research & Technology Transitions (SMARTT) LDRD project provided EED with the flexibility to leverage PNNL staff and capabilities to rapidly explore new scientific concepts and deliver initial proof-of-concept studies for innovative new technologies that aligned with the goals of DOE's Applied Energy Offices. Concepts that were successful were further developed through sponsor funding and private-sector partnership, or through follow-on LDRD investment.

Summary

The Small Money Agile Research & Technology Transitions (SMARTT) LDRD project's goal was to rapidly demonstrate proof of concept for emerging research ideas of interest to the Energy and Environment Directorate's applied energy mission, leveraging existing, or building new PNNL capabilities and supporting staff development. Over the course of three years, SMARTT conducted 21 research and development tasks ranging from validating the recyclability of membrane components in polymer electrolyte membrane fuel cells, to demonstrating cloud-empowered stochastic distribution grid applications.

Acknowledgments

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Introduction

The Energy and Environment Directorate (EED) is challenged by its DOE sponsors and other stakeholders to accelerate innovation through fostering of creativity and innovation targeted to address their current and future mission needs. Over the past several years, first through its Agile Research & Technology Transitions (ARTT) project and followed by this Small Money Agile Research & Technology Transitions (SMARTT) project, EED has made the ability to make quick small dollar research investments throughout the fiscal year a foundational part of its mission seed LDRD portfolio. Many of the concepts explored through these projects have translated to follow-on sponsor funding and publications in the peer-reviewed literature.

Such small, short-duration research efforts can beneficially serve multiple purposes. For example, staff may think of an innovative new idea to advance the S&T state of the art and require a small amount of research funding to validate the idea sufficiently to propose it to sponsors. Alternatively, opportunities may be identified during the course of ongoing research to demonstrate the application of a developing concept or capability beyond the scope of the original project (and sometimes beyond the mission space of the original sponsor). In addition, small, time sensitive follow-on research tasks may be needed, involving publishing, technology marketing, and/or staff development, after a research project ends. In all these situations, providing the ability to deliver early demonstrations of technologies and to enhance research outcomes can expand the application of PNNL capabilities and increase the probability of sponsor uptake of new research concepts.

Methodology

The SMARTT project made a small amount of funding available (dependent on scope, but notionally up to $40K for each task) to facilitate the demonstration of new concepts and/or new capabilities for application to Energy and Environment missions. Funded concepts may have had their origin in sponsor- or LDRD-funded projects, or they may have originated from formal or informal ideation processes. Research scope considered appropriate as SMARTT tasks included:

- "Proof of concept" studies for a new idea, to strengthen the case for funding in a subsequent proposal or pitch to EED stakeholders.
- Demonstration of the applicability of existing PNNL capabilities to new EED mission sponsors and stakeholders and/or new applications.
- Conduct of analyses and finalization of observations and conclusions, in order to complete a technical manuscript for submission to a peer-reviewed journal or publication as a PNNL Report.

In all cases, the scope of the research for each SMARTT task was limited to that considered necessary to validate or demonstrate the idea.

Concepts for potential funding were reviewed by the EED CSTO's office on an on-going basis throughout the fiscal year (dependent upon the availability of funds). Upon receipt, each concept was reviewed by a small team chartered by the CSTO that included relevant division directors and sector managers, as well as one or more technical subject matter experts. Concepts were selected for funding based on the following review criteria:

- Technical merit of the concept and level of potential impact if the concept could be validated.
- Likelihood of the proposed work scope to deliver the anticipated outcome(s).
- Alignment with EED's applied energy mission.
- Relevant line manager and sector endorsement.

For less research-intensive SMARTT tasks, such as completing a journal article after a research project has ended, an abbreviated submission process was employed. In these situations, an email request that included a brief statement of scope; a description of the anticipated outcome(s); and the funding amount requested, was sufficient to launch the process, with line manager and/or sector manager endorsement.

The scope for each SMARTT task was approved through the PNNL LDRD Tool Suite, and included completion of its own Electronic Prep and Risk (EPR) to ensure proper risk management.

Results

A summary of the 21 tasks that made up the SMARTT LDRD project follows.

PI Name	Task Title	SMARTT Task Summary	FY
Addleman, R Shane	Inexpensive Combustible Solvent	This effort developed methods for the creation of inexpensive, high performance combustible sorbent materials. A wide range of cheap sorbent bent substrate, “green” cost effective chemical modification methods and high efficacy sorbent chemistries were explored. The new materials demonstrated the ability to capture and concentrate a minerals/contaminants from solutions ranging from river water to industrial brines. These new sorbent materials can be burned to further concentrate any captured/concentrated minerals. Combustion of loaded sorbent materials removes the significant costs and wastes associated with acid stripping (the traditional method for recovery or materials captured on sorbents). The combustion concentrated metals can be sent for disposal or mineral processor for refining as relevant.	2022
Barrows, Sarah E	Greener Agricultural Practices in Washington State	This task analyzed the regional greenhouse gas abatement potential of soil management practices in Washington State, as well as practical limitations or barriers to their adoption. The task utilized responses from the Washington State Soil Health and Drought Survey to investigate the GHG mitigation potential of adopting no-till and cover cropping conservation practices in dryland wheat farming in Washington State. We found that, on average, switching from intensive tillage to no-till led to overall emissions abatement but did not significantly affect N2O emissions. Cover cropping also led to emissions reductions, though combined tillage practices appeared to affect this abatement potential. Our results also indicated that the primary barriers to the adoption of no-till included the costs of necessary equipment as well as limitations associated with no-till practices, including weed control and compaction. Primary barriers to adopting cover cropping were climatic limitations related to precipitation and soil moisture, knowledge gaps, and associated costs such as seed. Interestingly, non-monetary factors were also cited as among the most influential motivators and barriers to no-till and cover cropping systems. A nuanced understanding of the physical applicability of different soil health management practices to specific regions will be critical to assessing and promoting adoption in applicable areas.	2022
Bredt, Paul R	Nuclear Sciences Division Publication Auction	The goal of this task was to build staff’s technical reputation and expand their influence in the professional community through publication of research in the scientific literature. This task solicited publication proposals from staff who have very little to no experience in publication. A small amount of funding, generally <$5K, was provided to collect any data needed to prepare material for a journal and labor hours to complete the authorship and peer review process. A total of nine scientists and engineers received LDRD funding through this process and published several articles in peer reviewed journals. These publications supported the mission of the Department of Energy though the public release of information in the peer reviewed literature targeting scientific technical challenges facing department offices. Mission relevance was a criterion in the task selection process and resulting publications reported results of interest to multiple DOE offices including DOE-NE, DOE-EM, and DOE-SC.	2022
Fernandez, Nick	Validation of the Building Re-tuning Simulator (BRS)	This task created identical building models in EnergyPlus and the Building Re-tuning Simulator (BRS) and implemented a variety of simulations in different climate zones and with different operating conditions to validate that the calculations in the Building Re-tuning Simulator produced results that were within	2022

		appropriate tolerances as the results in EnergyPlus. Comparison of these results was presented at the 2023 Energy Exchange Conference, in the context of validating the BRS. A manuscript for a journal paper was prepared demonstrating this validation and investigating the use of the BRS and EnergyPlus for optimizing the control of supply air temperature in variable air volume air-handling systems. The abstract for the paper is as follows: "Variable Air Volume (VAV) Air-Handling Units (AHUs) in commercial buildings are controlled to heat and/or cool supply air to a supply air temperature (SAT) setpoint. Best practice for comfort and energy performance is to reset this setpoint automatically. In the field and among practitioners of heating, ventilation and air-conditioning control, there are a variety of different strategies for performing such a reset, however the comparative performance of such strategies remains poorly studied and defined. This study simulates the energy savings and thermal comfort performance of a variety of different SAT reset strategies under a range of conditions, including the climate, the number of zones in the VAV network, and the state of sensor and actuator faults pre-existing in the system. The results of this study indicate that the best strategies for SAT reset use feedback variables that are averaged across the zones, rather than using feedback from the most demanding zone".	
Kilgore, Uriah J	Oxidative Coupling of Methane	This task conducted a brief experimental program in which select catalysts and reactor conditions were evaluated in order to gather critical data related to oxidative coupling of methane to C2 products, with a specific interest in ethylene production. The experimental results found that numerous multicomponent catalysts of the types M–Na2WO4/SiO2 were capable of oxidatively coupling methane to C2 products, and that some reactivity could be recovered by oxidation cycling of the catalyst. However, none of the new catalysts evaluated exceeded the conversions reported for Mn–Na2WO4/SiO2.	2022
Shao, Yuyan	Recycling membrane electrode assembly (MEA) key components PEM electrolyzers	The goal of this task was to provide initial proof-of-concept for an approach for the recycling of proton exchange membrane (PEM) electrolyzers. The focus was on key component materials of the membrane electrode assembly (MEA), i.e., precious metal catalysts (IrO2) and Nafion membrane, which contribute to ~45% of total PEM electrolyzer stack cost. Results led to the filing of a patent "METHOD FOR RECYCLING ION CONDUCTING MEMBRANES (iEdison No. 0685901-22-0168)". In addition, the results were included in a proposal to HFTO titled "Clean Hydrogen Recover, Recycle, Refurbish and Reuse (4R) Consortium", during which a collaborative network was built among 10 industry companies, four national labs and four universities.	2022
Silverstein, Joshua A	Broad Ion Beam Milling	This task focused on providing proof of concept for a method to prepare native gold materials using broad ion beam polishing techniques for the purpose of advanced characterization using SEM and EBSD. Traditional methods, such as chemical-mechanical polishing, often result in plastic deformation, which hinders accurate characterization of gold. By employing advanced broad ion beam polishing at PNNL, researchers were able to achieve high-quality sample preparation, preserving the structural integrity of materials like native gold. The impact of the results of this task extends beyond immediate technical advancements in material preparation. By establishing these capabilities, the task strengthened collaborative ties with Central Washington University's Department of Geological Sciences.	2022
Van Rooyen, Isabella J	Advanced Materials and Manufacturing: Microstructural Comparison of Solid State and Liquid State	The performance of heat exchangers is impacted by surface roughness, residual stresses, and heat transfer properties, which have a direct link to microstructure consistency and associated repeatability of the manufacturing process. The overarching objective of this task was to provide a foothold for solid state additive manufactured (AM) components in the nuclear energy domain, using a comparative microstructural study to benchmark advantages and benefits of such for less sensitivity towards residual stresses during the manufacturing process.	2022

	Additive Manufacturing Processes	We leveraged 316L stainless steel samples fabricated previously with specific microstructural characterization for three modes of AM-(i) Direct energy deposition (DED), (ii) Digital Light Photoluminescence (DLP), and (iii) Fused Filament Fabrication (FFF). The results of the study were presented as an invited talk at the ICAM 2022, ASTM International Conference on Additive Manufacturing, Orlando, Florida, October 31 - November 4, 2022: Advanced Materials and Manufacturing Development for Heat Exchanger Applications: Microstructural Comparison of Solid State and Liquid State Additive Manufacturing. Although the residual stresses were not quantified, results showed comparatively lower strain in the FFF sintered samples compared with the powder DED samples. The EBSD examination further showed the advantages of the FFF process by randomly distributed equiaxed grain sizes irrespective of build direction. As expected, the laser-based DED process revealed a grain size modularity corresponding to the columnar growth in the print direction.	
Brown, Newton B	Pedagogical approaches to Cyber-Physical Systems for Energy and Environmental Applications	This task created a successful collaboration with Georgia Tech University that focused on the development of several curricula of mutual interest, including criteria, environment, and fundamentals for a range of Cyber-Physical laboratory studies for both undergraduate and graduate students. Existing PNNL laboratory infrastructure was evaluated and analyzed with the focus being on Industrial IOT Labs, Advanced Wireless Communication Labs, Prime, and miscellaneous other grid related labs in SEF, CSF, 3820 & 3860. Issues revolving around costs, direct and remote access to hardware, software frameworks, and virtualized assets were studied for the purpose of supporting control systems, simulation and co-simulation projects that involved combinations of virtualized and non-virtualized components, local and remote components, multiple security models, and other computation and communication models.	2023
Day-Lewis, Frederick D	Subsurface Sensing to Guide Autonomous Intelligent Excavation	This task investigated the relation between spectral induced polarization (SIP) and ore grade for two different minerals using two sets of cores provided by industry partners. The preliminary results from this work showed the potential for using SIP measurements within a machine-learning classification framework to enable autonomous real-time sorting of material. This work led to external proposals to further explore the use of SIP to understand mineralogy, classify materials autonomously, and support real-time decision making at mining operations.	2023
Sprinkle, Parker	Compressive Sensing for Distributed Acoustic Sensing Data	We proposed to take a small amount of recorded DAS data from a variety of experiments observing different signal types and implement multiple compressive sensing algorithms at varying degrees of compression to determine which algorithm and degree of compression is necessary to accurately reconstruct signals across the data types in the analysis. After exploring the parameter space of the problem our results indicate there are two key parameters that determine the degree to which DAS data are able to be satisfactorily reconstructed. The first is the sparsity of the original signal when cast to its representation basis. This dictionary (basis) is key to ensuring that the solution is as sparse as possible. We suggest "dictionary learning" as an approach to determining the ideal representation basis (dictionary). Secondly, the dictionary and measurement matrix must be as incoherent as possible. In practice, the measurement matrix is often limited by hardware constraints meaning that a sub-optimal dictionary must be used to achieve incoherence with the measurement matrix. These results will allow our team to determine the feasibility of applying these CS methods to future DAS experiments that may require long-term monitoring and provide insight for incorporating these changes into the DAS hardware itself. These results provide a "stepping-stone" to enable real-time processing and interpretation for datasets collected in the field and allow for more timely operational decision making.	2023

Yoder, Tim A	Carbon Intensity Signal to Enable 24x7 Carbon-Responsive Control at PNNL	We implemented a near-real-time carbon intensity signal for BPAT with data from EIA. The carbon intensity signal is published to an access-control API and an online dashboard. We investigated the correlation of this carbon data with the wholesale price data for a year and found a slight correlation. This suggests that directly optimizing for carbon emissions would reduce those emissions more than control strategies minimizing the cost of electricity. We created and trained three different machine learning (ML) models to predict the day ahead carbon signal. The models were able to predict the future signal accurately, with the bidirectional long short-term memory (LSTM) recurrent neural network (RNN) model producing the lowest error. Additional model development time could improve prediction with different model architectures, feature selection, and alternate prediction time windows. Unfortunately, the carbon emissions data from EIA lags by up to seven days. To enable real-time carbon aware control, the carbon intensity signal would need to be available closer to real-time. Some options to accomplish this would be implementing the multiregional input-output (MRIO) model methodology used by EIA in-house or using a paid subscription. Implementing a MRIO model would enable additional analysis such as creating a similar signal for the percentage of carbon-free electricity for a given BA, which could be valuable to additional external sponsors. On the other hand, leveraging a subscription, although simpler in the short term, would likely involve proprietary data, have unknown accuracy, and allow less insight into signal construction. Finally, the facilities at PNNL could easily be used as a test bed for flexible load control. The battery energy storage system (BESS) and thermal energy storage systems are both available for testing, well instrumented, and have safeties to prevent negatively impacting facility operations. Using these systems as a test bed for a carbon-aware control strategy would provide valuable for real-world demonstration. Existing optimization algorithms could easily be adapted to minimize carbon “price” instead of the electricity monetary cost.	2023
Levitskaia, Tatiana	Rare Earth Element (REE) Recovery and Purification from Coal Fly Ash	Through this task we proved that recovery and purification of rare earth elements (REE) from coal byproducts such as coal fly ash (CFA) is feasible using etidronic and citric acid leachates. Leaching results demonstrated that etidronic acid is the most effective at leaching the REE in all fly ash samples with approximately all the REE content dissolved approaching 100% leaching efficiency at mass ratios greater than 1:20. Citric acid is less effective, but still dissolves an average of 77% of the REE content. This trend correlates with REE binding affinity, with etidronic acid being the strongest chelator followed by the weaker citric acid ligand.	2023-2024
Tarufelli, Brittany L	EverGREEN 2045: An Energy Mix to Decarbonize Washington State	In this task we developed an integrated economic and engineering modeling approach to analyze the stability and economic feasibility two new flexible, future energy resources: advanced nuclear reactors (ANRs) and superhot rock (SHR) enhanced geothermal systems (EGS), for their potential to provide the needed flexibility for future resource mix in Washington state. However, we had an important modeling limitation – the maximum allowable wind capacity was limited by the existing grid topology. We also developed a methodology to optimally add sufficient clean energy supply to meet Washington State’s Clean Energy Transformation Act 2045 100% Clean Energy Standard without upgrading existing transmission. We scaled up wind, solar, and advanced nuclear production to account for the retirement of all fossil-fuel based thermal units. We added new clean energy supply that would minimize transmission congestion and variable renewable energy spillage. We then assessed investment and operational costs for the 2045 100%-clean-energy standard using the above-designed scenario and assessed the stability of the scenario. We found that the SHR EGSs have a levelized cost of electricity that ranges from $45 to $56 depending on the availability of incentives, and ANRs have a levelized cost of electricity that ranges from $48 to $59, depending on the availability of subsidies. At these costs, we find that these new technologies will likely need capacity payments of up to $38 for SHR EGS, and of up to $38 for ANRs, depending on the future resource mix scenarios. We also found that	2023-2024

		there were other benefits to incorporating these flexible resources as they contribute to reduced generation costs and reduced carbon dioxide (CO2) emissions in the future resource mix. Our team has published the results of this research and attended two conferences to share results with national and international audiences: (1) at the IAEA International Conference on Small Modular Reactors and their Applications in Vienna, Austria; and (2) at the IEEE Power and Energy Society General Meeting in Seattle, WA.	
Dagle, Robert A	Glycolaldehyde as a bio-based C2 platform molecule: proof of concept demonstration for conversion to acetaldehyde intermediate	With this task, we believe we have obtained the proof-of-concept data that unlocks a new carbon efficient pathway for thermochemical conversion of sugars to ethanol, without the need for fermentation and CO_2 formation that is otherwise required. Renewably sourced ethanol can be used as a building block for a variety of chemicals or upgraded into jet or diesel blend stocks using existing PNNL technology. Here we have demonstrated a new catalyst system for carbon-efficient conversion of ethylene glycol (EG) into ethanol. This represents the last step needed to enable the entire thermochemical processing for conversion of sugars to ethanol. This new pathway could offer significant advantages over the conventional process of producing SAF and other chemicals from ethanol, that uses fermentation and brings associated carbon loss to CO_2. With fermentation for every mole of ethanol produced from glucose requires one mole of CO2 byproduct. Thus, we believe this new pathway could offer significant potential economic and life cycle advantages over incumbent technology for producing sustainable fuels and chemicals. Preliminary techno-economic (TEA) evaluation of this new thermochemical route compared to a benchmark biochemical route (based on fermentation) for the conversion of corn stover to ethanol indicated that this new thermochemical route has the potential to reduce the minimum fuel selling price (MFSP) of cellulosic ethanol by approximately 20%, if using grey H_2 from steam methane reforming (SMR). However, if green H_2 can be produced at a cost of $1/kg, as targeted by DOE's Earth Shot goal, the thermochemical route can reduce the MFSP of cellulosic ethanol to $2.2/gal, similar to that of corn ethanol.	2024
Das, Hrishikesh	Solid phase processing of MANC soft magnets for transformer applications	In this task we successfully demonstrated friction consolidation (FC) of Finemet powder. A range of tool rotation speed from 55-110 RPM with forge force (Fz) of 55-70 kN were implemented during FC and the measured process temperature was 800-900°C. Optical microscopy of the product puck indicated full consolidation during FC processing, and SEM and EDS analyses indicated the formation of nano-size grains with some Nb and Cu rich phases. TKD analysis revealed an ultra-fine grain size (average = 411 nm with min = 178 nm) in the FC puck. X-ray diffraction analyses indicate that the primary phase in the FC puck is Fe3(Si/B) (similar to the powder feedstock), with other complex phases such as NbFeSi, NbFe and Fassi also present. The consolidated sample showed a saturation magnetization of 146.9 emu/g (~1.03 T), obtained from the fitting of 'law of approach to saturation', consistent with previously reported results for Finemet and similar alloy compositions. However, the FC puck demonstrated higher coercivity than the values reported in the literature for this alloy. This work represents the first known demonstration of the successful FC of an amorphous-nanocrystalline soft magnetic alloy.	2024
Grubel, Katarzyna	Creation of Safe and Manageable Waste Streams	The goal of this task was to safely, and without accident, create a manageable waste stream of old reactive samples. The samples in question were reactive commercial samples that were transferred to a secondary container by persons no longer associated with the Laboratory and/or small quantities of research samples with the potential to be water and/or oxygen sensitive. The task was successfully completed, applying the best laboratory practices for creating waste streams consistent with all safety requirements.	2024

Maloy, Stuart A	Novel High Entropy Alloy	Refractory high-entropy alloys (RHEAs) have emerged as a promising new class of materials, attracting significant attention from the scientific community due to their high melting points, predominantly single body-centered cubic (bcc) phase, and exceptional physical and mechanical properties at elevated temperatures. These characteristics position RHEAs as potential candidates for applications at temperatures surpassing those of conventional nickel-based superalloys. However, many RHEAs exhibit brittleness at room temperature (RT), leading to a focus on their compressive properties and microhardness, with limited evaluations of their tensile properties. In this study, a novel Nb4Ta4V3Ti RHEA developed by Ames National Laboratory/Iowa State University demonstrates excellent RT tensile properties (strength 1000 MPa, ductility ≈ 26%) and substantial deformability, achieving more than 60% reduction through cold rolling. As part of our on-going collaboration with Ames, eight mother tubes were sent to PNNL for the development of fuel cladding tubes via pilger processing. Pilger processing at RT was conducted on three of these tubes, varying rotation, feed speed, and reduction percentage. Unfortunately, all three tubes failed during the pilger processing without any significant deformation. Our initial investigations revealed that all eight tubes contained significant porosity. Further examination revealed predominantly round-shaped pores, incomplete melting, sharp cracks, triangular pores, and elongated pores with aspect ratios of up to 17. The sharp cracks served as stress concentration sites, promoting unstable crack propagation.	2024
Nittala, Aditya K	Advanced Characterization of Aluminum Ultra-Conductors	This task focused on the in-depth characterization of aluminum (AA1100 alloy)/reduced graphene oxide (rGO) composite wires with enhanced electrical conductivity, to try to identify the specific microstructural features that contribute to bulk scale electrical conductivity enhancement. Three samples were characterized: a “control” sample wire which was ShAPE extruded from the AA1100 alloy with no added graphene; a ShAPE-extruded AA1100 wire with 0.10 wt.% unsonicated rGO powder; and a ShAPE-extruded AA1100 wire with 0.10 wt.% sonicated rGO powders. The AA1100 alloy with 0.10 wt % sonicated rGO showed the biggest improvement in electrical conductivity compared to the control sample. Microstructural analyses by transmission electron microscopy (TEM) showed that ShAPE facilitates effective exfoliation and dispersion of rGO in the aluminum microstructure. Sonication also played a large role in dictating the quality and efficacy of rGO dispersion. Imaging at multiple scales revealed the presence of rGO agglomerates in the unsonicated sample, with some regions having roughly co-axial channels of rGO which prevented the effective mixing of the inner and outer sections of the composite during ShAPE. In comparison, the grain-refined microstructure of the sonicated sample showed effective mixing of rGO, along with nanoscale wafers of rGO with graphene-like morphologies. TEM imaging also revealed defect-free interfaces between the aluminum and rGO lattices, with absence of significant interfacial reactions and oxygen. These features likely contribute to enhanced electrical conductivity in the AA1100/rGO at the bulk scale.	2024
Reiman, Andrew P	Cloud-Empowered Stochastic Distribution System Applications	Uncertainty in distribution grid planning is driven to some degree by the unpredictable spatial and temporal patterns in the adoption of electric vehicles (EVs) and solar photovoltaic (PV) systems. This complexity, stemming from interactions among EVs, PV systems, customer behavior, and weather conditions, calls for a scalable framework to capture the full range of possible scenarios and analyze potential grid responses, in order to factor in compound uncertainty. Although this kind of analysis is challenging for many utilities today, the need to model numerous grid parameters as random variables and evaluate their impact on the system from many different perspectives will become increasingly essential in the future, in order to facilitate more strategic and well-informed planning investments. In this task a scalable, stochastic-aware distribution system planning application was developed that addresses these uncertainties by capturing both spatial and temporal variability through a Markov	2024

model and conducting Monte Carlo simulations leveraging modular cloud-based architecture. The results demonstrated that 15,000 power flow scenarios generated from the Markov model could be completed on the modified IEEE 123-bus test feeder, with each simulation representing an 8,760-hour time series run, in under an hour. The grid impact extracted from this huge volume of simulated data provides insights into the spatial and temporal effects of adopted technology, highlighting that planning solely for average conditions is inadequate, while worst-case scenario planning may lead to prohibitive expenses.

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