Control Center of the Future Road Map

Prepared for the Perusahaan Listrik Negara (PLN) Sulawesi Control Center

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NOTICE

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List of Acronyms

AGC	automatic generation control
CCOTF	Control Center of the Future
DRC	disaster recovery center
EMS	energy management system
G-PST	Global Power System Transformation Consortium
IEC CIM	International Electrotechnical Commission Common Information Model
IPP	Independent Power Producer
IT	information technology
OCM	Operational Capability Model
ORC	operations readiness center
OT	operational technology
PLN	*Perusahaan Listrik Negara*
PMU	phasor measurement unit
RES	renewable energy source
SCADA	supervisory control and data acquisition
WAMS	wide area monitoring system
WAMPAC	wide area monitoring, protection and control

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1 Introduction

Power system control centers are staffed with people tasked with planning and managing the real-time operations of the electricity grid. Power systems across the world are undergoing transformative changes in their generation resource mixes, end-use load characteristics and scale, and grid architectures that are drastically altering the dynamic characteristics of all grids. Advanced technologies, methods, and tools will be required in control centers to maintain effective operations. Given high reliability requirements, regulation, and the historical pace of innovation, transmission control centers have generally evolved slowly over time, in tandem with the slow evolution of transmission grids. However, the recent rapid changes in transmission systems are leading to previously unforeseen system risks and challenges. This pace of change is anticipated to continue with increasing end-use electrification, shifts to inverter-based resources and distributed resources, and advances in demand-response capabilities. In weakly interconnected systems that have high renewables penetrations and/or rapid demand growth, older monitoring and control tools are not adequate for assessing and addressing the risks that are highly likely to impact the system.

While there are many interesting and useful solutions to these risks and challenges available today, the continuously evolving nature of power system requirements need continuous development and implementation of new solutions. Ongoing research and development are being carried out to help bring new approaches to data, applications, processes, and human factor considerations into the real-time control center environment. Road-mapping efforts generally serve to inform longer-term planning and system design decisions with a focus on the desired control center functionality that will support reliable, secure, and efficient provision of electricity. To maintain relevance in the rapidly evolving power sector, road maps do not focus on specific technical requirements, but instead lay out general functional capabilities that should be considered in the planning process.

This road map is intended to be used by decision makers at Indonesia's state electricity provider, PT Perusahaan Listrik Negara (PLN) for both near- and longer-term engineering design, as well as strategic and procurement planning. This document is not intended to be an implementation plan or course of action for PLN to follow; rather, it is an indicative and visionary way of considering optimal approaches for meeting the demands of the future power system.

PLN's Sulawesi power system will soon undergo rapid change with pending near-term upgrades and expansion that will introduce critical risks and challenges. Plans are underway to interconnect its north and south systems and implement disaster recovery capabilities; rapid load increases are expected as part of increased mining activities, and Sulawesi's renewable energy sources (RES) will continue to contribute to national commitments to a renewable energy mix of 23% by 2025. This road map will lay out a pathway for the possible implementation of a best-in-class structure and related functional capabilities for the Sulawesi Control Center of the Future (CCOTF). It is an ambitious and visionary plan that encourages an industry-leading control center for system operators. The road map covers all aspects of control center functionality, from monitored data and analysis needs to facility design considerations.

2 Sulawesi System Context

2.1 Focus on 2023–2030

The Sulawesi electricity system is anticipated to undergo significant growth in the next decades. Based on the 2021–2030 transmission plan update, it is anticipated that approximately USD $1.6 billion will be invested in transmission infrastructure projects. This will be necessary due to anticipated demand growth, which will require proportional generation growth. Approximately USD $981 million is envisaged for 11 projects and construction works, which were planned to start during 2020–21 and be completed by 2026. The remaining USD $659 million is earmarked for 13 projects, for which construction will begin after 2021.[1] Paramount in upgrading the Sulawesi system will be interconnecting the north and south systems, implementing a disaster recovery center (DRC) capability, and expanding generation and transmission capacity to align with anticipated mining-related load growth.

The following sections analyze the growth in Sulawesi system demand, generation, and network over the next decade, with reference to control center needs.

[1] PLN, "*Rencana Usaha Penyediaan Tenaga Listrik (RUPTL)*, 2021–2030 [Electricity Supply Business Plan, 2021-2030]." Jakarta, Indonesia, 2021.

2.2 Future Demand

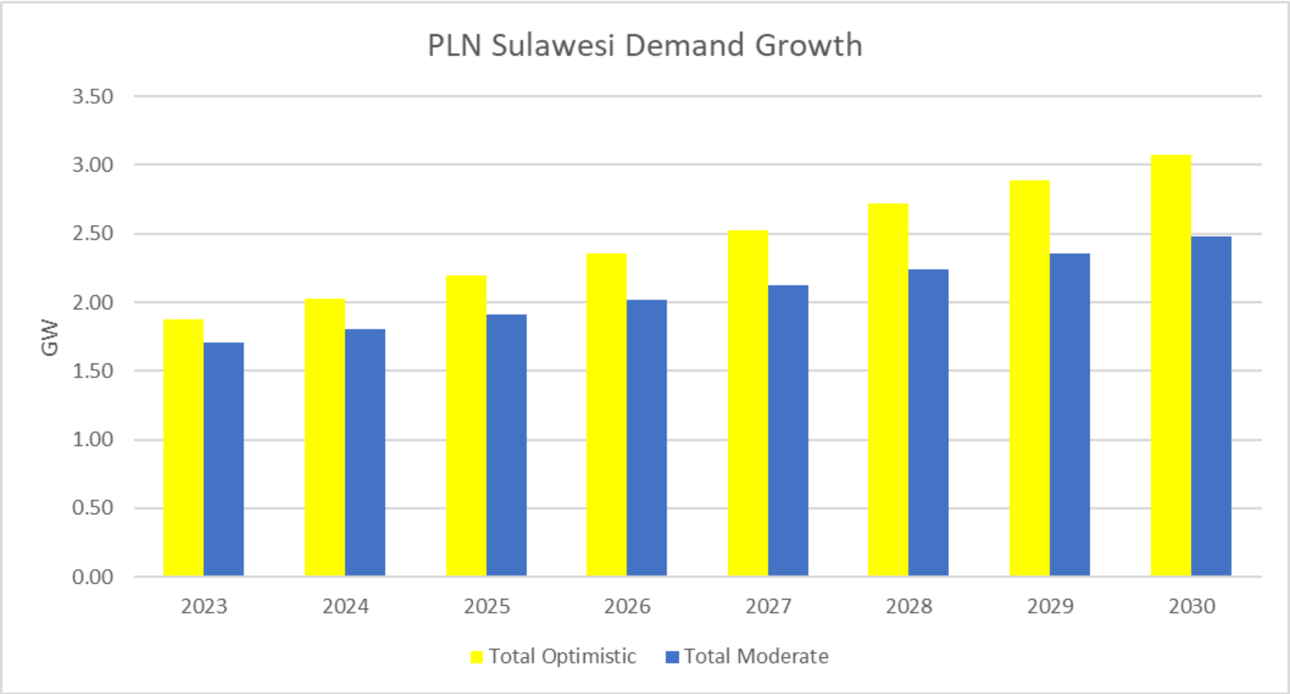


Figure 1. PLN Sulawesi demand growth 2023 to 2030 with two different scenarios for growth (moderate and Optimistic)

Source: RUPTL, 2021–2030

Based on an average of PLN's moderate and optimistic projections for growth from 2023–2030, peak demand is expected to grow from 1.8 GW to 2.8 GW, a 55% increase over 7 years. This is a significant rate of increase in demand, and it will require a commensurate increase in generation capacity and transmission network to connect the new generation to the growing demand.

What Does This Mean for the Operations and Control Center?

- Enhanced demand forecast
- Enhanced distributed energy resource forecast

- Demand response, variable power plants
- Smart meter data utilization.

Growth in demand will require significant generation and network assets to balance the system securely in real time. An enhanced forecast capability is required that can accurately approximate the demand use on the system in real time and with an adequate time horizon. Advanced operational forecasts today generally use artificial intelligence technology. Demand forecasting should incorporate distributed energy resources such as behind-the-meter solar photovoltaics, which impact demand. All of this requires deeper integration of transmission and distribution operations and capabilities.

Demand aggregation, sometimes described as a virtual power plant, may emerge as entities to be monitored and controlled in the future energy market. Having the capability to monitor, decide, and control the use of virtual power plants will be an important aspect of unlocking flexibility in the future system and for reserves.

In future years, smart meters may be installed that feed real-time meter data to the control center for use in forecasting and virtual power plant dispatch. Close coordination with the distribution system operators will be required to enable this capability.

2.3 Future Generation

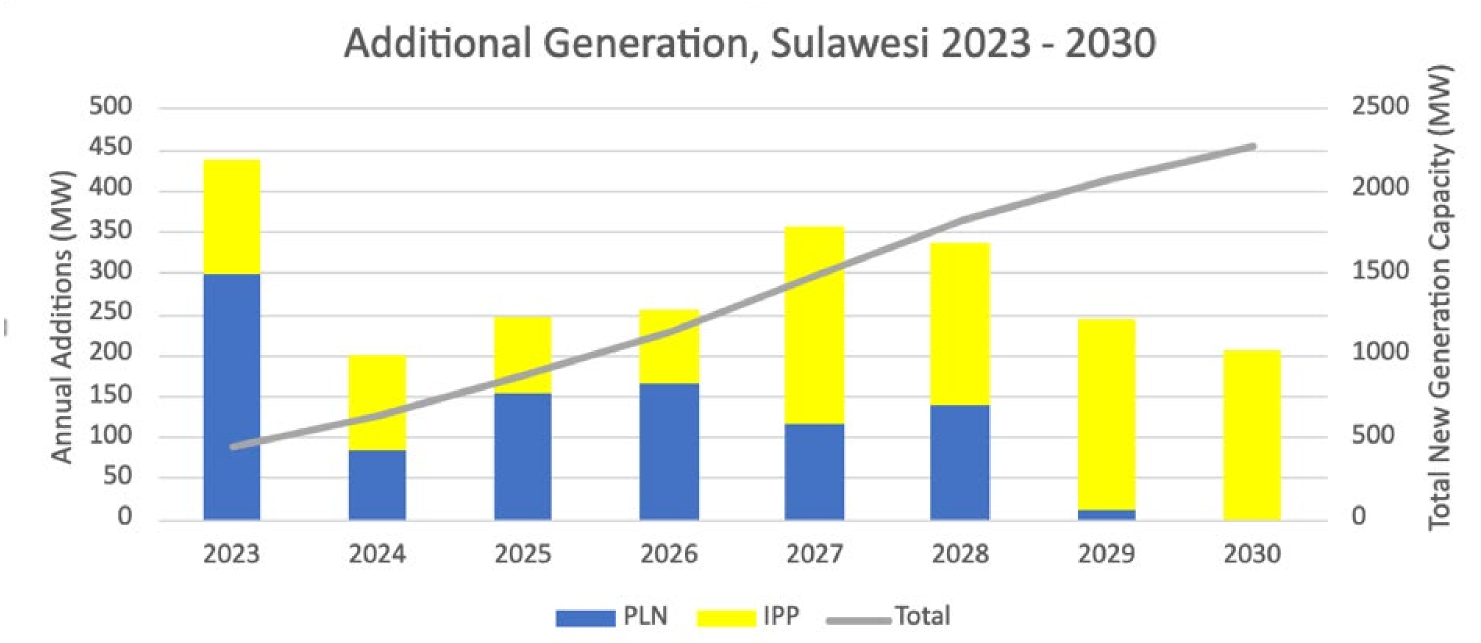


Figure 2. Sulawesi additional generation, 2023–2030

Source: RUPTL, 2021–2030

The PLN Sulawesi network is projected to add an additional 2.2 GW of PLN-owned and independent power producer (IPP) -owned generation capacity between 2023 and 2030. This projection appears to be adequate to cover the average of the moderate and optimistic scenarios (1 GW of extra demand growth) and the optimistic scenario (1.2 GW of demand growth) with reserves and headroom for contingencies, retirements, and continuous development and demand growth. This growth is split between the PLN and IPP sectors, with 0.9 GW of new PLN-owned capacity and 1.3 GW of independent power producer-owned capacity due to be connected in the coming years.

There will be an anticipated increase RES connections onto the Sulawesi grid in the years ahead, with approximately 400 MW being wind and solar photovoltaics. Globally, planned shares of wind and solar photovoltaics have been trending upward in recent years due to decreasing costs and increasing climate migration ambitions; this trend may continue in Sulawesi and should be considered when planning future control center capabilities and readiness. Weather based RES (such as wind and solar photovoltaics) connected to the bulk system at scale will require the capability to forecast as accurately as possible what the future output will be in the day-ahead time scale. Enhanced weather-based RES forecasting should also include the capability for enhanced weather forecasting to account for forecasting of major events.

With an increase in variable renewable generation capacity, there will be more challenges with dynamic system stability. In grids around the world that have incorporated RES rapidly at scale, new challenges with frequency stability, transient stability, and small-signal stability (frequency oscillations) have been observed. Proper planning and integration of the improvements to model the system at dynamic timescales, monitor and assess system stability, and support robust decision-making as highlighted in this road map will help address these new challenges and will be advantageous as the operations function evolves.

With the rapid increase in generation capacity in the years ahead, resources must be commissioned, added to operational technology (OT) databases, and modeled and verified with original equipment managers after commissioning. This will require human resources in the control center and subject matter experts to ensure models of resources are aligned and validated.

What Does This Mean for the Control Center?

- More weather-based renewable resources require forecasting capabilities.
- System stability and security issues will be present with less-conventional generation resources.
- Additional generation resources will be commissioned and tested and accurately modeled in OT systems.
- Additional independent power producer generation may present challenges with data and communication requirements, model validation, and commissioning and testing.

2.4 Future Transmission Network

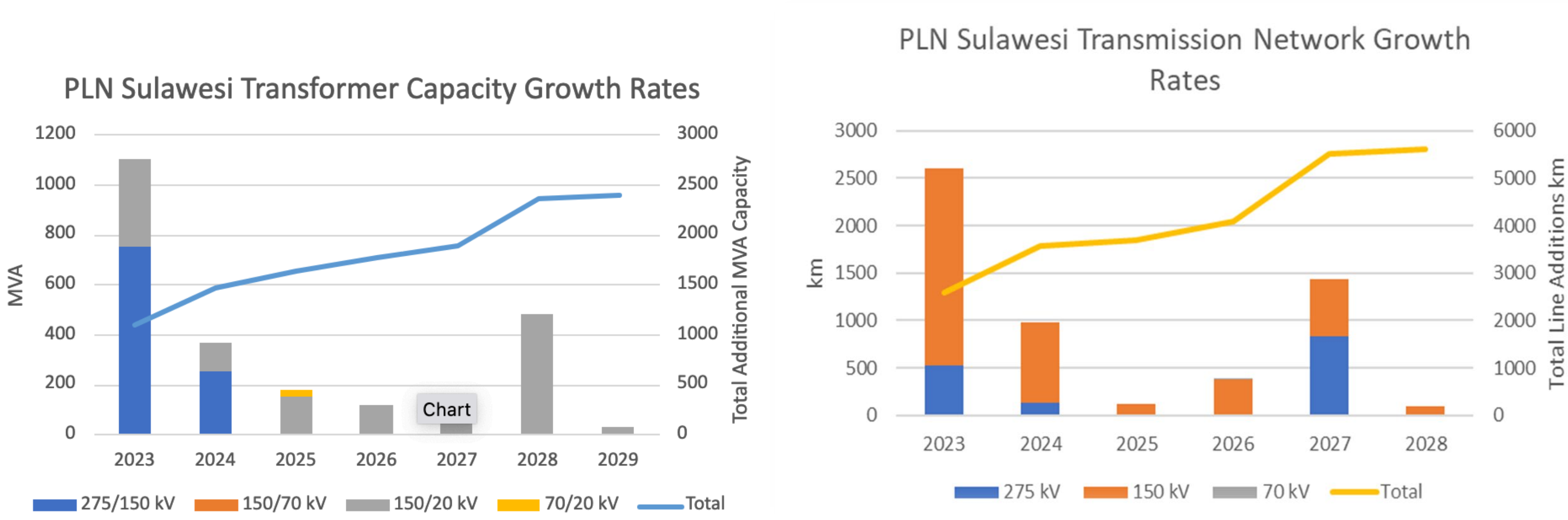


Figure 3. Sulawesi growth rates

Source: RUPTL, 2021–2030

Added to the major growth in demand and generation capacity is a significant need to upgrade the transmission network capacity in terms of new lines and substations. Transformer capacity growth is a good proxy for the growth in network capacity (as the number of substations may not reflect actual growth rates). Published PLN statistics and projections show a cumulative growth in transformer capacity of 2.4 GVA between 2023 and 2030. This matches approximately with the growth in demand over the ensuing years. The transmission network (lines and cable) is projected to grow by 5,611 km between 2023 and 2028. This projection includes the addition of 2,598 km in 2023, of which 2,078 km of 150-kV lines is for the interconnection of the two north (Sulutgo) and south (Sulbagsel) networks into one interconnected system.

The interconnection will be made through the Moutong-Tambu-Talise route (using one route and but two 150-kV lines for redundancy). In addition to the interconnection, a DRC capability will be implemented, with the primary control center placed at the Sulawesi Control Center at Makassar and two DRCs located at Kendari (southeastern Sulawesi) and potentially Gorontalo (northern Sulawesi), respectively. The primary DRC will be at Kendari, and a secondary DRC is being considered at Gorontalo.2 If the Sulawesi Control Center fails, the DRC at Kendari will

[2] Further study is necessary to relocate the existing North Sulawesi Control Center in Tomohon to Gorontalo as the secondary DRC. Currently, Gorontalo does not have appropriate control infrastructure. The existing control center in Tomohon has a better reliability, as it is connected to double-ring transmissions (66 kV and 150 kV), while Gorontalo has only radial connectivity.

take control of the entire system. If north and south become disconnected, the DRC at Gorontalo will operate the north subsystem independently, while the Sulawesi Control Center (Makassar) or DRC (Kendari) will operate the south subsystem. To operate the grid reliably, the Sulawesi Control Center and DRCs should be able to rotate roles. The industry best practice is to switch primary and backup roles every month or whenever there is a significant modeling update.

Additionally, the 2021-2030 RUPTL (PLN's electricity business plan) anticipates interconnecting the systems at Raha and Bau-Bau to each or the larger Sulawesi system in 2026.

What Does This Mean for the Control Center?

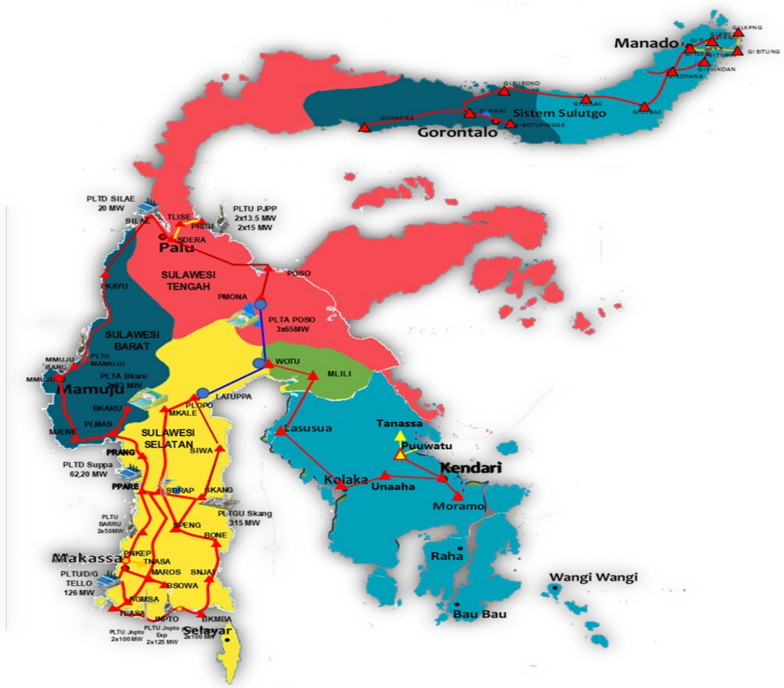
- For integration of the north and south systems, two issues should be evaluated and managed: one is to detect oscillations, and another is the N-1 contingency of running island mode. The connection of the main Sulawesi grid to the Gorantalo and Utara regions by means of long radial transmission interconnection creates the potential for grid instability. Further, if the north and south systems should become disconnected though a forced tripping outage, manual opening, or other event, the systems should be designed with the ability to monitor and control the voltage and frequency of each island independently. This can be done with remote communications from the Sulawesi Control Center or DRC (Kendari), or with redundant capabilities at the DRC at Gorontalo.
- The installation of inverter-based resource generators such as wind, solar, and battery storage systems could cause further concerns around instability, as experience has shown that decreasing system inertia can negatively impact dynamic grid stability. The installation of a wide area monitoring system (WAMS), which utilizes selective phasor measurement unit (PMU) installations, can be used to monitor and detect grid instability issues. A wide area monitoring, protection, and control (WAMPAC) system, discussed below, can also be used to initiate an automatic remedial action scheme to initiate tripping in the event of instability.
- The control centers will be consolidated from two separate control centers to one main control center and one DRC.
- With the merging of the control centers into one site, a single energy management system (EMS) will be commissioned for the interconnected system. This means datasets and communications pathways will need to be merged and integrated in the new EMS.
- One single EMS should be procured based on the Sulawesi vision and OT road map.
- Computing hardware must be enhanced for the new interconnection's EMS, supporting reliable infrastructure such as servers, workstations, and power backup supplies and redundancies.
- The network size will increase, meaning an increase in the number of assets to be monitored and controlled in real-time operations. This will require more commissioning, more control capability, more protection, and additional control devices.
- Size of network to be controlled will increase the number of points that need to be monitored, as well as analogs and the number of commissioning events and planned outages.
- Existing assets on the network must be replaced or refurbished, which will require an increase in outages to be scheduled and managed in real time.

- The number of needed protection and control devices on the network will increase.
- Needed special protection schemes will likely increase, as well as remedial action schemes and WAMPAC.
- The number of smart devices to control power flow on the network will increase, such as static VAR compensators, static synchronous compensators, dynamic line rating, power flow control, and other grid-enhancing technologies.

Comprehensive training procedures and documentation will be needed for the interconnected operation so any operators can support the Sulawesi network. Operators must be trained on all devices and new protection and controls on the network.

- As more devices and networks open to serve the community, the cybersecurity policy should be reevaluated.
- The operating point of the network will likely change with the change in transmission network topology, requiring optimization of the network as much as possible.
- The stability of the network may decrease with the change in conventional generation and the increase in length of network, which may require additional simulation capability.
- Major disturbances and faults will likely increase on the network because of high-impact, low-probability events such as storms, typhoons, lightning, etc.

PLN Sulawesi Transmission Lines (as of 2023)



PLN Sulawesi Transmission Lines Future Growth (~2030)

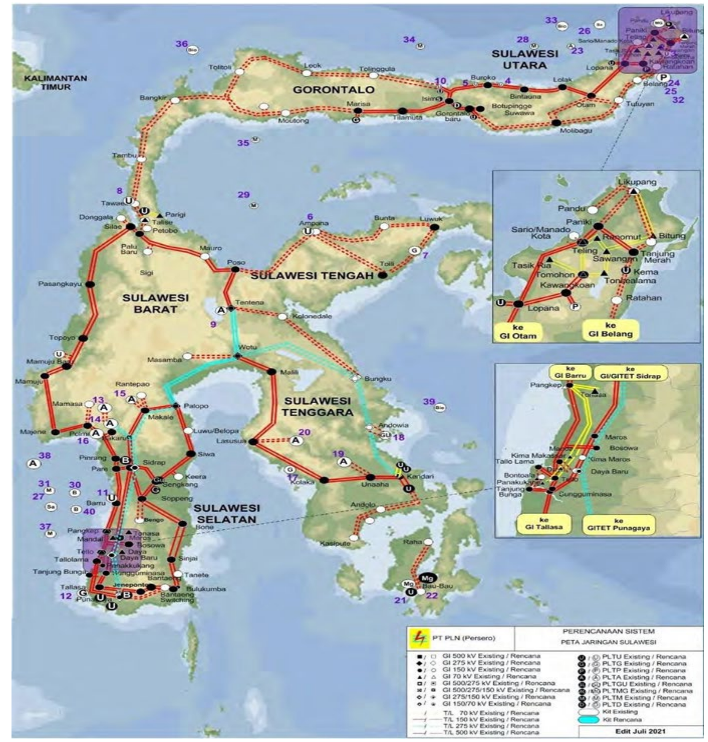


Figure 4. Sulawesi transmission lines, 2023 vs. future growth

Source: RUPTL, 2021–2030

2.5 Summary

The PLN Sulawesi networks will interconnect in the coming years, which will bring major growth in network size and complexity to be managed by the control center. In doing this, PLN will merge from two separate control centers and EMSs to a single EMS for the interconnected system and one main control center with a DRC.

In addition, PLN expects a rapid increase in projected load in the coming years, for which they are planning to connect a significant quantity of generation resources and demand and transmission network infrastructure. This increase in network size and capacity will have a significant knock-on impact on the operation of the network in the operations planning domain and in real-time operations. This will require an increase in operational capability across all domains of operation: real-time operations; planning, forecasting, and simulation; and look-ahead capabilities and optimization. The Electric Power Research Institute Operational Capability Model (OCM) utilized in this road map provides a tested framework for assessing the capability needs of a utility undergoing radical transformation. It will be used in the following sections to assess the status of, and project a pathway to, a more integrated, interoperable CCOTF.

3 PLN Vision and Mission Statement

When developing a road map for the future of operations and the control center, it is important to ensure the corporate direction of the utility organization is aligned and is a core part of the vision. PLN has an ambitious vision and mission statement to match their future projected network growth rates.

3.1 PLN Vision

"To become a leading transmission unit and system control center in Southeast Asia based on the quality of human resources with good morals."[3]

3.2 PLN Mission

- Manage power system operations reliably
- Carry out and manage the transmission of high-voltage electricity efficiently, reliably, and in an environmentally friendly manner
- Manage electricity transactions in a competitive, transparent, and fair manner
- Manage maintenance of electric power transmission system installations
- Manage company resources and assets efficiently, effectively, and synergistically to ensure optimal business management and meet occupational health, safety, environment, and security standards, as well as by using the principles of good corporate governance.

[3] PLN. 2023. "Core Values and Organization." Presented April 2023.

4 CCOTF Design Framework

4.1 Traditional Approach to Control Center Design

Traditionally, control center design and operational capability upgrades tended to iterate from preexisting infrastructure and designs. However, the power system of Sulawesi (and networks in general all over the world) are undergoing radical shifts and evolutions. This is driven by:

- New resources, such as variable renewable and distributed energy resources
- Energy and ancillary service markets, if available
- New smart devices and protection and control
- New information technology (IT) and OT, such as cloud computing, data visualization, and machine learning
- Wide availability and reliance on software applications and data streams for network operation.

4.2 G-PST CCOTF Vision

In 2023 the Electric Power Research Institute, together with the Global Power System Transformation Consortium (G-PST) founding system operators (the Australian Energy Market Operator, California Independent System Operator, EirGrid, Energinet, the Electric Reliability Council of Texas, and National Grid Electricity System Operator Ltd.) developed a vision for the CCOTF, presented in a white paper.[4] The vision is applicable to all transmission control centers, regardless of the function, and is detailed as:

- Accurate, validated, centrally managed, dynamic models and streamlined operational data feed the 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.

[4] G-PST. *Vision for the Control Room of the Future.* Washington, D.C.: Electric Power Research Institute. https://globalpst.org/wp-content/uploads/G-PST-Vision-for-the-Control-Room-of-the-Future-V0.5-Final.pdf.

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

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

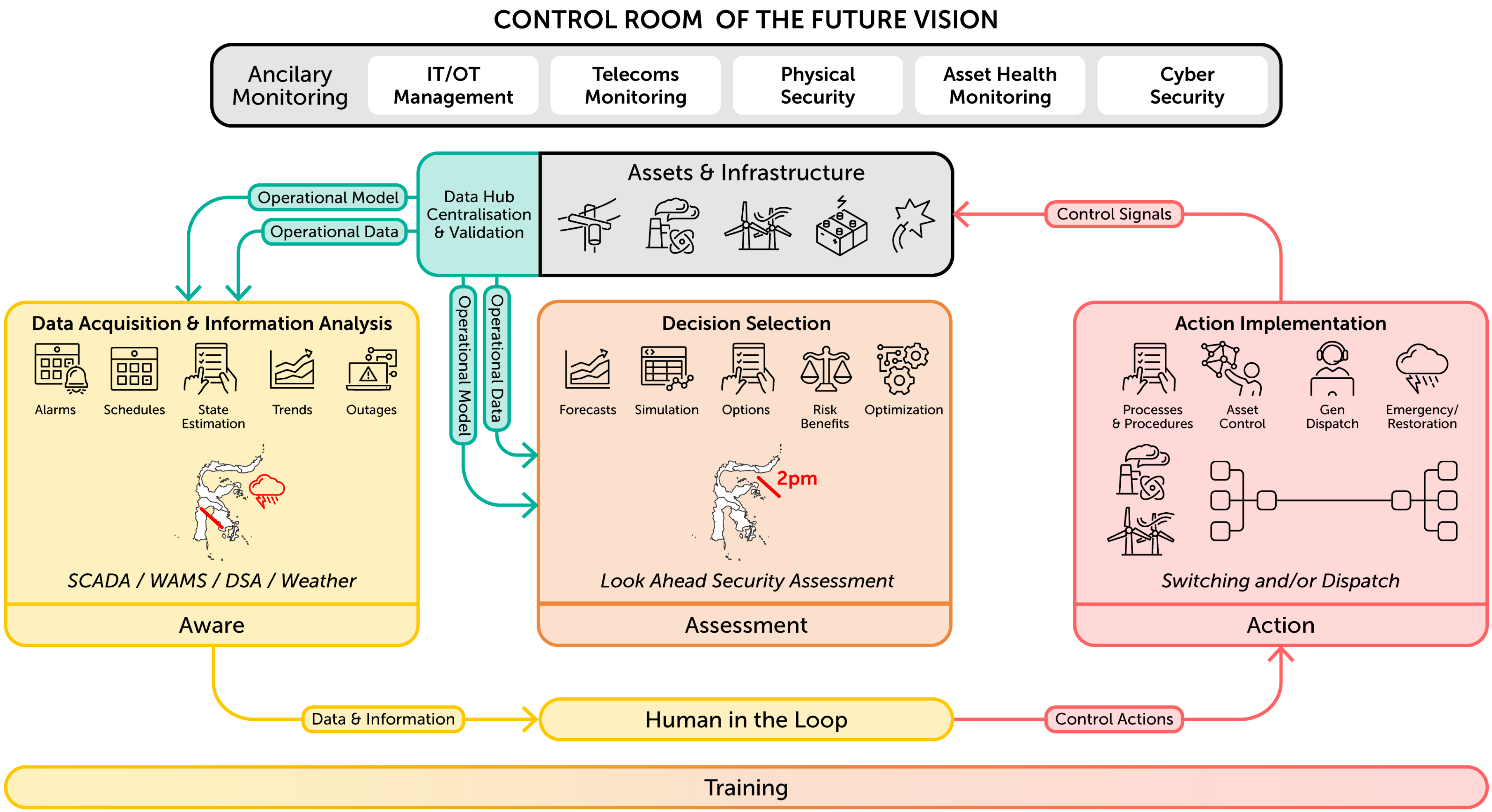


Figure 5. Graphic visualization of the vision for the CCOTF, based on the vision statement from the CCOTF G-PST report in 2023

Source: EPRI

The vision statement can be visualized with the graphical representation shown in Figure 5. This graphic shows three distinct color-coded modes of OT, which blend with operator situational and ergonomic visualization. There are essentially three modes of operator awareness and decision-making, as highlighted below.

- Aware – For data acquisition and information analysis, sensemaking. In general, information consists of data and context. In this mode, operators synthesize and make sense of data, given its context to define a given issue.
- Assessment - Decision selection. Forecasting, simulation, and optimization tools provide the operators and automated control devices with a range of decisions and potential solutions. In some cases, the optimal action is automatically deployed on the real assets, while in others a human operator must intervene to assess and make the right decision.
- Action - Decisions are actualized.

The three-mode model aligns with other models of situational awareness, such as:

- Scan, focus, act
- Observe, orient, decide, act
- Recognition-primed decision-making
- Perception, comprehension, projection.

The aim of the visualization is to show how the physical assets, data and models, OT, human factors, and visualization equipment blend to make a holistic, innovative vision for the future of operations.

The color-coding is intentional in the graphic and illustrates the three stages of awareness according to the Cooper Color Code: yellow for awareness, orange for alertness, and red for action. This yellow, orange, and red coding should also feed into visualization design and alarm rationalization.

4.3 The Electric Power Research Institute's OCM

After the vision for the CCOTF is established, the elements of the underlying capabilities within the control center can be collated and aligned, so that gaps can be identified, and the road map can be developed. EPRI has developed an OCM framework, depicted in Figure 6 below, to organize and help visualize how the capabilities relate to one another.

The OCM groups 11 core operational capabilities into four overarching layers:

- Facilities and Equipment
- Operational Technology

- Operational Data
- Human Factors.

The 11 capabilities are shown in Figure 6. These will be expanded upon in later sections for the development of the road map for each pillar.

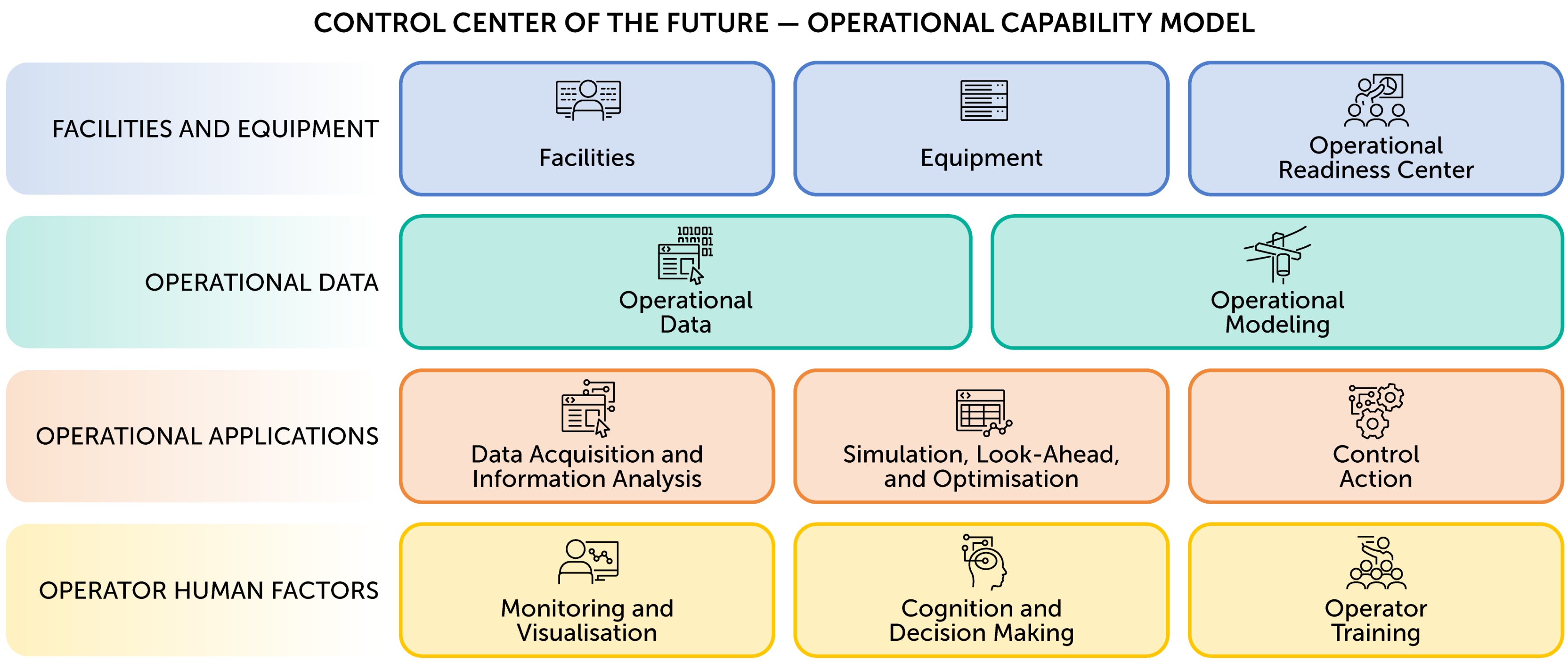


Figure 6. Framework for the CCOTF, showing the 11 color-coded operational capabilities within the four core blocks

Source: EPRI

5 CCOTF Operational Data

5.1 Drivers for Change and the CCOTF Vision

Data is the underpinning capability of all control center capabilities. Without data, the OT systems cannot operate, and the operator cannot maintain situational awareness.

When considering data, the CCOTF framework splits the capabilities in two: **operational models** (including room mean square, dynamic, electromagnetic transient, economic dispatch models, and short-circuit protection) **and operational data** (including supervisory control and data acquisition [SCADA], dispatch data, PMU, digital fault recorder, and inter-control center communications protocol data).

5.2 Value of Developing and Enhancing Control Center Data Management

Developing operational models and streaming data capability for the operations teams and the control center will allow human resources to be optimized, eliminate duplication, and ensure accuracy in all systems. The data in the system can be validated so that trust in the accuracy of the model is gained, as well as its tools for more detailed analysis such as stability assessment.

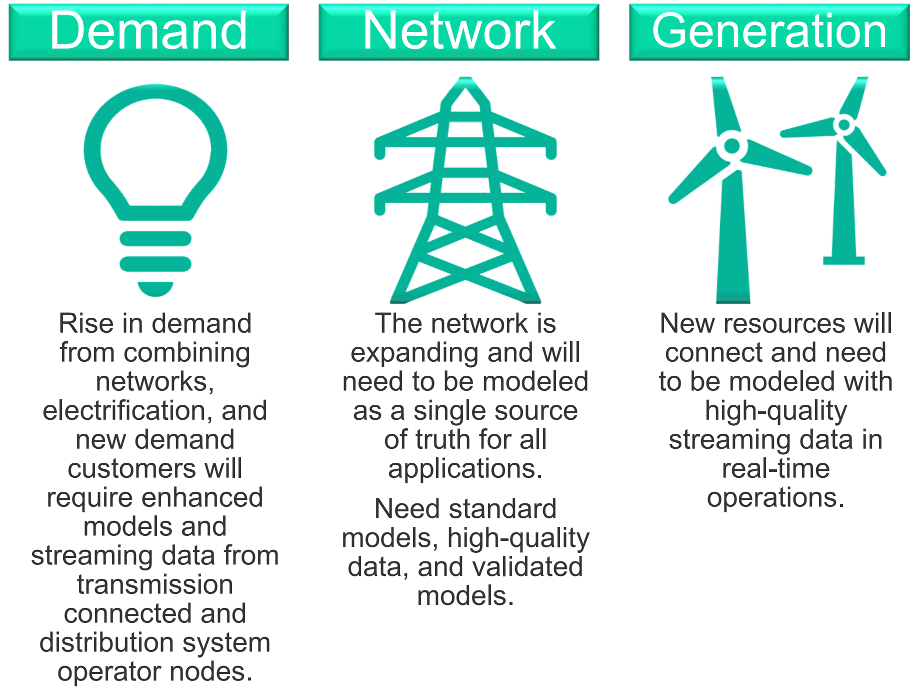


Figure 7. CCOTF vision ∞ PLN vision

Additionally, PLN may consider making applicable operational data available to the wider community to take advantage of the value provided to the wider Indonesian energy community and economy. This would enable companies to establish themselves based on the best available data and allow the energy industry to make the most advantageous decisions for investment in technical capabilities and service offerings.

Operational Models

Despite multiple time domains of operational simulation, the aim should be for a single model, managed from a single, centralized repository, that serves all systems that require simulation. For example, a generator has a certain format for the EMS state estimator and a more-detailed dynamic model for the dynamic stability assessment simulation, but its model parameters should be managed centrally in a standard format, such as the International Electrotechnical Commission Common Information Model (IEC CIM) using unique ID reference numbers. The distinction for operational modeling is important, as the types of tools and simulations required in the operations domain differ from the planning domain and are usually managed separately. The aim across the company should be a centralized repository for both planning and operational domains.

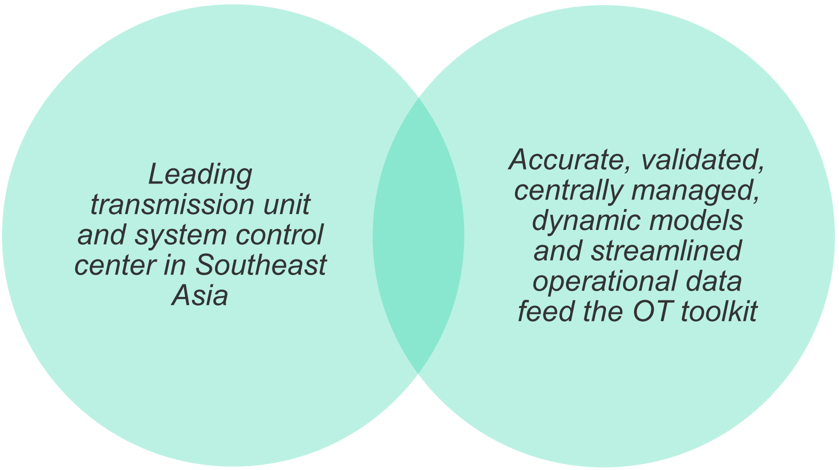


Figure 8. Vision for data models

Operational Data

Operational data refers to data that is fed to the control center OT in real time from physical assets on the system. Traditionally, this has been primarily from SCADA data, but today, more granular data from PMUs and substations' intelligent electronic device assets[5] is available to system operators. In general, while this might be useful data, careful consideration should be given to how this data is organized, governed, and structured, to improve decision-making and avoid information overload. The management of streaming data and model data will be the key enabler for machine learning and data analytics techniques to be used in the CCOTF.

[5] Although not in use today on PLN's system, in the future, this may be transmitted via IEC 61850 protocols.

CCOTF Network Model and Operational Data Management

A centralized model management system has an authoritative, single-base model of the system in a centrally managed database that feeds all systems that require model data for simulation and analysis. It conforms to the IEC CIM standards and can operate as an asset register or geographic information system. It uses variations of the base system for future or planned upgrades. Utilizing one model managed by one team of modeling experts that feeds all other systems has obvious benefits for system operations accuracy and error reduction. The integrated model manager in the EMS/SCADA may serve as a central model management system; alternatively, an external model management system can be used. Operational data can also be managed centrally in a "data lake" architecture. The centrally managed operational database should be:

- Structured
- Centralized
- Standardized
- Documented
- Validated
- High-quality
- Reliable and resilient
- Available and accessible.

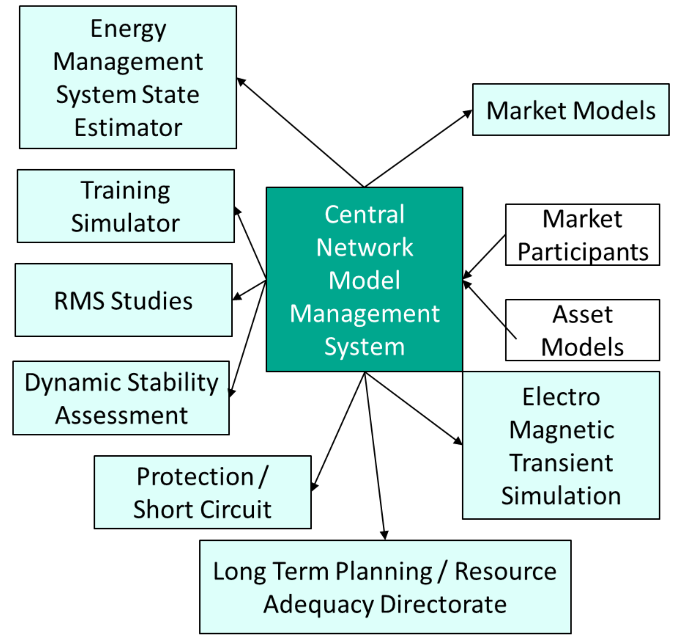


Figure 9. Utilizing a centralized system of model management

By working toward a CIM-based operational data structure and modeling in this way, the process of integrating new tools will be simplified. Having a central repository system for managing network models will be more efficient from a human resource perspective and should eliminate modeling errors. Structuring data and making it easily available will make utilizing machine learning techniques to solve system problems in the future easier.

Network Model Validation

Centralizing the model and data management capability and validating the model will also be a key underpinning enabling capability for the CCOTF. As more and more assets (generation, demand, distributed energy resources, RES, flexible AC transmission systems, etc.) will be added to the network, ensuring that the full system model accurately represents the actual as-built network assets will be critical. Unless the models are centrally managed, as the network and new simulation system expand, there is a risk of model divergence. The best way to mitigate model divergence is robust data governance and regular model validation, whereby all models are tested after a major event to assess their performance. If a divergence between reality and the model is found, the models should be updated, and in the case of newer grid-enhancing technologies, the original equipment manufacturer should improve the model. A further step is to develop automatic model validation, through automation that validates and suggests improvements after each event. Model validation will become a challenge with the connection of more and more distributed energy resources on the distribution network, so developing model validation capabilities will be an important enabler for the CCOTF.

5.3 Road Map for CCOTF Operational Data

Table 1. Road Map for CCOTF Operational Data

	Current State 2023	Probable 2025	Review 2027	Possible 2030	Future State 2030+	Vision State
Operation Models	Assessment and inventory of all model data and parameters with data owners and simulation systems. Known gaps include: distribution data, model consistency between tools and applications, model validation, and historian capabilities.	Establish data governance and responsibilities for all model data.	Centralized model management system to manage all models in the operational domain with potential to incorporate planning domain.	Automated model validation post-event with automatic tuning suggestions.	Model data interoperable with other sectors of the energy sector. Digital twin of the Sulawesi/Indonesian energy sector.	Single source of truth for all network data, accessible by all and automatically validated.
Operational Data	Assessment and inventory of all control center operational data and systems, including data-sharing links.	Data quality controls established. Standardize and structure data for analytics and machine learning.	Centralized data hub for all operational data with secure access to subject matter experts for analysis.	Utilization of artificial intelligence/machine learning techniques to solve operational issues.	Externally accessible hub for operational data for all interested stakeholders.	

6 CCOTF OT

6.1 Drivers for Change and CCOTF Vision for OT

The EMS/SCADA system is a key part of all control centers around the world. EMS/SCADA are “monolithic” or proprietary systems, requiring full, rather than piecemeal, replacement or upgrade. EMS/SCADA vendors have their own product road map incorporating their own research and development. These are not available to the wider industry and community due to intellectual property restrictions. EMS/SCADA typically are in place for at least 5–7 years before they require an upgrade or replacement, which can be major, resource-intensive information and communications technology update projects.

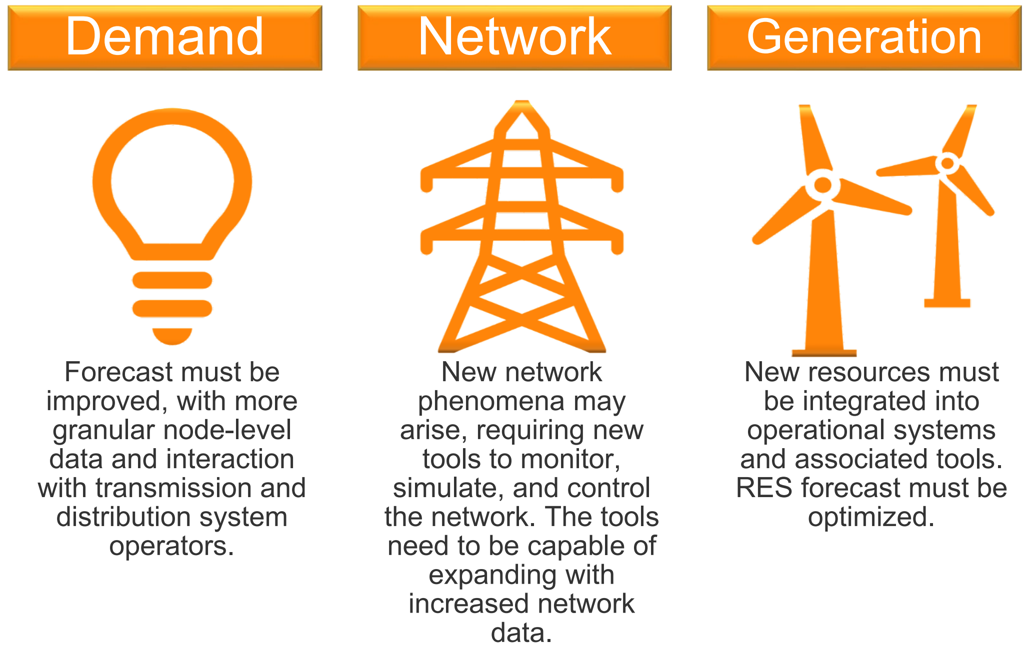


Figure 10. Key drivers for change

Procurement Lessons Learned

Upgrading or replacing EMS/SCADA should be based on the company’s vision and mission. After EMS/SCADA systems are evaluated to comply with the vision and mission, the purchaser should evaluate options for the system requirements.

The following lessons from independent system operators in the United States highlight several key factors worth considering when evaluating system requirements for an EMS/SCADA upgrade or replacement:

1. Modularity in the context of EMS/SCADA entails having applications that can function independently, allowing for the utilization of distributed computing. For instance, one server could seamlessly handle real-time contingency analysis, while another manages power flow. Modularity requires architecture design, subsystem interfaces, and communications protocols that support “plug-and-play” capabilities that allow for individual components to be replaced without disrupting other system operations. Modularity facilitates system flexibility, responding to evolving operating needs and solution options.
2. The need for updates arises from the necessity for utilities to make incremental changes to EMS/SCADA software, rather than undergoing lengthy upgrades that span years to integrate patches or modest system improvements. For instance, implementing security patches for the

operating system on a quarterly or monthly basis helps protect the system. EMS/SCADA software should adhere to best practices so that utilities can adopt proven features on a case-by-case basis.

3. Scalability allows control center operations to grow and perform in line with future growth and changes in the power system. EMS/SCADA should be scalable to accommodate additional devices, data sources, and increased demand for functionality as the grid evolves.
4. Interoperability, on the other hand, involves the ability to receive and share data and outputs between independent applications. Vendors may offer service-oriented architecture to facilitate required interfacing, but challenges can emerge during implementation. These challenges may be attributed to the purchaser's technical capabilities, but it is the vendor's responsibility to provide support throughout the entire implementation process.
5. Cybersecurity is a critical feature, as EMS/SCADA systems can be high-value targets for cyberattacks. Prioritize cybersecurity in the procurement process and ensure that the chosen system has robust security features, including encryption, access controls, and intrusion detection.
6. Operational training simulator capabilities should be able to support the restoration of the control room operation if both primary and backup EMS/SCADA systems are not available.
7. Configurability provides the utility with flexibility to set EMS/SCADA system parameters and operating features such as SCADA one-line designs and configuration, alarming attributes, and prioritization, among others.
8. The vendor must provide ongoing support, including updates, troubleshooting, and technical assistance, with minimal charges and minimal operational interruptions.
9. Throughout the procurement process, including specification design, contract negotiations, testing, and user manual development, documentation should be readily available and easy to follow to facilitate troubleshooting during the operating phase.

The CCOTF vision emphasizes the EMS/SCADA system as being interoperable with all other operational and control center tools, as well as operations planning support tools and any economic dispatch systems. This should be primarily enabled through data exchange and model management systems governed by the CIM (see Section 5, Operational Data).

Associated with the economic dispatch systems and the EMS/SCADA system are the other control center tools essential to operating the system. These could be software applications or platforms or even software as a service from external vendors. In general, they are linked via customized data connections to the data from the EMS/SCADA system. Control center tools can include voltage optimization, demand forecast, renewable generation forecast, WAMS, logging applications, workforce management, and asset monitoring. Some of these can be applications or modules within the EMS/SCADA system and do not necessarily have to be separate IT systems.

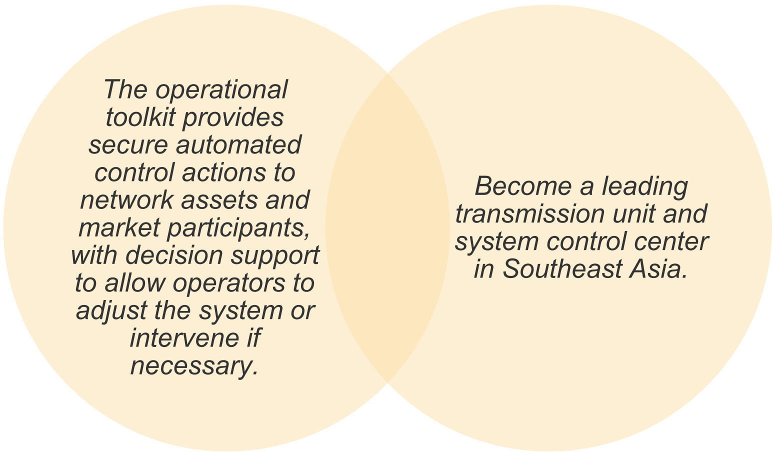


Figure 11. CCOTF vision ∞ PLN vision

Interoperability between EMS/SCADA systems and other tools can be a significant technical barrier with high variable RES penetration, as more heterogeneous data/tools must be integrated into EMS/SCADA systems. As discussed in Section 5, a thoughtful approach to operational model data management that utilizes standards-based data-sharing among the control center applications will be critical. The IEC CIM standards are recommended when designing and implementing a centralized model management system, as shown in Figure 9. By maintaining an accurate as-built grid model, the various control center applications that require model data become consumers of the data through standardized integration layers, which eliminates the need for maintaining a grid model in the various applications. This interoperability also eliminates the need for the design and maintenance of many custom data integrations between the applications.

The Systems Planning Division at PLN should study the network at a longer time horizon than the real-time system operators, at timeframes measuring weeks or months in advance. For the most part, the engineers in these teams utilize a similar, smaller set of tools used by the control center operators working in real time. The operations planning support tools should be interoperable with the control center tools and the EMS/SCADA system, utilizing the previously discussed consistent as-built model of the system under control and identical streaming system data; for example, outages should be studied with demand and renewable forecasts and generation schedules that are as synchronized as possible to real-time operations.

6.2 Value of Developing Control Center OT

Developing and enhancing the EMS/SCADA system and control center tools should lead to a reduction in errors, even as the system expands significantly. It should increase reliability, reduce the risk of major system disturbances by having advanced forecasting and study capabilities, and, when disturbances occur, it should provide adequate systems to restore service as quickly as possible.

Operational Requirements for CCOTF OT

Operators can use three modes of real-time situational awareness and operational decision-making:

- Aware – Monitoring -information acquisition and analysis
- Alertness - Decision-making - simulation, risk assessment
- Action -control.

All OT control center tools serve at least one of these domains. Operators can be most effective when the tools they utilize are easy to use and interpret, stable, reliable, and resilient. Ideally, tools should coordinate with one another seamlessly, with the network model management system and EMS/SCADA systems interoperable with one another. Manual processing (such as data entry) should be eliminated as much as possible. For example, Sulawesi's use of automatic generation control (AGC) currently relies on a phone conversation after an operator instructs dispatchers on the set point. Ideally, AGC should be fully automated to run when new units are coming online.

The output results or data visualization should be consolidated in displays and dashboards to optimize situational awareness (described in further detail in Section 7).

Twenty OT tools were identified as required for the operation of a future network. These are detailed in Table 2, which documents the likely future operational toolkit based on PLN's functional responsibility. The tools have headings for current state, idealized future state, and whether they should be classified as part of the information acquisition and analytics domain, decision-making domain, or control domain.

Table 2. Table of OT Tools Required To Monitor, Assess, and Control the PLN System of the Future

Control Center or Operations Planning Tool	Real-Time or Operational Planning	Information, Decision-Making, Control Action	Current State	Ideal Future State
SCADA Information Management	Real-time	Information, decision-making, control	EMS to be upgraded in coming years	Modular system, interoperable with all other OT tools via standard data-exchange scheme. Advanced analytics from underlying data and automated control actions are possible.
Wide Area Monitoring System (WAMS)	Real-time	Information	No WAMS	WAMS interoperable with SCADA/EMS system, identifying issues with oscillations in real time. WAMS used for model validation. Warehouse for information from digital high-speed recorders and protection relays.
Congestion Management	Real-time and operational planning	Information, decision-making, control	Real-time contingency assessment	Automated optimal power flow and control solution with network and redispatch for real time and look-ahead that mitigates congestion on transmission and distribution system based on cost, with probability.
Voltage Management	Real-time and operational planning	Information, decision-making, control	Manual process for reactive power control with contingency assessment	An automated control tool for optimized and look-ahead voltage setpoint tool based on forecast trajectories, cost of dispatch.
Alarm Management	Real-time	Information, decision-making, control	Manual and inconsistent alarm management and response	Standardized approach to alarm management with philosophy categorization.

Control Center or Operations Planning Tool	Real-Time or Operational Planning	Information, Decision-Making, Control Action	Current State	Ideal Future State
				Standardized structure for alarm and data points in the power system to enable artificial intelligence/machine learning analytics. Intelligent alarm handling, root cause analysis, asset health monitoring.
Alarm Root Cause Analysis/Disturbance Investigation Tool (Real-Time)	Real-time	Information	Manual alarm management and response	Umbrella tool for all data that instantly identifies alarm and disturbance root cause and directs operator's attention to issues and solutions. Likely to use machine learning.
Dynamic Security Assessment and Power Quality (Including Voltage, Frequency, Inertia, Transient, Small Signal Stability)	Real-time and operational planning	Decision-making	No dynamic security assessment system	Interoperable, with all tools running look-ahead stability assessment with suggested mitigation. Integrates with dashboard. Automated switching transient studies. Potential for automated control actions. Link to system strength evaluation tool. Link to training simulator.
Transient Modeling and Studies	Operational planning	Information, decision-making	Limited ability to assess dynamic characteristics	Implement transient modeling tools and studies capable of assessing dynamic characteristics and integrate into planning steps.

Control Center or Operations Planning Tool	Real-Time or Operational Planning	Information, Decision-Making, Control Action	Current State	Ideal Future State
System Strength Evaluation Tool	Real-time	Information	No system strength system	Online tool to monitor system strength in real time and look ahead based on forecast data, potential for automatic control. Link to dynamic stability assessment protection tool.
Protection, Short-Circuit, and Special Protection Scheme Coordination Tool	Real-time	Control	No protection, short-circuit special protection scheme tool	Interoperable with EMS, dashboard, and asset health tool. Feeds dynamic security assessment and is coordinated with system strength tool and congestion management tool.
Black-Start and Restoration Enhancements, Including RES	Real-time	Decision-making, control	No black-start restoration tool	Online tool that works during a blackout or major system restoration to guide operator through the process.
Demand Forecasting	Real-time and operational planning	Information	Manual process developed in-house	Continuous tracking of forecast accuracy, continuous improvement of forecast with improved customer data and methodologies.
Renewable Energy Forecasting	Real-time and operational planning	Information	No forecast tool	Continuous tracking of forecast accuracy, continuous improvement in forecast algorithms for increased RES penetrations.
Balancing, Dispatch, and Load Frequency Control	Real-time	Control	Manual control of generators; AGC	Interaction with virtual power plants and market participants on distribution system operators, as required.

Control Center or Operations Planning Tool	Real-Time or Operational Planning	Information, Decision-Making, Control Action	Current State	Ideal Future State
Reserve, Ramping, Flexibility Tool (Real-Time)	Real-time	Decision-making	Manual process	Integrated with market and balancing system, congestion management. Automated detection and redispatch for flexibility.
Outage Management	Real-time and operational planning	Information, decision-making	Various systems	Automated study of near-term and long-term outages with various realistic market generation scenarios. Interoperable tool.
Reporting and Workforce Management	Real-time	Information	Manual system	Automated logging of field workforce personnel and automated reporting of system issues, link to dashboard.
Environmental (Fire, Earthquake, Flood, and Weather) Forecasting	Real-time	Information	Various weather monitoring systems	All weather data is integrated into all control center tools with forecast confidence ranges. Congestion management, protection coordination, and stability tools.
Production Cost Modeling and Economic Dispatch	Operational planning	Information, decision-making	Limited modeling capabilities	Integrate production cost modeling and economic dispatch tools and capabilities into planning and operational decision-making to improve economic operations.
Set Points for Active and Reactive Power	Real-time and operational planning	Decision-making, control		Include control set points for active and reactive power for all resources, including inverter-based resources to support AGC and voltage control tools.

7 CCOTF Human Factors and Decision Support

7.1 Drivers for Change and CCOTF Vision for OT

This multifaceted pillar of the OCM is intended to encompass human interaction with the OT applications, as well as training, within the three modes of situational awareness and decision-making.

This accounts for the fact that much of the modern power system is automatically controlled, such as generation, demand, and reclosing of overhead lines and special protection schemes. This automation trend is expected to continue; eventually, all elements of the power system will be automatically controlled in some form, with operators likely to intervene when the automation is disrupted, or for major system events and emergencies.

User Interfaces and Display Design

Operators require streamlined, optimized interfaces of the software applications with which they interact, and information should be presented in the clearest, most unambiguous, and most actionable format. Display design should be standardized and follow best practice guidelines. Because the control center hosts vast quantities of streaming analog and alarm data from multiple tools, presenting this data in a clear, concise manner to improve situational awareness is a key focus of this CCOTF road map.

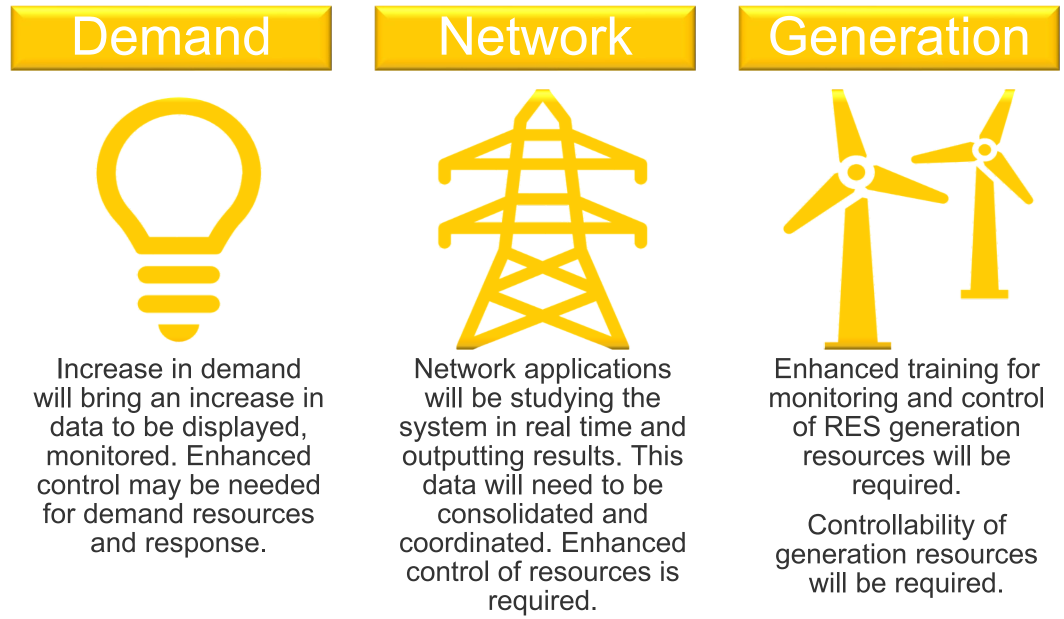


Figure 12. Key drivers for change

The idealized vision for the CCOTF for human factor optimization is to have fully automated control of all network assets and generation resources, and, if possible, demand response (via distribution system operators). Operators will generally plan the system based on forecasts and intervene when automation does not operate correctly.

Decision Support

The decision ladder developed by Jens Rasmussen in the 1970s (Figure 15) is the best formulation for operator decision-making and action in control contexts. It emphasizes three modes of decision-making and situational awareness using the following color code:

- Information acquisition and analysis
- Decision support
- Control action implementation.

Information acquisition and information analysis can be grouped or separated, if required.

In control center operations, each class within each process can be automated to different degrees, and all are interrelated. For example, an operational process such as voltage control may have high degrees of information automation (SCADA), low degrees of decision automation (operator decides), and low degrees of action automation (manual reactive compensation device switching).

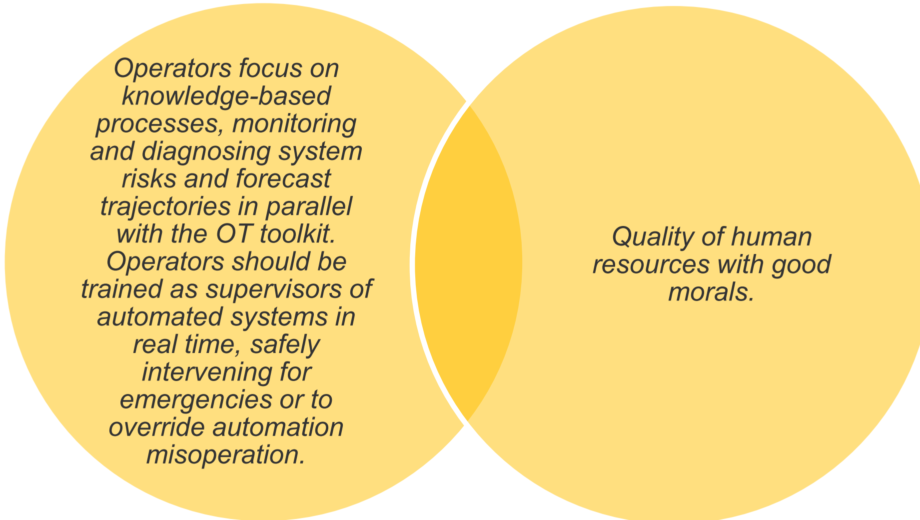


Figure 13. CCOTF vision ∞ PLN vision

Training

Operators should be fully trained and certified, with regular training refreshers and updates on all control center tools and intervention scenarios. Operators should be comfortable assessing risk and maintaining situational awareness to avoid the "out-of-the-loop" effect. The out-of-the-loop effect is a common risk in aviation when pilots use autopilot and they develop a degraded ability to intervene when the autopilot malfunctions. New operational procedures must be developed after Sulawesi's north and south systems are interconnected.

7.2 Value of Developing and Enhancing Operator Human Factors and Decision Support

The Human Factors and Decision Support pillar for operators in the CCOTF will be a key enabler for reliability and will be valuable to PLN and Sulawesi. Improved situational awareness should lead to fewer errors in the system and ensure that outages are restored as soon as possible. This should be complemented by tailored training in the ORC (discussed in Section 8).

System issues will be proactively identified and categorized ahead of time, reducing the need for operator action.

Enhanced system control, from the control centers to all resources, will ensure supply is restored as quickly as possible and power is optimally and economically transmitted around the grid.

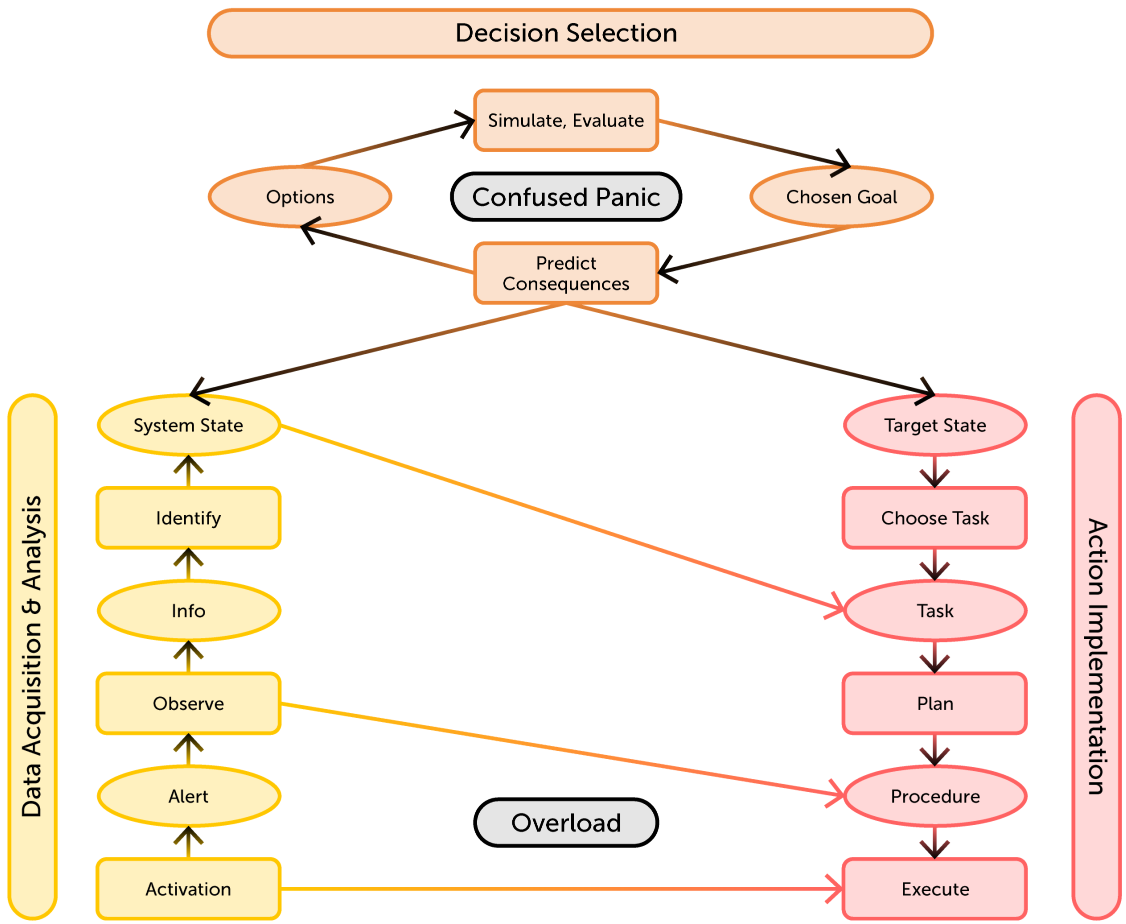


Figure 14. The Rasmussen decision ladder with three modes of operator decision-making

Source: EPRI

7.3 Road Map for Human Factors and Decision Support

Table 3. Human Factors and Decision Support

	Current State 2023	Probable 2025	Review 2027	Possible 2030	Future State 2030+	Vision State
Training	Rationalize all operational procedures into training programs	Digitize operational procedures and training materials. Training on automation and decision-making.	Development of ORC to facilitate new training and certification process.	Certifiable training programs on all OT tools in the ORC.	Multidomain team training with operators from other PLN systems.	
Monitoring and Visualization	Disparate screens and displays with various styles and philosophies	Human-machine interface philosophy with rationalized color-coding to red, orange, and yellow. All control center OT tools have consistent visualization and style.	Development of dashboards in new EMS and other IT tools to support monitoring, decision-making, and control actions	Guided decision-making for all tools.	Single pane of glass for all visualisations – combining data insights from multiple applications	Supervisors of automated systems, with guided decision support. Trained on realistic simulators in ORC.
Cognition and Decision-Making	Staff shortage for master station SCADA. Manual standard operating procedures rely on personal knowledge and competency/experience.	Options identified for all operational processes and are easily accessible. Improved decision-support dashboards.	Risk assessment framework with simulation and options.	Automated simulation, optioneering, and optimization for all operational processes.	Automated processes for information, decision support, and control action with trust and confidence metrics.	

8 CCOTF Facilities and Equipment Road Map

8.1 Drivers for Change and the CCOTF Vision

PLN will develop a new single control center to operate the interconnected Sulawesi network, with a disaster recovery backup control center. This is a major capital project and will consume planning, design, and development resources in the years ahead. It is important to design and procure state-of-the-art equipment for the control center, as control centers are multidecade assets, so the equipment is expected to remain viable for many years. The CCOTF vision is focused on innovative facility and equipment design for items such as displays and desk consoles that can enhance situational awareness and improve staff effectiveness through ergonomics.

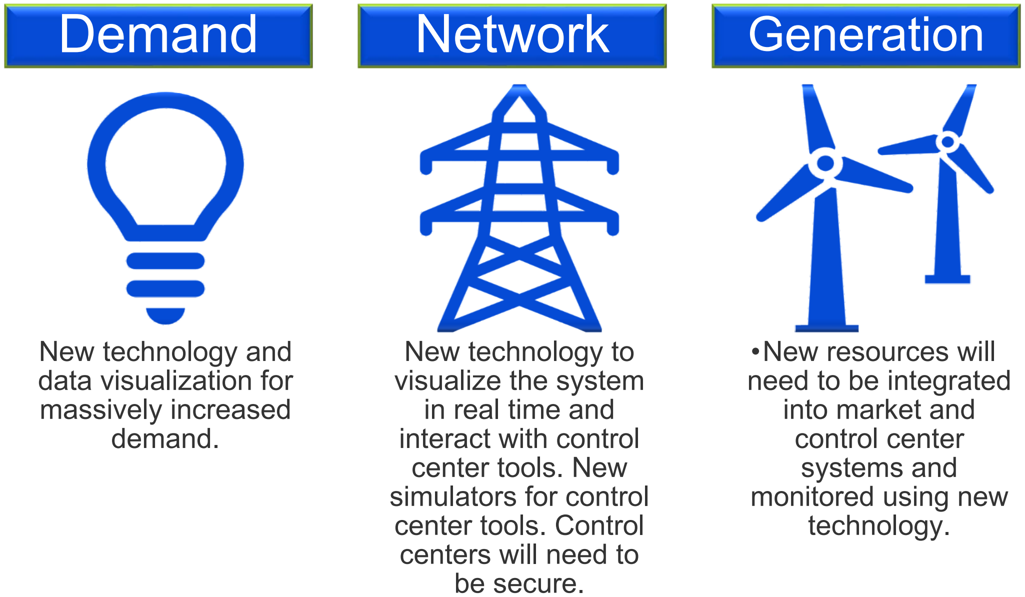


Figure 15. Key drivers for change

8.2 Value of Developing and Enhancing Control Center Facilities and Equipment

Reliability and resilience in control center operations are very important. In recent years, we have seen the value of operational continuity for pandemics and major climatic events, and we will likely see continued focus from the public and policymakers in the years to come. Many control centers around the world operate with dual main or active backup facilities and split their teams of operators into separate groups working independently. Having a main and active backup that can be easily used in the event of an emergency is critically important to the resilience of the Sulawesi network.

Utilizing the most advanced ergonomic equipment for operators has the added benefit of ensuring their health is protected and risk of injury is reduced. Developing facilities and operational spaces with 24/7/365 operation in mind will also help make the environment a more pleasant place to work, which will reduce operator fatigue, improve morale, and support recruitment. It is recommended that new ergonomic approaches be tested in the ORC before deployment in the real-time control center. It is recommended that, for the CCOTF, updates are made based on the ISO 11064 standard for control centers.

Operational Readiness Centers

To deliver on the vision and ambition for PLN and the CCOTF, the output of the control center tools requires a simulator environment for testing and facilitating operator training. At present, PLN has a training simulator but does not have a testing environment.

In the CCOTF vision, all software applications should have a simulator environment with a pristine model of the system (a digital twin). The operator training simulator facility should be upgraded to become an ORC for:

- User acceptance testing of software tools
- Training with operator's pre-deployment of new tools (e.g., EMS)
- Testing new user interface designs
- Testing new hardware devices and innovations
- Providing the core function of training and testing operators
- Real-time study simulator environment for control center tools
- Potential backup control center facility in an emergency.

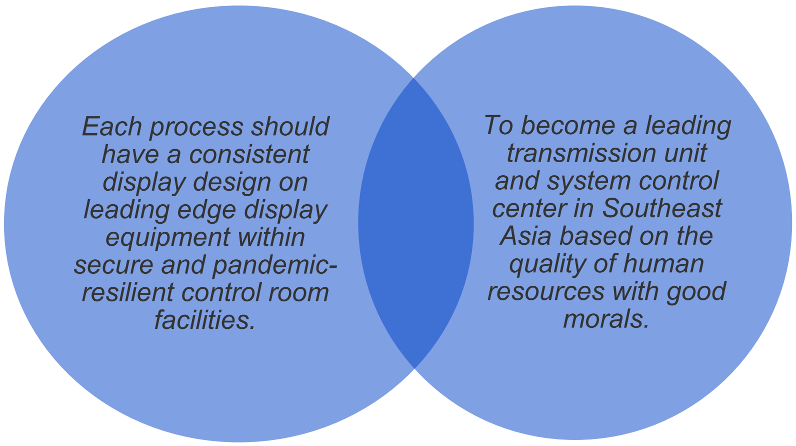


Figure 16. CROF vision ∞ PLN vision

None of the ambitions of the CCOTF road map may be achievable without an effective simulator environment to test new tools and technology and train the operators of the future.

8.3 Road Map for CCOTF Facilities and Equipment

Table 4. Facilities and Equipment

	Current State 2023	Probable 2025	Review 2027	Possible 2030	Future State 2030+	Vision State
Buildings Facilities	Separate control centers.	Integrated control center with full redundant disaster recovery control center to be able to operate interchangeably frequently (or active/active site configuration).	Interconnected main and backup control centers with secure video links.	Seamless integration between active control centers and ORC with consistent environments in all locations.	Secure virtual control centers for certain operational processes.	Digital, ergonomic workspaces in pleasant environment with a multifunctional ORC for training and simulation.
Control Center Equipment	Standard control center equipment.	Level 1, 2, 3 visualization screens for situational awareness.	Paperless digital control center.	Voice control interactivity with IT/OT systems.	Mixed reality and gestural interactions for monitoring and control.	
ORC	Stand-alone simulator for set piece training.	New training facility design and deployment in new control center.	ORC sandbox for new application testing. ORC can act as a backup control center facility.	All OT applications have a test environment for deployment in ORC for training on all tools.	Real-time digital simulator for the ORC to replicate dynamic response of network.	

9 Future Considerations

The table below highlights areas that deserve special consideration for upgrading the Sulawesi system, particularly during the near-term control center procurement process.

Table 5. Future Considerations for Upgrading the Sulawesi System

<table>
<tr><th>Topic</th><th>Context and Future Considerations</th></tr>
<tr><td>AGC</td><td>AGC is currently not fully implemented, requiring manual control of generation units.

AGC offers a range of benefits that can result in significant cost savings by reducing downtime, lost productivity, and revenue, including:

• Reduced fuel consumption and operating costs through generator output optimization
• Improved system efficiency through reductions in transmission and distribution losses and recued need for backup generation
• Resource optimization, particularly for variable RES
• Improved reliability through rapid response to changes in demand, reducing the risk of blackouts or brownouts.

Future considerations should include the potential for integrating AGC capabilities, appropriate communications support, related operational protocols and training, and free governor activation.</td></tr>
<tr><td>Transient Modeling and Studies</td><td>Transient modeling and related studies are not sufficiently integrated into planning.

Future considerations should include the potential for implementing transient modeling tools and studies capable of assessing dynamic characteristics, and integrating them into planning steps. This is a critical capability for ensuring system stability and should be investigated as soon as possible, as it can take a great deal of time (years) to reach a stable point.</td></tr>
<tr><td>Ancillary Services</td><td>Ancillary services are not currently leveraged. They can provide essential benefits for managing variability and uncertainty.</td></tr>
</table>

	Future considerations should include the potential for investigating mechanisms for integrating ancillary services into operations to support stability.
Distribution Data	Detailed distribution data is not assessed at the transmission level; such data can support maximizing system efficiencies and stability, for example, to support robust utilization of distributed energy resources and demand side management. Future considerations should include the potential for implementing distributed energy resource modeling and aggregated supervision. See the NERC guidelines, which could be adapted to PLN's needs: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/DERStudyReport.pdf.
Model Consistency Between Tools and Applications	Future considerations should include the potential for incorporating a unified model for all tools and applications to ensure the interoperability of the tools.
Model Validation	Future considerations should include the potential for improving model validation capabilities. NERC has some basic recommendations for power flow and dynamic model validation that can serve as a starting point: https://www.nerc.com/comm/PC/Model%20Validation%20Working%20Group%20MVWG%202013/NERC_Model_Validation_Procedures_v3.pdf. Consider also implementing procedures for recurrent testing facilitated with PMUs or other high-resolution disturbance monitoring devices to ensure that the modeled response to system events matches the actual response of the system.
Historian	Future considerations should include the potential for implementing a more robust data historian capability, such as OSI PI.
Production Cost Modeling and Economic Dispatch	Currently, limited production cost modeling capabilities result in a gap between effective modeling and economic dispatch. Future considerations should include the potential for integrating production cost modeling and economic tools and capabilities into planning and operational decision-making to improve economic operations.

Control Set Points	Set point management is an important AGC and voltage control tool. Future considerations should include the potential for investigating and implementing set points for key resources, including inverter-based resources, and for active and reactive power.
Alarm Management	Future considerations should include the potential for implementing a standardized approach to alarm management with philosophy categorization and a standardized structure for alarm and data points in the power system to enable artificial intelligence/machine learning analytics, intelligent alarm handling, root cause analysis, and asset health monitoring.
Restoration Training	Future considerations should include the potential for implementing regular system restoration/black-start exercises based on dispatcher training simulations.
Communications	Future considerations should include the potential for implementing mechanisms to ensure remote terminal units/gateways have multi-master and multi-protocol communications capabilities, and that communications capabilities between the Sulawesi Control Center and DRCs utilize inter-control center communications protocols. Consider a review of the telecommunications data structure relevancy as described in the grid code.
Weather Data	Future considerations should include the potential for the integration of weather sensor equipment for the management of variable generation sources.
SCADA	Future considerations should include the potential for implementing a cybersecurity certified/intrusion-proof SCADA architecture design and integrating WAMS/WAMPS into SCADA.
Staff Organization	Based on PLN staff discussions, future considerations could include the potential for investigating options for realigning control center organization hierarchy and staffing to facilitate efficient operations.
State Estimator	A state estimator is an essential tool for informing other system observation and management tools. Future considerations should include the potential for implementing protocols to run state estimators more frequently (seconds) to improve fidelity of other tools; also consider updating the state estimator to allow for hybrid measurements for remote terminal units and PMUs to improve analytical quality.