Bonneville Power Administration

Transmission Services Technology Roadmap





March 2017

Enhanced PDF Functionality

Functionality of the PDF version of this document has been enhanced in the following ways:

- Bookmarks: Enabled PDF reader applications (i.e., Adobe Acrobat) can navigate this document using the Bookmark feature.

- Embedded Links: The Table of Contents has been linked to the appropriate sections of the document.

- Control + F / Command + F: As always, one can navigate through the document in the Windows environment by searching for specific words or phrases by pressing the "Control" and "F" keys simultaneously; in a Mac environment use the "Command" and "F" keys simultaneously.

SPECIAL NOTE

Roadmaps are the publically-articulated research agenda for communicating the Bonneville Power Administration's (BPA) technology research, development, and demonstration (RD&D) needs to the research community. They are one of the four key components of the BPA Technology Innovation (TO) Office's "system of systems" in providing a "One BPA" approach to managing technology RD&D.[1] These documents are prepared as part of BPA TI's annual funding opportunity announcement.

Readers will find that the March 2017 version of the BPA's roadmaps differ in fundamental ways from documents published since 2006. These changes are a result of maturation work conducted in 2015–2016 that identified a number of opportunities to improve how we implement roadmapping as a process and how we communicate the results of this process more effectively in our deliverables.[2] Highlights of these changes include:

- **Clearer focus on Agency priorities:** Roadmaps for both our Power and Transmission Services organizations reflect a convergence among internal BPA staff and management upon higher-priority technology domains and research needs. This enabled the March 2017 roadmaps to communicate a fraction of the content that existed in earlier versions, thereby making priority topics clearer to external proposers.
- **Easier-to-interpret narratives and diagrams:** Adopting the Cambridge University Institute for Manufacturing's "Fast Start" roadmapping process enabled the creation of time-sequenced roadmap diagrams to communicate Agency RD&D needs in a more intuitive text-based and visual format.[3] This was done to
  - convey priorities more effectively, and
  - reflect a meaningful narrative articulating change over time from the current state to a desired future state.

As with previous iterations of Agency technology roadmaps, we consider these live, working documents and are always seeking ways to improve our process and deliverables. We welcome all feedback and comments. We are also happy to share details of our process, templates, tools, and techniques.

For more information contact:

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[1] BPA TI, "Technology Innovation Office Introduction & Overview," June 17, 2016.

[2] James V. Hillegas-Elting, "Roadmapping & Maturity Models: Coming to a View of the Forest." (Portland, Oreg.: Bonneville Power Administration Technology Innovation Office, Aug. 19, 2016); Hillegas-Elting, Chih-Jen Yu, Terry Oliver, Tugrul Daim, and Judith Estep, "Technology Roadmap Development Framework: A Case Study within the Energy Sector," *Research and Development Management (RADMA) Conference*, July 2016.

[3] See, for example: Clive Kerr and Robert Phaal, "A Scalable Toolkit Platform: Configurations for Deployment in Technology and Innovation Strategy Workshops," *Research and Development Management (RADMA) Conference*, June 2015; Kerr, Clare Farrukh, Phaal, and David R. Probert, "Key Principles for Developing Industrially Relevant Strategic Technology Management Toolkits," *Technological Forecasting and Social Change* 80: 6 (June 2013), 1050-1070; and Phaal, Farrukh, and Probert, *Roadmapping for Strategy and Innovation: Aligning Technology and Markets in a Dynamic World* (Cambridge, U.K.: University of Cambridge Institute for Manufacturing, 2010).

Letter of Introduction

A disciplined approach to technology research and development helps the Bonneville Power Administration (BPA) respond proactively to the rapidly-changing utility industry environment. Through effective research management practices, BPA's Technology Innovation (TI) Office brings tangible benefits to BPA's transmission system operations, the power operations of thirty-one federally-owned hydroelectric dams in the region, and to BPA's energy efficiency and demand response teams.

BPA funds an RD&D program with an annual budget of approximately $15 million (U.S.), which is about .05 percent of Agency revenues. While short of the 3.5 percent average across all U.S. industries, this amount is significantly higher than the electric utility average for such investments. With these funds BPA is demonstrating how a disciplined approach involving a well-articulated "system of systems" can deliver value. These systems—roadmapping, portfolio management, project management, and technology transfer—are fundamental, but equally important is collaboration with other innovators such as electric utilities, national laboratories, technology developers, research universities, nonprofits, and vendors. This collaboration has led to millions of dollars in savings to BPA through avoided costs, operational improvements, and increased efficiencies.[4]

At the front-end of these achievements are technology roadmaps—including the present document—which distill input from a diverse range of internal and external experts. These documents identify and link business challenges and opportunities with potential technical solutions, and then articulate these needs to the research community during the BPA TI Office's annual funding opportunity announcements each March. Since 2009, more than 430 people representing nearly 170 organizations have contributed to Agency technology roadmaps for energy efficiency, demand response, transmission, and hydropower asset management.

These many contributors—and the many organizations that have submitted proposals over the years—will find some substantial improvements in the current roadmap. The most obvious will be the organization and graphics, which have been modified significantly to help convey Agency priorities more clearly and concisely. A corollary to this is that the page count has been reduced markedly, reflecting more effective prioritization based on Agency needs.

We are indebted to the many earlier contributors to this roadmap for the insightful original content; we are, perhaps, even more indebted to the discipline exhibited by members of the BPA Technology Confirmation and Innovation Council, who reflected upon the various Agency strategic efforts in late 2016 and arrived at a sub-set of critical content from previous roadmap versions to carry forward and update for this current version.

We create roadmaps is to articulate pressing Agency technology RD&D needs to the research community: We endeavor to make our needs comprehensible to the creative minds at national laboratories, universities, vendors, and other organizations so we can continue to help drive regional innovation, energy security, and economic prosperity. We think we have matured in this regard in publishing this roadmap document, but we also recognize this is always a work-in-progress and welcome any and all input and suggestions.

Sincerely,

Terry Oliver

Chief Technology Innovation Officer

Bonneville Power Administration

[4] Terry Oliver, "Disciplined Research," *T&D World* Feb. 2016, p. 64.

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Executive Summary

The Bonneville Power Administration's (BPA) mission as a public service organization is to work in concert with others to create and deliver the best value for our regional customers and constituents. As part of this work, roadmaps are the publically-articulated research agenda for communicating the BPA's technology research, development, and demonstration (RD&D) needs. Roadmaps are one of four key components of the BPA Technology Innovation (TO) Office's "system of systems" in managing technology RD&D. These documents are prepared as part of BPA TI's annual funding opportunity announcement.

The BPA TI Office herein identifies research priorities for two operational groups within the Agency's Transmission Services Business Line: Transmission Planning and Asset Management and Transmission Engineering.

BPA Transmission Planning and Asset Management

The technology domains of interest to the BPA Transmission Planning and Asset Management organization are:

- System Control
- Situation Awareness

BPA Transmission Engineering

The technology domain of interest to the BPA Transmission Engineering organization is:

- Disaster Preparedness and Recovery

INTRODUCTION

The Bonneville Power Administration (BPA) is a nonprofit federal power marketing administration based in the Pacific Northwest. Although BPA is part of the U.S. Department of Energy, it is self-funding and covers its costs by selling its products and services. BPA markets wholesale electrical power from thirty-one federal hydroelectric projects in the Northwest, one nonfederal nuclear plant, and several small nonfederal power plants. BPA also operates and maintains about three-fourths of the high-voltage transmission in its service territory, which includes Idaho, Oregon, Washington, western Montana and small parts of eastern Montana, California, Nevada, Utah and Wyoming.[5]

The Agency pursues its mission, vision, and values in the context of rapidly evolving industry and environmental issues. The Agency regularly assesses the drivers of change in its operating environment and establish long-term direction and near-term targets to focus efforts and resources.[6]

One manifestation of this commitment to regional stakeholders is the proactive management of a technology research, development, and demonstration (RD&D) portfolio focused on bringing into operations technological solutions that meet critical drivers and respond to key opportunities, challenges, and risks. The Agency's Technology Innovation (TI) Office facilitates the processes of soliciting input from internal and external experts to clarify needs, generate research ideas, solicit and review proposals addressing these needs, and manage the resulting project portfolio.

The production and maintenance of technology roadmaps is a critical part of this process. Evolving primarily out of product development firms beginning in the 1960s and 1970s, since the 1990s roadmapping is no longer limited to its original application; it is now a highly customizable business process applicable to a wide array of tactical and strategic planning topics.

Maturing its use of the roadmapping process, the BPA TI Office herein identifies research priorities for two operational groups within the Agency's Transmission Services Business Line: Transmission Planning and Asset Management and Transmission Engineering.

[5] BPA, "About Us," https://www.bpa.gov/news/AboutUs/Pages/default.aspx.

[6] BPA, "Strategic Direction," https://www.bpa.gov/news/AboutUs/Pages/StrategicDirection.aspx.

BPA Transmission Planning and Asset Management

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Agency Priorities

The BPA's mission as a public service organization is to create and deliver the best value for our customers and constituents acting in concert with others to assure the Pacific Northwest:

- an adequate, efficient, economical and reliable power supply;
- a transmission system that is adequate to the task of integrating and transmitting power from federal and non-federal generating units, providing service to BPA's customers, providing interregional interconnections, and maintaining electrical reliability and stability; and
- mitigation of the impacts on fish and wildlife from the federally-owned hydroelectric projects from which BPA markets power.[7]

[7] BPA, "Mission," https://www.bpa.gov/news/AboutUs/Pages/Mission-Vision-Values.aspx.

BPA achieves its mission by focusing on five priorities (see Figure 1), guided by key strategic initiatives and measured by key performance indicators. The Agency has a unique position as a major motivating force of the Pacific

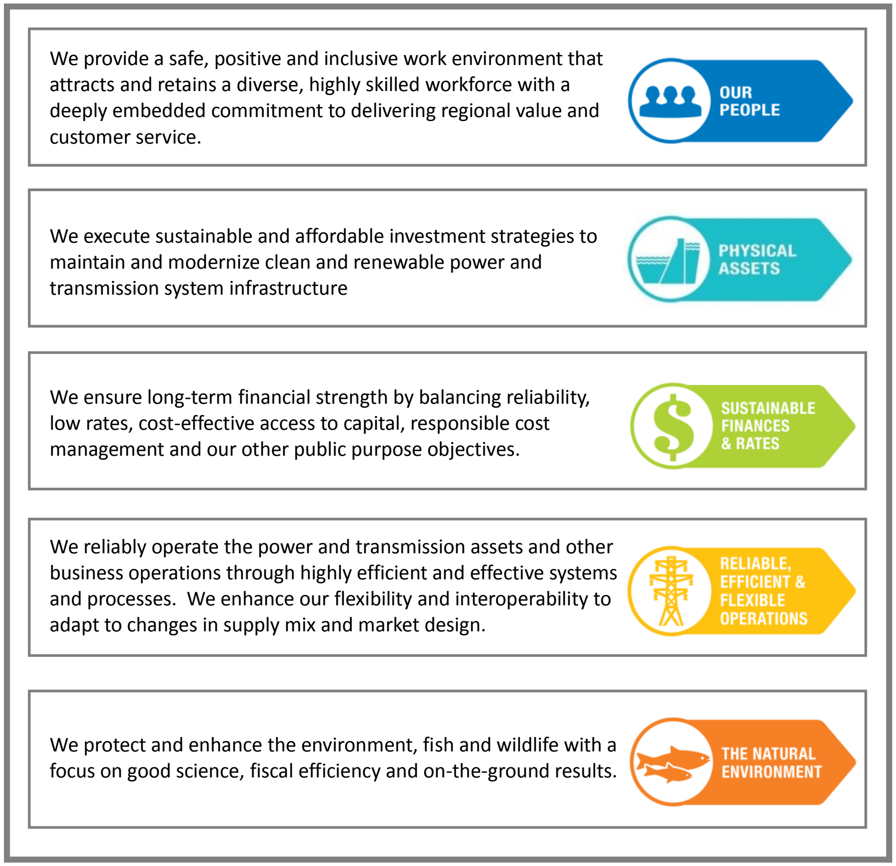

Figure 1: Bonneville Power Administration Strategic Priorities.

Northwest economy and way of life. Through the talent of *Our People*, we are maintaining and enhancing the region's investments in federal *Physical Assets* that we own or in which we have a significant stake. As an economic engine, we understand that our actions have impacts to our customers and their communities, so we are striving to accomplish our overall mission while also delivering *Sustainable Finances and Rates*. We also recognize that the dynamics of our industry are evolving faster than ever before, and so we continue to advance policies and investments that result in *Reliable, Efficient, and Flexible operations*. As well, the *Natural Environment* of the Northwest is inherently connected to both our economy and our way of life, and BPA remains committed to mitigation actions and environmental enhancements that will continue to add value for years to come.[8]

The technology RD&D needs articulated in this roadmap align with one or more of the Agency's five priorities. This alignment cascades down from the level of broad Agency-wide priorities, through increasingly more specific priorities and key strategic initiatives (KSIs) nested within these for the Power and Transmission business lines, and, finally, down into the applicable departments, groups, and teams within each business line. These interconnections and interdependencies are visualized in Figure 2.

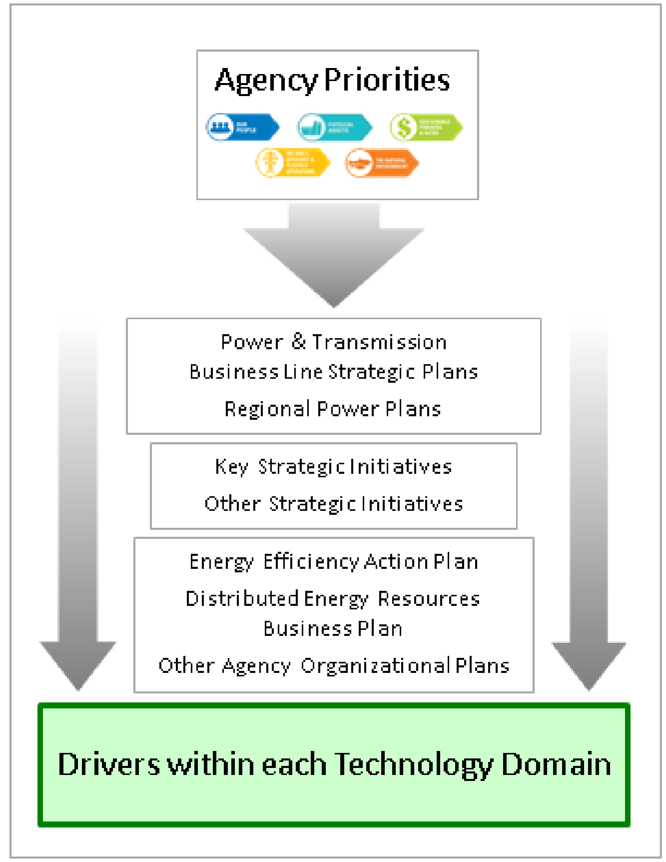

Figure 2: Relationship between Bonneville Power Administration Strategic Priorities and individual Drivers within the technology roadmap.

[8] BPA, "BPA's Fiscal Year 2016 Strategic Direction," available at https://www.bpa.gov/news/AboutUs/Documents/Strategic-Direction-FY-2016.pdf.

Drivers prioritized in this roadmap are those that can be defined as "utility enabling:" drivers for which technology-based solutions and apply and that enable BPA to achieve its mission. Drivers relying upon on-technology solutions (such as policies, business processes, and workforce training) may also be important to the Agency and its stakeholders, but have not been featured in this *technology* roadmap. Further, technology-focused drivers that are outside the purview of BPA's core areas of responsibility are also not featured in this roadmap. These might include consumer preferences—primarily the purview of product manufacturers—and non-energy benefits such as health and comfort which often are important but *not* what *primarily* drives Agency decisions.

What Is Technology Roadmapping?[9]

Clear, concise, and actionable definitions for "roadmap" and "roadmapping" may seem intuitive, but beyond the obvious cartographical reference, they are not. An Internet search quickly turns-up a wide array of implicit and explicit definitions, many of which lack substance and specificity. Turning to the academic literature for guidance may not always be as helpful as one might hope. The practice of roadmapping grew out of technology manufacturing firms in the 1960s and 1970s and continues to evolve within the academic discipline of engineering and technology management, but a survey of this literature uncovers definitions that often do more to obfuscate than clarify.

To avoid confusion, it is necessary to differentiate between similar terms used in the literature to distinguish process from artifact. *Roadmapping* is the process of creating an artifact or deliverable—the *roadmap* document itself. Kerr *et al.* call this the "dyadic nature of roadmapping" because it involves the complementarity of "method, tool, workshop, template, image, and document" required to achieve desired results from the process.[10]

Cambridge University IfM faculty offer succinct definitions that draw upon literature and extensive practical experience. Unlike many definitions focused on technology-centric "traditional" roadmaps produced by Motorola, IBM, SEMATECH, and others, theirs is inclusive of the wide variety of other kinds of roadmaps that have proliferated over the decades:

> A ***roadmap*** is a structured visual narrative of strategic intent. It supports comprehension, dialogue, and communication to enable strategic decision making, planning, and implementation.
>
> ***Roadmapping*** processes use roadmap principles to support integration, alignment, and synchronization for strategy, innovation, and other management purposes, often (but not necessarily always) leading to the development of roadmaps.

Thus, *roadmaps* are the deliverables produced as an outcome of the roadmapping process. *Roadmapping* is a scalable planning process in which key stakeholders collaborate to brainstorm, organize, and prioritize actions as a way to motivate collective efforts toward a future state of mutual interest. Often (but not always necessarily) resulting from this process is a deliverable documenting and summarizing the collaboratively-developed plan.

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[9] Content in this section excerpted from: James V. Hillegas-Elting, "Roadmapping & Maturity Models: Coming to a View of the Forest" (white paper) (Portland, Oreg.: Bonneville Power Administration Technology Innovation Office, Aug. 19, 2016).

[10] Clive Kerr, Robert Phaal, and David R. Probert, "Cogitate, Articulate, Communicate: The Psychosocial Reality of Technology Roadmapping and Roadmaps," *R&D Management* 42:1 (2012), 1-13.

Technology Roadmapping at BPA[11]

The Agency created a TI Office in 2005 to centralize technology RD&D efforts to help BPA continue its mission of providing safe, reliable, and cost-effective electricity. In doing so it has led the utility industry in applying technology management best practices to develop a "system of systems" guiding the management of the Agency's RD&D portfolio. Roadmapping is one of four core "systems," the others being project management, portfolio management, and technology transfer (see Figure 3).

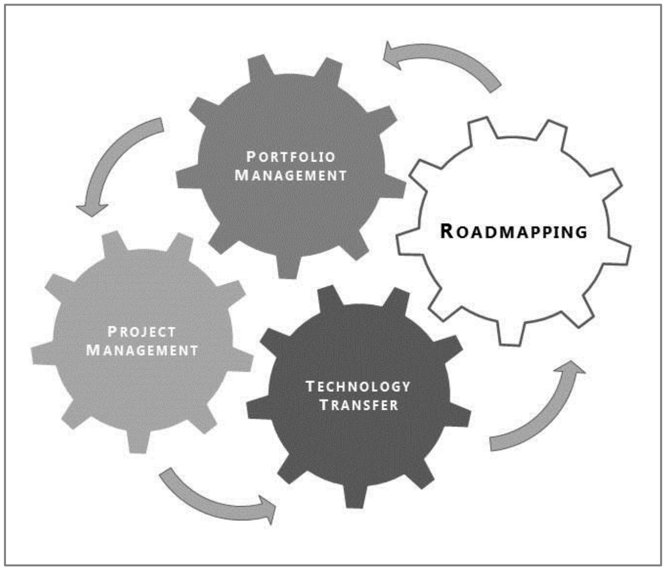


Figure 3: Bonneville Power Administration Technology Innovation Office's "System of Systems"

BPA TI's roadmaps are the publically-articulated research agenda for communicating the Agency's technology RD&D needs to the research community. They contribute to the Agency's innovation agenda by documenting needs in such areas as energy efficiency, demand response, transmission, and hydropower, and linking these to strategic goals, critical business drivers, and emerging opportunities. Further, roadmaps guide the BPA TI Office's annual solicitation for RD&D project proposals and help sustain the agency's role as stewards of ratepayer funds by ensuring due diligence.

Research needs are articulated by way of a narrative linking the following key elements:

- Current State: Where the Agency stands at present in relation to the given technology domain.
- Future State: Where the Agency would like to be at some point in the future.
- Drivers: Needs, assumptions, trends, opportunities, threats, etc. motivating change; why the Agency cares about a particular issue or topic.
- What needs to happen: Sequential steps to proceed from the current state to the desired future state, with corresponding milestones to denote progress along this path.
    - Capability Gaps: Milestones expressed as barriers standing in the way of responding to Drivers; Capability Gaps are linked to one or more Drivers.
    - Technology Characteristics: Technological solutions with the potential to overcome the barriers and reach the milestones expressed through linked Capability Gaps.
- RD&D Program Descriptions: Research programs and some Key Research Questions to pursue to develop technological solutions expressed in the form of linked Technology Characteristics; suggestions about how the work could be done to proceed from the Current State to the Future State.

This roadmap communicates *technology* RD&D opportunities where subject matter experts have determined that such research is needed to enable business processes, achieve cost-savings and reliability targets, support new and evolving market structures, and otherwise foster the Agency's mission, vision, values, and strategic priorities. These subject matter experts have represented two complementary (and not always mutually exclusive) categories, convened during two sequential workshops:[12]

- Workshop 1—Articulate Drivers and Capability Gaps: Senior-level leaders and operations managers involved in developing and / or implementing corporate strategy (such as public policy, regulatory

[11] Content in this section excerpted from: James V. Hillegas-Elting, Terry Oliver, Joshua Binus, Tugrul Daim, Judith Estep, and Jisun Kim, "Opening the Door to Breakthroughs That Address Strategic Organizational Needs: Applying Technology Roadmapping Tools and Techniques at an Electric Utility," Portland International Conference on Management of Engineering and Technology (PICMET), 2015, pp. 2564–2573; Hillegas-Elting, Chih-Jen Yu, Oliver, Daim, and Estep, "Technology Roadmap Development Framework: A Case Study within the Energy Sector," Research and Development Management (RADMA) Conference, July 2016; BPA, "Technology Innovation Office Introduction & Overview," June 17, 2016.

[12] Hillegas-Elting *et al.*, "Opening the Door to Breakthroughs That Address Strategic Organizational Needs."

compliance, and business development), as well as having some familiarity with the role played by technologies to achieve strategic goals. These experts framed the "strategic" level of the roadmap by linking Drivers with Capability Gaps.

- Workshop 2—Articulate Technology Characteristics and RD&D Program Descriptions: Subject matter experts from utilities, national laboratories, universities, non-governmental organizations, and the private sector develop "tactical" roadmap content—the Technology Characteristics and RD&D Programs—that can help meet "strategic" Drivers and Capability Gaps. These experts included engineers, operators, researchers, academics, and others with direct and deep knowledge and experience in envisioning, developing, and analyzing technologies, models, algorithms, systems, etc.

To date, the TI Office has facilitated roadmap development projects that have brought together subject matter experts from within BPA; from beyond the Agency to include regional stakeholders; and from beyond the region to involve specialists throughout North America. In the aggregate, since 2009 BPA's technology roadmaps for energy efficiency, transmission, demand response, and power generation asset management have benefitted from the input of more than 430 people representing nearly 170 organizations.

BPA Technology Innovation's Approach to RD&D

BPA TI strives to mange the Agency's RD&D portfolio in a way that not only balances needs articulated by its Transmission and Power Business Lines, but also based on the different types of research—Breakthrough, Incremental, and Confirmational—and technology readiness levels.

Types of research

Breakthrough: High-risk projects to deliver significant improvements in efficiency, effectiveness, and/or usability but that take longer to bring out of the RD&D realm and into full market implementation.

Incremental: Lower-risk projects offering step-by-step improvements in efficiency, effectiveness, and/or usability in new applications and likely to be ready for full market implantation in no more than three years.

Confirmational: Lower-risk projects to ratify or corroborate efficiency, effectiveness, and/or usability in new applications, within different climate conditions, or by proving something not yet used at BPA and likely to be ready for full market implementation in no more than three years.

Technology Readiness Levels (TRLs)

TRLs establish an objective scale for evaluating the relative developmental stages of a technology. This methodology allows for consistent comparisons between different types of technologies across a range of maturity levels, from low maturity or basic research (TRL 1) to the high maturity of a ready-to-implement technology (TRL 9).

The National Aeronautic and Space Administration (NASA) originally developed TRLs in the 1970s and the concept has since been adopted in other industries. In the electric utility industry, for example, the U.S. Department of Energy's Advanced Manufacturing Office (AMO) applies TRLs to "guide disciplined decision-making throughout the technology development pipeline" and to provide a "rigorous approach . . . to track the progression of each project and activity, from applied research to commercialization."[13] Adapted from NASA's scale, the DOE AMO's stages are represented in Table 1.

Table 1: Technology Readiness Levels (TRLs)

Phase	TRL	Definition
Innovation	1	Basic Research
	2	Applied Research
	3	Critical Function or Proof of Concept Established
Emerging Technologies	4	Laboratory Testing / Validation of Component(s) and Process(es)
	5	Laboratory Testing of Integrated/Semi-Integrated System
	6	Prototype System Verified
Systems Integration	7	Integrated Pilot System Demonstrated
	8	System Incorporated in Commercial Design
Market Penetration	9	System Proven and Ready for Full Commercial Deployment

[13] "Technology Readiness Levels (TRLs)," U.S. Department of Energy Advanced Manufacturing Office, available at http://www1.eere.energy.gov/manufacturing/financial/trls.html, accessed Sep. 9, 2013. See also "Technology Readiness Assessment (TRA) / Technology Maturation Plan (TMP) process Guide," U.S. Department of Energy Office of Environmental Management, March 2008 and John C. Mankins, "Technology Readiness Levels—A White Paper," National Aeronautic and Space Administration, April 6, 1995.

How to Use this Roadmap

The design of this roadmap is based on the reference process developed by faculty and students at the Cambridge University Institute for Manufacturing (IfM). They call it the "Fast Start" or "S-Plan/T-Plan" process, and it provides a scalable, highly modular, and eminently tailorable process that readily accommodates any kind of planning topic. The fundamental architecture of this process is a series of questions asked of experts within a structured brainstorming workshop environment to arrive at answers to five key questions:

1) *Where are we now*; what is our current state?
2) *Why* do we want to take some kind of action; why do we need to change?
3) *Where do we want to go* at some point in the future?
4) *What* are the sequential steps needed to proceed from our current state to our desired future state, and corresponding milestones to denote progress along this path?
5) *How* will we achieve our sequential steps—who will do the work and what resources are needed?

Figure 4 shows how these questions would generate content for a summary visual representation in graphical format—the *roadmap* deliverable produced through the *roadmapping* process. This content is represented using three "swim lanes" corresponding to the "Why," "What?," and "How?" categories.[14]

As applied in the current document, rather than being represented in a single visual diagram, "Why?," "What?," and "How?" content is arrayed on separate pages. This is done to simplify diagrams that users found to be confusing and cluttered in previous iterations of BPA TI's roadmaps. Thus, within each technology area addressed in the pages that follow, the following sections correspond to Cambridge IfM's reference process:

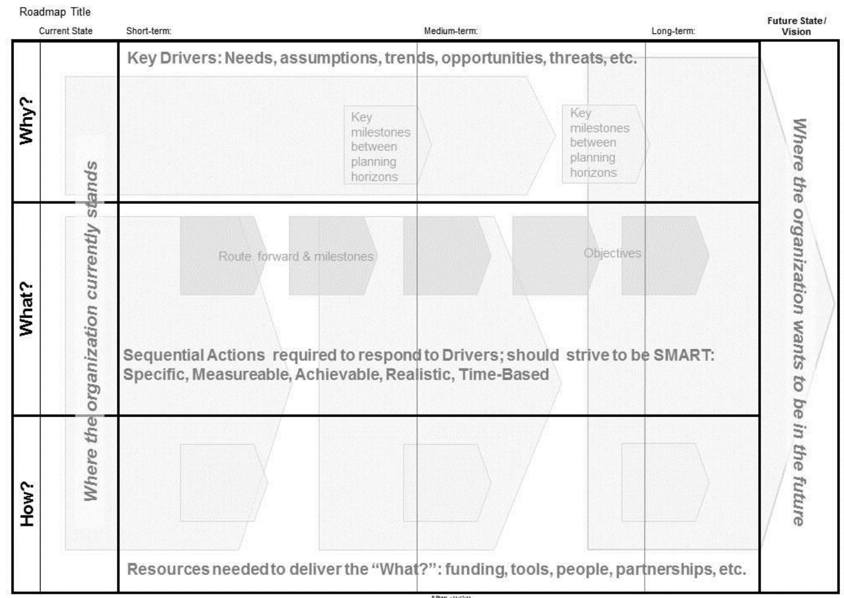


Figure 4: Cambridge University Institute for Manufacturing's basic roadmap template, showing graphical representation of the "Why?," "What?," and "How?" swim lanes (modified slightly for applications at BPA).

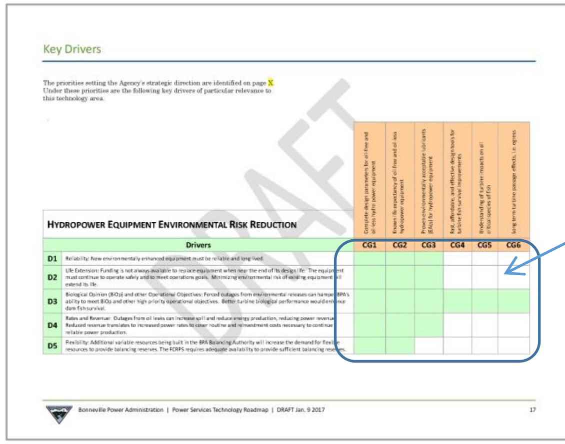
- Why: "Key Drivers" section conveying the needs, assumptions, trends, opportunities, threats, etc. motivating change. This section includes a grid linking each Driver with one or more Capability Gaps, thereby identifying why the Gap is important to address.
- What: Important actions—"Technology Characteristics"—and milestones—"Capability Gaps"—are arrayed sequentially along a timeline to help communicate the steps needed to progress from the current state to the desired future state.
- How: "Research, Development, & Demonstration Summaries" section providing titles, descriptions, key research questions, and any known ongoing research on this topic. Each summary shows its linkage to one or more Technology Characteristic.

[14] Clive Kerr and Robert Phaal, "A Scalable Toolkit Platform: Configurations for Deployment in Technology and Innovation Strategy Workshops," *Research and Development Management (RADMA) Conference*, June 2015; Robert Phaal, Clare Farrukh, and David Probert, *Roadmapping for Strategy and Innovation: Aligning Technology and Markets in a Dynamic World* (Cambridge, U.K.: University of Cambridge Institute for Manufacturing, 2010).

Cambridge University Institute for Manufacturing's "Swim Lanes"

"Why?"

Key Drivers pages

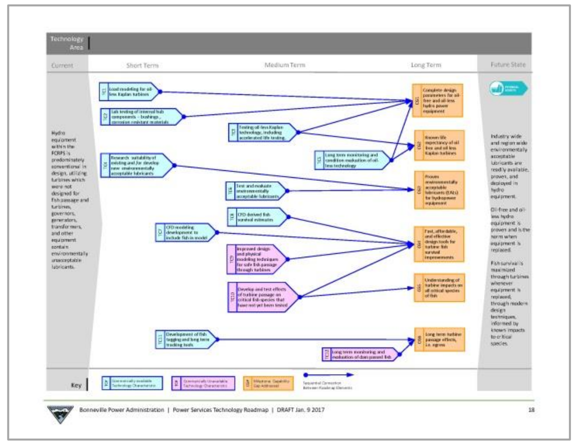


Grid showing linkages between Drivers and Capability Gaps, thereby identifying why the Gap is important to address.

Green shading denotes linkages.

"What?"

Technology Domain diagram pages



Important actions and milestones arrayed sequentially along a timeline to help communicate the steps needed to progress from the current state to the desired future state.

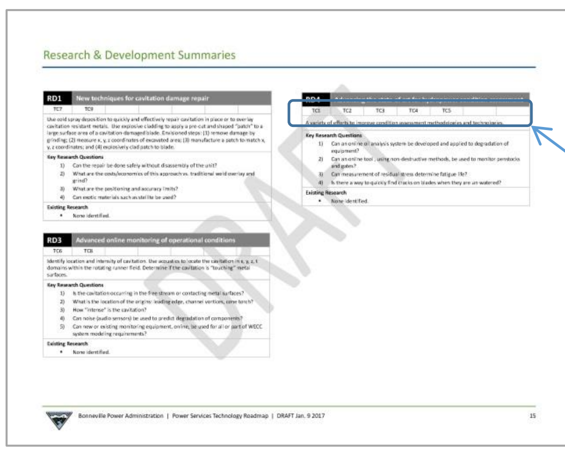
Technology Characteristic-Available

Technology Characteristic-Unavailable

Milestone: Capability Gaps

"How?"

Research, Development, & Demonstration (RD&D) Summaries pages



Provides titles, descriptions, key research questions, and any known ongoing research on this topic.

Each summary shows its linkage to one or more Technology Characteristic.

Transmission Planning and Asset Management (TP)

The BPA Transmission Planning and Asset Management organization (code "TP") is comprised of the following sub-organizations:

- Customer Service Engineering (TPC)
- Long Term Planning (TPL)
- Communications & Grid Modeling (TPM)
- Strategy & Program Management (TPO)
- Transmission Planning (TPP)
- Asset Management Oversight & Program Support (TPW)

Sections in this roadmap:

System Control

- Power Flow Controls for Congestion Management

Situation Awareness

- Synchrophasor Data Storage, Processing, and Visualization

BPA Transmission Planning (TPP): System Control

Section Definition

Well-designed, automated controls capable of processing and responding to power system information improve the stability, reliability and transfer capacity of the grid. Such controls can enable a "self-healing grid"— a grid that can routinely or automatically detect, analyze and respond to events, and restore the grid to maintain reliability, security, and power quality. Examples of technology needs include power system stability controls, improved remedial action schemes, power flow controls such as flexible alternating current transmission system (FACTS) devices, real-time tools for voltage and frequency control and support, etc.

In the current Agency technology roadmap, the primary interest is to advance Agency knowledge in the area of power flow controls for congestion management. Power flow control devices for transmission systems are used to modulate electron flow across conduits by actively increasing impedance along one line to re-direct flow to other lines. Boosting system capacity in this way can be a less-expensive option to building new transmission lines while maintaining overall system reliability, thereby postponing or potentially eliminating the need for expensive transmission construction projects. As such, power flow control devices can be one potential "non-wires" alternative.

Summary

Why this is Important to BPA

Fundamental to BPA's interest in power flow controls is the Agency's statutory obligation to provide sufficient capability to serve customers through a safe and reliable transmission system. Further, mandatory reliability standards and principles of good utility practice prohibit BPA from operating the transmission system beyond its capacity. Stemming from these over-arching driver are the following requirements motivating the Agency's interest in power flow controls technologies:[15]

- Respond to transmission system congestion by increasing long-term capacity and transfer capability
- Respond to growing system reliability concerns
- Respond to increasing local demand for electricity
- Respond to requests for long-term firm transmission service

Current State

Power flow controls are known solutions for transmission system congestion management and constraint relief, but Agency experience with them has been mixed. While BPA has been one of the leaders in deployment of fixed series capacitors, experience with controlled devices was not positive. Thyristor controlled series compensation (TCSC) equipment installed at BPA's Slatt substation has experienced numerous thyristor control and cooling system failures, making the device a reliability risk and resulting in device breaker bypass.[16] At the same time, there are several other successful TCSC installations around the world. Other power flow control technologies—such as phase shifters and smart wire—have been deployed successfully many times.

Future State

An expanded portfolio of technology solutions BPA Transmission planners can use in developing system reinforcement plans. Ultimately, these power flow solutions can defer or even eliminate the need for new transmission lines, resulting in significant cost savings for BPA and its ratepayers.

Research Opportunities

BPA Transmission Planning staff have identified three sequential areas of research needed:

1) Hardware Evaluation: Currently and into the short-term, identify existing hardware; assess potential of this hardware application to address BPA system needs; and conduct pilot testing to collect performance, cost, and operations data for modeling purposes.

[15] Bonneville Power Administration, "I-5 Corridor Reinforcement Project Final Environmental Impact Statement," Vol. 1, Chapter 1, Feb. 2016, available at https://www.bpa.gov/Projects/Projects/I-5/Pages/EIS.aspx.

[16] Vaithianathan Venkatasubramanian and Carson W. Taylor, "Improving Pacific Intertie Stability Using Slatt Thyristor Controlled Series Compensation," IEEE Power Engineering Society Winter Mtg., Singapore, Jan. 2000.

2) Modeling: In the medium-term, apply findings from the hardware evaluation phase to model power flow control devices accurately for planning and operational control purposes and verify existing power flow control models accurately to predict behavior of installed devices.
3) Operational Control: In the long term, achieve the ability to control power flow explicitly to enable accessing unused capacity to relieve congestion and outage constraints while improving system security as an alternative to building new transmission lines.

To address #1 above, BPA is currently collaborating with the Electric Power Research Institute (EPRI) on Technology Innovation Project (TIP) 362, "Assessment of Maturity and Technology Readiness of Power Flow Control Solutions for Congestion Management Problems," in two phases:

- Phase 1 (April 2016–Feb. 2017): Landscape analysis of maturity and readiness of various power flow control technologies to increase understanding among BPA Transmission Planning staff and enable risk-informed decision-making on using controllers as congestion management solutions.
- Phase 2 (Feb 2017–Sep. 2018): Apply knowledge gained during Phase 1 to evaluate sub-set of technologies deemed most relevant to BPA applications; engage the equipment manufacturers to develop methodologies for rating and sizing power flow control devices.

Phase 1 of this project will help overcome two Capability Gaps:

- To optimize the grid, need to understand what devices are available, where to put them, what sizes (capabilities) are needed, and then conduct longer long term assessment and evaluation of interactions.
- Develop specifications to compare power flow control device performance.

Overcoming these gaps in the nearer-term will enable the Agency to pursue sequential research projects as part of Phase 2 to develop the following Technology Characteristics:

- Pilot field test of power flow control devices to demonstrate feasibility and benefits.
- Collect data on actual performance, costs, and operating experience of power flow control products.

As TIP 362 nears completion, Agency staff expect to be in a position to specify research questions to frame one ore more projects after September 2018 on the following Technology Characteristic:

- Conduct planning studies to demonstrate cost-effective use of power flow devices to accommodate various generation resources such as renewable and distributed resources.

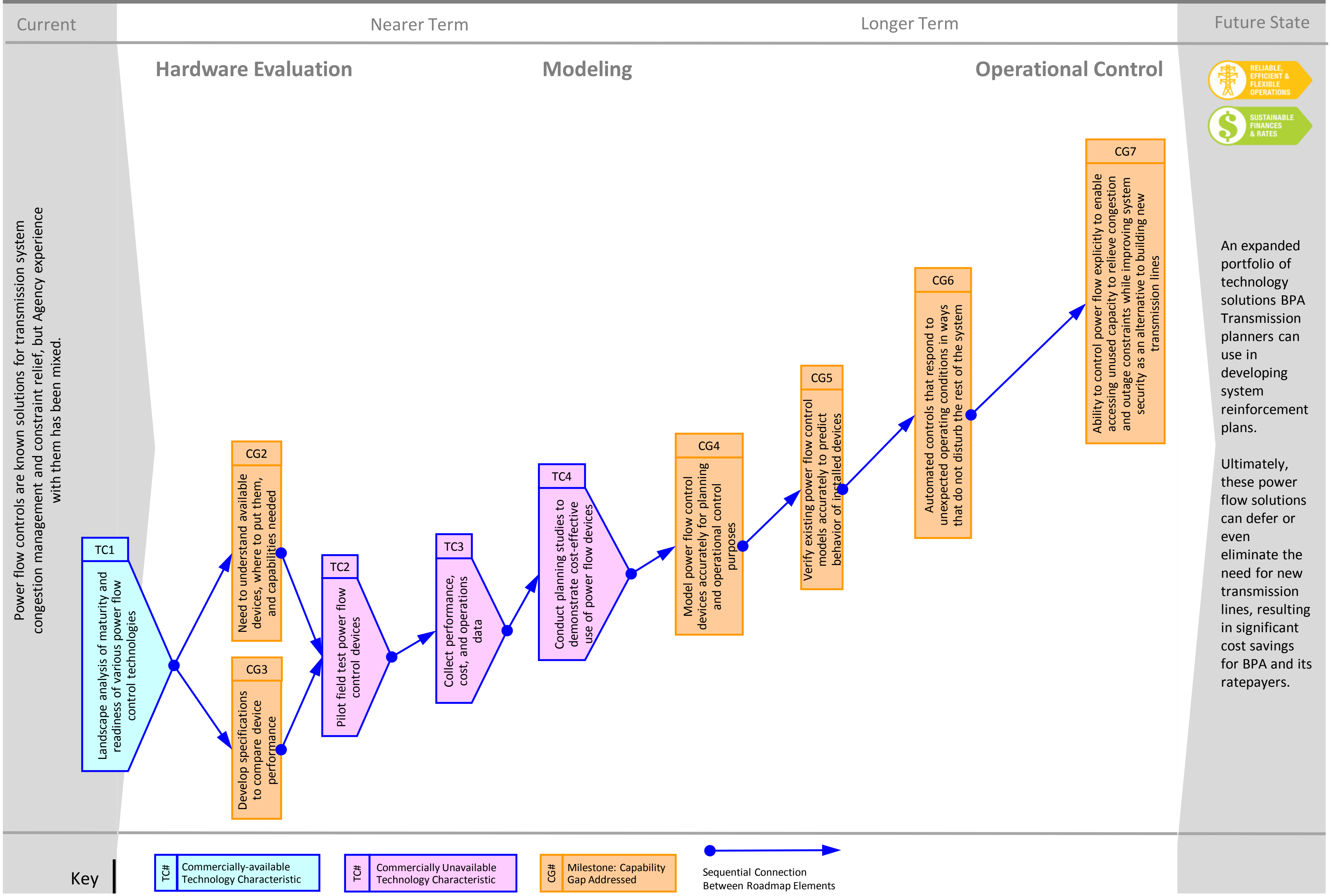
Power Flow Controls for Congestion Management

Key Drivers

The priorities setting the Agency's strategic direction are identified on page 6–8. Under these priorities are the drivers discussed in the "Why this is Important to BPA" section above. Even more specifically, the key drivers in the table below are both relevant to this technology domain and underlay important Capability Gaps.

SYSTEM CONTROL: POWER FLOW CONTROL FOR CONGESTION MANAGEMENT		**Capability Gaps**						
		Need to have ability to control power flow explicitly to enable accessing unused capacity to relieve congestion and outage constraints while improving system security as an alternative to building new transmission lines	To optimize the grid, need to understand what devices are available, where to put them, what sizes (capabilities) are needed, and then conduct longer long term assessment and evaluation of interactions	Develop specifications to compare power flow control device performance	Need ability to model power flow control devices accurately for both planning and operational control purposes	Need to verify existing power flow control models accurately predict behavior of installed devices	Automated controls with ability to handle sudden events (i.e., unplanned outages) or unexpected operating conditions in ways that do not disturb the rest of the system	Major load service paths that are voltage stability limited require additional cost effective devices that control voltage variability
Drivers		**CG1**	**CG2**	**CG3**	**CG4**	**CG5**	**CG6**	**CG7**
D1	Meshed transmission networks increase reliability at cost of capacity underutilization and inefficiency: Because electricity follows the path of least resistance (lowest impedance), the first line in the network to reach its thermal capacity limits capacity of the entire system, even though a majority of the lines are operating significantly below their limits							
D2	Increases in variable energy resources balanced within-hour by remote conventional resources adds variation to power flows and requires additional voltage support							

Technology Domain | **SYSTEM CONTROL: POWER FLOW CONTROLS FOR CONGESTION MANAGEMENT**



RD1	Assessment of Maturity and Technology Readiness of Power Flow Control Solutions for Congestion Management Problems					
TC1	TC2					

Develop understanding of the maturity and technology readiness of various power flow control technologies, so that BPA transmission planning can make risk-informed decision on using these controllers as potential solutions for congestion management problems.

Key Research Questions

1) Provide an overview of technology maturity and operating experiences of power flow control devices other utilities have installed to date to determine which technologies match BPA-specific needs.
    a. Consider the following technologies: Thyristor-controlled series capacitors; controlled phase-shifters; controlled series reactors; smart wire technologies; and back-to-back HVDC projects.
    b. Develop technology evaluation metrics.
    c. Provide examples of application needs.
2) Conduct further research based on outcomes of #1 above focused on specific technologies identified as most relevant to BPA applications, and then engage equipment manufacturers to develop methodologies for rating and sizing powerflow control devices.
    a. Review technical requirements for complex installations likely to be needed within BPA's transmission system in terms of equipment ratings and required control capabilities.
    b. Develop requirements for equipment control, protection and monitoring.

Existing Research

BPA and the Electric Power Research Institute (EPRI) are collaborating on TIP 362 to address the questions listed above.

BPA TRANSMISSION PLANNING (TPP): SITUATION AWARENESS

Section Definition

Power system visualization and situational awareness tools help transmission operators understand present conditions within and around the power system of interest and anticipate future conditions. Examples of technologies to enable situation awareness include: grid monitoring devices such as phasor measurement units (PMUs, devices that measure and report on time-synchronized quantities called synchrophasors); decision support and visualization tools; intelligent alarms; and real-time power system stability assessment.

In the current Agency technology roadmap, the primary interest is to build upon previous work within and outside BPA to mature synchrophasor applications beyond the development and demonstration phases such that they can be relied upon in the operational environment of utility control centers. The following technology domain addresses this focus:

- Synchrophasor Data Storage, Processing, and Visualization

The U.S. Department of Energy defines synchrophasors as

> time-synchronized numbers that represent both the magnitude and phase angle of the sine waves found in electricity, and are time-synchronized for accuracy. They are measured by high-speed monitors called Phasor Measurement Units (PMUs) that are 100 times faster than SCADA. PMU measurements record grid conditions with great accuracy and offer insight into grid stability or stress. Synchrophasor technology is used for real-time operations and off-line engineering analyses to improve grid reliability and efficiency and lower operating costs.[17]

Summary

The following narrative summarizes the background, key drivers, current state, future state, and research opportunities identified within the domain of Synchrophasor Data Storage, Processing, and Visualization.

Background

BPA engineers have been at the forefront of national and international synchrophasor research for more than two decades. Initial work in the 1990s helped advance the technology incrementally until by the early 2000s BPA began exchanging data real-time with Southern California Edison while also developing research-grade prototype analytics to make use of synchrophasor data.[18]

This work was spurred significantly by the U.S. Department of Energy's focus on grid modernization in 2009, enabled by $4.5 billion in funding under the American Recovery and Reinvestment Act (ARRA). More than $357 million of this amount was dedicated to deploying synchrophasor technology nationally.[19] As a partner with regional utilities in this effort, BPA installed PMUs at sixty-four substations; implemented several control room applications using PMU data; and developed real-time analytics for oscillation detection, mode metering, frequency event detection, islanding detection, and phase angle alarming. Agency engineers also participated in the Western Interconnection Synchrophasor Program (WISP) to develop infrastructure for real-time data exchange among operating entities in the West.[20]

Why this is Important to BPA: Key Drivers

Synchrophasor applications and analytics making use of real-time data streams help provide situation awareness, state estimation, and intelligence needed for future planning. To be useful in planning or operational environments, however, data must be transformed into actionable

[17] "Synchrophasor Applications in Transmission Systems," https://www.smartgrid.gov/recovery_act/program_impacts/applications_synchrophasor_technology.html.

[18] Dmitry Kosterev, Jason Burns, Nick Lietschuh, John Anasis, Ashley Donahoo, Dan Trudnowski, Matt Donnelly, and John Pierre, "Implementation and Operating Experience with Oscillation Detection Application at Bonneville Power Administration," CIGRE U.S. National Committee 2016 Grid of the Future Symposium, 1.

[19] U.S. Dept. of Energy, *Advancement of Synchrophasor Technology in Projects Funded by the American Recovery and Reinvestment Act of 2009* (Washington, D.C.: U.S. Dept. of Energy Office of Electricity Delivery and Energy Reliability, March 2016).

[20] Kosterev *et al.*, "Implementation and Operating Experience," 2-3.

information. This requires sequential processing and an array of intermediate transformations. Processed, transformed, and managed appropriately, the data can then be mined and visualized to help ensure system reliability. To be most useful, data processing and visualization tools need to identify events positively and effectively share relevant data and information. There should also be redundancy for any distributed computing capability. Transmission owners and operators also need real-time models.

Current State

Data is stored and managed in fractured, siloed manner, making it difficult to optimize research, planning, operations, maintenance, and other key Agency functions.

Data archiving and processing is done using traditional linear storage and computing environments, which is significantly less efficient than distributed environments

Future State

Enable more informed decision-making for planning, dispatch, maintenance, and other functions by:

1) using cloud-based storage and computing;
2) unifying multiple data sets; and
3) developing displays, alarms, and other notifications to turn data into information.

Research Opportunities

Build upon results of TIP 299, "Synchrophasor Linear State Estimator and PMU Data Validation & Calibration," to pursue the following research questions:

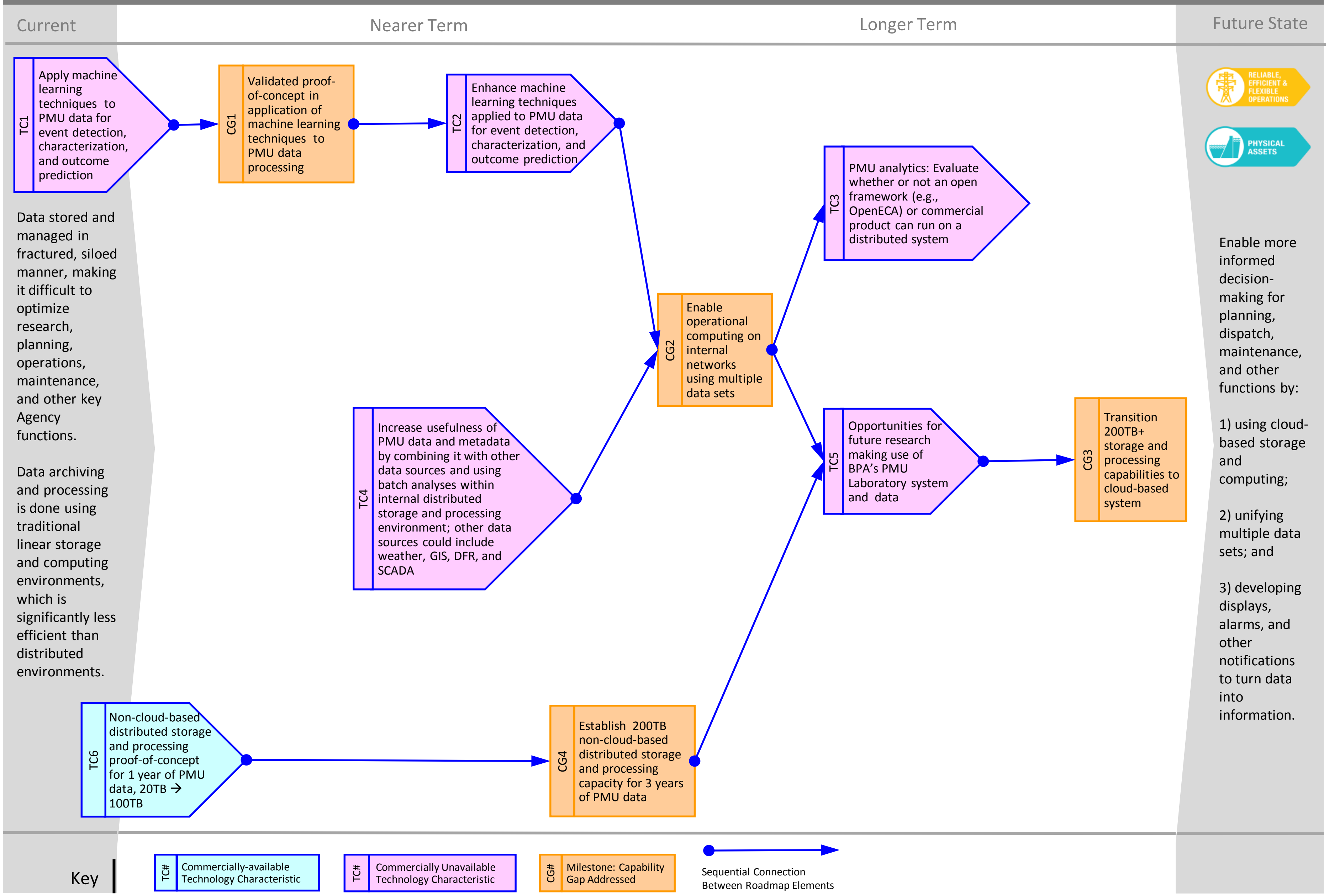
1) What other data sources—weather, geographic information systems (GIS), digital fault recorder (DFR), Supervisory Control and Data Acquisition (SCADA), etc.—could be used to complement and enhance PMU data?
2) How best to gather these other kinds of data, and make effective use of them (initially, at least, within BPA's internal system)?
3) How to optimize the BPA Synchrophasor Laboratory's 100TB cluster to process and store this data in a distributed fashion?

Synchrophasor Data Storage, Processing, and Visualization
Key Drivers

The priorities setting the Agency's strategic direction are identified on page 6–8. Under these priorities are the following key drivers of particular relevance to this technology domain.

SITUATION AWARENESS: SYNCHROPHASOR DATA STORAGE, PROCESSING, AND VISUALIZATION		**Capability Gaps**			
		Validated proof-of-concept in application of machine learning techniques to PMU data processing	Enable operational computing on internal networks using multiple data sets	Establish 200TB non-cloud-based distributed storage and processing capacity for 3 years of PMU data	Transition 200TB+ storage and processing capabilities to cloud-based system
Drivers		**CG1**	**CG2**	**CG3**	**CG4**
D1	Increasingly dynamic nature of the grid				
D2	Application of field data to decision-making				
D3	Need for more effective asset management approaches				
D4	Need to turn high quality data into actionable information that can rapidly identify and communicate stability, oscillation, and other system issues				

SITUATION AWARENESS: SYNCHROPHASOR DATA STORAGE, PROCESSING, AND VISUALIZATION



RD1	Multidimensional Learning on PMU Data for Event Detection					
TC1						

Apply machine learning techniques to PMU data for event detection, characterization, and outcome prediction.

Key Research Questions

1) Developed multiple machine learning approaches and compared their effectiveness. Found promising results in event detection, characterization, and outcome prediction—notably that the event detection classifier significantly outperformed hand-coded rules developed by a domain expert when identifying line faults from a distance, without losing any accuracy when applied at locations near to a line fault. Additionally, repurposed machine learning techniques used in event detection for data cleansing offers potential for identifying bad data within large data sets.

Existing Research

- BPA is currently funding TIP 377, "Improving Electrical Power Cyber Defense –Rapid Detection of Malicious Data Injections," with Principal Investigator Washington State University. To learn more about this project, contact BPA TI for a copy of the project brief. This follows from an earlier project, TIP 319, "Multidimensional Learning on PMU Data for Event Detection," Oct 2014 through Sep 2016. For TIP 319, see the project final report for more details: Scott Wallace, Xinghui Zhao, Duc Nguyen, Eric Klinginsmith, Richard Barella, and Kuei-Ti Lu, "Beyond Finding Faults: Multidimensional Learning on PMU Data for Event Detection, Characterization, and Prediction," Sep. 2016.

RD2	Synchrophasor Linear State Estimator and PMU Data Validation & Calibration					
TC6						

One of the major challenges for real-time operations is having a comprehensive, trustworthy snapshot of the power system. Many utilities deploy SCADA state estimators to capture an unsynchronized, validated view of the system state (complex voltage magnitude and phase angle) and rely heavily on these tools.

Any improvement to conventional measurement and monitoring of the system state reduces the probability and risk of low-probability, high-consequence events.

Recent deployments of wide-area synchrophasor systems have improved real-time situational awareness, providing higher-accuracy synchronized snapshots from across the grid. These implementations have brought additional challenges, including the validation of millions of data points per day, and the processing of large quantities of PMU measurements both in real time and from historical archives.

As system operators incorporate synchrophasor-based applications in the control room, validating measurements becomes paramount to ensure system reliability.

Key Research Questions

Within the BPA Synchrophasor Laboratory, pursue the following:

1) Research and develop approaches for data mining and validation using synchrophasors through two methods: PMU-based Linear State Estimator (LSE) and formal data mining tools.
2) Develop applications to detect system events contained within real-time PMU data and perform automated analysis when events are found.
3) Create data mining tools to scan synchrophasor archives for past events and perform long-term baselining of power system measurements.
4) Envision progression plans for real-time implementation within operational applications at BPA.

Existing Research

- TIP 299, "Synchrophasor Linear State Estimator and PMU Data Validation & Calibration": Oct 2014 through Sep 2017.

RD3	Open and Extensible Control and Analytics (openECA) Platform for Phasor Data					
TC3						

Next-generation synchrophasor data systems and analytical tools are needed to support transmission operations. Such systems ought to provide easy-to-implement, end-to-end configuration and change management; identification and management of bad data; easy points of integration with analytics both for new cutting-edge and legacy systems; and storage designed for the volume and speed of phasor data, among other features. The openECA project goal is to develop real-time decision support tools integrated through an open-source platform that incorporate synchrophasor data and enhance system reliability.

Key Research Questions

1) Develop and test the openECA platform and 8 initial analytics in 3 categories:
    a. Real-time: Oscillation Detection Monitor; Oscillation Mode Meter; Topology Estimation.
    b. Control: Wide Area Volt-Ampere-Reactive (VAR) Control.
    c. Off-line: Dynamic PMU Transducer Calibration; Line Parameter Estimation; Synchronous Machine Parameter Estimation; Acceleration Trend Relay (ATR) Improvement.

Existing Research

- BPA is contributing to a project led by the Grid Protection Alliance, TIP 361, "Open and Extensible Control and Analytics (openECA) Platform for Phasor Data." The project runs Nov 2015 through Sep 2017.

RD4	Increase usefulness of PMU data and metadata by combining it with other data sources and using batch analyses within internal distributed storage and processing environment					
TC4						

TIP 299, "Synchrophasor Linear State Estimator and PMU Data Validation & Calibration," will conclude September 2017. This project enabled the build-out of a high performance cluster computing environment within the BPA Synchrophasor Laboratory. Test cases analyzed within this environment included phase angle baselining, frequency detection, abnormality detection, and remedial action scheme (RAS) algorithms. One key finding was that while long-term data mining is critical in extracting useful information from archives, current techniques can require unreasonable processing times to analyze large data sets.

The project team has identified the need for follow-on work in areas such as:

- Upgrading event detection tools installed at the Synchrophasor Lab with additional or modified algorithms.
- Investigating the potential integration of other data sets to enhance the value gained from PMU data.

Potential benefits from such research could include:

- Improved event detection and identification and development of next-generation of applications, including synchrophasor RAS.
- More effective data mining techniques involving data-intensive tasks (e.g., phase angle baselining over multiple years); turning archived data into actionable information for system operators; providing blueprint for implementation of big data tasks for utilities.
- Establishing a platform for future R&D projects of importance to BPA.

Key Research Questions

Build upon results of TIP 299, "Synchrophasor Linear State Estimator and PMU Data Validation & Calibration," to pursue the following research questions:

1) What other data sources—weather, geographic information systems (GIS), digital fault recorder (DFR), Supervisory Control and Data Acquisition (SCADA), etc.—could be used to complement and enhance PMU data?
2) How best to gather these other kinds of data, and make effective use of them (initially, at least, within BPA's internal system)?
3) How to optimize the BPA Synchrophasor Laboratory's 100TB cluster to process and store this data in a distributed fashion?

Existing Research

- None.

Transmission Engineering (TE)

The BPA Transmission Engineering organization (code "TE") is comprised of the following sub-organizations:

- System Control Engineering (TEC)
- Contract Management Office (TED)
- Internal Standards (TEI)
- Transmission Engineering (TEL)
- Internal Compliance Operations (TEO)
- Transmission Project Management (TEP)
- Real Property Services (TER)
- Substation Engineering (TES)
- Commissioning and Testing (TET)

Sections in this roadmap:

- Disaster Preparedness and Recovery

BPA Transmission Engineering (TE): Disaster Preparedness and Recovery

Section Definition

Electrical transmission lines are a complex system of towers and conductors installed over varying terrain. The transmission lines are interconnected by substations with their own complexity of high voltage equipment and building support facilities. The power system is a critical lifeline infrastructure that the Pacific Northwest (PNW) depends on for economic and social stability. The expanse of this system makes it vulnerable to different types of extreme events (such as wind and ice storms, and earthquakes). BPA's wind, ice, and earthquake vulnerability studies have demonstrated that an extreme seismic event is the higher risk to the transmission system. The majority of BPA's electrical grid and supporting facilities were built before the higher seismic hazard was identified in the current design codes. As a result, BPA's electrical transmission system is vulnerable to an extreme earthquake event, such as Cascadia Subduction Zone (CSZ).

The Disaster Preparedness and Recovery section of the current roadmap includes the following technology domain:

- Extreme Event Hardening—Transmission Line Facilities

Summary

Why this is Important to BPA

As caretakers of the PNW critical high voltage transmission system it is BPA's responsibility to mitigate the vulnerability to an extreme CSZ seismic event to improve the resiliency of the grid. The following drivers are more specific to this technology domain:

Stemming from these broad drivers, the following drivers are more specific to this technology domain:

- Reduce risk of extended disruptions of critical transmission assets, services, and functions due to extreme events.
- Human safety considerations: Minimize injury and loss of life.
- Enhance future grid reliability, interoperability, and extreme event protection for increasingly complex system operations.
- Reduce system restoration times.
- Need to protect critical physical assets.
- Enhance resilience of the bulk electric system.

Background

BPA has been proactive in studying the seismic vulnerability of the high voltage transmission system. Projects at BPA have developed mitigation options for substations to reduce the seismic vulnerability. Mitigation options have been developed for replacing rigid bus systems with flexible and flexible-hybrid bus, the addition of supplemental damping devices, and development of horizontal based isolation technology for high voltage transformers. Computer analysis has been performed to investigate the seismic vulnerability of the transmission line facilities. BPA is currently developing a vertical base isolation system to be combined with horizontal isolation to protect power transformers, and supplemental damping devices for retrofit of legacy instrument transformers.

BPA TIP 316 will conclude September 2017. It investigated a combined horizontal-vertical seismic isolation system for high-voltage power transformers. This project built upon a prior BPA project (TIP 156) developing a horizontal ground motion base isolation system for high voltage transformers using triple friction pendulum (TFP) technology, resulting in the world's first base isolation installation using TFP.

Current State

BPA has been focus on the potential physical damage of transmission line assets. Though significant vulnerability analysis has been performed, there are still questions and concerns that are unresolved. These issues include both physical damage and the electrical performance of the power grid at different stages of an extreme CSZ seismic event. The historical performance of transmission line towers have been good and typical failures are attributed to earthquake generated landslides, liquefaction, lateral spreading, and rock falls. But there are still questions in the industry on transmission line performance to earthquake input ground motions. In substations there is a

need for additional options to reduce the seismic vulnerability of legacy high voltage equipment using supplemental damping or base isolation technology. Electric power system analysis to determine the operability of the power system using predicted facility damage has not been fully demonstrated.

Future State

The ability to harden an existing power system would help to improve the resiliency of BPA's critical infrastructure system. Mitigation of the power grid will be a long term program, whether it is by mitigation of legacy components or replacement with seismically qualified equipment. Options to improve the seismic performance of existing components are required to have a successful long-term seismic mitigation program. The ability to model the electrical system performance during and after a damaging extreme CSZ event will help to identify current and future transmission system resiliency. Technology development of earthquake early warning systems should be investigated to determine their application to the high voltage transmission line system.

Research Opportunities

Some immediate research opportunities in the area of extreme CSZ event mitigation are:

- Analysis of critical seismic parameters to determine their effect on the performance of transmission line tower/conductor configurations and the development of transmission line tower seismic fragility function.
- Development of supplemental damping and/or base isolation options for legacy substation equipment.
- Guidelines for placement of transmission towers in vulnerability sites with earthquake generated landslides, liquefaction, lateral spreading, and rock falls hazards.
- Analysis tools for assessing the power flow of a transmission line system from physical earthquake damage.
- Investigate application of earthquake early warning systems for operation of a transmission line system.
- Study the resilience of BPA's transmission line system relative to customer electrical system interconnections and interdependencies.

Extreme Event Hardening—Transmission Line Facilities
Key Drivers

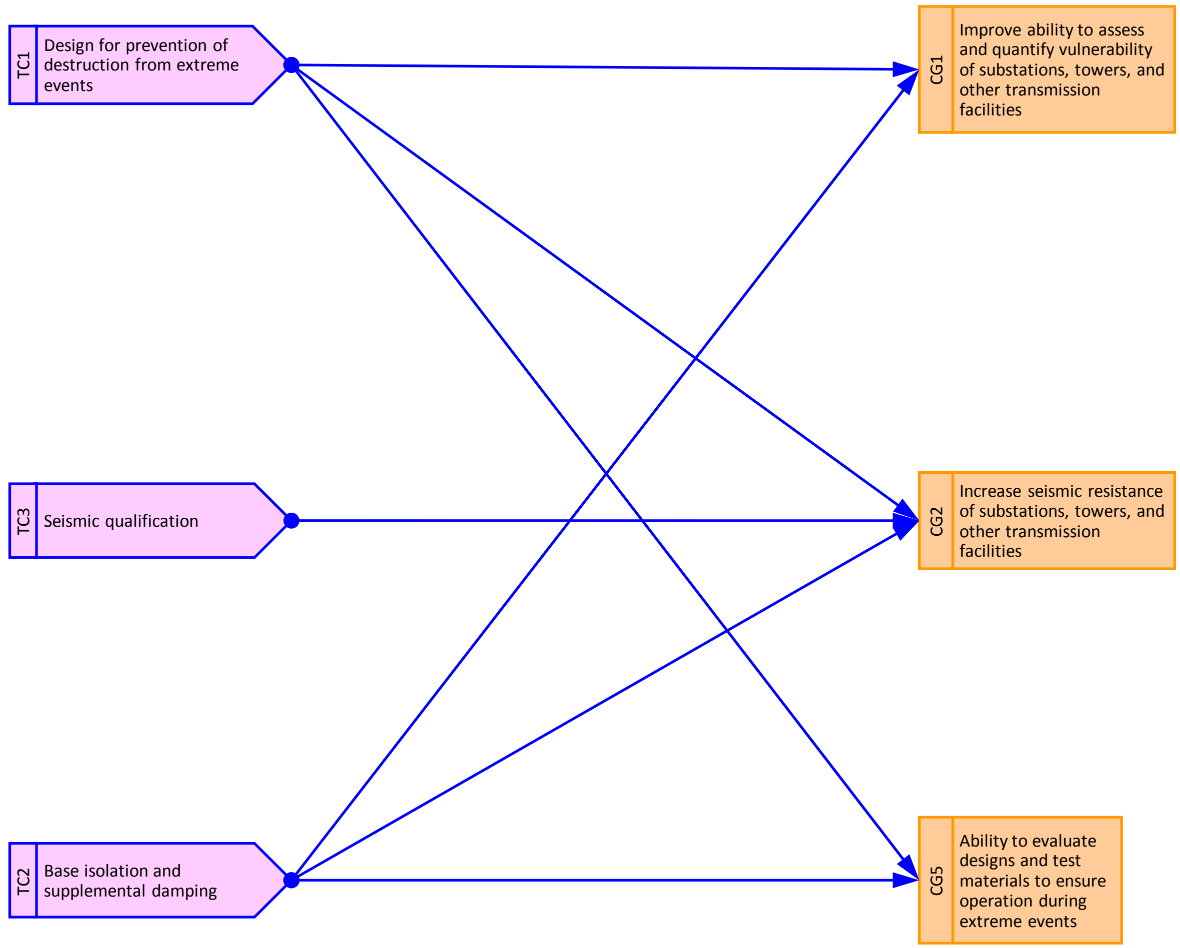
The priorities setting the Agency's strategic direction are identified on page 6–8. Under these priorities are the following key drivers of particular relevance to this technology domain.

Disaster Preparedness and Recovery **Extreme Event Hardening—Transmission Line Facilities**		Capability Gaps: Improve ability to assess and quantify vulnerability of substations, towers, and other transmission facilities	Increase seismic resistance of substations	Increase seismic resistance of transmission towers	Ability to build transmission lines that resist conductor galloping	Ability to evaluate designs and test materials to ensure operation during extreme events
Drivers		**CG1**	**CG2**	**CG3**	**CG4**	**CG5**
D1	Reduce risk of extended disruptions of critical transmission assets, services, and functions due to extreme events					
D2	Human safety considerations: Prevent injury and loss of life					
D3	Enhance future grid reliability, interoperability, and extreme event protection for increasingly complex system operation					
D4	Reduce system restoration times					
D5	Need to protect critical physical assets					
D6	Enhance resilience of the bulk electric system					

Extreme Event Hardening—Transmission Line Facilities

Current	Nearer Term	Longer Term	Future State

Current: Seismic base isolation systems for high-voltage power transformers only provide protection against horizontal components of earthquake motion—vertical ground motion is transmitted or sometimes magnified



RELIABLE, EFFICIENT & FLEXIBLE OPERATIONS

SUSTAINABLE FINANCES & RATES

Future State: Effective and practical 3-dimensional seismic isolation system for use with high-voltage power transformers

Key

- TC# Commercially-available Technology Characteristic
- TC# Commercially Unavailable Technology Characteristic
- CG# Milestone: Capability Gap Addressed
- Sequential Connection Between Roadmap Elements

Research, Development, & Demonstration Summaries

RD1	Analysis of critical seismic parameters to determine effect on the performance of transmission line tower/conductor configurations and development of transmission line tower seismic fragility function					
TC1	TC2	TC3				

The historical performance of transmission line towers/conductors has been good. Worldwide, typically failures have been caused by earthquake generated landslides, liquefaction, lateral spreading, and rock falls. Recent papers from China on the analysis of transmission line towers/conductor systems have stated that this system is vulnerable to seismic loads. Only a few studies, including BPA's, have been completed that shows a conflicting conclusion with the Chinese data. Transmission line tower fragility functions could be developed to help with the seismic vulnerability of a transmission line configuration. It would be beneficial to BPA and the transmission line industry to perform a comprehensive study to resolve this conflict in analysis results, to validate the observed historical performance, develop a library of transmission line tower fragility functions, and provide guidelines for preforming a structural analysis of a transmission line system earthquake response.

Key Research Questions

1) What are the critical ground motion parameters that affect the seismic performance of a transmission line (towers/conductors) system?
2) What are the critical transmission line configurations for seismic performance evaluation analysis?
3) What is the difference in seismic performance between standard towers vs. major river crossing towers?
4) What is the difference in structural seismic performance using tubular poles, lattice towers, and wood pole structures?
5) Can transmission tower seismic fragility functions be developed to assist utilities performing risk assessments?
6) How does seismic response results compare with the traditional BPA extreme event loadings: Wind, Ice, Unbalanced longitudinal loads, etc.?

Existing Research

- BPA have per earthquake response analysis of a standard double circuit transmission line and river-crossing for both self-supporting lattice and tubular steel pole. There are a number of recent papers published in China on this subject.

RD2	Development of supplemental damping and/or base isolation options for legacy substation equipment					
TC1	TC2	TC3				

BPA's transmission line system has a significant number of non-seismic legacy high voltage equipment. This equipment is seismically vulnerable to an extreme CSZ earthquake event. It is anticipated that this equipment will be replaced during BPA's long-term mitigation program, but in certain cased this could take 25–30-plus years. Seismic mitigation options, such as supplemental damping and/or base isolation, to retrofit high voltage substation equipment installations are necessary to minimize damage in the period before replacement with seismically qualified equipment.

Key Research Questions

1) What are the mitigation options for non-seismic legacy high voltage substation equipment?
2) What is the effect of different mitigation options considering minimal interruption or outage period for installation?
3) How much improvement can the different mitigation option provide by reducing input ground motion affects, while accounting for equipment connection interaction?

Existing Research

- BPA has performed significant research in the area of supplemental damping and base isolation.

RD3	Guidelines for placement of transmission towers in vulnerability sites with earthquake generated landslides, liquefaction, lateral spreading, and rock falls hazards					
TC1	TC2	TC3				

Transmission lines extend over large regions with varying terrain which can include earthquake generated landslides, liquefaction, lateral spreading, and rock fall hazards. The placement of transmission lines and individual towers is sometimes restricted to address non-engineering concerns. Mitigation options and guidelines are necessary to address these special site hazards for both legacy and new installations.

Key Research Questions

1) What mitigation options are available for addressing legacy installation to earthquake generated landslides, liquefaction, lateral spreading, and rock falls?
2) Can applicable engineering guidelines be provided for installation of transmission lines and towers in special locations with the potential for earthquake generated landslides, liquefaction, lateral spreading, and rock falls?
3) Can engineering limits be provided to improve the transmission tower seismic performance on sites subject to liquefaction and lateral spreading hazards?

Existing Research

- BPA has performed investigations on major river-crossings for both liquefaction and lateral spreading hazards. Mitigation options have also been developed based on deflection limits.

RD4	Analysis tools for assessing the power flow of a transmission line system from physical earthquake damage					
TC1	TC2	TC3				

BPA has analysis software for assessing the physical damage to the transmission line system from an extreme CSZ event. The next step would be to input this information into an electrical transmission power flow-type program to assess the electrical performance/condition of the transmission line system. The combination of these two analysis capabilities would help BPA to better understand the seismic vulnerability and resulting performance of the grid.

Key Research Questions

1) Can existing electric power flow software be used to study the significant damage (N+1000 plus) caused by an extreme CSZ event?
2) Can a simplified analysis procedure be used to tract the initial damage and subsequent restoration stages from a CSZ event?
3) What are the limitations of the proposed simplified procedure?

Existing Research

- BPA has performed this type of study, combining the asset damage states and an electrical condition assessment of the power grid.

RD5	Investigate application of earthquake early warning systems for operation of a transmission line system					
TC1	TC2	TC3				

Earthquake early warning system (EWS) technology is being implemented into other critical lifeline infrastructure systems. This technology can provide a warning that can range from 15 – 45 seconds prior to the arrival of damaging ground motions. BPA should investigate EWS technology for potential high-voltage transmission system application.

Key Research Questions

1) What are the potential applications of earthquake early warning systems for a high voltage transmission line system?
2) What are the options for EMS applicable to the high voltage power grid?

Existing Research

- PG&E is currently investigating EWS for its power grid.

RD6	Study the resilience of BPA's transmission line system relative to customer electrical system interconnections and interdependencies					
TC1	TC2	TC3				

It is important that the BPA's high voltage transmission system be resilient for internal operability. But, it is equally important that BPA understand the seismic effects on interconnections and interdependencies with our customers and other non-electrical infrastructure systems, such as transportation, water, wastewater, fuel, and emergency facilities. Understanding these parameters could help BPA to develop mitigation strategies to support the resiliency efforts of the PNW.

Key Research Questions

1) What are the customer critical interconnections and interdependencies for the BPA high voltage transmission system?
2) What are the critical interconnections and interdependencies to other lifeline systems for the BPA high voltage transmission system?
3) What mitigation procedures can BPA implement to improve the interconnections and interdependencies of the power grid?

Existing Research

- None identified.

ACKNOWLEDGEMENTS

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