GLOBAL PST
CONSORTIUM

Vision for the Control Room of the Future

A product of the Global Power System Transformation Consortium

About the Global Power System Transformation Consortium

In 2019, the chief executive officers of six of the fastest decarbonizing energy systems in the world came together to form the Global Power System Transformation (G-PST) Consortium. These founding system operators (FSOs) lead and disseminate G-PST's cutting-edge, applied research to solve pressing challenges for the world's leading system operators.

G-PST is not a single organization, but convenes expertise across a network of system operators, manufacturers, utilities, standards bodies, and research institutions to accelerate proving and deploying solutions that enable grids across the world to run on 100% renewable energy and help keep global temperature rises below 1.5 degrees Celsius.

G-PST's Core Team organizations coordinate and contribute expertise to its technical pillars and inform G-PST's strategic approach. G-PST also coordinates peer learning networks and country-level technical assistance delivery efforts for Africa, Asia, and Latin America and the Caribbean through regional partner organizations. International agencies and multilateral and regional development banks are also serving as key implementing partners to ensure G-PST activities complement and reinforce existing programs.

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) currently functions as G-PST's secretariat, which coordinates cross-pillar work programs, partnerships, support, and outreach.

Disclaimer

The report was developed by the Electric Power Research Institute (EPRI), with input from G-PST's founding system operators – the Australian Energy Market Operator (AEMO), California Independent System Operator (CAISO), the Electric Reliability Council of Texas (ERCOT), EirGrid, Energinet, and National Grid Electricity System Operator (NGESO).

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The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof.

Introduction

From the earliest days of electricity network development and operation to today, the primary function of real-time operations has been to maintain reliable power supply to customers while ensuring the ability to be resilient to system disturbances. This core tenet of network operation is not anticipated to change and is relevant to any transmission control centre, regardless of the functions, processes, or tasks they carry out.

Control rooms have been a key part of electricity network operation from when networks were first developed. While the look and feel of the rooms have maintained some consistency, the visualisation technology and computer processing power has evolved steadily to manage the increasing complexity of the underlying power system. Today, and for the coming decades, transmission operators are facing radical changes to the underlying networks they operate, including new modes of operation, resource adequacy concerns, and the provision of new markets and ancillary services. System operators globally are leaning into these changes by uplifting their control rooms and operational capability to help manage these changes. Maintaining reliability, security, and resilience in the face of these evolutions requires agile adaptation of processes and advanced analytical capability. Maintaining and expanding real-time operation capability will be essential for societies as they navigate the transition to clean energy futures.

This report summarizes the current status of the Global Power System Transformation (G-PST) founding system operators' (AEMO, CAISO, EirGrid, EnergiNet, ERCOT, NGESO) (FSO) control room operations processes and technology. It aims to identify some of the gaps that exist to allow the industry to collaboratively develop the control room of the future. Often the report focuses on the impact of the transition of energy systems on generation resources and network developments. This document is intended to bridge the gap in understanding of operational issues by:

- Building awareness and a common understanding of the challenges system operators face,
- Providing a reference point for industry partners, from manufacturers to asset owners and regulators,
- Providing a useful reference to other system operators that are working to uplift operational capabilities.

Report compiled by: EPRI

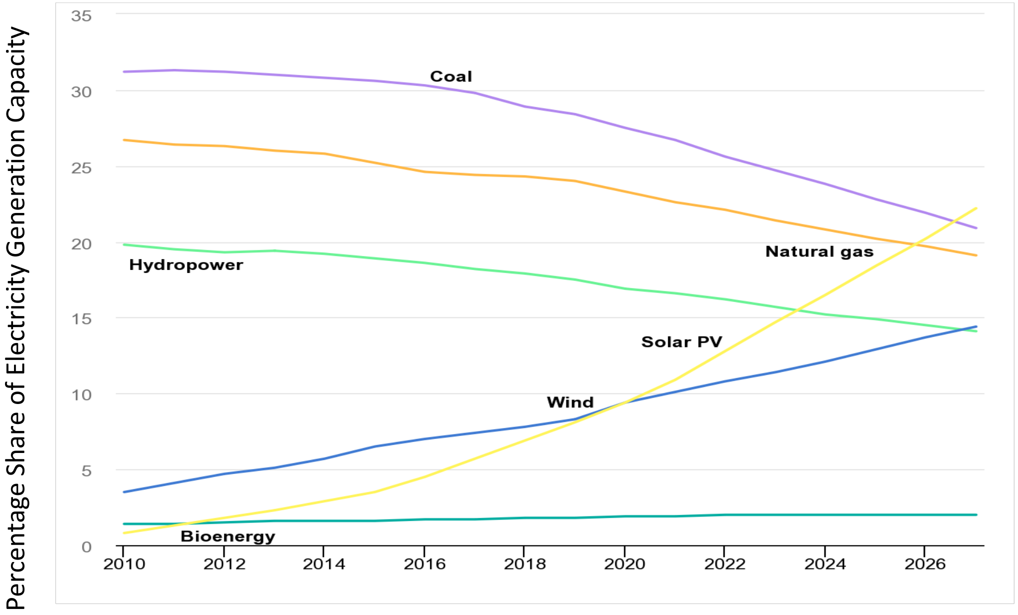
The Evolving Power System - Generation

Generation resources are currently undergoing a transition from centralized, predictable, thermal, large synchronous plants to decentralized, variable, renewable, smaller asynchronous generation sources, often connected on distribution networks.

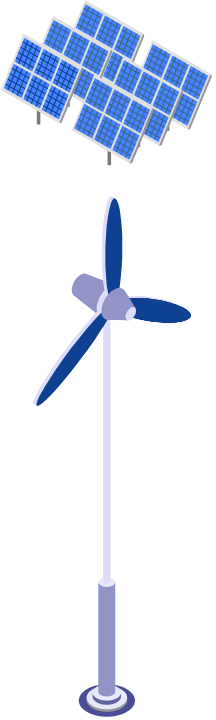
This global drive towards decarbonization has had major knock-on impacts on markets and network operation across the world.

This trend is expected to continue as thermal, fossil fuel plants are likely to decline in penetration, and solar PV, battery energy storage, onshore and offshore wind farms, and hydrogen plants proliferate.

Different generation resources require new and different market services, which adds further complexity.



Share of cumulative power capacity by technology, 2010-2027, from the IEA Renewables 2022 Report

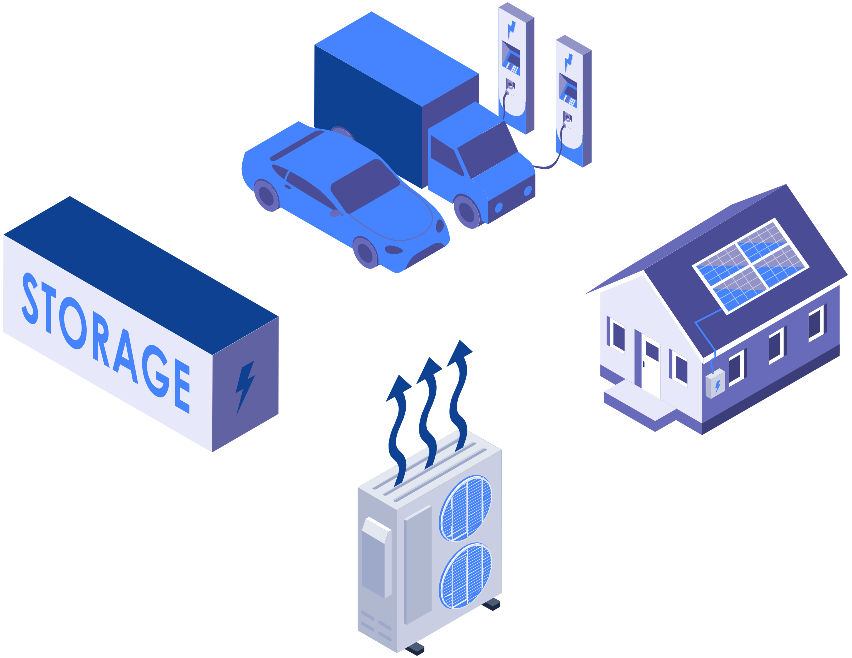


The Evolving Power System - Demand

Demand, like generation, is changing radically from predictable, stable growth patterns to less predictable, more rapidly growing profiles, owing to behind-the-meter domestic solar; electrification of space heating, cooling, and transport; and large energy users (such as demand centers and digital mining).

Additionally, demand response initiatives are proliferating, with large energy users becoming pro-sumers via “virtual power plants” responding to market price signals in real time.

Forecasting and controlling demand in real time is anticipated to become a major challenge for control operators in the years ahead. Managing periods of high solar PV, which can mask aggregate demand during sunny periods, will also continue to cause issues for system operators around the world.

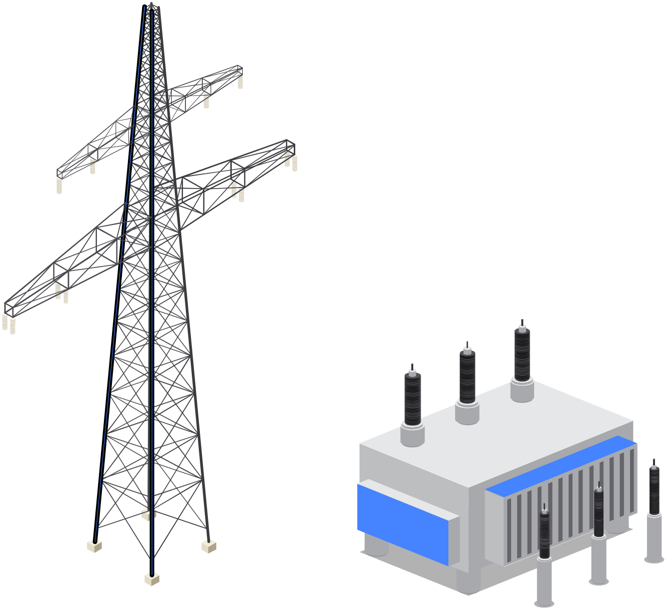


The Evolving Power System - Networks

While demand is fluctuating and the generation portfolio is evolving, transmission network development has remained relatively static, resulting in networks being operated closer to the boundary of secure operations. Networks that have not developed in line with generation and demand changes will become more congested, making outages more difficult, exacerbating the underlying issues.

Internal high voltage AC cable networks are expanding, and new high-voltage direct current (HVDC) connections are proliferating between countries around the world.

Smart network technology devices are also becoming more common to release network flexibility. Additionally, there has been a noticeable uptick in weather-related disturbances around the world (such as hurricanes, wildfires, cold snaps, and extreme heat), which have caused major network disruption and destruction. Monitoring and managing decentralized resources on the distribution network is an increasing challenge for transmission (T) and distribution (D) system operators, as they manage the nexus between balancing generation and demand while managing congestion on both networks.



Evolving Network Requires Evolving Operations Capability

Monitoring, analysing, risk assessing and controlling assets on the evolving network is an increasing challenge for system operators. The evolution of the underlying assets and resources is posing challenges and requiring a re-evaluation of the architectures, data and operations technology requirements for control centres. In addition, increased automation within operational technology and simulation is reducing the operator's manual interaction with the network and resources.

The Operational Challenges

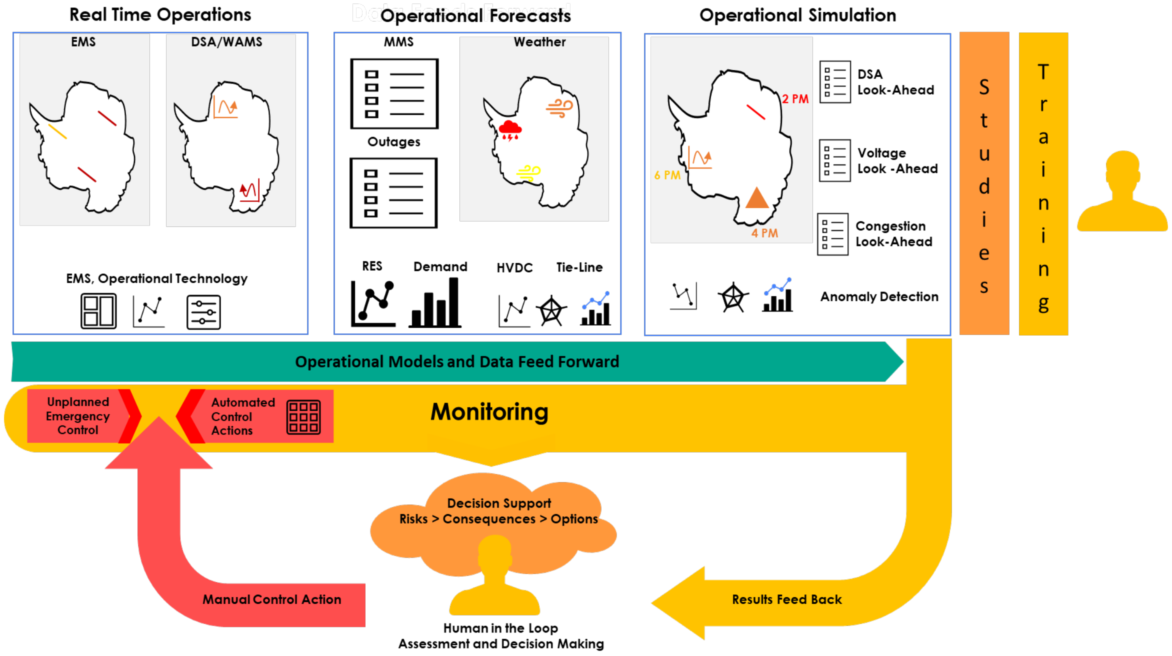
- Network optimisation, new operating modes, and congestion caused by decentralised generation
- PV, wind, demand HVDC ramping, and minimum operating period challenges
- Security and stability in lower-inertia systems or systems with more frequent operational minima.
- Variability, associated with decentralised renewable resources and weaker grids
- Battery energy storage modelling and charge/discharge strategies for energy market services and reserve management
- Observability and controllability of behind-the-meter resources in real time, transmission, distribution interactions
- Outage management and optimisation, smart network technology integration

Control Room of the Future Vision Statement

Accurate, validated, centrally managed, dynamic models, and streamlined operational data, feed the operational technology (OT) toolkit in a modularized, service-oriented architecture. The operational toolkit provides secure automated control actions to network assets and market participants, with decision support to allow operators to adjust the system or intervene if necessary.

The OT toolkit has parallel processes for reliability and security assessment in real time, and for forecasted future states to be assessed by the operator, allowing them to adjust the system ahead of time. Machine learning applications, trained on operational datasets, are deployed to enhance the monitoring and assessment domains of operation and decision support.

Manual processes are automated and there should be clear linkage between both, as well as processes in the operational and training simulator or operations readiness center. Each process should have a consistent display design on leading edge display equipment within secure and pandemic-resilient control room facilities.



Operators focus on knowledge-based processes, monitoring and diagnosing system risks and forecast trajectories in parallel with the OT toolkit. They should be trained as supervisors of automated systems in real time, safely intervening for emergencies or to override automation mis-operation. They should have advanced knowledge and engineering know-how for risk assessment and the management of forecasted risks.

Control Room of the Future Capabilities

The elements of the vision statement and graphic on slide 8 define the color-coded elements of the control room of the future framework - shown on the right.

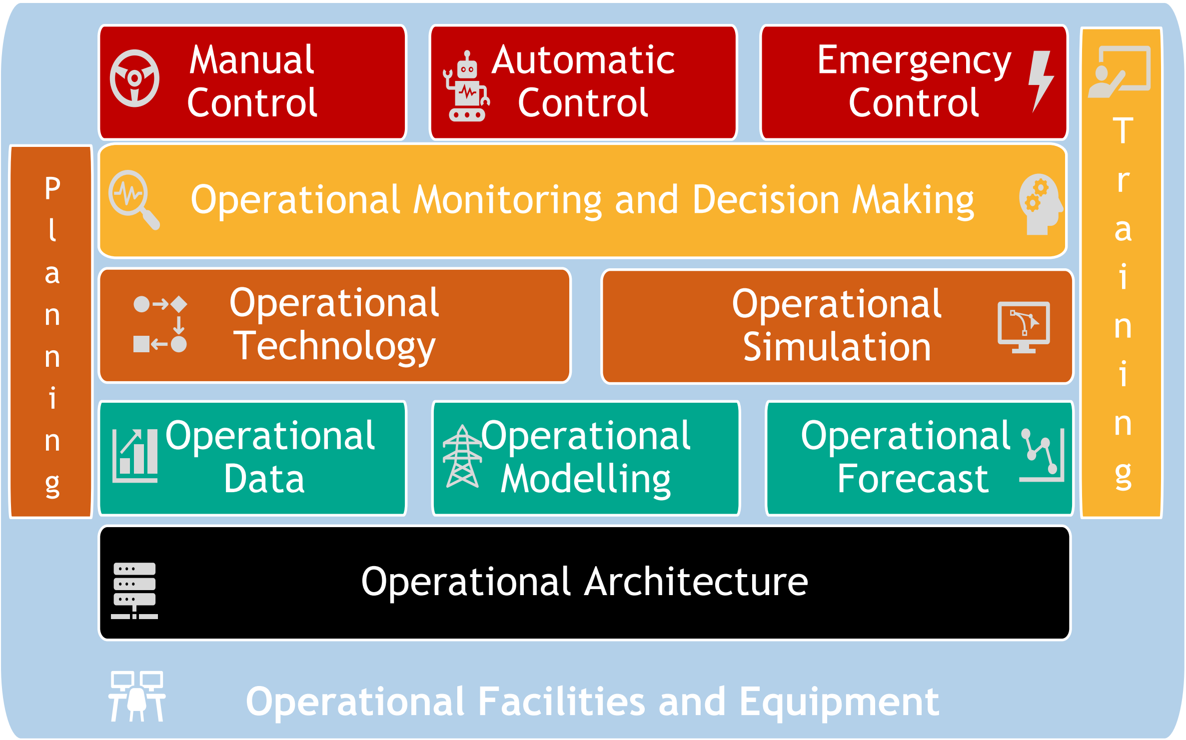
Each block of the framework represents an operational capability, (called operational capabilities to distinguish from other enterprise capabilities).

Each capability is dependent on one another, and the blocks are linked via a complex architecture design and data flows. Each capability in this framework should be developed in the coming years to enable system operation of the network of the future.

The control room operators are in the control loop focusing on:

- **Monitoring and decision making**
- **Operational processes and the operational technology toolkit for reliability and security risk assessment**
- **Control (manual, automatic and emergency)**

These domains will be expanded upon in the following sections.



G-PST FSO Key Research Questions - Architecture

The following key research questions were identified by G-PST's founding system operators for the operational architecture capability in the G-PST control room of the future research pillar. These are key gaps that should be addressed by the industry and academic community. Coordinated research and development will help system operators transition to managing the system of the future. The operational capabilities are closely interrelated to other capabilities, as shown below. View and download the G-PST Research Agenda (2021).

		Linked Capabilities
Operational Architecture	32. What is a suitable data architecture for distributed energy resources (DERs) monitoring and modeling? Once DER resources have been aggregated spatially and temporally, how should this information be provided to the control room? Can DER categories be developed that allow groupings based on their ensemble response to system level events? What is the appropriate data architecture required to monitor/predict and control DER in real-time?	Operational Modelling
	33. What is the communication capability needed to support monitoring and control of DER? What is the suitability of existing communications infrastructure – in terms of reliability, latency, bandwidth, (cyber)security – relative to investing in a bespoke system? For DER control purposes, what two-way communication protocols are necessary?	Operational Control
	34. What are the relative merits of different control architectures for DER? What might an efficient distributed control architecture be for DER which: (1) makes use of appropriate device characterizations and real-time monitoring data; (2) accounts for practical constraints around device level communication; and (3) accounts for heterogeneous subgroup controls of DER and various existing DSO/TSO control schemes?	Operational Control

Operational Architecture

🟩 Implemented 🟧 Planned ⬜ Not Planned/Applicable

Capability Initiative	FSO Maturity Level					
Modular apps-based SCADA/EMS architecture	🟩	🟩	🟧	🟧	🟧	🟧
Usage of open source/university-developed tools	🟩	🟩	🟧	⬜	⬜	⬜
Self-healing systems	🟩	⬜	⬜	⬜	⬜	⬜
High-availability data platform	🟩	🟩	🟩	🟩	🟧	🟧
Broadband low latency network	🟩	🟩	🟩	🟩	🟩	⬜
Carrying out computationally heavy calculations in the cloud	🟩	🟩	🟩	🟩	⬜	⬜

Short to Medium Term Challenges

- Management of "big data" infrastructure and processes

FSO Context

Architecture and Development

Given the ever-increasing range, variety, and complexity of the operational toolkit modules, no one system can perform all processes. The FSOs are mostly favoring a move from siloed, multi-vendor products to integrated modular and service-based architectures. Many FSOs are strategically evaluating their architecture with a view to evolving it for the future network and market operation paradigms. The common information model (CIM) is the primary data exchange standard between modules, and this will continue to evolve as required by system operators. FSOs are also exploring micro-services and event-based architectures—given their suitability to network and market operation processes.

A model of continuous delivery/continuous integration for development of OT modules is emerging, supported by containerization and web-based tooling for rapid deployment. Having vendor maintenance and support for all operational tools is critical, given the high-reliability context. User interface design is a critical component of development. Modern displays with decision support ensures a consistent experience across all applications and should help minimize the transition between applications and ultimately reduce human error.

Cloud and Computationally Intensive Calculation

On-premises data centers and servers are used exclusively for critical operations processes. This is unlikely to change in the near future. However, some FSOs are exploring the use of cloud computing to support non-critical operational processes—moving non-critical services to a hybrid cloud, using public cloud for processes such as machine learning, model training and analytics, while execution of processes remain on premises.

Some FSOs are constrained by regulation, security, or other factors, while others prohibit the use of cloud for anything other than rudimentary applications. Private clouds are being explored but are mostly at an early stage of development and application.

G-PST FSO Key Research Questions – Operational Data

The following key research questions were identified by G-PST's founding system operators for the operational data, modeling, and forecasting capability in the G-PST control room of the future research pillar. These are key gaps that should be addressed by the industry and academic community. Coordinated research and development will help system operators transition to managing the system of the future. The operational capabilities are closely interrelated to other capabilities as shown below. View and download the G-PST Research Agenda (2021).

		Linked Capabilities
Operational Data, Modeling and Forecasting	26. Are there sufficient flexibilities available in the near-term to compensate variations in load and generation (fast changes as well as long lasting extreme situations such as prolonged periods of no solar and wind)?	Operational Technology
	27. How do control rooms address uncertainties in weather conditions that impact loads and renewable energy output and rate of change (ramps)? How can probabilistic forecasting techniques be better incorporated into real-time operations?	Operational Technology
	24. What quantities must be monitored, screened and validated to ensure reliable service provision from aggregated flexibility resources in distribution systems, supporting stable system operation?	Operational Monitoring
	36. How can the status (generation output, state of charge, etc.) of each key category of DER be monitored/estimated in real-time? What are appropriate DER categories and the appropriate spatial and temporal resolution to monitor DER effectively? What are the appropriate technical means of achieving this level of aggregation?	Operational Architecture

Operational Data

Operational Modelling

Operational Forecast

Initiative	**FSO Maturity Level** 🟩 Implemented 🟨 Planned ⬜ Not Planned/Applicable					
Data Input/output monitoring	🟩	🟩	🟩	🟩	🟨	⬜
Secure and standardized communication	🟩	🟩	🟩	🟨	⬜	⬜
Ancillary services forecast	🟩	🟩	🟩	🟨	⬜	⬜
Automatic model validation	🟩	🟩	🟨	🟨	⬜	⬜
Consolidated data and models, cross-platform coordination	🟩	🟩	🟨	🟨	🟨	🟨
Real-time probabilistic PV/WT forecast	🟩	🟩	🟩	🟩	🟩	⬜

Short-Medium Term Challenges

- Model accuracy
- Dynamic models of inverter-based resources (IBRs)
- Sector coupling, distribution network observability, gas, water
- EMT (electromagnetic transient) model development and maintenance
- Forecasting accuracy – 5-minute to 7-day horizon
- Implementing digitalisation of electricity system
- Secure data management
- Distributed energy resources and virtual power plant models and operational data
- Data quality

FSO Context

Operational Forecasting

FSOs typically use one of two approaches to operations (demand and renewable energy sources) forecasting: Operational forecasting “platforms” or systems that combine wind, solar, DER (distributed energy resources), and demand in one application, using a team of internal forecast subject matter experts (SMEs), or external forecast providers, with internal demand forecasts.

Most FSOs use aggregated DER forecasts and include it as part of the demand forecast, but all identify increased difficulties in forecasting demand and RES due to increased embedded DER and behind the meter (BTM) solar, electric transportation and heat pumps. Operational forecasting is a key enabler of look-ahead tools in the operations environment, so their accuracy is critical to the future vision. Demand and RES forecasts ramps (solar and wind ramps) must be assessed to ensure there is enough online generation ramping capability to meet the demand. Weather, environmental, and geomagnetic forecasts are usually part of geographic information systems and are usually provided as services by external providers or public services.

Data Management and Storage

Most FSOs envisage data warehouse or data platforms for the management and access of data and data quality control with potential for data analytics in the future. Significant investment in capital and operational expenditure is required. However, in the long run efficiencies will be gained by making data easily accessible and available to stakeholders and for detailed analysis including machine learning. Most FSOs store data in servers on premises with limited applications of cloud storage for non-operational data.

G-PST FSO Key Research Questions – Operational Technology

The following key research questions were identified by G-PST founding system operators, for the operational technology and simulation capability in the G-PST control room of the future research pillar. These are key gaps that should be addressed by the industry and academic community. Coordinated research and development will help system operators transition to managing the system of the future. The operational capabilities are closely interrelated to other capabilities as shown below. View and download the G-PST Research Agenda (2021).

		Linked Capabilities
Operational Technology and Simulation	20. How can operators identify critical stability situations in real-time and optimize system security?	Operational Monitoring
	21. How can system strength, inertia, and limits of stable frequency range be monitored in real-time in high IBR systems?	Operational Monitoring
	24. What quantities must be monitored, screened, and validated in real-time to ensure that there will be adequate flexibility availability from uncertain system resources in the near-term?	Operational Data - Forecasting
	35. What is the best way to integrate large data sets, streaming information, and historical system performance to create actionable operational insights?	Operational Data

Operational Technology

Operational Simulation

Initiative	FSO Maturity Level	🟩 Implemented	🟨 Planned	⬜ Not Planned/Applicable		
Real-time probabilistic N-1	🟩	🟨	🟨	⬜	⬜	⬜
Real-time stability margins calculation	🟩	🟩	🟩	🟩	🟩	⬜
Real-time Dynamic Security Assessment	🟩	🟩	🟩	🟩	🟩	🟨
Demand response and redispatch forecast	🟩	🟩	🟩	🟩	🟨	🟨
Inertia and short-circuit capacity real-time calculation	🟩	🟩	🟩	🟩	🟩	⬜
Dynamic line/component rating	🟩	🟩	🟩	🟩	🟩	🟨

Short-Medium Term Challenges

- Managing weaker grids and stability challenges with increased IBR
- Dynamic stability assessment and other operation support tool implementation
- Identification of boundaries of secure operation in real time and with look-ahead using dynamic security assessment and EMT analysis.
- Resource adequacy assessments
- New ancillary services to ensure reliability and security
- New energy and balancing markets - closer to real time market gate closures

Real-time power flow (including dynamic line rating)

Real time congestion and contingency analysis

Smart device optimization

Unit commitment & security constrained economic dispatch

Transient stability assessment

Voltage stability assessment

Frequency stability assessment

Inertia calculation

System strength assessment

Short circuit calculation

Steady-state and look-ahead voltage assessment

Electromagnetic transient assessment

Resource adequacy assessment

Reserves calculation and assessment

FSO Context

Operations Technology Toolkit

The list of modules used in the typical OT toolkit, shown above, covers most of the key processes for transmission network and market reliability and security risk assessment. Not all FSOs use all the modules, and some FSOs have more advanced capability than others, depending on particular system needs, resources, and priorities.

Voltage Control

The management of voltage on the network is dependent on the functional model and owner/operator arrangements. Some FSOs have a manual voltage control process where the operator interacts with the transmission network owner or market participant and requests an action or target voltage level.

Most FSOs recognise the need for look-ahead capability for steady-state voltage management, with a voltage profile range for secure operation visible to both operators and participants. This can also potentially be enhanced with automatic control actions or dispatches to market participants where appropriate, to streamline the process.

Dynamic Security Assessment

The FSOs have mostly all developed the capability to monitor dynamic stability and security in real-time operations. Dynamic security assessment encompasses voltage stability, frequency stability, rotor angle or transient stability, small signal stability. Resonance and converter stability are less-well established dynamic security assessment processes.

This gives a real-time assessment for security, based on the real-time network and market scenario. More recently, the capability to assess stability based on forecast state (including market schedules, renewable energy sources (RES) forecasts, outages, and a secure voltage profile) has been explored and deployed by some FSOs. In the future, parallel processes of dynamic security assessment—for real time and look-ahead—will allow operators to mitigate future security risks by adjusting the system and the market schedule before they occur in real time. Developing dynamic security assessments in operations planning and outage scheduling processes is another area of exploration for some FSOs. Accurate security assessments are based on accurate dynamic models of generators, demand, and network assets.

Risk-Based Operations

As network development is slower to develop than resource mix and demand evolution, operating the network with more flexibility by using risk-based approaches to supplement deterministic approaches has been proposed as a solution. Most FSOs use some element of probability and risk in their processes, including forecasts, remedial action scheme (RAS) invocation, and reserve and resource adequacy assessments. The use of risk-based approaches in outage scheduling and network security assessment—i.e., changing from the N-1 standard to an approach that assesses contingency likelihood and cost—is not actively being pursued by FSOs. This is primarily due to complexity and owner/operator boundaries. Some operators use manual interventions and constraints in the market based on ambient weather conditions, lightning, fire, or storm forecast trajectories. Typically, this applies some N-2 contingencies to standard N-1 assessments that will result in a more secure operational posture. There are some moves in Europe (as part of network codes) and North America to explore this approach to security assessment, but it is early stage.

G-PST FSO Key Research Questions – Operational Monitoring

The following key research questions were identified by G-PST founding system operators, for the operational monitoring capability in the G-PST control room of the future research pillar. These are key gaps that should be addressed by the industry and academic community. Coordinated research and development will help system operators transition to managing the system of the future. The operational capabilities are closely interrelated to other capabilities as shown below. View and download the G-PST Research Agenda (2021).

		Linked Capabilities
Operational Monitoring and Decision Making	23. What are the appropriate methodologies to visualize and interpret relevant information for improved decision support for fast real-time control actions?	Operational Control
	28. How can data be best utilized to ensure system operations include the ability to detect and mitigate a range of uncertain disturbances?	Operational Data
	21. How can system operators get relevant real-time visibility and situational awareness of the state of the power system with increasing penetrations of IBR and DER?	Operational Data

Operational Monitoring and Decision Making

🟩 Implemented 🟧 Planned ⬜ Not Planned/Applicable

Initiative	**FSO Maturity Level**					
Asset's state & meteorology (component aging, icing, salt etc.)	🟧	⬜	⬜	⬜	⬜	⬜
Visualization of big data in control room	🟩	🟩	🟩	🟧	⬜	⬜
Oscillation location detection	🟩	🟩	🟩	🟩	🟧	🟧
Wide PMUs coverage	🟩	🟩	🟩	🟧	🟧	🟧
Remedial actions assessment (voltage control, frequency control, redispatch, transient stability)	🟩	🟩	🟩	🟧	⬜	⬜
List of suggested actions (voltage control, frequency control, redispatch, transient stability)	🟧	🟧	🟧	🟧	⬜	⬜
Simulation of 'what if' scenarios of current situation by operator	🟩	🟩	🟧	🟧	🟧	🟧

Short – Medium Term Challenges

- Improved visualisation of real time, post contingency and look-ahead projections of system strength, inertia etc.
- Data-based decision support in tools
- Risk assessment, analysis, judgement training for operators

SCADA / EMS

State estimation topology estimation

Phasor Measurement Units, Wide Area Monitoring System

Market schedule

Geographic visualisation

Weather and environmental forecast

Market participant information

Network asset information

FSO Context

Phasor Measurement Units (PMU) Wide Area Monitoring System (WAMS)

All FSOs have some form of WAMS capability, with varying quantities of operational phasor measurement units (PMU) devices on their networks. WAMS are used to identify frequency oscillations and their sources, determine phase angles for switching, and can be a good backup or verification for SCADA data. Modern WAMS can also determine short circuit level, inertia, and system strength.

Operational Monitoring and Decision Making

Skills, Rules, and Knowledge Taxonomy

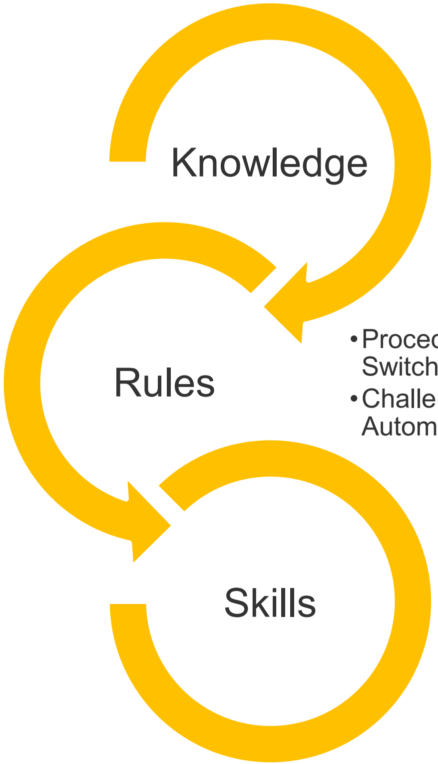
Work processes can be categorised as being either **skills, rules or knowledge** based:

- Skills-based processes rely on automatic motor skills of operators to control a process, such as acknowledging alarms, manual data entry or logging or voltage control.
- Rule-based processes are procedure driven, such as outage and switching procedures or reactive compensation switching.
- Knowledge-based processes are at the highest order and require an operator to assess and diagnose a situation, simulate, risk assess, and formulate an action plan. Knowledge-based processing is common for operators, as they develop creative and non-trivial solutions to emergency situations.

Skills- and rules-based tasks are ideal for automation, eliminating operator intervention into structured processes which can introduce human error. Knowledge-based processes cannot easily be replicated or replaced with automation. By focusing on automation of skills and rules-based processes, operators can focus their attention on the knowledge-based tasks, including intervention when automated processes mis-operate, when a contingency occurs on the network, or when using forecasts and look-ahead analysis tools to plan ahead.

Decision Support

Decision support refers to the ability to identify the risk on the system, quantify its cause and effect, and suggest actions to solve the issues. Decision support is a knowledge-based process that involve advanced simulation and optimisation capability and to date has limited applications in control room modules. Decisions are primarily planned, developed, simulated, and actioned manually by the control centre operator. Decision support is the most challenging process to automate.



Knowledge

- Experience, e.g. Emergency Response
- Difficult to Automate

Rules

- Procedures, e.g. Switching
- Challenging to Automate

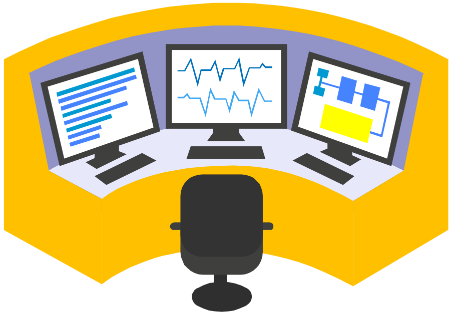
Skills

- Signal Following, e.g. Generation Dispatch
- Easy to Automate

Source: Skills Rules and Knowledge, Signals, Signs and Symbols and Other Distinctions in Human Performance Models, J. Rasmussen 1983

Training

Initiative	**FSO Maturity Level** 🟩 Implemented 🟧 Planned ⬜ Not Planned/Applicable					
Training simulator	🟩	🟩	🟩	🟩	🟩	🟧
"Trial and error" testing of new tools in control room concepts/procedures	🟧	🟧	🟧	⬜	⬜	⬜
Extreme situations drill training	🟩	🟩	🟩	🟩	🟩	🟩



FSO Context

Training

Regular training sessions on new and existing processes, modules and capabilities is critical. Ensuring that modules are deployed, tested, and trained on in the simulator or operations readiness center before deployment in production and operations is important to build trust and ensure issues are addressed before deployment. Traditionally, dispatcher training simulators consisted solely of EMS replicas. The breadth of OT and IT applications in control room environments now requires that training environments of all modules are available and interoperable, so that the simulation exercise is as close to reality as possible. Multiple vendor system co-integration for training simulators is a challenge that needs to be addressed in the coming years.

The future focus of training will be on interventions and emergency operations, when automation mis-operates. This is a specific form of training that is standard in the aviation industry and can be adapted for transmission network control. Developing simulators that replicate the control room, where real-time environments can also be securely deployed, is also advantageous for pandemic resilience. Developing and implementing workable, realistic training operational scenarios has been identified as a challenge by system operators, and all require a team of people working on training full time.

Operator Mindset

As outlined, the transmission networks of the world are undergoing rapid evolution. The most critical people in this transition may well be the operators, working 24/7/365. Given their criticality to the process, it is essential that they are key collaborators for the control room of the future and strategic operational initiatives. The FSOs ensure that the views of operators are incorporated through regular interviews, feedback sessions and inclusion of operators in the project team for tool delivery. The ease of adaption is not a uniform process: some people adapt more quickly than others, and some are more open to improved processes and new systems. Identifying and empowering thought leaders among the operator group can ease the transition. Allowing open communications where operators can freely express their needs and suggest solutions can also be valuable.

G-PST FSO Key Research Questions – Operational Control

The following key research questions were identified by G-PST founding system operators for the operational control capability in the G-PST control room of the future research pillar. These are key gaps that should be addressed by the industry and academic community. Coordinated research and development will help system operators transition to managing the system of the future. The operational capabilities are closely interrelated to other capabilities as shown below. View and download the G-PST Research Agenda (2021).

		Linked Capabilities
Operational Control	25. How can control capabilities for IBR-based system assets flexible AC transmission systems (FACTS), line Impedance adjusters etc. and network flexibility more generally be maximized to enhance reliability and/or reduce costs.	Operational Technology
	30. What type of digital architecture is necessary to enable the variety of software required to operate a control room in real-time, near real-time and in auto pilot mode?	Operational Architecture
	31. How can grid topology be flexibly adapted at various operating conditions?	Operational Technology

Manual Control | **Automatic Control** | **Emergency Control**

🟩 Implemented 🟧 Planned ⬜ Not Planned/Applicable

Initiative	**FSO Maturity Level**					
Early warning prevention (closed-loop full control autopilot)	🟧	⬜	⬜	⬜	⬜	⬜
Group-controlled wide area system protection	🟩	🟩	🟩	🟧	⬜	⬜
Automatic execution of switching commands	🟩	🟧	⬜	⬜	⬜	⬜
Automatic centralised voltage control	🟩	🟧	⬜	⬜	⬜	⬜
Operators' mindset change relying on AI/autopilot	🟩	🟧	🟧	🟧	⬜	⬜
Power flow control devices	🟩	🟩	🟩	🟧	⬜	⬜

Short-Medium Term Challenges

- Challenges with increased automation in control actions
- Change in culture of control
- Reliance on automated systems due to complexity of the system and tools
- Asset owner operator arrangements
- Trust in automation proposed solutions

Generation Dispatch

Network Asset Control

Distributed Energy Resource Control

TSO-DSO Control Framework

Demand Response / Control

Automatic Reclosing

FACTS, PST

HVDC

Protection

Special Protection Schemes

Remedial Action Schemes

Under Frequency Load Shedding

Blackstart

Restoration

FSO Context

Flexible Demand

Flexible demand is becoming an increasingly important aspect of balancing and network operation and the trend is expected to continue in the years ahead. Some FSOs use bilateral contracts with large energy users to provide demand response. Other FSOs have demand units participating in energy, reserve, or stability markets in the same way generators do. Demand units can be dispatched for energy or to alleviate congestion or stability issues.

Emergency load shedding has traditionally been a last-resort security measure; however, this is becoming increasingly difficult for some FSOs, as DER connected to distribution feeders may be disconnected and exacerbate a frequency stability contingency. Battery energy storage systems (BESS) and HVDC are proving capable of providing excellent fast frequency response, thus limiting the frequency nadir to a level where load shedding is less useful for contingencies. (It will always be useful for slowly evolving resource adequacy or capacity challenges).

Automated Operation

There is much talk in the industry of “auto-pilot”-like automated operation for transmission network control. Some control room operations processes have been automated and in reliable operation for many years. For example: automatic generation control (AGC), fed by security constrained economic dispatch (SCED) schedules control the frequency and automatic reclosing for lines; special protection schemes (SPS) act to restore the network almost instantaneously; and voltage control actions such as reactive compensation switching are straight forward to automate. With the variety of new, smaller generation resources, markets, and market participants, HVDC and flexible alternating current systems (FACTS) devices, this trend towards increased automation will likely continue.

However, control centres are high-reliability organisations, requiring expertise and knowledge among a team of trained experts. Transmission networks are too complex and important to society for control to be fully automated. High Impact Low Probability events are, by their nature, infrequent and may not lend themselves to training machine learning algorithms for all tasks.

Human in the Loop

Automation of skills- and rules-based processes will inevitably result in reduced manual operator action, or longer periods of time of observation, without action. This lack of manual action may pose a risk to reliability, as operators will be taken “out of the loop” of normal operations processes. Since it is difficult for operators to be always hyper-vigilant, the transition from the relaxed state to the knowledge-based state will be critical. Training in maintaining awareness and processes for intervention and override will be important parts of future operator training programs.

Root Cause Analysis and Corrective Action

Typically, when a major disturbance or operational technology disruption occurs, there is a flood of data into the control room screens. The process of identifying the cause of the issue, identifying mitigation measures, simulating the responses and executing the action is usually time consuming, even for experienced operators. This is especially challenging if the event occurs on a neighbouring network, distribution network or network where asset data is not available to the operator. Generally, there is an abundance of data points (unless the operational technology mal-functions) from SCADA, market, WAMS, DSA but the human capability to parse the data in different formats and time-stamps is limited. A lot of the data points come from different operational technology systems and the operator must toggle between systems and displays to get the fullest picture.

Developing the capability to automatically analyse and group data in real time to aid operator decision making – will be an important capability for future operations. A further advanced iteration of this capability may be suggested control actions post-event. This should tie into the vision of automated control with the human in the loop.

Artificial Intelligence and Machine Learning

Viewed externally, control room operations is an ideal environment for the deployment of machine learning and artificial intelligence. This is true in some ways due to quantity of data available and the control-feedback mechanisms. Operational forecasting has used neural network-based techniques to forecast demand for many decades. However, beyond the forecasting use cases, system operators have struggled to get production-grade systems into operation using machine learning. Most operators see the potential value of machine learning and artificial intelligence applications to time-series, data rich application. However, the data structure, security, computer infrastructure, and development overheads are proving prohibitive at present to advanced innovation.

Challenges for System Operators

- **Data Quality**

  Operational data comes from a variety of systems and simulation platforms, that are not aligned by data points or by time. There are no common data standards for naming conventions and structure so unstructured text and data must be parsed.

- **System Criticality**

  Due to the critical status of operational systems, technology must be proven and secure before deployment. Experimental technologies are not favored, and simulation platforms may not always align with the production version of systems, critical network and market data is required for training but must be securely held by network operators.

- **Computer Infrastructure**

  System operators generally do not host high performance computing power on premises. Transitioning from premises-based solutions to public cloud with high performance computing will allow broader use of the ML applications.

Potential Operational AI/ML Use Cases

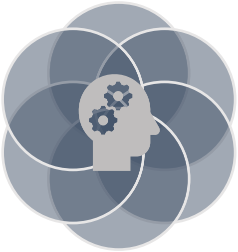
- Operational Forecasting
- Data Clustering
- Control Action Learning
- Text & Language Processing
- Network Data Abnormality Detection

Call-to-Action for the Control Room of the Future

Given the ambition of the control room of the future vision, there are several challenges to be overcome by system operators, architects, vendors, and the wider industry, if the vision of future system operations is to be achieved in the medium to long term. Some of the short-medium term challenges in operational capabilities, identified by the FSOs, were highlighted throughout. In the longer term, the G-PST research agenda and questions specific to the CROF need to be addressed to realize the CROF vison.

To address the gaps and achieve this vision, the industry at large should work to form collaborations between transmission and distribution system operators, regulators, standards bodies, research and academic institutions, engineers, scientists, software developers and vendors.

The vision for the CROF cannot be realised without close collaboration, coordination and delivery. Investment in human and technology capability is vital to ensure development of control capability tracks underlying network and resource evolution is also essential. Scientists and engineers in the academic and research community will need to coordinate with technology vendors to quickly advance concepts through technology readiness levels and into real time operations.



System Operators

Technology Vendors

Academic & Research Community

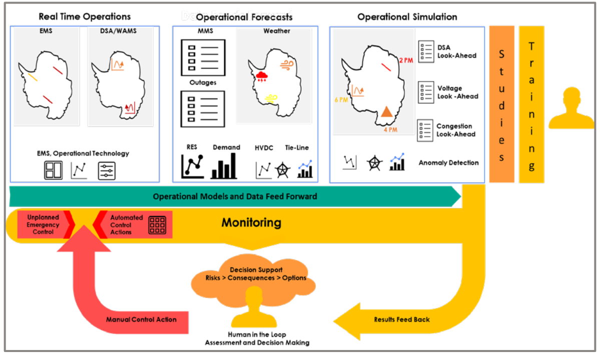
Regulatory Authorities

Software Developers

Scientists & Engineers

Short-Medium Term Challenges

G-PST CROF Research Questions



Further Reading and Resources

- G-PST Website: https://globalpst.org/
- G-PST Research Agenda: https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf
- G-PST, Control Center of the Future Assessment for COES Peru: https://globalpst.org/control-center-of-the-future-assessment-developed-for-peruvian-system-operator/
- CSIRO, Australia’s Global Power System Transformation Research Roadmap: https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap

globalpst.org/