GLOBAL PST
CONSORTIUM

Inaugural Research Agenda

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Email: globalpst@nrel.gov

Website: www.globalpst.org

How to Read this Document

This document summarizes the outputs from a nine-month consultation process led by the Global Power System Transformation (G-PST) Consortium's Research Agenda Group to build an organized, consensus-based global research agenda for the G-PST's Founding System Operators (FSOs).

This document strives to capture the research needs of a group of the world's leading system operators in a series of research questions. While other groups have attempted to map research roadmaps for groups of utilities or system operators, it is evident that the collective needs of the G-PST's FSOs represent the cutting edge of the accelerated transition to increasingly variable renewable-powered, decentralized, and inverter-based power systems. The FSOs have firsthand experience with the advances required to reliably and cost effectively plan and operate these future power systems.

Note that while this document represents the needs of the FSOs, it is also a snapshot in time which we fully expect to evolve as we collectively embark on the path toward answering these research questions, hence the document title, Inaugural Research Agenda. The authors strongly welcome your feedback and further interaction on this report.

ARE YOU A SYSTEM OPERATOR? *Please reach out to provide us with your feedback, share your relevant ongoing work, and explore opportunities to collaborate.*

ARE YOU AN INDUSTRY THAT PROVIDES SOLUTIONS TO POWER SYSTEM OPERATORS, SUCH AS AN EQUIPMENT OR SOFTWARE VENDOR? *Please reach out to provide us with your potential solutions, share your relevant ongoing work, and explore opportunities to collaborate.*

ARE YOU A RESEARCHER? *Please help us better articulate the research questions, and please share if you or your colleagues are already working to answer these questions.*

ARE YOU A RESEARCH FUNDER? *Please provide us with your feedback and inform us of your aligned research funding and opportunities for us to provide appropriate input to your activities.*

Executive Summary

The primary objective of a power system is to safely provide reliable energy services to society at an affordable cost. Achieving this objective with existing planning and operational paradigms is potentially compromised by the rapid transition occurring globally, characterized by increasing penetration of variable renewable energy (VRE), inverter-based resources (IBR), and distributed energy resources (DER). These trends, driven by changes in technology, consumer preferences, and government and societal expectations show little sign of abating and will continue to influence the power system transformation for the foreseeable future. To continue to meet the primary objective as power systems transition, advances in the operation and planning of the power system are required.

The Founding System Operators (FSOs) of the Global Power System Transformation (G-PST) Consortium are at the leading edge of this transition and have come together, at the Chief Executive Officer level, within the G-PST to keep pace with the transition and work with the research community globally to develop and deploy innovative solutions at the pace and scale that are required.

The Research Agenda Group (RAG) of the G-PST Consortium consists of senior technical staff of the FSOs and leading researchers within the global research community. The RAG's primary objective is to define a common research agenda for the FSOs and to oversee its execution by stimulating funding sources and supporting aligned research.

This Inaugural Research Agenda focusses on bulk power system issues that will need to be addressed in the near term (ten years). It consists of 59 research questions organized into six Research Programmes: Inverter Design, Stability Tools & Methods, Control Room of the Future, Planning, Restoration & Black Start, and Services (Table ES-1). As the G-PST evolves, more comprehensive, longer term and more broadly based research agendas will be made public when appropriate.

This Inaugural Research Agenda is meant to stimulate input from others in the power systems community, encourage collaborations, and promote the G-PST activities more broadly, thereby creating a global and coordinated effort to address them. The focus now of the RAG is on getting new research activities funded globally that will address the research questions and provide direct input from the FSOs and other G-PST members including data, advice, testing, etc. In parallel the RAG is identifying, supporting, and coordinating with existing aligned research activities with the provision of similar direct input from the FSOs and other G-PST members.

Table ES-1. Summary of Inaugural Research Agenda

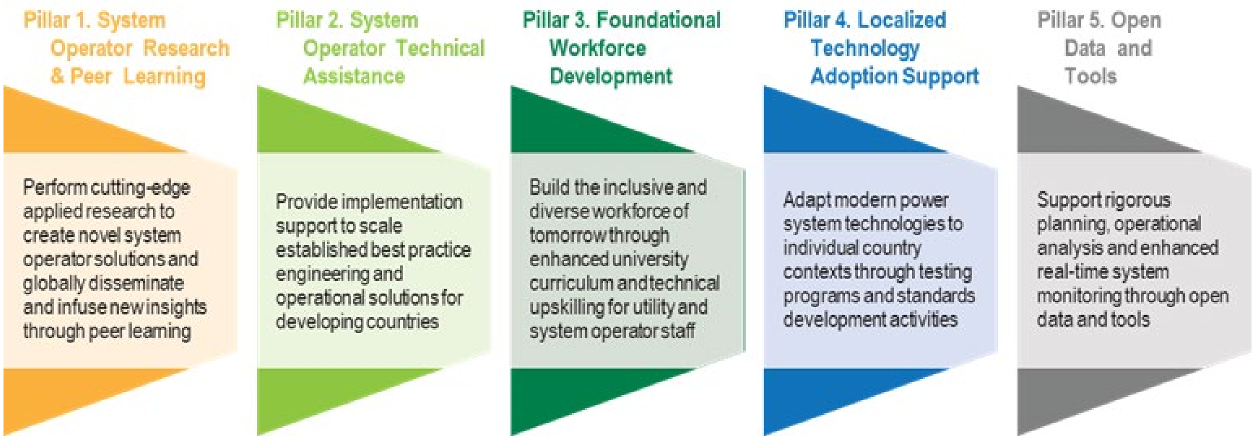
Research Program	Description	Number of Questions
Inverter Design	Development of capabilities, services, design methodologies and standards for IBRs.	11
Stability Tools & Methods	Development of new tools and methods, as well as modifications or supplements to existing tools and methods, required to ensure reliability, security, and stability in power systems.	8
Control Room of the Future	Development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms.	17
Planning	New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix.	15
Restoration & Black Start	Creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations.	1
Services	Quantifying the technical service requirements of future power systems to maintain the supply-demand balance reliably and at least cost.	7

1 Background & Scope

The Global Power System Transformation (G-PST) Consortium is an expert- and practitioner-driven initiative which engages key power system operators, research and educational institutions, governments, businesses, and stakeholders in all regions of the world to accelerate transitions to energy systems of the future. The bulk power system is the natural starting point. Its primary objective, to safely provide reliable energy services to society at an affordable cost, must be observed at all times.

The Consortium features eleven "Core Team" technical institutions[1] and a group of six Founding System Operators[2] (FSOs). The FSOs are a unique group that are on the absolute leading edge of power system transformation characterized by increasing penetration of variable renewable energy (VRE), inverter-based resources (IBR), and distributed energy resources (DER). The FSOs are all grappling with a common set of challenges caused by the power system transformation and indicative of its importance their participation in the G-PST is being led by their Chief Executive Officers.

The Consortium has two core objectives: (1) supporting cutting-edge research and development activities for the FSOs and other advanced power system operators; and (2) supporting developing and emerging economy system operators as they transform their power systems.



Perform cutting-edge applied research to create novel system operator solutions and globally disseminate and infuse new insights through peer learning

Provide implementation support to scale established best practice engineering and operational solutions for developing countries

Build the inclusive and diverse workforce of tomorrow through enhanced university curriculum and technical upskilling for utility and system operator staff

Adapt modern power system technologies to individual country contexts through testing programs and standards development activities

Support rigorous planning, operational analysis and enhanced real-time system monitoring through open data and tools

Figure 1 - Five Pillars of the Global Power System Transformation Consortium

The G-PST Consortium is organized into five key pillars of activities to support power system operators (Figure 1). 'Pillar 1 - System Operator Research & Peer Learning' is primarily focused on the first objective: supporting cutting edge research activities that can be applied by system operators as they transition to future, geographically distributed, primarily inverter-based power systems with a high variable renewable primary energy source.

Pillar 1 is driven forward by the Research Agenda Group (RAG) which consists of senior technical staff of the FSOs and leading researchers within the global research community. The RAG's primary objective is to define a common research agenda for the FSOs and to oversee its execution by stimulating funding sources and supporting aligned research. The RAG reports to the FSO CEO Group of the G-PST which consists of all six FSO CEOs.

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[1] Energy Systems Integration Group (ESIG), Imperial College London, Council of Scientific and Industrial Research (CSIR), Fraunhofer Cluster of Excellence for Integrated Energy Systems, National Renewable Energy Laboratory (NREL), Latin American Energy Organization (OLADE), Institute of Electrical and Electronic Engineers (IEEE), Electric Power Research Institute (EPRI), Commonwealth Scientific and Industrial Research Organization (CSIRO), the Danish Technical University (DTU), and ASEAN Center for Energy, are actively developing the consortium and will be engaged in implementation of technical work as well as coordinating specific pillars.

[2] Australian Energy Market Operator (AEMO), California Independent System Operator (CAISO), EirGrid, Electric Reliability Council of Texas (ERCOT), Energinet, and National Grid Electricity System Operator (NG ESO).

The RAG investigated a very broad research landscape in terms of time horizon and breadth. The research agenda seeks to include all possible advances, from fundamental research to applied solutions, driving solutions which are expected (but not assumed) to be globally applicable to all system operators. These advances will vary from system to system and will range from simple modifications of existing technologies and practices to fundamental research to develop new and better ways to plan and/or operate the power systems of the future.

At this initial stage of the G-PST, there is a clear sense that the scope of the research agenda must be highly focused for the overarching G-PST initiative to be successful. Through a deliberative process, it was unanimously agreed that the initial research scope would focus on near-term issues (i.e., next decade) reflecting the recent rapid and continuing cost declines in wind and solar photovoltaic (PV) technology and the aggressive near-term policies that have together fueled a dramatic and continuing increase in penetration levels of inverter-based wind, solar PV, and energy storage that may be highly distributed in many jurisdictions. Counterbalancing this sentiment and recognizing the highly integrated nature of the power system, it is difficult to focus on just a few discrete topics in practice and a holistic scope is required. Therefore, the scope of this Inaugural Research Agenda includes all technical aspects of operational and planning activities within the bulk power system that will need to be advanced and/or adapted in the next decade to maintain reliability in a cost-effective manner.

There are a multitude of adjacent and broader energy system issues which - now and in the future - will continue to interact with and influence the planning, operation and performance of bulk power systems. These include aspects such as integration with other energy vectors (i.e., sector coupling), electricity market design, policy and regulatory frameworks, the emergence of distributed energy resources, and others. While all these issues are respectfully acknowledged, they have at this time been set aside to varying extents as “out of scope” for the G-PST Research Agenda. This is not a judgement as to their importance, but a pragmatic choice to ensure the G-PST’s focus remains sharp, while also accepting the need for a holistic approach to the entirety of the bulk power system. Notably, “out of scope” does not imply that these issues will be ignored and that research questions will be addressed without their consideration - these interface issues must undoubtedly be represented in a meaningful and appropriate manner. Two issues are out of scope but require special attention, DER and electricity market design.

RAG members share a common sentiment that rapid changes in power systems are happening - not only at the bulk power system level, but also in the distribution network and connected generation and demand therein, i.e., DER. There were strong views expressed by some FSOs that DERs are becoming very important and an integral factor in their bulk power system operations and planning. Therefore, great care and attention will be needed to represent their impact and influence on the many aspects of the Inaugural Research Agenda. For example, validated and high-quality aggregated representations of DER performance, load modelling and emergency controls will undoubtedly be required to ensure success of the Inaugural Research Agenda, and DER will be a major theme in the evolving research agenda of the G-PST.

Electricity markets are common in many regions of the world but are not ubiquitous, with many regions adopting different means of reflecting the economics of electricity. While market design is a very important interface with the bulk power system, it has a tendency, in a detailed sense, to be highly localized in its nature. Therefore, detailed market design research was determined to not be within the scope of the G-PST Inaugural Research Agenda. However, the research agenda does focus on defining the various physical/technical requirements of bulk power systems (e.g., see Services Research Program) that are common globally, which might be used as critical inputs to more localized discussions on market design or other economic mechanisms.

2 Research Agenda

The RAG identified 59 research questions that cover the FSOs' collective short term (ten-year) horizon research needs, i.e. the research landscape. They are organized according to their primary membership of six groupings that represent themed "Research Programmes", as depicted in Table 1.

Table 1: Summary of Inaugural Research Agenda

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Below are details of each research programme, whose research questions are detailed in Tables 2 - 7.[3] Research questions vary with level of depth and specificity but are written in a generalizable (rather than system-specific) manner. To find a solution to a research question, there are many more embedded research questions requiring solutions; some of these embedded research questions are overlapping with the other 58 research questions. Therefore, the research questions have varying degrees of overlap, possible redundancy, and are tightly coupled with one another with many dependencies. The 59 research questions could easily be replaced with a smaller or larger number of research questions that cover the research landscape equally well.

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[3] A compilation of these questions and their primary and secondary associations with the research programmes are presented in Appendix A, Table A1.

2.1 Inverter Design

Bulk power systems, after some early-stage prototype systems, evolved as synchronous systems with synchronous generators at their core and alternating current (AC) transmission and distribution to interconnect the power system and deliver power. On the demand side, loads were sometimes connected via synchronous machines although the bulk of the loads were asynchronous (i.e., induction machines) and resistive loads. The displacement of synchronous generation with IBRs, addition of loads connected via inverters, and the increasing prominence of energy storage devices in IBR form, are changing the fundamental synchronous nature of the bulk power system. To maintain high levels of reliability in the bulk power system, the designs of both the bulk power system and IBRs need to change. This is not a case that an IBR-dominated system is fundamentally less or more reliable than a synchronous system; it is a case that they are in many ways fundamentally different and the differences need to be reflected in the design, analysis, operations, and planning of systems.

The prospect of systems with 100% penetration, or close to, of variable renewable generation interfaced by inverters has emerged relatively recently and is well beyond what many in the research community have been studying. There is a vast difference between a 75% penetration of VRE supported by some synchronous generators and synchronous compensators and a 100% VRE all-IBR system. The need for fundamental research to establish an evidence base for the best way forward is pressing, and it will take time to produce credible results.

The changes are so profound that a fundamental rethinking of power systems is required. Incremental tweaking and artificially forcing IBRs to look like synchronous machines is a short-term strategy that is limited and does not leverage the true potential of IBRs. IBRs can be highly flexible and controllable, with independent control over real and reactive current, and an ability to shape the equipment's response to various grid conditions. Because of this, there may be opportunities to make IBRs behave better than synchronous machines in some respects. However, the control algorithms that dictate the response of IBRs to grid conditions are not heterogeneous across various inverter designs and manufacturers, and these can interact at both a local and system-wide level and with other elements in the power system, such as high voltage direct current (HVDC) transmission terminals. This dramatically complicates the analysis of IBRs in the power system and may lead to stability challenges. Also, the challenges are compounded, as currently most inverters do not provide certain services like inertia response and high fault current, both of which contribute to maintaining stability.

One of the biggest challenges is how to manage the bulk power system where it is at times dominated by IBRs and at other times (only hours apart) dominated by synchronous machines and all the other possible combinations in between, both spatially and temporarily.

The Inverter Design Research Programme focuses on capabilities, services, design methodologies and standards for IBRs (Table 2). Inverter design considers:

1. characteristics of the physical circuits and how they may be changed,
2. characteristics of the energy source/sink and its limitations, and
3. control systems.

This body of inverter research should be approached as part of a grid co-design effort that considers grid operational principles and controls. This co-design of the system and the inverter is needed to reach a low-cost and effective overall solution and it requires close working relationships and collaboration with industry solution providers such as inverter manufacturers. This research programme should examine the cost implications of these designs in terms of additional hardware and tradeoffs with other performance measures like efficiency or load factor. This cost should be put into context with conventional non-IBR approaches.

Table 2. Inverter Design Research Programme Questions

1. What are the needs of a power system (to achieve security and good regulation) expressed in technology neutral form and how do these needs map to services that any resource, including IBR or synchronous machine, can provide?
2. For each service defined in (1), how feasible is it to provide from IBR, what “cost” does it add and what limitations exist on its magnitude and duration of service? What implications do these have for system operations?
3. What are the limitations of each IBR technology option to provide frequency control services and how do the various frequency services overlap and compete?
4. What design standards or dispatch guidance should be introduced to avoid instability (e.g., caused by PLL or other elements) in weak grids? This is a more widely drawn version of the question on minimum ratios of grid-forming to grid-following inverters.
5. What are the appropriate inverter capabilities and, consequently, control design methods for operation in grids with high percentage of IBR? Are standard configurations and combination of services helpful in simplifying operational decision making?
6. Are the black-box models (impedance-spectrum and binary code) favoured by manufacturers for disclosure sufficient for stability assurance and system design across all problem types?
7. What recommendations should be made for standard behaviours of IBR in certain frequency ranges for different power system conditions to aid system design? For example, should a contribution to damping be mandatory at certain frequencies?
8. What impedance requirements should be placed on IBR to suppress negative-sequence and low order harmonic currents?
9. How will protection systems need to change to accommodate high penetrations of IBR and what possible actions might an inverter take during a fault that would aid fault detection and location?
10. What is the future of frequency control as the synchronous generation fraction reduces? Might tightened or loosened frequency limits lead to a more reliable, secure, lower cost IBR-based power system?
11. At what point is it better to break from trying to replicate synchronous machine features and exploit the wider flexibility of inverters?

2.2 Stability Tools & Methods

Power system operators have a large variety of existing tools and methods to underpin their power system planning and operating decisions. However, with increased penetrations of VRE, IBRs, and DERs and coupling with other sectors, the underlying nature of the power system is changing. As highlighted above (see Inverter Design Research Program), with increasing IBR penetrations the underlying nature of the power system is changing from one based largely on a synchronous paradigm to one based on a non-synchronous paradigm. These changes will both limit the applicability of some existing tools and methods as well as dictate the development of new tools and methods to ensure the reliability, security, and stability of the power system. Furthermore, an increasingly variable, distributed and IBR based power system will also compound existing challenges to analyzing and interpreting results from existing power system models. Therefore, analytical tools that help evaluate the operation of a power system with a large number of IBRs must be developed, specifically tools to capture the interactions and impact of IBR control algorithms that can be detrimental or beneficial to the power system's stability and performance.

Reflecting the holistic and integrated nature of the research agenda, the development of sufficiently refined IBR models touches on several research programmes. IBR models pose a challenge in that there are various proprietary control schemes across IBR manufacturers. Depending on the type of stability modeling conducted, existing generic models may not be adequately detailed to capture their behavior under a variety of grid conditions. As IBR penetrations increase, the converging issues of appropriately designing and modeling IBR responses and integrating these tools into planning and operation practices will become increasingly pressing. Highlighting the dependencies amongst the 59 research questions, this Research Programme will develop benchmark tools and methods for application in the Inverter Design Research Programme.

New stability tools and methods will need to be fully integrated into the existing tools and methods, which are part of the system operator "toolbox", to conduct analysis in the planning and operating time frames. The use of these tools in long term planning and online applications may face computational limitations that may require additional hardware and/or software and/or refinements and approximations in order to make them tractable while maintaining accuracy. Ensuring proposed solutions are scalable and adequately cover the diversity of power system contexts and IBR designs are two of the main issues to be solved as new methods and tools are developed.

This research programme is focused on fully understanding the limitation of existing tools and methods and developing new and/or improved tools and methods to "… identify potential reliability, security and stability issues and the associated least cost solutions in future power systems". These tool sets will focus on core stability issues, with the ability to evaluate small signal stability and large signal stability. Ultimately, they would have to cover an entire suite of prospective issues including frequency stability, frequency domain profile (eigenvalue analysis), protection equipment performance, network reduction, power quality assessment, and other dimensions. The Stability Tools & Methods Research Programme will attempt to yield both (1) new methods which can be implemented as new capabilities within existing tools for detecting incipient instabilities, as well as (2) new analytical tools for detecting instabilities and other foreseen power system issues, using both legacy and new methods for assessment. New tools would need to take traditional concepts related to dynamic stability, plus newer concepts related to IBR control interactions and system strength and merge them with concepts of economic dispatch and unit commitment.

Table 3. Stability Tools & Methods Research Programme Questions
12. What approaches can be taken to near real-time system modelling with large quantities of IBR that make design for system stability sufficiently accurate and still tractable?
13. What methods can be used for off-line and on-line monitoring tools for detecting incipient instabilities? What new capabilities are needed to address these limitations?
14. What type of on-line contingency and stability analyses should be conducted at changing levels of IBR?
15. What analytical tools and models should be provided to planners and operators for robust assessment of system performance?
16. What tools are needed for operational analysis of higher impedance grids?
17. What analytical methods and tools should be used to determine the appropriate mix and capabilities of Grid-Forming and Grid-Following inverters to mitigate low inertia conditions for a given power system?
18. What are the appropriate analytical methods and tools to determine – for a given power system – the extent to which very fast frequency response can substitute for inertia. Relatedly, what tools and methods are needed to effectively compose a mix of Δf and df/dt responses?
19. What tools and methods are needed to identify the best mitigation strategies for voltage-collapse problems under high IBR conditions? And how effective is IBR in recovering from deep voltage dips (bearing in mind lack of short-term overload current)?

2.3 Control Room of the Future

The increasing role of inverter interconnected, highly distributed variable renewable generation, storage and DER brings about a control room challenge unlike anything seen before in the bulk power system. There are many more variables that need to be observed at faster rates and controlled in a much more variable and stochastic environment. The control room of the future thus needs to be able to manage significantly higher volumes of data that need to be quickly converted into actionable information (via novel tools and methods). Furthermore, human operators need to be able to effectively interface with this information and take well-informed actions. Otherwise, information on power system conditions needs to lead to automated actions if humans cannot reasonably respond in time to avoid reliability issues. The control room is at the core of all efforts to monitor and maintain reliability in the face of shifting power system conditions. As the grid becomes more dynamic and stochastic, the control room must be equipped to collect, process, and react to more information than ever before. Failure to keep pace with these challenges will result in additional costs and/or reduced reliability and performance.

Wind and solar PV renewable energy variability and uncertainty, combined with the fundamental, almost instantaneous, supply/demand balance requirement of the power system, mean that wind and solar PV should be forecasted as accurately as possible in advance to dispatch other flexibility resources to maintain the balance. The flexible resources need to be scheduled accordingly across multiple time horizons and account for the inevitability of inaccurate forecasts.

Demand has historically been a ‘given’ quantity for power system operators, and the load patterns predictable and homogenous, simplifying the process of anticipating demand and dispatching the supply accordingly. With the rapid adoption of DERs (e.g., distributed solar PV, electric vehicles, and smart homes), load patterns have become significantly more heterogenous and more difficult to predict, especially as bulk power system operators may not have good visibility into their operation at the distribution level. This is a double-edged sword, as such technologies also offer a significant source of flexibility that could help maintain power system reliability while saving both system operators and consumers money. However, this will require good visibility and controllability of these resources, which is generally not the case at present. To avoid additional challenges of dimensionality, the visibility and controllability should be at an aggregate level which brings with it its own limitations.

System operators are also tasked with managing numerous natural and man-made disasters that may impact the power system, even as the frequency and severity of natural disasters continues to increase. System operators must be able to ensure continuous supply-demand balance even as both supply-side and demand-side resources are impacted by conditions such as severe hot- or cold-events or fires and storms. Preparing and responding to such events will require significant visibility into real-time system operations and the ability to dispatch resources at nearly every level of the power system. Given the speed at which many of these factors can change due to either changes on the distribution system impacting DERs, sudden changes in resource availability (e.g., cloud cover), or interactions between IBRs, power system operators will need to process information and reach decisions significantly more quickly than in the past. With an increase in the sources of these changes, not only must the information be processed more quickly, but significant events will become more common. Addressing these issues may require a combination of telemetry and communication infrastructure to collect data, novel visualizations and tools (e.g., machine learning or artificial intelligence) to help system operators interpret the data, and potentially automated responses.

Reflecting the centrality of the control room to operating the power system, this research programme is very diverse. It ranges from development and/or adaptation of tools and methods for real-time application to data management and visual presentation of the results to the operators in a meaningful way. It also includes real time management of emerging network technologies that make the network more flexible, improve flexibility forecasting efforts, and maximize the flexibility available to power system operators. It also reaches out beyond the bulk power system to aggregate DER in smart ways that will again maximize the value to the bulk power system.

Stemming from its centrality and diversity, the Control Room of the Future Research Programme has the largest number of research questions in the Inaugural Research Agenda. Its focus is on the development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms. Topics include accuracy of wind/solar forecasts, ramping forecasts and forecasts of net load that properly account for DER (i.e., distributed solar, electric vehicles, demand response, distributed storage, etc.). Other topics include operational strategies to increase the efficiency of network capacity, such as dynamic line rating, coordination of critical maintenance outages and management of environmental threats (fires, floods, hurricanes). Data needs may include phasor measurements and real-time state estimation to allow the system operator to monitor real-time risks. Computational and telemetry limitations in collecting and processing data to conduct real-time analysis are also important topics within this Research Program. So also is the potential applicability of machine learning and artificial intelligence technologies and the visualizations that provide necessary information for operators to make decisions (manual or automated) to mitigate reliability risks.

Table 4. Control Room of the Future Research Programme Questions
20. How can operators identify critical stability situations in real-time and optimize system security?
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?
22. How can system strength, inertia and limits of stable frequency range be monitored in real-time in high IBR systems?
23. What are the appropriate methodologies to visualize and interpret relevant information for improved decision support for fast real-time control actions?
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?
25. How can control capabilities for IBR-based system assets (FACTS, Line Impedance adjusters, etc.) and network flexibility more generally be maximized to enhance reliability and/or reduce costs.
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)?
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?
28. How can data be best utilized to ensure system operations include the ability to detect and mitigate a range of uncertain disturbances?
29. What quantities must be monitored, screened and validated to ensure reliable service provision from aggregated flexibility resources in distribution systems, supporting stable system operation?
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?
31. How can grid topology be flexibly adapted at various operating conditions?’

32. What is a suitable data architecture for DER monitoring & modelling? 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?

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 2-way communication protocols are necessary?

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?

35. What is the best way to integrate large data sets, streaming information, and historical system performance to create actionable operational insights?

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?

2.4 Planning

As the primary energy resources change from fossil/nuclear fueled to more variable renewable resources, and as more of these resources become inverter-based and distributed, the planning paradigm needs to change to account for their different characteristics. As other technologies (e.g., batteries) become more pervasive, they also impact the need to change power system planning. Electrification and integration of the other parts of the energy system (e.g., transport and heat) can dramatically alter demand patterns which will also impact the planning paradigm. While VREs, IBRs, DERs, and broader sector coupling complicate traditional planning processes, new tools and growing communications and telemetry infrastructure can provide planners with the data and insight they need to develop cost-optimal reliable power systems.

Driven in part by climate change, the events on power systems are starting to become more extreme and highlight some common mode failures, which are also important to account for in the planning activities. As the consumer becomes more active on the power system, possibly creating a more heterogenous demand side, the whole concept of planning standards may need to be adapted to enable a more optimal system. DER, in particular, can influence traditional reliability control services like under frequency load shedding, impacting operating practices in important ways that must be accurately accounted for in planning practices. Finally, the more dynamic a power system is with VRE, consumer participation, etc. the more complex its operations become (see Control Room of the Future and Inverter Design Research Programmes) and the more important it is to account for the operations in more detail within the planning process. This poses a computational burden that can be addressed by advanced computational methods, both hardware and software, and/or methods for representing power system operations accurately in a reduced form.

The multitude of changes in the power system are challenging existing planning metrics and methodologies. In order to keep up with technology trends, the metrics and the methodologies needed to plan reliable and resilient power systems must be continuously updated in order to ensure that they are “fit for purpose” and deliver the required levels of reliability in the future. System operators all have their own unique variation on long-term planning, driven in part by their regulatory, policy and market environment. In common with the entire Research Agenda, this research programme must navigate this reality as it generates broadly applicable research insights. One area of clear consensus among the FSOs was a need to focus on network infrastructure planning, as there is shared responsibility and shared need to plan and build transmission systems that are robust to a range of future generation portfolios, given the relatively limited responsibility that system operators may have to steer generation investments. Thus, development of processes and tools required to plan the future bulk power system in a liberalized market setting, where the generation side of the equation is market and/or policy driven, should be focused on the transmission system and ensuring there are enough services to ensure reliability and resilience. Defining the network infrastructure of least-regret is growing more complex. Power system operators must establish the necessary tools and processes to plan and build (and eventually, operate) a future power system that is highly variable, and dominated by VRE, IBRs, and DERs, while accounting for risk and uncertainty holistically.

Developing new planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix is the focus of this research programme. The research programme will not consider distribution network planning, nor will it include detailed considerations of electrification and sector coupling impacts or distributed energy resources. Nevertheless, these will need to be represented in aggregate in planning exercises, or in the case of sector coupling, as demand response or long-duration storage assets.

Table 5. Planning Research Programme Questions
37. What additional probabilistic planning methods and tools are necessary for planning a power system with a high share of IBRs and in particular, variable renewable energy resources?
38. What studies and metrics are required to identify long term scarcity of capacity to maintain reliability?
39. What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables?
40. What additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments in a paradigm of increasing electrification and growing IBR and DER penetrations?
41. How should sufficient black-start capability and the performance and integrity of the protection system be modeled in long term reliability studies?
42. What features need to be added to long-term planning methods and studies to consider other reliability services in addition to traditional resource adequacy and deliverability?
43. How can system security be balanced against lower costs for operation and investment?
44. What studies and metrics are required to evaluate resource adequacy with hybrid plants (e.g. PV-plus-storage) and virtual power plants?
45. How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand side flexibility)?
46. What mechanisms are necessary to accurately model and account for DER in planning exercises to ensure a reliable power system is being planned? What data is necessary to accurately model various levels/paradigms of DER control, including influence on under frequency load shedding schemes?
47. What additional load and resource forecasting models are necessary to account for electrification of the transportation and building sectors?
48. What changes can be incorporated into the transmission planning process to accommodate new drivers of uncertainty in electricity demand (e.g., large growth due to electrification or low growth due to increased use of DER)?
49. What additional planning models and methods are needed to plan for a system that can withstand expected or unexpected lulls in the weather driving much of the resource mix, e.g. an extended wind drought?
50. What are appropriate aggregate DER models and methods for inclusion in transmission-level modeling?
51. What models and methods are necessary to quantify the need and requirements for long duration energy storage?

2.5 Restoration & Black Start

Restoring a power system from a black state is a challenge. Traditionally, flexible hydropower or fossil fuel power plants, such as simple cycle gas turbines or diesel generators, have provided the first step of black start. They are specifically equipped with the necessary auxiliary equipment to provide this service. Inverter-based resources such as wind and solar PV cannot currently provide black start, and their participation in the subsequent steps of system restoration is generally avoided. As the fossil resources that have traditionally provided the backbone of restoration are displaced, IBRs will need to fill this gap. Additionally, high penetrations of DERs complicate traditional “cold load pickup” practices, as blocks of load that have embedded distributed PV or distributed storage may result in complex behavior that must be considered in the restoration process.

There are several unique problems associated with “bootstrapping” the system with solar and wind IBRs from a black condition back to normal operation. The first challenge is to ensure that in planning and operational time frames that the IBRs have a sufficient energy source available to enable the black start (i.e., sufficient wind speeds, solar irradiation or charged energy for storage). The second challenge is to extend the capability of IBRs to allow the creation and control of stable voltage waveforms (i.e., grid forming inverters). Subsequent steps in the restoration process each represent a complex data and decision-making process to assure that each stage is safe and viable. The physical capability of the “pieces" (i.e., substations, lines, distribution feeders, and more generators) as they are being reassembled must be respected, and there must be sufficient control range in the controllable elements to maintain acceptable voltage, frequency and power balance. Restoration is often done under difficult conditions, with uncertain and imperfect information. For example, following a blackout due to destructive weather, system elements may be damaged and unavailable, and information about the state and availability of components may be imperfect.

The focus of this research programme is creating new procedures for black starting and restoring a power system with high or 100% IBR penetrations. This programme is not only about black starting a single IBR plant, but rather the careful sequencing of restoring the entire system while simultaneously ensuring stability, security, proper protection, etc. This is challenging given increased complexity due to imperfect information of instantaneous capability of variable renewables, protection concerns due to lower and different fault current behaviors of IBRs, and changed load due to potentially high penetrations of different types of DERs.

This research programme consists of a single research question and focuses on

1) grid code specifications for IBRs to be able to black start
2) equipment needed to black start and restore a power system with various penetrations of IBRs, up to 100%.
3) additional tools, methods or equipment is needed to support system restoration
4) monitoring the network to know if they have sufficient grid formation, inertia, system strength during the system restoration process.

Table 6. Black Start Research Programme Questions
52. How do system operators black start a system with very few (or no) synchronous machines?

2.6 Services

Increasing penetration of VREs leads to a set of increasingly difficult challenges: they are weather dependent, which leads to variability and uncertainty that must be managed at a sub hourly and seasonal timescale; they are interfaced to the power system by inverters, which drives a variety of system challenges (see Inverter Design Research Programme); and they are inherently more distributed, which can pose a challenge to system operators tasked with monitoring them. Other changes, including increasing energy storage deployment and more actively varied demand driven by DER, can pose additional challenges independent of or compounded by VRE.

At the heart of these research challenges are "services" that need to evolve with the changing characteristics of the power system and are fundamental to supporting the socio-technical objective of "reliably maintaining supply-demand balance, at all points in time, at all locations, at least cost, equitably, and with minimum impact on the environment". These services determine: the operation and planning of the electricity grid across all time scales; the required characteristics of the technologies connected to the power system; and, through commercial mechanisms, the incentives to innovate and invest and to do so equitably. Current state-of-the-art services (e.g., capacity adequacy, ancillary services, etc.) fall far short of future service requirements; there is a danger of developing electricity grids that are costly, unreliable, inequitable, and not resilient and will therefore not deliver the step-change needed for the energy transition.

For example, with increasing penetrations of variable renewables there is a decline in "inertial response", and a deterioration in frequency control. There are also several compounding factors, for example distributed solar PV is reducing the efficacy of existing emergency frequency controls in place to arrest frequency declines. Inertia was something not in short supply previously as it came inherently with synchronous generation and therefore it was not deemed to be a service. There are several candidate solutions to declining inertial response, starting with focusing directly on supply demand balance and ignoring frequency control, as it is only an indicator of supply demand balance. Maintaining frequency as the indicator of supply-demand imbalance and deploying synchronous condensers, fast frequency response, and grid forming converters as substitutes for physical synchronous inertia is another approach. There are many other examples, including a possible change in the most fundamental of all services, energy. With increasing penetrations of variable renewables there may well be a point where the energy service, because of oversupply, is replaced in the hierarchy of services by capacity. Due to how rules for participation have been developed, many services today may be biased towards provision by the more established technologies, in particular synchronous machines, as other technologies (e.g., IBRs & storage) were not in existence. Developing system services such that the full capabilities of all eligible technologies are utilised, including those on the distribution grid and in customer premises, can help system operators meet reliability in a cost optimal fashion. However, what is missing is a unifying framework for defining and procuring services so that the "best" combination of solutions is found, recognizing that system characteristics, both technical and societal, vary by location.

A set of new services and/or a reordering of the services hierarchy based on their importance, all based on fundamental electrical engineering, economics, and social factors, is needed to guide the transition towards higher penetrations of variable renewables in electricity grids. These services need to:

1. define physical characteristics of services across the entire range of time scales from milliseconds to seasons;
2. ensure that these services cover the whole space parsimoniously, avoiding negative interactions and redundancy;
3. be robust and economic under all possible systems;
4. be forward looking with respect to an electricity grid that has increasing levels of variable renewables; and
5. be non-discriminatory towards various potential technical routes and hence both stimulate and be open to radical innovation.

The research questions of the Services Research Programme aim to quantify the technical requirements of a future power system to maintain the supply-demand balance reliably and at least-cost. The Services Research Programme also aims to characterize the ability of power system connected technologies (e.g., generation, demand, etc.) to meet these requirements in a cost-effective manner. Put differently, this Research Programme is "where the markets meet the physics" – it is an important bridge to detailed electricity market design, which is out of scope for the G-PST.

Table 7. Services Research Programme Questions
53. How should the definitions of services for IBR dominated grids be structured? Can standard services and standard characteristics be defined that are reasonable for large and small IBR and across VRE, storage and demand response interfaces?
54. What methodologies can be employed to determine if strong/stiff voltage control services can be reliably provided through reactive power droop or active regulation?
55. What models and methods are necessary to quantify the ability of VRE to provide essential reliability services to the grid, and how do system operators quantify the value of these reliability services (for example, as an input to system-specific market/incentive design questions)?
56. What roles can offshore wind and HVDC clusters play in providing energy system flexibility?
57. How can system performance requirements be translated into reliable new technology solutions?
58. How can system operators quantify the transmission level service opportunities from DER? What are the practical and technical limitations to the reliable provision of various DER services?
59. How can transmission-level services provided by DER be valued? What DER transmission-level service valuation methodologies are best suited as a compromise between simplicity and full cost-reflectiveness?

3 Discussion and Execution of the Research Agenda

This Inaugural Research Agenda has multiple objectives. First and foremost, it is an organized list of research needs of the G-PST FSOs. It should not be taken literally, as the questions are expressed in a single sentence here. There is more detail behind each of these and it is stated at the outset that the objectives include encouraging other researchers, system operators, industry, funding agency etc. to get in contact to provide feedback, details of omissions, constructive criticism, potential solutions, existing relevant research, details of funding opportunities, and details of potential collaborations. The details behind the research questions provide context which can be somewhat system specific, but also has a high degree of generic applicability. As stated previously, there is a very high degree of overlap in the research questions, but there is little merit in trying to reduce the questions down to some lowest common denominator.

There is a clear and immediate benefit in the sharing of knowledge between the FSOs and system operators broadly, as well as the migration of solutions across the FSOs. In addition, there are potential solutions that have been or are being developed outside the FSOs and/or the G-PST more broadly that can be deployed successfully. These solutions could be from other system operators, vendors and/or research institutes.

The research questions described here are not entirely new and there is activity already taking place to solve many of them. The very applied and fast-moving nature of the research in this area results in poor visibility of breakthroughs and successes. Therefore, it is difficult to get a complete picture of what research is going on that is complementary and/or indeed substitutive. The G-PST Consortium is particularly interested in feedback on details of existing research that is tackling these and similar questions.

Some of the research questions (or parts thereof), are by their nature transitory and near term, i.e., they will no longer be relevant when power systems reach a certain stage in the transition. For example, one key question in the Inverter Design Research Programme asks how inertia and limits of stable frequency range can be monitored in real-time in IBR grids. After the Inverter Design Research Programme develops solutions there may no longer be a need to monitor grid inertia levels as it may have been competitively superseded by other services that can also provide the need, which is supply-demand balance. Research efforts solving “transition” issues must be considered as a cost of the transition, and their application needs to be considered in the light of their transitory nature.

This Inaugural Research Agenda has been informed by the six FSOs immediate needs and is limited to an initial scope, a ten-year horizon and a focus on the bulk power system. In time, the ambition of the G-PST is to expand the scope and the involvement of others, including DSOs and actors in the broader integrated energy system. Therefore, a fuller scope, provided there is support from the relevant stakeholders, could expand into adjacent areas (e.g., DER, coupling between other energy vectors, etc.) and to the longer time horizon (e.g., 20 to 30 years).

While each of the FSOs (and system operators, generally) are facing similar research challenges, each power system is different when considered technically, institutionally, and geographically. This leads to potentially different detailed solutions in applications and different levels of urgency and pathways to solutions. Great care will be taken to ensure that the solutions being developed under the G-PST are not skewed towards a particular system operator’s needs and are “generic” and can be applied more generally to all of the FSOs and all system operators globally. This “generic” approach does not need to come at the expense of applicability to individual system operators – this is rather a theme that can be kept top-of-mind by the FSOs and researchers as research activities ensue.

The primary objective of a power system is to safely provide reliable energy services to society at an affordable cost. Reliability (and resilience) are convertible into costs in theory, but in practice this is extremely difficult because of the difficulty of estimating the value to the customers. Therefore, achieving the balance implied in this primary objective is extremely difficult. In transitioning the power system, it is important to endeavor to strike this balance. Too low on the cost and reliability risks major societal and economic damage if the power system fails catastrophically. Too high on the reliability and cost risks stifling innovation and hampering society with additional unwarranted costs.

The integrated nature of the power system, combined with the rapid changes across nearly all its aspects, dictate that a holistic and adaptable research plan that focuses on robust solutions is required. Simply stated, a well-defined research project can be influenced by the outcomes of many other research projects that are going on in parallel within the G-PST and/or elsewhere. This means that progress with any individual research endeavor cannot be made without consideration of progress elsewhere and that research outcomes, where possible, need to be adaptable and robust. Managed incorrectly, this dynamic could lead to very slow progress and/or progress that results in solutions that are far from ideal for system operators and possibly redundant. Therefore, a holistic, adaptable, and timely management of progress in a centralized manner is required to ensure success. It is also worth noting that perfection is not the objective here, as this could lead to very slow progress.

4 Conclusion

The G-PST RAG has produced an Inaugural Research Agenda consisting of 59 research questions organized into six Research Programmes. It is focused on the near term (ten years) core bulk power system issues. The questions are overlapping, dependent and interacting. A holistic and/or coordinated global effort is required to solve these questions quickly so the transition to future power systems is not hampered or delayed. Feedback is requested from the entire global power systems community with an eye to collaboration, refinement, and addition of research questions, all targeted at a coordinated global approach. Existing research activities that are aligned are also requested to engage. Most importantly, research funding agencies and sources are asked to consider this research agenda a priority. Broader and longer-term research agendas will be developed when this Inaugural Research Agenda is well resourced and progressing towards solutions.

APPENDIX A: Full Research Agenda

Here all 59 research questions are listed and associated with their primary and, where appropriate, secondary research programme.

Table A1. Summary of Research Programmes

Research Question	Primary Research Programme	Secondary/Related Research Programme
1. What are the needs of a power system (to achieve security and good regulation) expressed in technology neutral form and how do these needs map to services that any resource, including IBR or synchronous machine, can provide?	Inverter Design	Services
2. For each service defined in (1), how feasible is it to provide from IBR, what "cost" does it add and what limitations exist on its magnitude and duration of service? What implications do these have for system operations?	Inverter Design	N/A
3. What are the limitations of each IBR technology option to provide frequency control services and how do the various frequency services overlap and compete?	Inverter Design	N/A
4. What design standards or dispatch guidance should be introduced to avoid instability (e.g., caused by PLL or other elements) in weak grids? This is a more widely drawn version of the question on minimum ratios of grid-forming to grid-following inverters.	Inverter Design	Services
5. What are the appropriate inverter capabilities and, consequently, control design methods for operation in grids with high percentage of IBR? Are standard configurations and combination of services helpful in simplifying operational decision making?	Inverter Design	Control Room
6. Are the black-box models (impedance-spectrum and binary code) favoured by manufacturers for disclosure sufficient for stability assurance and system design across all problem types?	Inverter Design	N/A
7. What recommendations should be made for standard behaviours of IBR in certain frequency ranges for different power system conditions to aid system design? For example, should a contribution to damping be mandatory at certain frequencies?	Inverter Design	Services
8. What impedance requirements should be placed on IBR to suppress negative-sequence and low order harmonic currents?	Inverter Design	N/A
9. How will protection systems need to change to accommodate high penetrations of IBR and what possible actions might an inverter take during a fault that would aid fault detection and location?	Inverter Design	N/A
10. What is the future of frequency control as the synchronous generation fraction reduces? Might tightened or loosened frequency limits lead to a more reliable, secure, lower cost IBR-based power system?	Inverter Design	N/A
11. At what point is it better to break from trying to replicate synchronous machine features and exploit the wider flexibility of inverters?	Inverter Design	N/A

12. What approaches can be taken to near real-time system modelling with large quantities of IBR that make design for system stability sufficiently accurate and still tractable?	Tools & Methods	Inverter Design
13. What methods can be used for off-line and on-line monitoring tools for detecting incipient instabilities? What new capabilities are needed to address these limitations?	Tools & Methods	Control Room
14. What type of on-line contingency and stability analyses should be conducted at changing levels of IBR?	Tools & Methods	Control Room
15. What analytical tools and models should be provided to planners and operators for robust assessment of system performance?	Tools & Methods	Control Room / Planning
16. What tools are needed for operational analysis of higher impedance grids?	Tools & Methods	N/A
17. What analytical methods and tools should be used to determine the appropriate mix and capabilities of Grid-Forming and Grid-Following inverters to mitigate low inertia conditions for a given power system?	Tools & Methods	Inverter Design
18. What are the appropriate analytical methods and tools to determine – for a given power system – the extent to which very fast frequency response can substitute for inertia. Relatedly, what tools and methods are needed to effectively compose a mix of Δf and df/dt responses?	Tools & Methods	N/A
19. What tools and methods are needed to identify the best mitigation strategies for voltage-collapse problems under high IBR conditions? And how effective is IBR in recovering from deep voltage dips (bearing in mind lack of short-term overload current)?	Tools & Methods	N/A
20. How can operators identify critical stability situations in real-time and optimize system security?	Control Room	Tools and Methods
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?	Control Room	N/A
22. How can system strength, inertia and limits of stable frequency range be monitored in real-time in high IBR systems?	Control Room	N/A
23. What are the appropriate methodologies to visualize and interpret relevant information for improved decision support for fast real-time control actions?	Control Room	N/A
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?	Control Room	N/A
25. How can control capabilities for IBR-based system assets (FACTS, Line Impedance adjusters, etc.) and network flexibility more generally be maximized to enhance reliability and/or reduce costs.	Control Room	Tools and Methods

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)?	Control Room	N/A
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?	Control Room	N/A
28. How can data be best utilized to ensure system operations include the ability to detect and mitigate a range of uncertain disturbances?	Control Room	N/A
29. What quantities must be monitored, screened and validated to ensure reliable service provision from aggregated flexibility resources in distribution systems, supporting stable system operation?	Control Room	Tools and Methods
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?	Control Room	N/A
31. How can grid topology be flexibly adapted at various operating conditions?’	Control Room	N/A
32. What is a suitable data architecture for DER monitoring & modelling? 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?	Control Room	N/A
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 2-way communication protocols are necessary?	Control Room	N/A
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?	Control Room	N/A
35. What is the best way to integrate large data sets, streaming information, and historical system performance to create actionable operational insights?	Control Room	N/A
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?	Control Room	N/A
37. What additional probabilistic planning methods and tools are necessary for planning a power system with a high share of IBRs and in particular, variable renewable energy resources?	Planning	Tools and Methods

38. What studies and metrics are required to identify long term scarcity of capacity to maintain reliability?	Planning	N/A
39. What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables?	Planning	Tools and Methods
40. What additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments in a paradigm of increasing electrification and growing IBR and DER penetrations?	Planning	N/A
41. How should sufficient black-start capability and the performance and integrity of the protection system be modeled in long term reliability studies?	Planning	Black Start
42. What features need to be added to long-term planning methods and studies to consider other reliability services in addition to traditional resource adequacy and deliverability?	Planning	Services
43. How can system security be balanced against lower costs for operation and investment?	Planning	N/A
44. What studies and metrics are required to evaluate resource adequacy with hybrid plants (e.g. PV-plus-storage) and virtual power plants?	Planning	N/A
45. How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high renewable energy future (wind, solar, demand side flexibility)?	Planning	N/A
46. What mechanisms are necessary to accurately model and account for DER in planning exercises to ensure a reliable power system is being planned? What data is necessary to accurately model various levels/paradigms of DER control, including influence on under frequency load shedding schemes?	Planning	N/A
47. What additional load and resource forecasting models are necessary to account for electrification of the transportation and building sectors?	Planning	N/A
48. What changes can be incorporated into the transmission planning process to accommodate new drivers of uncertainty in electricity demand (e.g., large growth due to electrification or low growth due to increased use of DER)?	Planning	N/A
49. What additional planning models and methods are needed to plan for a system that can withstand expected or unexpected lulls in the weather driving much of the resource mix, e.g. an extended wind drought?	Planning	N/A
50. What are appropriate aggregate DER models and methods for inclusion in transmission-level modeling?	Planning	Control Room
51. What models and methods are necessary to quantify the need and requirements for long duration energy storage?	Planning	Services

52. How do system operators black start a system with very few (or no) synchronous machines?	Restoration & Black Start	Inverter Design
53. How should the definitions of services for IBR dominated grids be structured? Can standard services and standard characteristics be defined that are reasonable for large and small IBR and across VRE, storage and demand response interfaces?	Services	Inverter Design
54. What methodologies can be employed to determine if strong/stiff voltage control services can be reliably provided through reactive power droop or active regulation?	Services	N/A
55. What models and methods are necessary to quantify the ability of VRE to provide essential reliability services to the grid, and how do system operators quantify the value of these reliability services (for example, as an input to system-specific market/incentive design questions)?	Services	N/A
56. What roles can offshore wind and HVDC clusters play in providing energy system flexibility?	Services	N/A
57. How can system performance requirements be translated into reliable new technology solutions?	Services	N/A
58. How can system operators quantify the transmission level service opportunities from DER? What are the practical and technical limitations to the reliable provision of various DER services?	Services	N/A
59. How can transmission-level services provided by DER be valued? What DER transmission-level service valuation methodologies are best suited as a compromise between simplicity and full cost-reflectiveness?	Services	N/A

Appendix B: RAG Members and Advisors

Founding System Operator Designates

Jeff Billo – Senior Manager of Transmission Planning, ERCOT
Anders Bavnhøj Hansen – Chief Engineer, Energinet
Julian Leslie – Head of Networks, National Grid ESO
Julia Matevosyan – Lead Planning Engineer, ERCOT
Phil Pettingill – Director of Regional Integration, CAISO
Nicolaj Nørgaard Peulicke – Vice President for Innovation and Digitalisation, Energinet
Liam Ryan – Chief Innovation and Planning Officer, EirGrid
Luke Robinson – Manager Grid Performance & Integration, AEMO

Research Institute Members

Thomas Bowen – Grid Systems Researcher, NREL
Janusz Bialek – Professor of Power and Energy Systems, Newcastle University
Martin Braun – Director of Grid Planning and Operation Division, Fraunhofer IEE
Nicolaos A. Cutululis – Professor of Offshore Wind Power Integration, DTU
Tim Green – Director of Energy Futures Lab, Imperial College London
Ben Kroposki – Director of the Power Systems Engineering Center, NREL
Debra Lew – Associate Director, ESIG
Mark McGranaghan – Vice President of Innovation, EPRI
Mark O'Malley – Chief Scientist, ESIG; Professor of Electrical Engineering UCD; Chair of RAG
Charlie Smith –Executive Director, ESIG
Aidan Tuohy – Research Program for Bulk System Integration of Variable Generation, EPRI
John Ward – Research Program Director of Grids and Energy Efficiency Systems, CSIRO
Owen Zinaman – Senior Power System Researcher, NREL

Advisors

Frede Blaabjerg, Aalborg University
Bethany Frew, NREL
Anish Gaikwad, EPRI
Hannele Holttinen, IEA TCP WIND Task 25, Recognis Oy
Juha Kiviluoma, VTT
Jason McDowell, ESIG/GE
Nick Miller, Hickoryledge
Russ Philbrick, ESIG/PSOT
Deepak Ramasubramanian, EPRI
Matthias Resch, Fraunhofer IEE
Roland Singer, Fraunhofer IEE
Goran Strbac, Imperial College London
Xiongfei Wang, Aalborg University