Pacific Northwest
NATIONAL LABORATORY

PNNL-38361

Use Case Specification

September 2025

Michael Brown
Jay Barlow
Isabel Van Dyke

U.S. DEPARTMENT of ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Summary

Over the past three years, the Use Case Specification project has provided scenarios that have driven the development of key E-COMP capabilities and demonstrated their application to problems that the electric power industry is facing. These scenarios have provided the basis for which each Thrust has performed technical work, tying together E-COMP work under a common umbrella.

Documented in this report is a summary of the background, motivations, and work – completed or proposed – under the three E-COMP use cases pursued to date: Offshore Wind, Remote Communities on the Olympic Peninsula, and Large Electric Loads.

Acknowledgments

This research was supported by the E-COMP initiative under the Laboratory Directed Research and Development (LDRD) Program at Pacific Northwest National Laboratory (PNNL). PNNL is a multi-program national laboratory operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.

Acronyms and Abbreviations

AI – Artificial Intelligence
BESS – Battery Energy Storage System
BPA – Bonneville Power Administration
CAMEO – Co-design Architecture for Multi-objective Energy System Optimization
DSO – Distribution System Operator
ECOMP – Energy System Co-Design with Multiple Objectives and Power Electronics
EGRASS – Electrical Grid Resilience and Assessment System
EGRET – Electrical Grid Research and Engineering Tools
GODEEEP – Grid Operations, Decarbonization and Environmental and Energy Equity Platform
HVDC – High Voltage Direct Current
IM3 - Integrated Multisector Multiscale Modeling
IRA - Inflation Reduction Act
LEL – Large Electric Load
MESP – Multi-Entity Simulation Platform
MMC – Modular Multi-level Converters
MVDC – Medium Voltage Direct Current
MTDC – Multi-Terminal Direct Current
NERC – North American Electric Reliability Corporation
OP – Olympic Peninsula
OSW – Offshore Wind
PNNL – Pacific Northwest National Laboratory
PUD – Public Utility District
RECOOP – Remote Communities on the Olympic Peninsula
WECC – Western Electricity Coordinating Council

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1.0 Introduction

Throughout the duration of E-COMP, the Cross-Thrust Use-Case Specification project has driven capability development and enabled compelling capability demonstrations through the development of use cases. In the context of E-COMP, a use case is an application of capabilities to a specific, real-world inquiry. The use case focuses the analytical exercises and unites the Thrusts towards solving a problem that the electric industry is facing. The Use Case team works across the three Thrusts and is responsible for articulating and documenting the initial specifications of use cases. The Thrusts then carry out analytical inquiries with collaboration as needed by the Use Case team.

1.1 Use Case Process

In order to develop complex, applicable use cases for the Thrusts to execute work within, the use case team follows a three-step process with input from E-COMP PIs and Thrust leads throughout. This process may be seen in Figure 1 below.

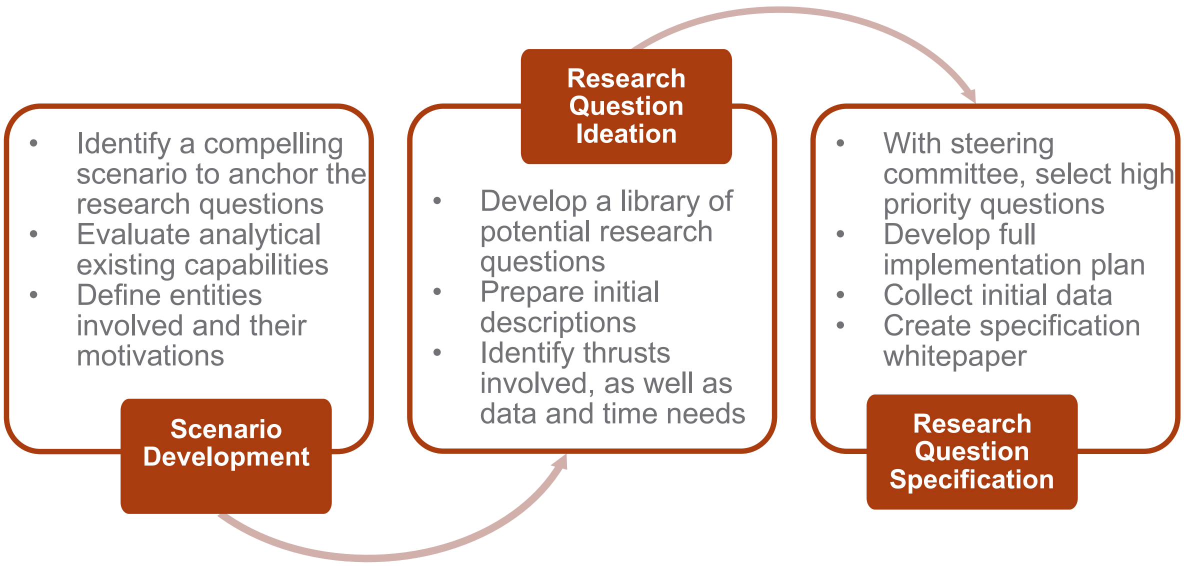

Figure 1: Use Case Development Process

The first stage, scenario development, is the point at which the use case team finds an emerging problem area within the electric power industry. Once potential industry problems are identified, the use case team identified which scenarios can be uniquely solved via multi-objective co-design and thus align with the E-COMP initiative’s goals. Finally, a scenario is developed that effectively demonstrates the problem and provides an avenue for the problem to be solved. Throughout this stage, consideration is given to ensure alignment with potential sponsor interests, as well as to ensure the scenario will provide a new area for Thrusts to develop capabilities.

Once a scenario has been identified and interest is confirmed with Thrusts, E-COMP leadership, and the review board, the scenario moves into the second stage – research question ideation. In this stage, specific research questions are posed that each of the Thrusts may answer through their work on the scenario. Initial data needs, timelines, and cross-thrust interactions are identified at this point to ensure rapid execution as thrust work begins.

The final stage for each scenario is the research question specification stage. This stage takes the list of potential research questions from the ideation stage, identifies the questions that best align with Thrust interests and E-COMP capability needs, and finalizes the specification needed to begin work. A full implementation plan is developed in this stage, and proposals are developed by Thrusts for consideration for future funding. This stage often lasts for multiple years, as new work will be proposed within a use case as old work is concluding. For instance, the offshore wind use case (Section 2.0) had 2-3 years in this stage, and RECCOP (Section 3.0) is entering its second year in the final stage.

1.2 Use Case Overview

Utilizing the process identified in 1.1, the project team has developed three key use cases that have driven technical work in E-COMP. The first use case, Offshore Wind (OSW), sought to look at problems and opportunities that arise when connecting large, isolated generation to an existing transmission system. This use case is in its final stages, and this report will provide a synthesis of the background, motivation, and technical Thrust work carried out during the duration of the offshore wind use case. Related to the process outlined in 1.1, this use case has progressed through all three development stages.

Following the OSW use case, the Remote Communities on the Olympic Peninsula use case was developed to drive work related to distribution microgrid optimization from multiple perspectives. This scenario has some technical work in progress, and other work proposed for FY26. Based on this work status, an overview of this use case is provided along with a summary of work in progress and proposed work. This use case is in the third stage discussed in 1.1, and is moving through technical work completion.

Finally, the most recent use case looks at what problems arise from connecting large electric loads, and how these problems can be optimally solved. The large electric loads use case directly applies many of the technical capabilities developed by the offshore wind use case to the rapidly emerging problem area of data center related load growth. As this use case has recently entered the third stage of the use-case development process, this report will focus on providing the background and motivations for the large electric loads use case, along with an overview of potential research topics.

2.0 Offshore Wind

Offshore wind integration was selected as the first use case for E-COMP. This section describes the background and initial specifications of a case study question, which was selected for immediate tractability and to serve as an entry point for demonstrating E-COMP's analytical capabilities. Additionally, an overview of the Thrust work completed under the OSW umbrella is provided; this overview captures the theme of work completed, and is not comprehensive of all OSW work completed by E-COMP. This section will highlight work that the use case has directly driven, and capabilities developed as a result of the use case.

2.1 Background

E-COMP's first use case was grid integration of large generation capacity. This use case was prompted by the significant additions – actual and planned – of inverter-based generating resources and how they may shape the grid's operation and design. Offshore wind was selected as the focus of this initial use case. It is a variable, inverter-based resource and a significant buildout of offshore wind could involve new offshore and onshore electric transmission infrastructure, all of which E-COMP is equipped to examine. Many of the E-COMP capabilities developed through examining offshore wind can be applied to other inverter-based resources, like battery energy storage, or to the integration of large amounts of generation capacity more generally. Large load integration is in some ways a mirror image of large generation integration and is being explored in a follow-on use case focusing on power-electronics-based loads like data centers.

The initial scenario identified in the first stage of developing this use case focused on a hypothetical buildout of approximately ten gigawatts of offshore wind capacity on the U.S. West Coast. Leveraging PNNL's research in this area (especially Douville et al. 2023), E-COMP's use case team worked with the project teams to develop guiding specifications that would lead to new research results and new capabilities.

The central research question identified in the second use case development stage was seemingly simple: What is the optimal sizing and operational strategy of an offshore wind farm and battery energy storage system to support energy generation and grid frequency regulation?

As this use case development moved into its third stage, it became clear that answering this question involved researching multiple supporting inquiries. The project teams designed offshore wind farms with integrated energy storage, explored the tradeoffs of electrical transmission topologies for connecting these resources to the grid, examined the electrical stability of the modeled western U.S. grid system to ensure it could integrate this resource, and simulated the economic dispatch of this new resource in a model energy market. The work involved iteration among the projects. Some projects developed entirely new models that filled gaps in existing tools and will serve as open-source contributions to the research community. Underlying these projects, a real-time power electronics testbed team validated certain experiments at highly refined timescales, taking the research one step closer to demonstrating how these modeled systems might perform in the real world.

The highlights in this report were compiled to provide a storyline representing the body of work generated under the initial use case, starting with a modeled offshore wind farm and tracing its optimization, its integration into the grid, its interaction in the market, and the underlying power electronics modeling and validation. Additional research and capabilities are still being developed.

2.2 Use Case Motivation

Offshore wind integration was chosen as the initial E-COMP use case theme for several high-level reasons:

- **Broadly applicable fundamental capabilities.** Capabilities developed under this use case, including MTDC interconnection, energy storage optimization, and new control policies, may be applied to a variety of generation types. These capabilities are also broadly applicable to large loads, providing avenues for future research.

- **There are novel technical challenges, including power electronics.** Offshore wind is an inverter-based resource. High-voltage direct-current (HVDC) transmission may also be used for long-distance connections between offshore wind farms and load centers; HVDC is increasingly based on modular multi-level converters (MMC) that bring new complexities for system control (Ren, Huang, Wang, Cui, & Peng, 2023)

- **The timing is significant.** As load growth expectations have rapidly evolved over the last five years, there has been a growing concern regarding adequate generation capabilities (NERC, 2024). To meet this need, extensive new generation is needed from a variety of sources, including offshore wind. Specific to offshore wind, past national goals of deploying 30 GW by 2030 from a starting capacity of less than 1 GW currently installed indicated a rapid deployment pace (The White House, 2021) (US Department of Energy, 2023).

- **Policy interactions can be examined.** The Inflation Reduction Act (IRA) of 2022 extended and expanded tax credits for renewable energy, including for offshore wind (Congressional Research Service, 2022). The IRA also incentivizes transmission studies and expansion, including reconductoring and potentially reconfiguration (Congressional Research Service, 2022) (Eisdorfer, Barlow, & Peacock, 2023).

- **Socio-technical interactions can be examined.** E-COMP aims to be able to “evaluate the impact of localized optimization (via co-design) on the broader system” and evaluate decarbonization in the context of other objectives including cost, resilience, and equity. These factors will all be part of offshore wind development, which involves energy and non-energy stakeholders, including coastal communities and ports.

Each of these areas provides significant cause for large generation, and specifically OSW, to be explored by E-COMP. Due to the significant technical concern, there are many areas to improve E-COMP’s theoretical and modeling capabilities. With the numerous design parameters and constraints inherent to OSW, co-optimization and co-design capabilities have been pushed forward. Finally, because of the numerous entities involved and complex simulations required to execute on the use case, E-COMP’s system integration and simulation capabilities improved significantly throughout the use case.

2.3 High-Level Research Topics

While developing the OSW scenario, the use case team in conjunction with each of the Thrusts identified several key areas for research. These include:

- **Multi-terminal direct current (MTDC) grids:** There is a need to research MTDC controls, topologies, and protection standards. There is an opportunity to reduce the time required to conduct reliability and resilience interconnection studies involving large MTDC grids. These inquiries are policy relevant; for example, New York's offshore wind development solicitation includes a technical requirement that wind farms support a meshed-ready topology and that both the steady state and dynamic performance are studied (NYSERDA , 2022).The solicitation specifies that dynamic performance of the high-voltage DC system should be studied using the tool PSCAD.

- **Inter-regional coordination on infrastructure:** New generation development may involve transmitting power over long distances or may affect the electrical system across regions. Generation planning has so far not prioritized these inter-regional considerations (Douville et al, 2022) (Bothwell et al 2021). Inter-regional transmission build could promote greater adoption of renewable energy, but transmission development involving two or more regions within an interconnect is relatively uncommon (Congressional Research Service 2022).

- **Socio-technical considerations.** Offshore wind must be considered in the context of broad technical and social stakeholders. Analyses should factor in social and cultural aspects alongside technical and economic (Douville, Severy et al. 2023). The Department of Energy and the Bureau of Ocean Energy Management have identified these considerations as priorities (DNV, 2022).

- **Resilience:** Offshore wind can potentially contribute to energy resilience in several ways, including by providing black-start capability (Douville et al, 2020) Resilience was identified as a research gap for both the Atlantic and Pacific coasts (Bothwell, Marquis et al. 2021, Douville, Severy et al. 2023). High impact, low-probability events – like tropical cyclones on the Atlantic coast, and extreme heat waves and wildfires on the Pacific coast – should be considered as resilience contingencies. Resilience metrics (Homer, Lippert et al. 2022) and cost tradeoffs (Costello, 2023) are also important emerging areas of research.

Ongoing offshore wind integration research at PNNL has complemented E-COMP throughout the OSW use case. Relevant tools utilized by E-COMP include:

- Tool to translate extreme weather events into electric power contingencies, based on the Electrical Grid Resilience and Assessment System (EGRASS)

- MTDC PSCAD models for offshore wind, using grid-following controls; aligns with E-COMP Thrust use of PSCAD

The use case team also identified potential to integrate with ongoing PNNL-led modeling initiatives like Grid Operations, Decarbonization and Environmental and Energy Equity Platform (GODEEEP) and Integrated Multisector Multiscale Modeling (IM3).

2.4 Thrust Work

The offshore wind use case has been in development for the duration of E-COMP and is coming to a close at the end of FY25 as the capabilities are transitioned to the Large Electric Loads use case. Throughout this time, the Thrusts have completed extensive technical work. This section will provide an overview of a subset of this work with a focus on how the individual work ties into the larger use case.

2.4.1 Designing an optimal offshore wind farm

The fundamental building block of the use case was a model offshore wind farm. In addition to the individual wind turbines, the offshore wind farm was defined to include a high-voltage direct current (HVDC) link to the onshore grid and an energy storage system located at the grid point of interconnection. HVDC is expected to be the preferred technology for transmitting offshore wind power on the U.S. West Coast, as it can efficiently transmit power over the long distances envisioned. HVDC power transmission involves a pair of power-electronics-based converter stations – one on each end of a subsea transmission cable – that introduce additional capabilities and challenges for controlling the transmission of power. Energy storage was included in the wind farm design to explore if it could add value by buffering the variability of the wind power and by providing additional grid services.

The design exercise was to simultaneously optimize these elements of the wind farm to provide for maximum net lifetime profit while ensuring electrical stability for the wind farm system and the greater grid. The optimization also considered the operation and control of the wind farm while determining the upfront design. This technique, termed co-design, is an advancement on traditional design and is one of E-COMP's main research pillars.

The optimization exercise began by fixing the point of interconnection with the onshore grid and the rated capacity of the offshore wind farm, drawing on specifications previously identified in Douville et al. 2023. The capacity of the energy storage system, the capacity of the HVDC cable system, and the electrical control parameters for the overall wind farm system were then determined through co-design optimization. **Error! Reference source not found.** provides an overview of this setup.

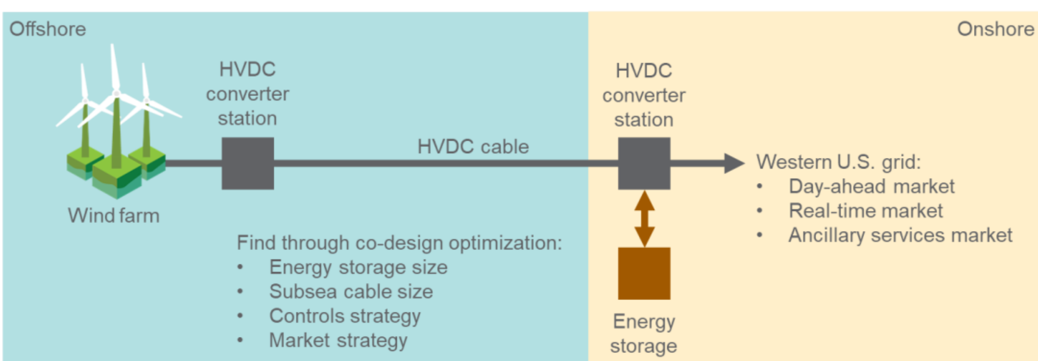

Figure 2: overview of wind farm system and co-design optimization

Energy market revenues were a key input to the optimization. These included a day-ahead market, which procures energy in one-hour blocks at least 24 hours before delivery, a real-time market, which procures energy in 5- or 15-minute blocks in the hours before delivery, and the ancillary services market, which provides grid stability and reliability services at lead times of less than ten minutes.

Including ancillary services in the optimization was a relatively novel approach that enabled examination of how a variable, power electronics-based resource like offshore wind with storage could contribute to grid stability, which has traditionally been supported by resources like hydropower and thermal generators. The model offshore wind farm can provide ancillary services in two main ways. Under one method, kinetic energy from the spinning of the turbines can be expended and converted to additional electrical output to support grid stability on short timescales. The downside of this method is that the kinetic energy must later be recovered by reducing electrical output, and this strategy therefore requires the wind farm to reserve extra capacity or risk not delivering on its other energy market commitments. Alternatively, an energy *storage* system can provide ancillary services, thereby allowing the wind farm to send more of its output to the energy market. The energy storage must be recharged at some point, but there is considerable time flexibility. The optimization exercise examined a battery providing these ancillary services. Future optimization formulations may broaden this to examine the tradeoff between battery participation and direct wind farm participation.

The optimization found that BESS capacity was generally only 3-5% of the offshore wind farm capacity across numerous scenarios – indicating that this was sufficient for providing ancillary services to participate in the reserves market for additional revenue and that the additional cost of larger storage systems could not be economically justified. The HVDC cable size was also scaled in the optimization to reduce capital cost. Overall, the co-design approach suggested that net profits could be increased by about 3%, compared to a baseline design. The exercise demonstrated that variable, inverter-based resources like offshore wind combined with energy storage can contribute to grid stability with the proper design and market signals. Future work may examine additional design variables and additional objectives.

Additional details on the work detailed here may be found in (Sharma et al, 2024) and (Sharma et al, 2025)

2.4.2 Optimizing transmission topology for resource integration

Building off the foundational wind farm model above, the co-design exercise was expanded to consider how to optimally connect multiple offshore wind farms to the onshore grid. There are many conceivable transmission configurations – topologies – for achieving this, and tradeoffs associated with each. At one end of the spectrum is a radial topology, where each windfarm has its own connection to the onshore grid. At the other end of the spectrum is a meshed or networked topology, where individual wind farms are connected to one another and to multiple points on the onshore grid. A meshed topology provides more paths for power transmission, and this can provide additional opportunities for market revenue and resilience in the case of a line fault. At the same time, the additional HVDC transmission equipment can add significant cost. Figure 3 illustrates these topologies.

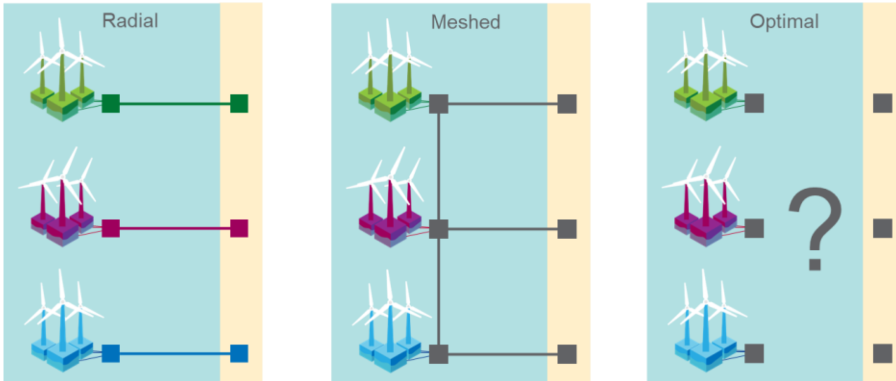

Figure 3: Illustrative comparison of topologies.

The optimal topology could be shaped by many factors. As with the foundational wind farm optimization above, this exercise considered maximizing profit while providing for electrical stability. Five offshore windfarm locations and five onshore grid points of interconnection were drawn from PNNL's previous research (Douville et al. 2023). The HVDC topology, cable size, and energy storage capacity were then optimized, using expected wind energy generation for each offshore wind farm and historical market price data for each point of grid interconnection. As above, the energy storage system was modeled to participate in an ancillary services market to contribute to grid stability.

The optimization found topologies that differed significantly from the baseline radial case. This was largely driven by the high cost of HVDC lines, with the optimization seeking to reduce this cost by reducing the total length. This results in a meshed topology in all optimized cases, which considered variations on inflation rate and power injection limits. In each optimized case, the size of the energy storage system was determined to be relatively small (less than 0.05% of the power capacity of the smallest transmission cable), indicating that most value was generated from providing energy into the day-ahead and real-time markets, rather than through ancillary services.

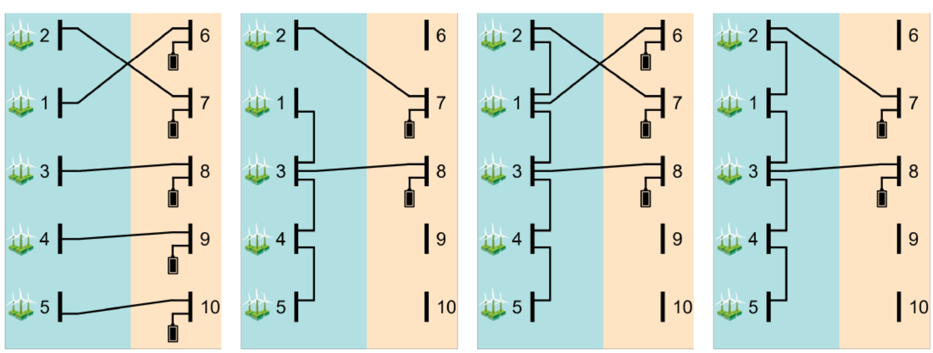

Figure 4: Topologies from optimization exercise. The radial topology (a) was a baseline for comparison with several optimized scenarios. Topologies (b), (c), and (d) consider variations in economic inflation rate and power injection limits.

The results highlighted the significant potential cost savings achieved through optimization: the optimized topologies had capital cost reductions of 16-27%, compared to the radial case. The optimized topology with the highest profit was a 19% improvement over the profit of the radial case.

Topology optimization modeling has conventionally involved manual model iteration while adding and removing individual lines. The algorithmic method developed in this work is therefore a significant research contribution and could be applied to other kinds of topology optimization like onshore grid transmission expansion modeling.

For additional details on this work, please see (Wang, et al., 2025).

2.4.3 Examining electrical stability

This large generation integration use case is centered on power electronics: offshore wind turbines, battery energy storage, and HVDC converters all rely on this technology. Power electronics technology introduces challenges for grid controls and modeling. It is a paradigm shift from the electro-mechanical technology that has been the foundation of the grid since its origin. Power electronics devices can change behavior on fine timescales (nanoseconds to microseconds), and modeling their behavior therefore also requires examination at these fine timescales. This challenge posed by power electronics is also a key opportunity, as controls schemes can have greater responsiveness and flexibility on these fine timescales, given proper design.

For more information, please see (Sharma et al, 2025).

2.4.4 Power electronics modeling

Power electronics modeling is one of the main E-COMP research pillars and underlies the optimization and market models above. In the co-design optimization of the offshore wind farm, an electromagnetic transient simulation was conducted to validate the electrical stability of the system during a fault. The simulation considered a major generator outage on the western grid – with a capacity of two gigawatts – and found that the system remained stable even with the addition of over ten gigawatts of offshore wind. The stability modeling also confirmed that the co-designed wind farm had superior performance during this transient event. The team ran these experiments on a 240-bus model of the western U.S. grid built in the power electronics software PSCAD (Figure 5). This model and methods developed by the research team can be readily applied beyond offshore wind to other power-electronics-based generators and loads.

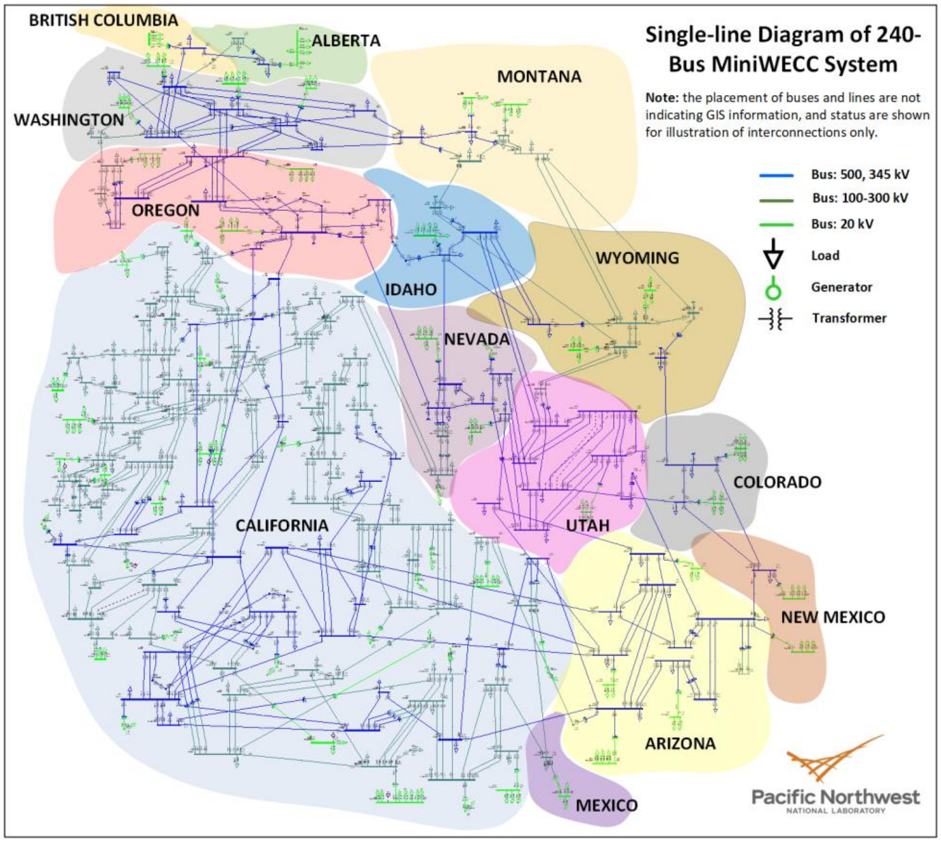

Figure 5: E-COMP's power electronics model of the western U.S. grid.

Additional details on this model may be found in (She et al, 2025)

2.4.5 Testbed simulation

E-COMP's power electronics modeling capabilities include a real-time testbed simulator for validation of certain experiments. E-COMP's testbed is a combination of computer hardware and software that enables high-resolution simulation of power electronics dynamics. Testbed experiments can aid early discovery of potential issues with electrical components or control schemes at the design stage, before larger scale validation with physical prototypes.

For this use case, the testbed team focused on the multi-terminal direct-current technology modeled in the optimization of the offshore wind system. The team developed and simulated a black start capability for offshore wind, demonstrating the ability of inverter-based resources to contribute to grid recovery after large-scale outages. The modeled system consisted of an offshore wind farm connected to a multi-terminal high-voltage direct-current grid with energy storage and both grid-forming and grid-following inverters (Figure 6). Given the complexity of modeled system, the real-time simulation experiment linked multiple simulators together, which was likely a novel research demonstration.

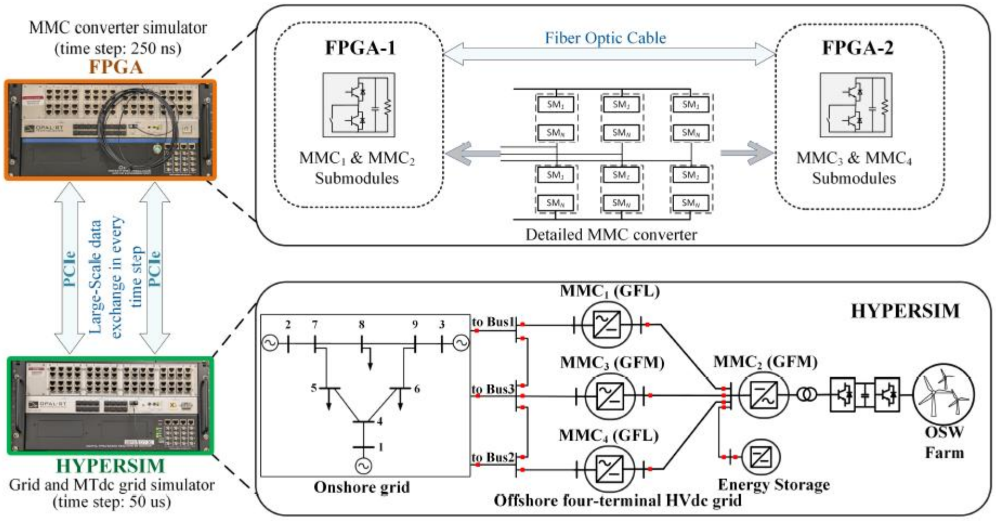

Figure 6: Testbed experiment of offshore wind providing grid black start capabilities.

E-COMP's testbed capabilities can be applied to other applications like medium-voltage direct current microgrids and reinforcement of the grid with high-voltage direct current technology to accommodate new large loads like data centers.

Details on this work may be found in (Sadeque et al, 2025)

2.4.6 Interacting with the energy market

The co-design optimization of the wind farm and topology relies on spatially-resolved energy market price signals at multiple timescales. Historical prices from energy markets were used for the modeling exercises above but may not fully reflect the future dynamics expected on the evolving grid. Production cost models, which forecast electricity cost based on economic dispatch of generators on a grid system, can provide these future insights, but these tools are often black-box commercial models accessible only to licensed users. E-COMP developed an open-source production cost model of the western U.S. grid to help address this gap.

E-COMP's open-source production cost model is based on the Electrical Grid Research and Engineering Tools (EGRET) model. The research team applied data from the Western Electricity Coordinating Council's 2032 Anchor Data Set to a 240-bus simplification of the western grid, the same general model used in the power electronics modeling above. The open-source market model was then calibrated to align with commercial-grade model results for locational marginal prices. The 240-bus simplified model can run a year of simulations at hourly resolution in about an hour, whereas the same task on a ~20,000 bus model takes about two days. The simplified model can therefore help accelerate E-COMP's capabilities development through future experiments.

The production cost model lives within a broader open-source model architecture that can examine how multiple generators, loads, or other actors interact in a market-based energy system. Ongoing research is examining how the offshore wind farm optimization above could be made iterative with the forward-looking locational marginal electricity prices across multiple points of interconnection with the grid. Future applications of this model architecture are expected to include the coordination of large power-electronics loads like data centers and power-electronics-enabled microgrids.

2.5 Capability Transition

As the OSW use began to near its final stages, E-COMP identified the need to quickly transition the capabilities developed into a new use case. This fast transition provides evidence that E-COMP's capabilities are widely applicable and are not reliant on any single generation or load type to be useful. When searching for a suitable use case, Large Electric Loads was identified as an area that shares many similarities with the OSW use case. The most key similarities may be found in Table 1: OSW and LEL Similarities below.

Offshore Wind Problems	Large Electric Loads Problems	Solution
Overvoltage	Undervoltage	Reactive power compensators, voltage regulators
Potential to Increase frequency	Decrease frequency	Energy storage, power flow controls, load-shedding
Potential to Increase fault current	Change fault current paths	Circuit breakers, relay settings
Power electronic harmonic injection	Harmonics and flicker	Filters, power factor correction devices
Transmission line congestion	Transmission line overload	Line construction, power flow control
Poorly damped/asynchronous behavior	Abrupt load change impacts	Power system stabilizers

Table 1: OSW and LEL Similarities

Due to the numerous similarities between the two use cases, a substantial amount of previously completed work will directly transition from the OSW to the LEL case. This includes the Mini-WECC model developed for transient stability analysis, system stability characterization techniques, optimization techniques, the CoSim Toolbox, and MESP. For additional details on the LEL use case, please refer to Section 4.0.

3.0 Remote Communities on the Olympic Peninsula

While the OSW use case focused on interconnecting large, isolated generation to an existing transmission system, the Remote Communities on the Olympic Peninsula (RECOOP) use case has developed E-COMPs distribution focused capabilities. Specifically, RECOOP has provided a framework to develop MVDC models, expand multi-entity simulation, and improve multi-objective co-optimization techniques. This use case is in progress with some work completed and some work underway. This section will highlight the background, motivations, and proposed work for RECOOP.

3.1 Background

RECOOP is a multi-faceted use case designed to test and mature E-COMP's multi-objective co-design and power electronic integration capabilities in a distribution-first scenario. Building on tools developed in the first two years of the E-COMP Initiative across all Thrusts, RECOOP functions as an umbrella for use cases focused on community-based energy system planning, where resilience, system optimization, and scalable integration are core pillars.

The initial study area for this use case is Washington State's Olympic Peninsula (OP), selected for its distinctive mix of characteristics that directly stress-test the target capabilities: geographic remoteness, isolated load pockets, and limited, largely radial transmission. Much of the OP's electric service is fed by a single Bonneville Power Administration (BPA) radial line operated in coordination with local public utility districts (PUDs) as can be seen in Figure 7. This topology creates single-contingency risks, longer outage durations at line endpoints, and constrained flexibility for local restoration. Policy and contractual contexts—including BPA resource contracts (BPA) and state decarbonization legislation—shape what local generation or distributed energy deployments are feasible and how they interconnect. Additionally, the limited existing transmission infrastructure combined with the rugged terrain in the OP makes a transmission infrastructure first approach non-viable for improving reliability on the OP.

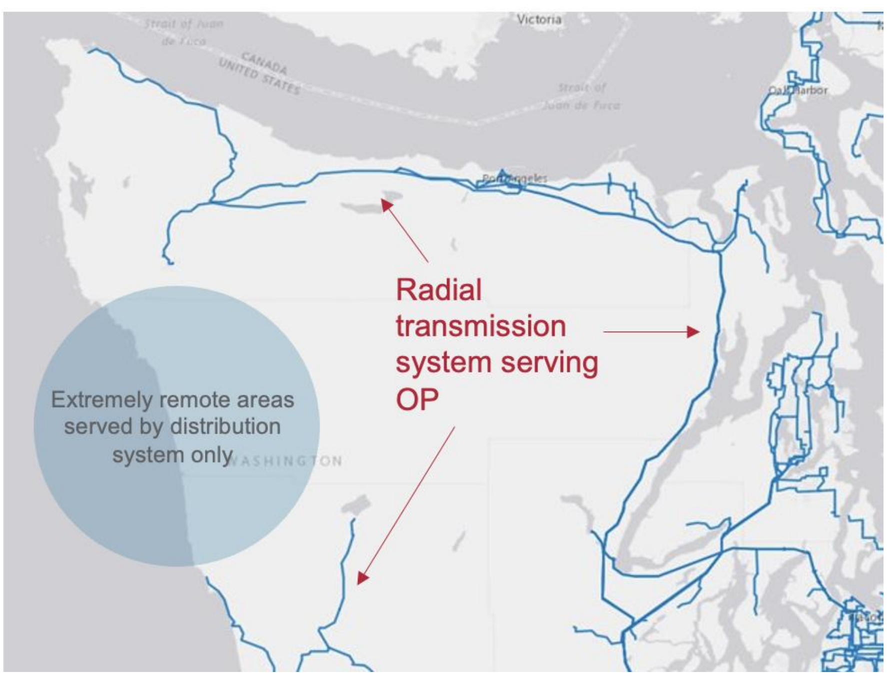

Figure 7: Transmission Lines on the Olympic Peninsula (HIFLD n.d.)

RECOOP's community-based planning lens emphasizes fit-for-purpose system design that aligns with each community's goals, constraints, and governance while ensuring prudent integration with the larger grid and potential for independent operation when needed. The OP's diverse land jurisdictions (Tribal nations, federal and state lands, military, and private property), varied local needs, and existing PNNL relationships (via the Sequim campus and ongoing projects) make it an effective demonstration of this and may be seen below in Figure 8. The case will integrate socio-technical objectives – reliability, cost, and affordability – across multiple spatial and temporal scales. Technically, RECOOP will examine how power-electronic-based solutions, storage, and distributed power generation can improve reliability and stability in radial, weakly connected systems, while meeting protection, ride-through, and operational coordination requirements. Organizationally, it will align E-COMP's modeling, control, and planning tools with real decision processes, enabling traceable links from engineering choices to social and economic impacts. Together, these elements position RECOOP to generate transferable methods and capabilities for other remote communities facing similar constraints.

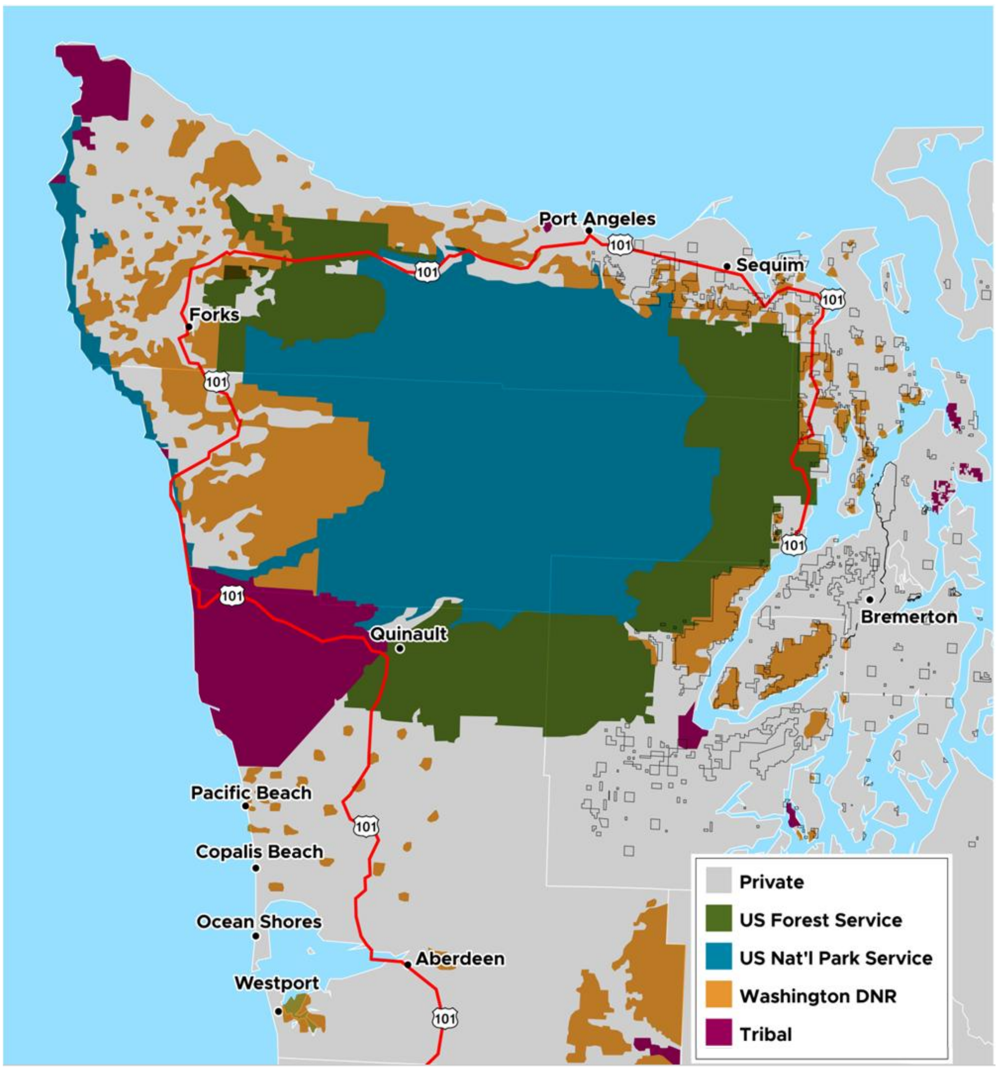

Figure 8: Entities on the Olympic Peninsula

3.2 Use Case Motivation

RECOOP was chosen to address pressing reliability and affordability challenges that arise when geographic remoteness, isolated load pockets, and limited transmission converge – and to do so in a setting where results can generalize to other remote communities. The OP provides a compelling testbed to integrate E-COMP's technical and social-science capabilities under realistic policy, market, and infrastructure constraints. Key motivations for the selection of RECOOP include:

- **Reliability gaps in remote, isolated load pockets**: Rural and distant communities experience more frequent and longer outages due to aging/limited infrastructure, sparse redundancy, long repair times, and end-of-line exposure in radial systems. The OP's primarily radial BPA supply makes it a representative case for improving continuity of service, contingency performance, and restoration pathways. The remoteness and limited load base also prevent traditional infrastructure-first approaches from being cost effective.

- **Limited transmission and system optimization needs**: A single major feed with minimal alternative paths constrains resilience, power quality, and operational flexibility. RECOOP enables exploration of targeted network reinforcements, non-wires alternatives, and operational strategies (e.g., sectionalization, microgrids, grid-forming resources, advanced protection) suited to weak and radially served systems.

- **Load growth and changing demand patterns**: Anticipated load increases from electrification and regional development will stress the OP's limited infrastructure (EFI Foundation, 2024). The use case will evaluate options to manage peak growth, align demand flexibility with system needs, and coordinate large or sensitive loads so that consumption changes do not destabilize lightly meshed networks or exhaust balancing reserves.

- **Rise of distributed power generation**: Increasing adoption of distributed generation and storage can improve local resilience but also introduces control, protection, and ride-through challenges in weak grids. RECOOP will assess architecture and power-electronic controls that enable safe islanding, black start support, and frequency/voltage stability, while ensuring interoperability and scalable integration.

- **Overlapping political, economic, and stakeholder constraints**: Real projects proceed (or stall) at the intersection of policy, regulation, finance, contracts, and community priorities. The OP's mix of BPA contracting, state policy, multi-jurisdictional land uses, and Tribal sovereignty surfaces the need for multi-objective co-design that is both technically sound and institutionally feasible.

3.3 High-Level Research Topics

A collaborative meshed-microgrid design serves as a framework for scenarios under the RECOOP umbrella. This framework assumes a condition in which the OP is sectioned into multiple microgrids based on existing identifiable boundaries (such as city borders or utility service territories) to form a larger system made up of the collection of smaller microgrid building blocks. Under this framework, each microgrid cell can exist autonomously, or be connected to any array of other microgrids, nearby or not, in a collaborative or supportive sense. In some scenarios, each of the individual microgrids may represent a single entity, in others, it could represent multiple entities. Similar fractal/connected microgrid designs have been explored in previous literature (Schneider et al, 2020; Carter, et al., 2019). Additionally, the model microgrid boundaries and operations could be shaped by community-level constraints, objectives, and interactions.

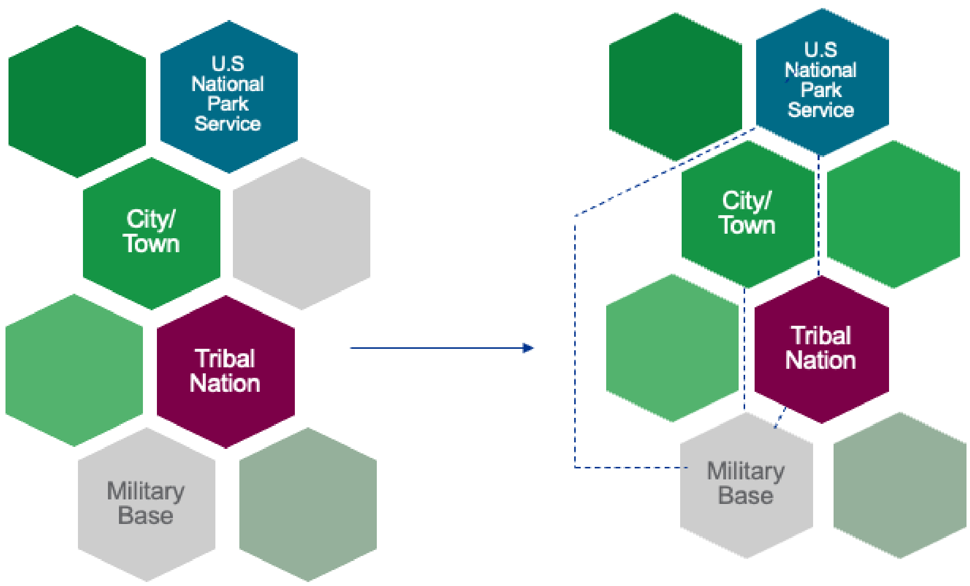

Figure 9: Hypothetical depiction of the meshed microgrid framework

High level considerations to be made by the Thrusts in their design of such a system include:

- **Resilience:** Minimizing the frequency and duration of power outages as well as maintaining power in extreme weather conditions are critical for a resilient energy system. Currently, remote communities on the OP are subject to a higher frequency of outages than more populated regions. The main transmission line owned by the BPA is the main power source for the OP, and if this line experiences an outage, remote communities do not have another source of power to rely on for their energy needs. Diversifying energy generation sources, installing energy storage, and supplementing the existing transmission line with local power electronics are potential ways to increase reliability for these communities.

- **System Optimization:** Reliable access to energy is key for the energy system to properly serve the people. As power electronics, local generation, and local storage technologies are increasingly introduced to the electric grid, the system will need to be optimized to avoid service interruptions to the communities it is powering. How adjacent entities work together in the context of the local power grid and how microgrids could be introduced and potentially connected to one another should be investigated to provide context for how a modernized electricity system could be optimized.

- **Scalable Integration and Energy Independence:** Scalable integration refers to the ability of the electric system to balance energy autonomy and islandability with collaborative connections. Within the context of the RECOOP case, a community's energy autonomy can be measured by their ability to meet local energy needs with localized and distributed energy sources without reliance on the larger transmission system. Additionally, energy autonomy refers to a community or entity's' ability to island themselves and serve their needs during outage scenarios in which the main line is unavailable. Collaborative approaches refer to a community's ability to partner electrically with other communities/entities to build resilience and share costs.

From these areas identified, the following primary research questions were developed:

- How do we quantify and integrate complex qualitative constraints and goals into a model?
- How can resilience be implemented in a systematic manner across diverse types of stakeholders?
- How does decision-making at multiple levels affect different communities as well as the whole system?

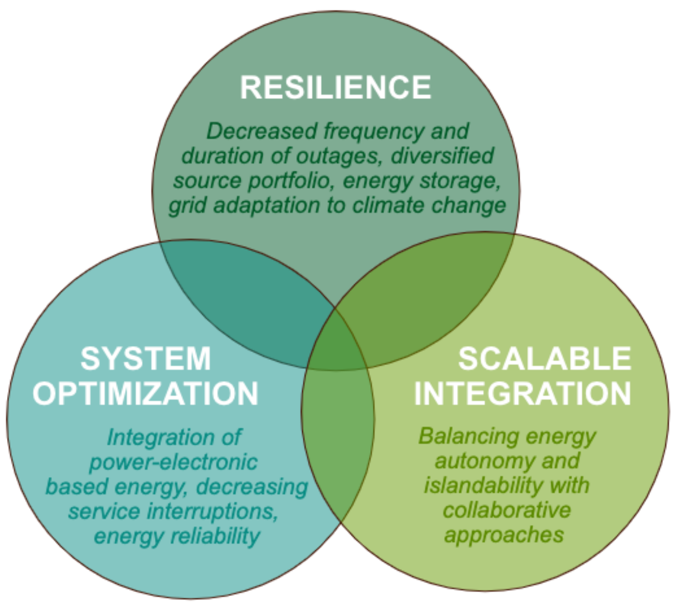

Figure 9: High-Level research concepts

3.4 Thrust Work

While some Thrust work for the RECOOP use case began in FY2025, additional work is proposed to take place in FY2026. This section provides summary of Thrust work that is in progress or proposed for the RECOOP use case.

3.4.1 Thrust 1

Medium-voltage direct current (MVDC) system integration on the Olympic Peninsula

Thrust one has been performing research work related to implementing medium voltage direct current (MVDC) systems into real-life applications (e.g. advancement of electrical infrastructure & power electronic integration). The rising costs of power electronics in addition to the increased complexity that accompanies the integration of MVDC, presents challenges to stakeholders. The project seeks to address these challenges by developing models and associated publications highlighting MVDC applications on the Olympic Peninsula. These capabilities would be the first applications of this groundbreaking technology in North America, and will address problems within existing infrastructure, seeking to improve power delivery and reliability. For instance, with MVDC, a critical transmission line could be taken out (due to damage, decommissioning, or other) without majorly disrupting the power supply. This capability could allow utilities and other grid operators to enhance system redundancy, stability, and resilience, and support the variety of stakeholders on the Olympic Peninsula.

The Olympic Peninsula in the United States emerged as a prime candidate for pioneering DC power systems due to existing models through the E-COMP project that facilitate steady-state power flow experiments. The application of MVDC in this region is not only poised to resolve current issues related to the lack of redundant lines, but also to provide a framework that increases grid adaptability for future expansion and modernization. This application will provide critical insights for researchers in the US, as existing data on the subject is sparse. By thoroughly documenting the processes and outcomes, this initiative will offer insights to regulators, utilities, and researchers. Additionally, the methodologies are designed to be generalizable beyond the Peninsula, allowing users to apply the technology in other regions.

Preliminary results concerning the MVDC system have recently been completed. Comprehensive documentation, including detailed models and publications, is in progress

3.4.2 Thrust 2

2D Simulation-based co-design for community energy planning

The 2D Simulation-based co-design for community energy planning project is one of the foundational RECOOP initiatives focused on the co-design of multiple microgrids, with a particular emphasis on managing contingency events. This project outlines three key deliverables: devising a method for individual microgrid owners to optimize their designs autonomously, developing an algorithm for the Distributed System Operator (DSO) to coordinate effectively between varying microgrids, and crafting an additional algorithm for Public Utility Districts (PUDs) to utilize. The project team has developed a relationship with Clallam PUD, which has been pivotal, as they have shared their microgrid topology model with E-COMP.

Currently, the Neah Bay area of the Olympic Peninsula serves as a case study to demonstrate the feasibility and efficiency of the co-design approach. The capabilities developed in this project aim to be generalizable across any remote or rural communities. Additionally, efforts are underway to extend these capabilities to other use cases, including the Large Electric Load case. Initial findings and results are anticipated in FY26.

This project and Thrust 3's 2D Simulation-based co-design for community energy planning project are in direct collaboration.

Single-Objective Function Design

The Single-Objective Function project represents an extension of earlier foundational E-COMP work. This project explores single-objective functions and solutions to comprehensively investigate varying dimensionalities. Designed for system planners and utilities, the project facilitates an understanding of trade-offs inherent in variable electric grid scenarios. Planners, utilities, and others can employ these methodologies to gain invaluable insights and ensure informed decision-making processes that optimize operational efficiency and grid expansion.

CAMEO

The CAMEO project is an innovative computational tool designed to empower system modelers through high-performance computing capabilities tailored for variable scenarios. This tool is integral to building optimization formulas and is applicable both within and beyond the E-COMP framework. Key features include large-scale contingency evaluation and facilitating efficient and effective distribution system expansion. Capabilities developed under Thrust 2 increase the DSO's ability to collaborate with microgrids, which is a realm traditionally unexplored from the vantage of multiple stakeholders (including individual microgrid owners).

3.4.3 Thrust 3

Game theory approaches for system-level incentive design

The Game theory approaches for system-level incentive design project aims to upgrade system devices and create game-theory style incentives that encourage distributed energy resource investment in communities to improve system reliability. The total cost for upgrading system devices and providing incentives is limited by a budget. Thus far, the team has formulated a general model and applied it to a three-community use case. They continue to work on the code and expect to have results this calendar year. This project is in direct collaboration with project "2D Simulation-based co-design for community energy planning". Additionally, any system device updates or infrastructure additions will be updated accordingly with the Simulation Execution project. Upon the completion of the RECOOP use case, the team will have developed a portfolio of system device upgrades and incentive strategies that can be applied to improve system reliability.

Simulation Execution project

Using the resilience metric originally developed for the Offshore Wind Use Case, the project team plans to gather outage data and create Monte Carlo outages to run for a base case simulation. The simulation will factor in a hardened distribution/transmission system, the microgrid Thrust 2 entities to measure resilience.

4.0 Large Electronic Loads

As the OSW use case concluded, the need to rapidly pivot the technical capabilities developed under the use case became apparent. Throughout FY25, the use case team identified several areas that overlapped with OSW-developed capabilities. Among these, large electric loads stood out as the most similar and pertinent use case, while still providing significant areas for capability expansion. This section will document the background, motivation, and potential research topics for the large electronic loads use case.

4.1 Background

Recent developments in power systems have created a significant paradigm shift with the rapid expected growth of large power electronics loads (LELs), particularly in the form of data centers. These loads are becoming a critical element in the modern energy landscape due to their increasing size and complexity, presenting unique challenges for grid stability, reliability, and optimization.

Data centers, which are integral to AI computation, cloud computing, and cryptocurrency processing, often exceed 75 MW in load (NERC, 2024) and some can scale up to over 1,000 MW (EPRI, 2024). The complexity of these systems arises not only due to their size but also a myriad of characteristics, including rapid ramp rates and potential stability constraints. Moreover, the rise in demand for large power electronics is occurring simultaneously with the global push for decarbonization and new generation sources, leading to more interactions between these systems and inverter-based resources in addition to traditional generation sources.

As these loads grow in both size and number, their impact on the electric grid will increase as well. Connecting these loads to minimize negative impacts and maximize grid operator flexibility is central to ensuring continued grid stability and adequate power quality. Simultaneously, there are large economic benefits associated with LELs (CBRE, 2024). Ensuring these future loads can connect quickly and efficiently will help spur economic growth and development.

While load growth due to LELs and potential LEL siting has considerable work performed to date (Roberts, 2025) (Shehabi, et al., 2024), limited work has been performed optimizing LEL buildout from multiple perspectives.

To address these challenges and opportunities, the use case team has developed a Large Electric Loads, specifically datacenters, focused use case. This use case will allow exploration of how to optimally build out and site LELs while considering grid stability, economic development, national security, ratepayer affordability, and resilience. This work can include power electronics model development, incentive structures, operational control development, and co-design of loads with onsite storage and generation.

This use case will build on capabilities from the OSW wind case as discussed in Section 2.5. The LEL use case will provide a valuable example of the transferability of core E-COMP concepts and demonstrate that the underlying principles can be applied to many different load and generation types.

4.2 Use Case Motivation

The primary motivation behind this use case is to advance modeling, optimization, and coordination frameworks for large electronic load systems, predominantly focusing on data centers. There are numerous pressing concerns and opportunities driving this need for advancement.

Data centers, particularly AI training facilities, can see rapid fluctuations in power draw as models are trained and used. Fluctuating power draw during training may be seen in Figure 10 (Shehabi, et al., 2024), and fluctuating power consumption may be seen in Figure 9 (Li, Mughees, Chen, & Li, 2024).

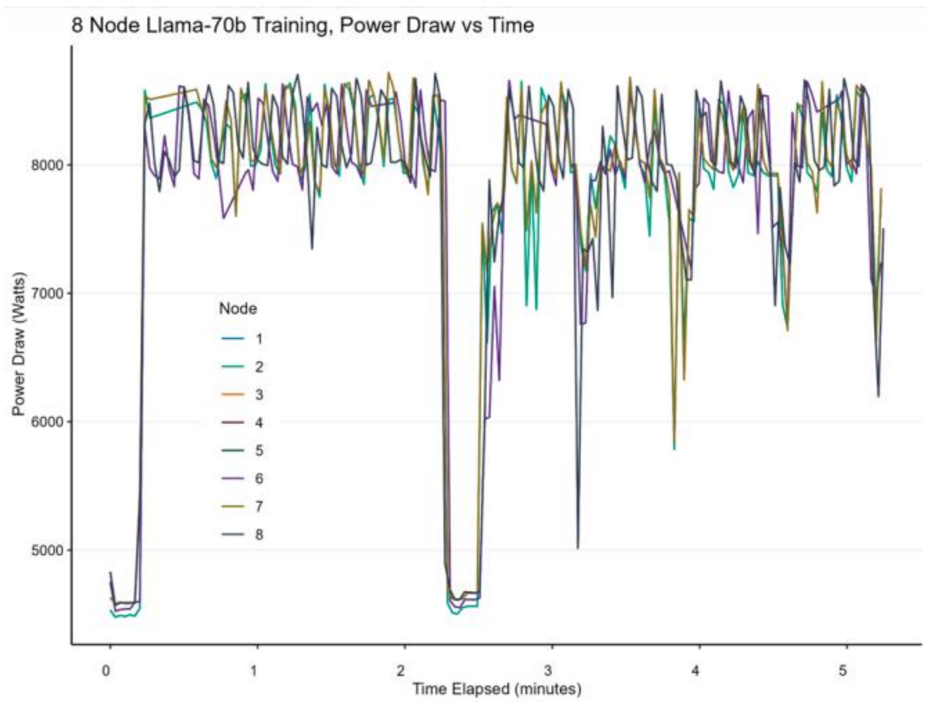

Figure 10: AI Training Consumption Fluctuations

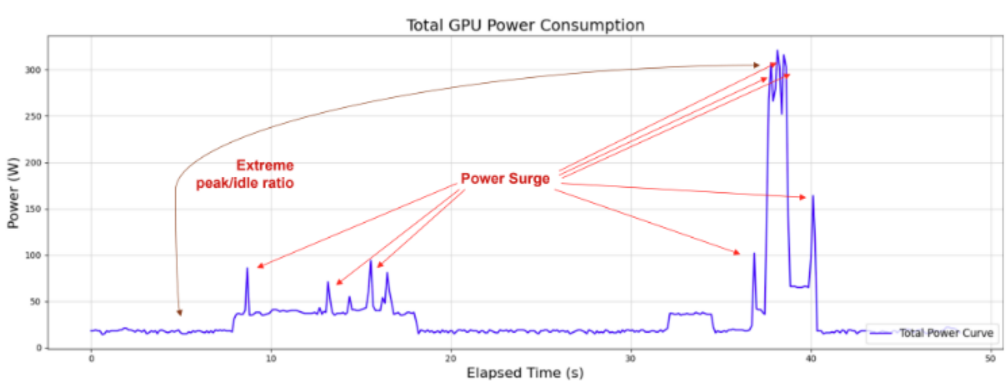

Figure 11: AI Model Inference Load Surges

These rapidly fluctuating loads have caused significant concern among utilities. This includes concerns around grid stability (Li, Mughees, Chen, & Li, 2024), service reliability (NERC, 2024) power quality (NERC, 2024), and abnormal fault responses (NERC, 2024).

In addition to potential concerns, LELs provide the option for operational flexibility if they are designed appropriately. For instance, there is the potential for data centers to serve as fast frequency response services (Kez, Foley, Ahmed, O'Malley, & Muyeen, 2021). There are additional opportunities for demand side load management with well-design data centers (Kez D. A., Foley, Ahmed, & Morrow, 2022).

Beyond grid stability and power quality concerns, there is also the need for improved power electronics modeling. While there are numerous potential topologies for data centers as shown in Figure 12 (Paananen, 2023), there are few to no representative models available for transient modeling.

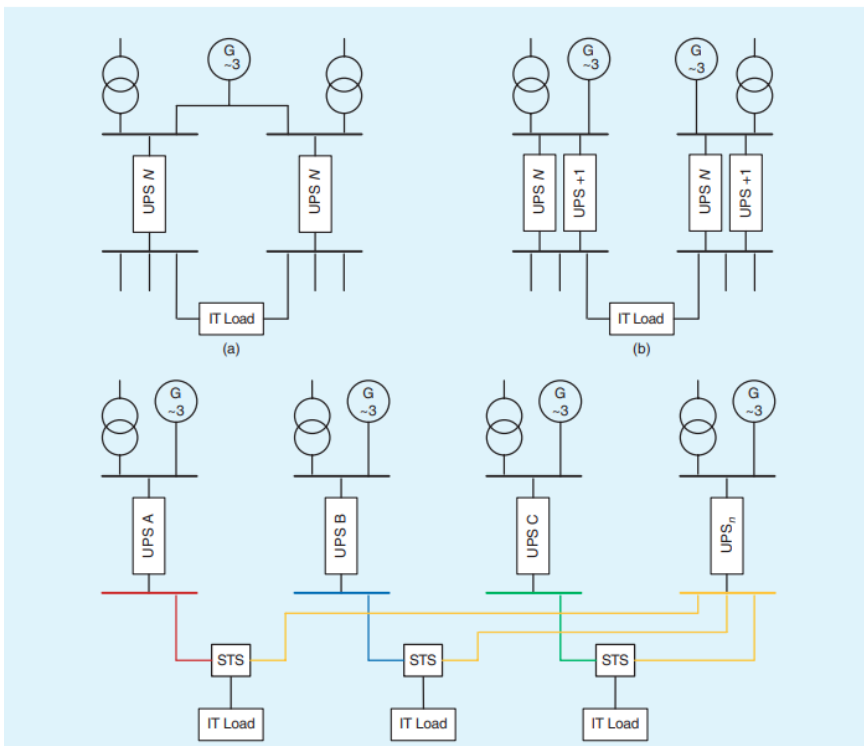

Figure 12: Data Center Topologies

The areas of power electronics modeling, stability modeling, capacity expansion, and physical testbeds are areas for which E-COMP is well-positioned to provide valuable insights across all three Thrusts.

Because of these growing concerns, applicability of core OSW-developed capabilities, and research potential for all three Thrusts, the LEL use case will provide a valuable opportunity for further E-COMP capability development.

4.3 High-Level Research Topics

The development of this use case emphasizes several key research areas that are necessary for addressing the challenges and leveraging the opportunities presented by large electronic loads. These areas revolve around the concept of data center islands as shown in Figure 13. These islands include data center loads, onsite generation, and onsite storage. From the grid operator perspective, there is concerned to be opportunity for signal exchange between the islands and the grid, as well as the potential for additional infrastructure build out to meet the load requirements.

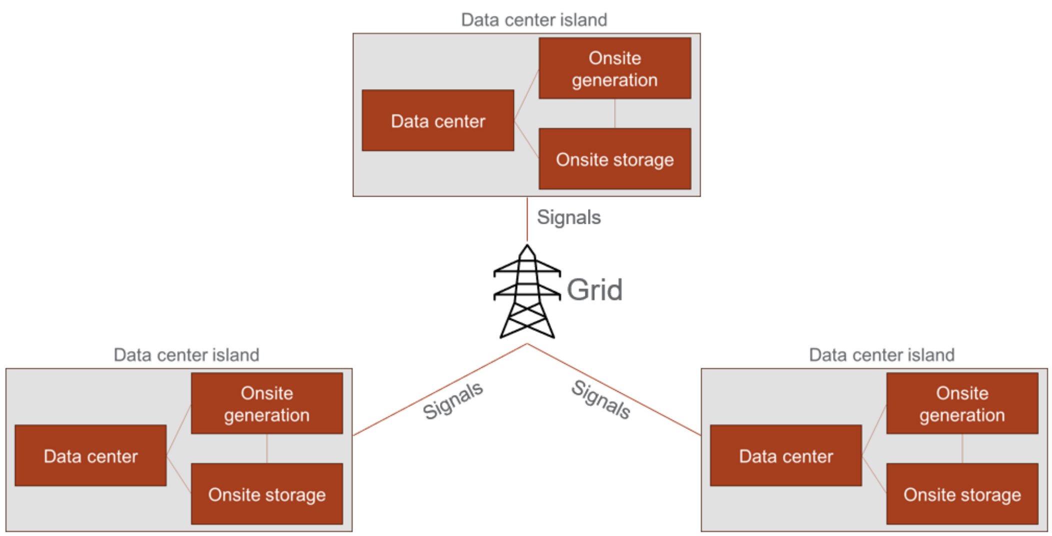

Figure 13: Datacenter Islands

While there are extensive areas for research within the LEL use case, the use case team has worked with each Thrust to identify the primary areas for initial exploration. These areas include the following:

1. **Thrust 1: Theory and modeling**
    - Simultaneous capacity expansion modeling to accommodate loads, generation, and transmission needs.
    - Stability analysis to address reliability issues and resilience concerns emerging from large power electronics loads.
    - Improved power electronics modeling and representative model development for data centers.
2. **Thrust 2: Multi-objective co-design**
    - Collaboration between data centers and onsite energy generation/storage systems to identify optimal balance scenarios.

- Co-design incorporating varying perspectives, such as grid operator requirements and data center priorities.

3. **Thrust 3: System Integration and Simulation**

    - Study cooperative behavior through advanced simulation tools, possibly incorporating elements of game theory.
    - Coordinate multiple data centers to optimize grid-level operations and security.
    - Investigate mechanisms for promoting demand response and ramp rate management services by data centers.

By pursuing these research areas, E-COMP will further develop capabilities for improving load integration.

5.0 Conclusions and Next Steps

In summary, the Use-Case Specification team has developed three use cases that have been pivotal to the E-COMP initiative. Through the offshore wind use case, E-COMP rapidly applied its capabilities to solve problems associated with the interconnection of large generation. With RECOOP, E-COMP demonstrated that these same principles and techniques can be applied to solve reliability and affordability challenges in remote areas through distribution microgrids. And finally, the Large Electric Loads use case will pivot and adapt capabilities to meet the needs of rapid load growth.

As E-COMP moves towards pursing outside funding, these use cases will prove to be instrumental in effectively demonstrating what E-COMPs capabilities are. The use cases will serve as a basis for more targeted applications of co-design and will continue to develop and improve E-COMP’s capabilities.

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