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5G Enabled Transformative Co-design and Co-simulation Framework for Grid Decarbonization and Modernization

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X Fan
J Ogle
Y Chen
D Wang
J Ang

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1.0 Introduction

5G is a breakthrough technology to enable a fully mobile and connected society, and a 5G-enabled digital continuum will be one of the critical foundations for clean energy economy and grid modernization. It can enable new architectures and frameworks that support a dynamic, near-real-time, end-to-end fabric to assist critical infrastructure operation in a continuously evolving environment [1]. As a complex distributed engineering system, the Power Grid not only encompasses numerous assets and various power generation resources, but also requires dynamic, sustainable, reliable, and resilient operation in support of uninterrupted social and economic development.

High penetration of renewable generation will be realized by ubiquitous power electronics in a decarbonized grid [2,3], in which the uncertainty and intermittency may dominate and propagate throughout every layer of grid operations, following by the deepening interdependence between power system and communication networks [4,5]. More importantly, the significantly increasing amount of high-resolution sensing data (typical continuous point-on-wave data frequency is from 1 kHz to 10 MHz, annual data size from 0.5 TB to 5 PB for single data point) [6], calls upon more complex modeling approaches (power electronic proprietary models, artificial intelligent [AI] surrogate models [7,8]), as well as significant communication network capability demands on bandwidth, latency, massive connection, secure/reliable interoperability, and innovative data-driven democratized control mechanism [9], besides existing physical-model based engineering operations and control [5,10].

More importantly, this clean energy transformation not only requires innovative manufacturing, algorithm, application, and cross-domain co-simulation, but also a systematic evaluation and comprehensive support on the microelectronic and architectural computing customization to enable and maximize the high renewable penetration in the future power grid. The co-design of decarbonized grid, reliable yet efficient communication, and affordable yet ubiquitous computing will unlock the potential of almost any available tools for the undergoing clean energy transformation. This also echoes the dramatic paradigm shift of the roles and functions of conventional energy service providers and emerging prosumers countrywide—a prosumer is both an energy producer and energy consumer; their emerging demand on computing, communication, and sensing for their distributed energy resources (DERs) also inspires new market opportunities and business models (i.e., FERC Order 2222) [11].

Therefore, it is critical to develop a quantitative methodology to evaluate the benefits of 5G integration to support the energy industry and stakeholders, for the transition from traditional centralized operational yet compliance-centric systems toward large-scale distributed infrastructure, which can collaboratively perform complex learning and provide resilience services, that is, a forward-looking perspective from grid modernization.

2.0 DOE funded Project Overview: 5G Energy FRAME

The ultimate goal of 5G Energy FRAME (Fabricated Resource and Asset Management Encompassment) [12] is developing a quantitative methodology to evaluate the benefits of 5G integration, and support industry in the transition to the high DER, decarbonized energy future where dynamic energy flows require fast-acting response to localized conditions. Embracing 5G technologies bridges the gap between energy stakeholders and computing/ML resources to enhance grid asset management through cohesive data integration and intelligent analytics. 5G is an opportunity to rethink the paradigm of infrastructure planning, as computing will be one of the core services for society alongside electricity and communication services.

Figure 1 shows various levels of potential computing/learning applications in the 5G fabricated sensing and control infrastructure for power grids. The high throughput, lower latency of 5G enable unique streaming analytics and data fusion functions at the level of edge, zone, and cloud; an open/private edge-based energy zone enabled by 5G not only caters to varying needs from different groups of stakeholders while supporting high connection density, but also balances computational burden at edge devices while minimizing the overflow of data. This establishes a novel physics-informed data structure to analyze the communication and compute needs in various DER, energy storage, and grid configurations.

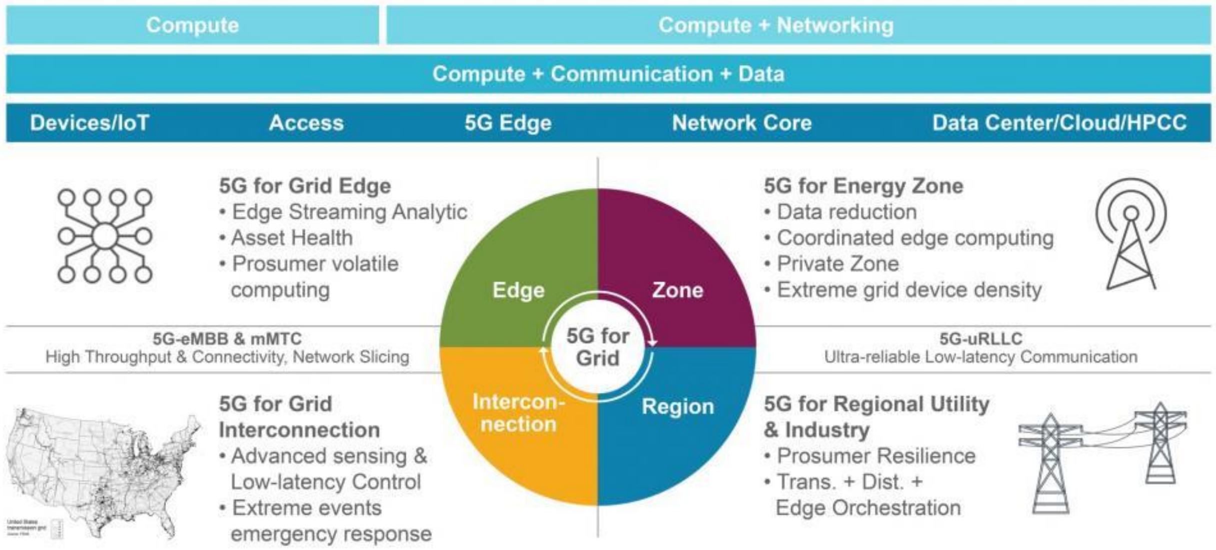

Figure 1 An integrated landscape of 5G communication, Grid, and Computing.

More specifically, to pilot the co-design methodology for Energy, Communication, and Computing, three objectives are given as follows:

Objective 1: Explore and evaluate the benefits of 5G-enabled grid edge and edge-based energy zone under high penetration of DERs.

Objective 2: Provide a transparent and collaborative energy data harvesting platform and enable organic data flow in the 5G fabricated digital continuum.

Objective 3: Enable a balanced and sustainable computing ecosystem and empower potential energy stakeholders with better resource and asset management by optimized 5G integration.

PNNL will leverage its existing 5G Advanced Wireless Communications (AWC) Innovation Studio [13] and perform lab-environment 5G simulations with data-driven hot predictive analytics at the model edge for DER availability and asset health management. A variety of hardware embedded testing scenarios will be designed and validated, which include: 1) single 5G edge equipment testing; 2) multiple 5G edge equipment testing; 3) single 5G edge-based energy zone testing with multiple edge equipment; and 4) integrated grid simulation platform with individual scenario 1, 2, and 3, and interface with the cloud-based platform. This will translate 5G capabilities into practical configurations to support grid-edge and edge-based energy zones, to provide industry with a procedure to evaluate the benefits of 5G integration and tune deployments, that is, fulfill and deliver *Objective 1*.

In addition, a cloud-based platform will be developed for optimized data harvesting and facilitate interconnected learning and computing. It achieves the optimal energy data harvesting by serving as both Energy Data Marketplace (EDM) and Energy Learning Warehouse (ELW) to host all the data, model, and extracted intelligence that are connected through 5G fabric, while it also presents a unified access for a wide range of stakeholders in the clean-energy future. In summary, this 5G digital continuum, including cloud, grid edge, and edge-based energy zones, proactively aggregates the data and distills them into intelligence for further distribution. As a result, we have addressed our *Objective 2*.

Operations for the future high DER and storage grid architecture will include centralized, distributed, and decentralized control modalities that dynamically shift across that continuum, depending on the state of the grid. Therefore, an adaptive and scalable compute management is favored to streamline the communication and between a wide range of high-performance computing (HPC) resources, including multi-core CPUs, GPUs, cluster machines, cloud computing, as well as 5G edge computing, across multiple stakeholders at various locations as desired by users for providing resilient energy service. This results in strong support to real-time monitoring, coordination, predictive analysis and planning for better reliability, resiliency, and security. By designing and implementing the streamlined computing and orchestration workflow, we fully realized the proposed *Objective 3*.

Clean energy economy envisions an evolving energy infrastructure with emerging affordable technologies being adopted. By realizing the above three objectives, we aim to assist U.S. energy infrastructure under the transformational clean-energy vision, provide prosumers with the best available technologies to deliver affordable, reliable, and sustainable energy service, and support the grid operator and field crew under extreme environments, across urban and rural communities in all U.S. states and territories.

3.0 Impacts & Opportunities beyond 5G Energy FRAME

Operations for the future high DER and storage grid architecture will include centralized, distributed, and decentralized control modalities that dynamically shift across that continuum, depending on the state of the grid. The physics-informed data structure can be enhanced to support a more dynamic architecture model spanning the control methodologies. The methodology developed in the 5G Energy FRAME project can be customized to fit different future grid scenarios to evaluate multiple (dynamic) configurations (computing, sensing, communication, environment) for different stakeholders. The complex multi-domain behavior can then be analyzed in the co-simulation environment across varying operational and environmental scenarios. Based on a set of configurable objectives across the different domains, simulation driven multi-factor optimization can lead to an optimal co-design.

This ties to the DOE and PNNL mission of decarbonization and net zero-energy closely as it can improve renewable management and integration, with PNNL team's unique capability of co-design and co-optimization for integrating various components across energy systems adaptively and effectively. The platform will be used to explore and validate novel and potentially disruptive microelectronics and power electronics technologies [14], grid control and protection schemes [15], and advance scientific computing, artificial intelligence and machine learning, cybersecurity, and architectural computing customization [16].

Going forward, having the platform in place, PNNL and collaborators from academia, national labs, and industry will be able to dive deeper into a variety of cross-domain use cases in energy systems. The 5G Energy FRAME project can be extended to further promote and accelerate the application of advanced computing and communication technologies in power systems considering the increase penetration of DERs and energy storage, migration of Data Centers, Offshore and Onshore wind development, as well as high voltage direct current (HVDC) interregional transmission projects.

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Pacific Northwest National Laboratory

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