C1

SPECIAL REPORT FOR SC C1

POWER SYSTEM DEVELOPMENT AND ECONOMICS

Special Reporters:

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Introduction to SC C1

The work of Study Committee C1 covers all the system development and economic challenges relevant to the electricity power industry including those relating to asset management.

Planning grids and developing systems world-wide is experiencing a paradigm shift. As decarbonisation targets are driven worldwide, change in the energy sector and choice of generation sources is heavily influenced. With the continued diffusion of distributed renewable generation sources, both distribution and transmission network planning functions are influenced significantly. Holistic system development and coupling with other energy sectors (gas, mobility, heat) and, in particular, new hydrogen applications affect planning and economics assessment; this needs to be researched to allow the energy transition to be fully deployed and lead towards a resilient future system.

SC C1 aims to support electricity system planners worldwide to make the best plans possible in a changing energy environment which includes increased renewable and distributed generation and heightened uncertainty in social, environmental, and regulatory frameworks and expectations. System plans must address these changes, while considering economic and public acceptance difficulties. Such plans require a more resilient and more flexible grid that recognizes the increasingly critical role of integrated transmission and distribution systems as enablers of the Energy Transition.

SC C1 events and engagements in the Paris session 2026

Tuesday 25 Aug

- C1 Workshop joint with ISGAN on Lighthouse project – 10:30-12:30 (Room MAILLOT)
- Workshop on Mediterranean systems cooperation by MedTSO joint with C1 – 14:00-16:00 (Room MAILLOT)
- C1/C2/C4 workshop on ‘Large Inverter Based Loads’ – 16:00-18:00 (Room MAILLOT)

Wednesday 26 Aug

- SC C1 closed meeting – 08:45-18:00 (Room 343)

Thursday 27 Aug

- C1 Poster session: 08:30-12:30 (HALLE TERNES)

- Meeting with contributors to GDM: during C1 Poster session, in control room inside HALL TERNES
- Workshop joint with IEC TC 123 on standards for coordinated management of network assets 14:00-16:00 (Room 342AB)
- C1 tutorial on 'Global Grids including Hydrogen' – 16:10-18:00 (Room BORDEAUX)

Friday 28 Aug

- SC C1 General Discussion Meeting – 08:45-18:00 (Room HAVANE)

Contributions for C1 Group Discussion Meeting (GDM)

The GDM of SC C1 shall take place on **August 28, 2026 in Room 343, starting 8:45 until 18:00**.

Special Reporters have compiled a number of questions, not specifically aimed at the papers' authors, rather synthesised from common issues and trends identified across the papers. This provides the opportunity for a broader response and participation in the discussion session. We encourage you to share your views or experiences in response to the specific questions in this report ("Prepared Contributions").

Prepared Contributions must address each a specific question in this report, and can only be made by registered attendees, who will attend the GDM in person. They have the form of power point slides (to be shown during the GDM) and word document (for Conference proceedings) and must be uploaded to the ConfTool platform **by August 11th 2026 for review by the Special Reporters**.

Each prepared contribution will have a time slot of about 2 - 3 minutes (depending on how many we receive), so the number of slides shall be limited to 2 – 3 plus cover slide (please do not make the slides too busy), to be easily read and clearly illustrate your message; small size logo of your company/organisation is allowed, while no commercial information/advertising are allowed. Special Reporters will check and validate the contributions on-line using the Session Papers portal. Any recommendations or changes to the contributions will be provided to the contributors by the Special Reporters directly on the Registration platform **until 18th of August 2026**. Contributors are encouraged to visit their account on the Registration Platform to see and act upon the result of this review.

A **meeting with contributors** shall be held on **August 27, 8.30 - 12.30 inside the Poster Session in Hall Ternes**, to check contributor's attendance and finalise the GDM time schedule with contributions slots. Considering the overall time available, there will be a limit of about 30 contributions for each Preferential Subject, also to allow some vivid exchanges in reaction to the prepared contributions (spontaneous verbal contributions). Attendees who provide a spontaneous contribution may provide a summary of it as a short, written text for the Proceedings, to be forwarded **within two weeks after the Session** to the Secretary Peter Roddy: peter.roddy.c1@gmail.com.

Poster session

Independently of Contributions to GDM, paper authors are kindly reminded to present their papers during the **Poster Session scheduled for Thursday 27th August (08:30 to 12:30)** in Halle Ternes on level 1. Template and instructions on poster preparation are available on the CIGRE 2026 Session website. Posters will be displayed on digital screens. **A draft copy** of the poster must be uploaded to the ConfTool platform **by Wednesday 29th June** for review

by the poster session convener (Jana Breedt, BreedtJn@ntcsa.co.za). A **final version**, incorporating any requested changes, must be uploaded by **Friday 21st August 2026**. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session he/she or the relevant National Committee is requested to appoint a substitute for attending the poster session.

Preferential Subjects

The three preferential subjects of C1 and their sub sections for 2026 session are:

PS1. Holistic planning of an integrated energy system for the energy transition

PS2. Strategic investment decisions in the context of the energy transition

PS3. Planning the cyber-physical system

Papers and Questions for Group Discussion Meeting

PS1: Holistic planning of an integrated energy system for the energy transition

There are 44 papers in this preferential subject, with discussions structured around the following topics:

1. Sustainable scenarios encompassing gases, heat, mobility, IT (data centres) as loads and as flexibility sources.
2. Planning methodologies and modelling targeting net zero while ensuring adequacy of resources and increased resilience.
3. Prioritisation of asset management plan and allocation of capital, including role of private investments in transmission networks

PS 1.1. Sustainable scenarios encompassing gases, heat, mobility, IT (data centres) as loads and as flexibility sources

The papers in this section focus on how net zero planning must increasingly account for new forms of electricity demand and cross-vector interaction, including hydrogen production, gas system coupling, electric mobility, heat, and large digital infrastructure such as data centres. A common theme is that these emerging loads are not simply passive additions to the grid; if sited, designed and operated intelligently, they can also provide flexibility, reduce curtailment, support local balancing, and improve overall system efficiency. The papers therefore point toward a more integrated view of energy planning in which electricity, gas, transport, heat and industrial demand are coordinated as part of a wider system rather than planned in isolation.

Paper C1-10848. *Stochastic sizing for off-grid green ammonia plants powered by wind energy.* This paper investigates how to design an off-grid green ammonia plant powered solely by wind energy, where the main challenge is coping with the high variability and uncertainty of wind supply without any grid backup. It shows that relying only on wind creates significant risks of prolonged low-wind periods, requiring careful trade-offs between oversized storage and allowing temporary plant shutdowns. To address this, the authors develop a stochastic optimisation framework that uses multiple years of wind data to size

process units (electrolysers, Haber–Bosch) and storage systems (hydrogen, nitrogen, batteries), capturing both short-term variability and rare extreme events.

Paper C1-11049. *Tool for Automatic Evaluation of Large Loads Placement Using Transmission Margin Concepts in the Brazilian Interconnected Power System.* This paper provides a fast, automated, and scalable decision-support framework that helps system planners and investors identify optimal locations for large loads, while also improving system utilisation, particularly by aligning demand with renewable generation and reducing curtailment, thereby enhancing overall grid efficiency and reliability. The paper presents a software tool for automatically evaluating the optimal siting of large electricity loads, such as data centres and hydrogen production plants, by adapting the established Transmission Margin concept from generation planning to load integration in the Brazilian Interconnected Power System.

Paper C1-11113. *Planning heavy-duty en-route charging stations considering freight traffic and grid availability***.** This paper proposes a holistic methodology for planning en-route and overnight charging infrastructure for heavy-duty electric trucks, explicitly integrating freight transport demand, regulatory requirements, and electricity grid availability. It combines origin–destination freight flow data, trip-chain modelling based on driving/rest constraints, geospatial analysis of existing truck stops, and the topology of the high-voltage grid to identify optimal charging locations across Italy. The approach uniquely incorporates grid proximity as a core siting criterion, ensuring that selected locations are feasible for high-power (multi-megawatt) connections while minimising cost and deployment delays.

Paper C1-11198. *Approaches to incorporating new consumer types in long-term power system development planning in the time of energy transition.* This paper analyses how the rapid emergence of new electricity consumer types – such as data centres, crypto mining, electric vehicles, charging infrastructure, and electric heating – fundamentally changes demand patterns and challenges traditional long-term power system planning methodologies. It shows that these consumers are spatially heterogeneous, exhibit distinct and often highly predictable or extreme load profiles, and can create concentrated demand hotspots—sometimes in weak parts of the system—making conventional forecasting approaches based on historical trends insufficient. The paper proposes practical adjustments to forecasting methodologies and connection strategies, including revised coefficients, differentiated modelling by consumer type, and flexible or interruptible connection arrangements for certain loads.

Paper C1-11349. *Hydrogen sector impact on the power sector: power system development, grid planning and operation.* This paper examines how large-scale development of the hydrogen sector, particularly through electrified hydrogen production, will reshape power system planning, development, operation, and markets within an integrated "system-of-systems" energy framework. It identifies electrolysers as the central interface, introducing significant new electrical demand but also offering valuable flexibility if optimally deployed and operated. Key contributions include a structured assessment of grid planning impacts, a system-wide perspective showing how hydrogen production and storage can enhance overall energy system efficiency, an operational framework detailing how electrolysers can provide short- and long-term flexibility services, and an analysis of evolving hydrogen market design, to support investment and scalability.

Paper C1-11617. *Bridging Network Planning and Municipal Decarbonisation: How Local Area Energy Planning Connects Municipalities to DNO Scenario Models in the UK.* This paper examines the disconnect between UK Distribution Network Operators' (DNOs) Distribution Future Energy Scenarios (DFES) and municipal Local Area Energy Plans (LAEPs), arguing that misalignment between top down network forecasting and bottom up local decarbonisation planning risks inefficient investment and undeliverable plans. It demonstrates how LAEP digital tooling acts as a translation layer between these domains—enabling municipalities to create their own spatially detailed energy scenarios, compare them with DNO forecasts, and convert them into network-feasible project pipelines that can be integrated into formal planning processes.

Paper C1-11625. *Approaches to the Design of Internal EHV and HV Networks for Large Data Centres – Three Case Studies.* This paper examines how internal EHV (≥400 kV) and HV (>100 kV) network design for large (500 MW–GW scale) data centres is evolving, and how different design philosophies materially influence system performance, resilience, and integration with transmission networks. It makes three key contributions. First, it distinguishes two overarching approaches, top-down and bottom-up, and demonstrates through three case studies how each drives fundamentally different outcomes. Second, it highlights emerging technical challenges unique to hyperscale data centres. Third, it provides a set of practical design considerations, notably early definition of grid-code compliance and alignment of end-user redundancy agreements, arguing that these up-front decisions are critical because downstream changes are often prohibitive.

Paper C1-11648. *An Integrated Framework to Enhance Power and Gas Reliability under High Renewable Penetration: Case of Saudi Arabia.* This paper develops and applies an integrated planning and simulation framework for coupled power and gas systems to address reliability challenges under high renewable penetration, using Saudi Arabia as a case study. It identifies a critical phenomenon, the "gas demand duck curve", in which variability in renewable-driven electricity demand causes large intra-day fluctuations in gas consumption, resulting in curtailment risk and cascading reliability issues across the energy system. The key contribution is a bi-directional iterative modelling approach that links power system production cost optimisation with dynamic gas hydraulic simulations, allowing cross-system constraints to influence electricity dispatch decisions in real time.

Paper C1-11934. *Implications of rapid data centre growth on the British power system and environment.* This paper assesses the system-wide and environmental impacts of rapid data centre growth on the Great Britain electricity system using a detailed 14 zone market and network model, providing new insight into how large, variable digital loads interact with a decarbonising power system. It demonstrates that increasing data centre demand drives higher reliance on gas generation, leading to material increases in carbon emissions that could jeopardise Clean Power 2030 targets if not managed through system design and policy. The paper further shows that the geographic siting of data centres is a critical system lever. The paper also highlights emerging operational and environmental challenges, including large and fast demand variability, interaction with system stability and significant water consumption for cooling.

Paper C1-12015. *Inclusion of distributed generation planning and associated local control strategies as key factor for holistic system planning.* This paper examines how the rapid growth of distributed generation (particularly rooftop PV) fundamentally changes power

system behaviour and challenges traditional planning approaches, arguing for the integration of distributed generation planning and local control strategies into holistic system planning. It shows that high penetration of distributed PV alters load profiles seen by transmission systems and creates voltage and reactive power challenges in distribution networks. The paper highlights the growing complexity of smart grids, where bidirectional flows, prosumers, and rapid developments at the distribution and customer level occur on much shorter planning timescales than transmission infrastructure, creating coordination challenges between TSOs, DSOs, and end-users.

Paper C1-12072. *A Decarbonised Railway Supports Power System Operations Case Study of Energy Hub Concept in Southwest Scotland.* This paper presents a whole-system approach to integrating decarbonised railway electrification with power system operation, demonstrating how railway infrastructure can actively support grid resilience rather than acting solely as an additional demand source. Its key contribution is the introduction and validation of a "railway energy hub" concept which combines renewable generation and battery energy storage to both supply railway traction demand and provide grid services, such as voltage regulation and curtailment reduction. The study shows that energy hubs can shift demand, reduce peak stress, and utilise otherwise curtailed renewable energy. A further contribution is the development of a multi-layer control strategy, including real-time voltage control and day-ahead optimisation, to coordinate railway and grid objectives.

Paper C1-12382. *Linking bottom-up and top-down prognosis in integrated distribution grid expansion planning.* This paper presents an enhanced forecasting and planning methodology for distribution grid expansion that integrates top-down national scenarios with bottom-up, location-specific projections, addressing the growing mismatch between centralised forecasts and real-world developments. It demonstrates that traditional top-down models, based on coarse temporal and geographic assumptions, systematically underestimate near-term demand and technology uptake, particularly for emerging. The proposed approach combines these models with high-resolution bottom-up forecasts derived from local data, enabling detailed geospatial allocation of demand and generation across network levels to produce a more accurate and actionable demand outlook.

Paper C1-12518. *Optimal configuration method of electric-thermal hybrid energy storage for Desert-Gobi-Wasteland new energy base considering retrofitted coal-fired power plants*. This paper proposes an optimal configuration methodology for electric–thermal hybrid energy storage in large-scale Desert-Gobi-Wasteland new energy bases, addressing the challenge of renewable variability and curtailment in remote, high-renewable systems. Its key contribution is the design of a hybrid storage architecture combining electrochemical energy storage for short-duration flexibility and thermal energy storage (TES) integrated with retrofitted coal-fired power plants for long-duration balancing, enabling multi-timescale system regulation. The paper develops a techno-economic and operational model of retrofitted coal plants coupled with molten-salt TES, capturing energy flows across electrical and thermal domains and enabling enhanced system flexibility and renewable accommodation.

Q 1.01 How should planners value flexible new loads versus inflexible demand in future network design?

Q 1.02 What is the biggest barrier to coordinating electricity planning with hydrogen, heat, transport, and data centres?

Q 1.03 Are current planning frameworks moving fast enough to reflect emerging demand types and cross-vector interactions?

Q 1.04 What would better coordination between electricity, hydrogen, transport, heat, and digital infrastructure planning actually look like in practice?

PS 1.2 Planning methodologies and modelling targeting net zero while ensuring adequacy of resources and increased resilience.

This section brings together papers that advance the analytical methods needed to plan decarbonised power systems while preserving adequacy, operability and resilience. Across the set, there is a clear move away from static deterministic planning toward probabilistic, climate-aware, time-series-based and operationally realistic approaches that better represent renewable variability, extreme weather, storage behaviour, system strength, voltage support and interconnection effects. The overall message is that net zero planning requires more sophisticated modelling frameworks that can simultaneously test energy sufficiency, stability, flexibility and resilience under uncertain future conditions.

Paper C1-10114. *New York grid performance gaps study.* This paper uses an integrated planning approach which combines capacity adequacy, system operations and stability analysis to show how New York's power system will cope as it replaces fossil fuel plants with renewables like wind, solar, and batteries. It finds that this shift creates new reliability challenges because renewables are variable, transmission is constrained and traditional grid stability from large generators is reduced. Around 25 GW of firm capacity must be replaced by clean solutions, with particular pressure in New York City during evening peaks when solar drops and wind may be low. The analysis highlights that future solutions must ramp quickly around 6 pm, provide local capacity where transmission is constrained, and include grid-forming capabilities to maintain stability. The paper demonstrates that a fully integrated planning approach is essential to identify reliability gaps and design effective solutions for a high-renewables grid.

Paper C1-10188. *Evolving Planning Criteria for a Sustainable Power Grid.* This paper argues that traditional power system planning methods, particularly the long-standing "1 day in 10 years" reliability standard, are no longer sufficient for renewable dominated power systems with rapidly changing demand and characterised by extreme weather. It highlights that future planning must account for how often supply shortfalls occur and their duration. The paper proposes a shift towards multi-metric, probabilistic, and integrated planning, combining resource and transmission assessments, incorporating chronological and extreme weather scenarios, and improving coordination across regions, to provide a more realistic and robust assessment of reliability risks in a low-carbon electricity system.

Paper C1-10232. *Planning for Uncertainty and Variability: Integrated Modelling for Transmission Adequacy.* This paper explains that traditional transmission planning approaches based on a small number of static "worst-case" scenarios are no longer adequate for modern power systems facing growing uncertainty from renewable generation, extreme weather, and rising demand. It introduces an integrated modelling framework that links weather and climate data with power system models to better understand how generation availability and demand vary over time and location. Using tools such as EPRI's RiSc and

HiLS methodologies, the approach identifies high-risk periods and reduces thousands of potential operating conditions into a small set of representative scenarios that capture critical stress on the system.

Paper C1-10884. *Rethinking Capacity Accreditation in High-Renewable Power Systems: Discrepancies, Drivers, and Practical Insights from a CAISO Case Study.* This paper examines how traditional capacity accreditation approaches break down in high-renewable power systems, where the shift from peak gross load to peak net load fundamentally changes when reliability risks occur and how different resources contribute. Using the California Independent System Operator system as a high-renewable testbed, it compares six accreditation methods and shows that they can produce significantly different valuations due to their treatment of risk hours, benchmarks, and resource interactions. The paper highlights the need to move from static, single-metric accreditation toward integrated, probabilistic, multi-metric frameworks that explicitly model resource interactions and evolving risk windows, in order to provide accurate reliability assessment and investment signals in decarbonised power systems.

Paper C1-10950. *Initiatives to Supply 100% Renewable Energy on Hahajima Island Microgrid Project.* This paper presents the design and operational validation of a fully automated microgrid achieving 100% renewable energy supply on Hahajima Island, an isolated Japanese island previously reliant on diesel generation. It develops an integrated system combining photovoltaics, battery storage, diesel backup, and a newly developed Energy Management System that optimally schedules generation and storage to maximise renewable utilisation across day–night cycles. The key technical contributions address two fundamental challenges of high-renewable systems: reduced inertia and diminished fault current.

Paper C1-11012. *Strategic Electricity System Expansion for Net-Zero Transition using the STELLAR Model: Integrating Thermal Emission Constraints and Ensuring Resource Adequacy.* This paper presents the application of the STELLAR (Strategic Expansion for Long-Term Resource Adequacy and Resilience) model, a national-scale capacity expansion optimisation framework developed for India, to evaluate pathways for achieving a net-zero-aligned power system while maintaining reliability. The model integrates chronological system modelling, unit commitment constraints, co-optimisation of energy and ancillary services, demand response, and zonal transmission representation, enabling realistic assessment of high-renewable electricity systems.

Paper C1-11114. *Extending the Terna-RSE Methodology for Power System Resilience Assessment to Hydrogeological Threats.* This paper extends the Terna–RSE risk-based resilience assessment methodology to explicitly account for hydrogeological threats, particularly substation flooding, in power system planning. It combines probabilistic hazard modelling (including climate-driven flood projections) with detailed component-level vulnerability models for substations, covering equipment, control systems, and auxiliary circuits, to estimate failure probabilities and outage return periods. The paper provides a robust, forward-looking framework for resilience-driven investment planning, enabling TSOs to prioritise interventions under increasing climate-related risks.

Paper C1-11126. *Reactive Power Demand Projection from Distribution Networks in Great Britain.* This paper analyses the changing nature and future projection of reactive power flows at Grid Supply Points in Great Britain. It shows a clear shift from traditional import of

reactive power from transmission to increasingly frequent capacitive export driven by distribution network evolution and high penetration of distributed energy resources. The paper develops a hybrid methodology that combines physics-based network simulations with statistical emulation to provide a robust, scalable framework for long-term reactive power forecasting in increasingly complex, decarbonised electricity systems.

Paper C1-11197. *The impact of climate factors on the operation and forecasting of operating conditions of the United Power System of Russia to increase power system resilience.* This paper examines how climate change is increasingly influencing electricity demand patterns and system operation in the United Power System of Russia It shows that rising temperatures, greater variability, and more frequent extreme conditions are altering load profiles, increasing sensitivity of demand to temperature, and shifting seasonal peaks. The paper introduces improved forecasting methodologies, including region- and consumer-specific temperature sensitivity coefficients, approaches to capture delayed demand response during prolonged extreme weather events, and the integration of additional climatic variables such as cloud cover, wind effects and icing intensity into forecasting models.

Paper C1-11258. *Application of Procedures for Building Models for Poland's Long-term Energy Policy.* This paper develops an improved modelling framework for long-term power system planning in Poland, addressing the limitations of traditional optimisation models in accurately representing operational realities in high-renewable systems. It shows that conventional long-term models tend to overestimate renewable integration due to simplified time resolution and omission of operational constraints, particularly for weather-dependent generation. The paper demonstrates that integrating operational realism into long-term planning reduces investment risk, improves cost efficiency, and supports more credible energy policy decisions in the transition to high-renewable power systems

Paper C1-11470. *Scenario-based bi-level optimization approach for enhancing multi-DC infeed capacity and renewable energy integration of receiving-end grids.* This paper makes three main contributions to improving multi-infeed HVDC planning under high renewable penetration. First, it develops a scenario construction method that more accurately captures the uncertainty and correlation between wind generation and load. Second, it proposes a scenario-based bi-level optimisation framework to maximise infeed capacity and voltage support while minimising cost, and to optimise coordinated generation–storage dispatch to minimise operating cost and wind curtailment. Third, it demonstrates that the integrated approach enhances DC hosting capacity and renewable utilisation simultaneously, while highlighting the system-level trade-off between increasing renewable penetration and reducing allowable DC infeed capacity due to reduced inertia and stability margins.

Paper C1-11471. *Renewable Generation Expansion Planning Considering Wind-Solar Spatiotemporal Complementarity under Climate Change.* This paper contributes to climate-aware renewable generation planning. It introduces a dynamic, seasonally resolved Copula-based framework to quantify wind–solar spatiotemporal complementarity, enabling identification of optimal geographically paired resources that reduce aggregate variability. It also proposes a hierarchical planning methodology that decouples physical system design from economic optimisation by minimising net load variability, thereby improving system resilience and avoiding instability seen in purely cost-driven models. Finally it integrates these insights into a two-stage stochastic expansion planning model that explicitly incorporates multiple CMIP6 climate scenarios, demonstrating that coordinated planning can

substantially reduce flexibility requirements and system costs while maintaining high reliability under long-term climate uncertainty.

Paper C1-11863. *The importance of temperature and heat waves as variables in the methodology for estimating long-term maximum integrated demand and their impact on the National Electric System.* This paper develops a climate-informed methodology for forecasting long term maximum integrated electricity demand in Mexico's National Interconnected System, demonstrating that temperature and extreme weather, particularly heat waves, are critical drivers of peak demand behaviour. The paper introduces a framework that establishes a strong positive relationship between temperature and demand, shows that demand sensitivity increases sharply under extreme heat conditions, and it incorporates precipitation as a moderating variable. It proposes multivariate, climate-sensitive models that improve accuracy and support more resilient system planning, operational preparedness, and infrastructure investment under increasing climate variability.

Paper C1-11968. *Modelling Climate Impacts on Long-Term Energy Infrastructure Planning.* This paper develops a climate-integrated capacity expansion modelling framework to improve long-term energy infrastructure planning by explicitly incorporating the effects of climate change on both demand and supply. It demonstrates how traditional planning approaches based on historical weather patterns are no longer sufficient, and proposes a method that converts global climate projections into hourly, state-level profiles of temperature, wind, solar and precipitation for direct use in system planning models, linking these to electricity demand, renewable generation, and asset performance. The paper shows that integrating climate dynamics into planning models is essential to avoid suboptimal investments and ensure resilient, cost-effective energy systems, positioning climate-aware modelling as a critical evolution in long-term infrastructure and decarbonisation planning.

Paper C1-12080. *Reliability Assessment in the Chilean Power System in a Full Coal Phase-Out Scenario by 2030.* This paper presents a reliability assessment of Chile's National Electric System (SEN) under a full coal phase-out scenario by 2030, focusing on how high renewable penetration affects both adequacy and operational security. Its key contribution is an integrated modelling framework combining long-term capacity expansion, chronological unit commitment simulations, and dynamic system studies, enabling a holistic evaluation of reliability under both normal and stressed conditions. The analysis demonstrates that a system dominated by solar and wind generation, supported by hydropower, energy storage, and limited dispatchable gas capacity, can meet demand and peak load under expected conditions, with storage playing a central role in shifting energy and reducing curtailment.

Paper C1-12136. *Optimization model for determining scenarios of maximum integration of renewable energy plants with identification of Synchronous Must-Run units.* This paper proposes a mixed-integer linear optimisation framework to maximise the integration of variable renewable energy while maintaining system stability. It co-optimises renewable dispatch and the minimum set of "must-run" synchronous units, identifying the technical trade-off between maximising renewable output and preserving essential stability services. The methodology introduces the SCRIF (Short Circuit Ratio with Interaction Factor) index as a more advanced metric of grid strength,

Paper C1-12316. *Adaptive Network Planning with Integrated Time Series Simulation and Investment Decisions in a Decarbonizing Energy Transition Landscape***.** This paper proposes an adaptive transmission planning framework that integrates high-resolution time series simulation with probabilistic analysis to better support network investment decisions in a decarbonising energy system. It demonstrates that traditional deterministic, peak-snapshot planning methods are no longer sufficient for systems with high renewable penetration, as they fail to capture temporal variability, uncertainty, and evolving load patterns. The proposed methodology provides deeper insights into non-intuitive system stress conditions that are not aligned with traditional peak demand assumptions, improving the identification of constraints such as congestion, voltage violations and reverse power flows.

Paper C1-12388. *Identifying Nodal Reactive Power Demand for Steady-State and Dynamic Voltage Control Using Linear Programming.* This paper addresses the growing challenge of reactive power scarcity and increasing voltage control requirements in decarbonised transmission systems. It proposes a new methodology to identify where reactive power is needed rather than how it should be supplied. Its key contribution is a two-stage linear programming approach that determines technology-neutral, nodal reactive power demand for both steady-state and dynamic voltage control, shifting away from traditional optimisation methods that focus on siting specific compensation devices. The approach enables TSOs to decouple demand identification from technology choices, supporting emerging procurement frameworks that combine regulated provision, TSO assets, and market-based mechanisms.

Paper C1-12453. *Comparative Assessment of Conventional and Resilience-Oriented Planning strategies for Distribution Grid Networks under Future Climate Risk Scenarios.* This paper presents a framework to evaluate conventional versus resilience-oriented distribution grid planning under future climate risk scenarios, highlighting how planning strategies influence long-term system robustness and economic performance. Its key contribution is introducing a structured, scenario-based methodology that integrates site-specific climate hazard information into grid planning decisions, while keeping all technical and regulatory conditions identical to enable transparent comparison. Using life-cycle economic assessment, which includes climate-induced disruption and restoration costs, the paper demonstrates that while resilience-oriented planning requires higher upfront investment, it reduces long-term risk exposure and total cost variability.

Paper C1-12516. *A novel power generation planning method designed for future power system development.* This paper proposes a novel power generation planning methodology tailored for high-renewable power systems, addressing the limitations of traditional deterministic approaches that cannot adequately capture uncertainty, flexibility needs, and multi-objective trade-offs. Its key contribution is the development of a multi-dimensional evaluation framework structured around five core planning objectives - clean and low-carbon, safe and sufficient, economical and efficient, supply–demand coordination, and flexible and smart, each quantified through measurable indicators, enabling systematic comparison of alternative generation expansion schemes.

Paper C1-12584. *From Scarcity to Security: The First Adequacy and Flexibility Assessment across MENA Region and Interconnected Operation Challenges.* This paper delivers the first probabilistic adequacy and flexibility assessment for a set of Med-TSO member power systems in the MENA region, focusing on Morocco, Tunisia, Egypt, Jordan and Lebanon for 2027 and 2030, and explicitly comparing isolated versus interconnected operation to quantify the value of cross-border exchanges for security of supply. Its key methodological

contribution is coupling Monte Carlo adequacy modelling with a multi-timeframe flexibility assessment based on residual load dynamics, thereby treating adequacy and flexibility as linked problems rather than separate studies.

Q 1.05 How should planning methodologies evolve for a net zero power system? How far should climate risk be embedded into mainstream power system planning?

Q 1.06 Are we still planning tomorrow's grid with yesterday's standards? What planning tools are most critical for dealing with climate and weather uncertainty?

Q 1.07 Are we underestimating how much climate change will reshape grid investment needs? Is "reliability" becoming a dangerously narrow lens for net zero planning?

Q 1.08 What changes most when planning shifts from deterministic to probabilistic approaches?

PS 1.3 Prioritisation of asset management plan and allocation of capital, including role of private investments in transmission networks

These papers are most relevant to questions of where and how to prioritise network investment, particularly for transmission expansion, offshore coordination, major asset design choices and strategic reinforcement under uncertainty. While relatively few papers deal explicitly with capital allocation or private finance, several offer practical insights into how planners can identify the most valuable reinforcements, compare alternative architectures, sequence major projects, and create the technical and regulatory conditions needed for anticipatory and coordinated investment. Together, they reinforce the idea that transmission investment decisions should be guided by whole-system value, resilience, scalability and interoperability, rather than narrow asset-by-asset optimisation.

Paper C1-10335. *Powering Australia's Clean Energy Future: Challenges and Innovations in EHV Renewable Energy Zone Development.* This paper examines how Australia is using Extra High Voltage Renewable Energy Zones (REZs) to enable large-scale integration of renewable generation, but highlights that these developments introduce complex, interconnected technical, commercial, and governance challenges that cannot be managed through traditional project-by-project approaches. This paper proposes a holistic, system-level approach to REZ planning and operation, combining integrated technical and economic modelling, continuous model validation using real-time measurement data, and deployment of digitally enabled substations, and wide-area monitoring systems.

Paper C1-10408. *Greening the Island Initiative: Interconnection of Islands in Andaman & Nicobar Islands and HVDC link from mainland India.* This paper examines how India plans to decarbonise electricity supply for the Andaman & Nicobar Islands, which currently rely heavily on expensive and polluting diesel generation, by developing an integrated transmission solution. It proposes a combination of inter-island grid integration (via a new 66 kV transmission backbone) and a high-capacity HVDC submarine link from mainland India to provide reliable, clean power where local renewable deployment is constrained by land and environmental limits. The study shows that this approach can significantly improve reliability, reduce emissions and dependency on diesel, and become cost-effective within a few years while delivering long-term economic savings.

Paper C1-10409. *Design of Inter-state Transmission System for the World's Largest RE Park in Gujarat, India - Planning Perspective & Transient Stability Analysis*. This paper presents the design of a large-scale inter-state transmission system to evacuate power from the Khavda Renewable Energy Park in Gujarat, expected to be the world's largest renewable energy complex (42 GW), and highlights the challenges of integrating such a large, remote, inverter-dominated generation source into the grid. The study demonstrates that with strong grid-strengthening measures, such as synchronous condensers, reactive power compensation, and maintaining adequate short-circuit ratios, the system can remain stable and meet dynamic performance requirements.

Paper C1-10847. *Techno-economic comparison of grid planning scenarios for AC/DC grids: a North Sea case study.* This paper introduces a scenario-based techno-economic methodology that integrates operational simulation, uncertainty, and economic metrics to support more informed, system-level grid planning decisions in highly renewable, multi-country electricity systems. The paper develops and applies a techno-economic framework to compare different AC/DC grid expansion options for the North Sea, focusing on how offshore HVDC networks can best support large-scale renewable integration and cross-border power exchange. . The analysis shows that while all reinforcement options can reduce system operating costs and deliver positive economic benefits, the optimal design depends strongly on both network topology and future energy scenarios; in particular, meshed multi-terminal DC (MTDC) grids with limited redundancy emerge as the most cost-effective solution, balancing investment cost with operational savings and avoiding underused assets.

Paper C1-10951. *Evaluation of Adequacy and Flexibility of Interconnection in case of Japan with over 90% Renewable Electricity Ratio in FY2040.* This paper evaluates how inter-regional transmission expansion enables adequacy and flexibility in a highly renewable Japanese power system (~90% renewables by 2040), focusing on the HVDC corridor linking resource-rich northern regions (Hokkaido and Tohoku) to major demand centres such as Tokyo. The analysis highlights strong non-linear reliability effects, showing that systems with insufficient transmission capacity become highly sensitive to outages, with sharp increases in unserved energy and reliability risk once capacity falls below critical thresholds. It also shows that transmission expansion delivers substantial economic benefits by reducing fuel import costs and improving system resilience.

Paper C1-11115. *Offshore transmission network and Multi-Purpose Interconnectors: Optimal Configurations for the System.* This paper analyses how offshore transmission networks and Multi-Purpose Interconnectors (MPIs) can be optimally configured to integrate offshore wind into future decarbonised electricity systems, using the Italian system as a case study. It compares a range of architectures, from single MPIs to increasingly complex meshed offshore grids with multiple offshore bidding zones, assessing socio-economic welfare, renewable overgeneration, and total system cost under different market designs and support schemes. The paper demonstrates that coordinated, meshed offshore grid solutions with hybrid assets and appropriate market arrangements provide a more efficient and scalable pathway for offshore energy integration and decarbonisation than traditional radial or single-interconnector designs.

Paper C1-11472. *HVDC carrying characteristics of receiving end power system considering the VSC-HVDC support.* This paper assesses the HVDC carrying capacity of receiving-end power systems under high penetration of renewable energy and power electronics. First, It contributes a combined analytical and simulation-based assessment approach to quantify how

increasing HVDC and renewable penetration degrades system strength and reduces permissible infeed capacity. Second, it provides a systematic characterisation of stability impacts, showing that higher levels of power-electronics penetration reduce voltage support capability and system inertia constraining HVDC hosting capability. Third, the paper demonstrates that VSC-HVDC can materially enhance system stability, supplying both reactive power for voltage support and virtual inertia/primary frequency response, increasing the achievable infeed capacity.

Paper C1-11492. *Developments in Regional Offshore Transmission Planning and Coordination.* This paper argues that scaling offshore wind to the levels required for net zero demands a fundamental shift from radial, point-to-point connections to a coordinated, multi-terminal offshore transmission grid, and provides a structured assessment of the technical, regulatory, and commercial changes needed to enable this transition. The paper analyses the complexity of multi-terminal control and protection and highlights interoperability challenges across multi-vendor systems, with innovation programmes positioned as critical enablers. The paper demonstrates that existing regulatory frameworks, largely designed for single-purpose assets, must evolve to treat offshore hybrid assets as shared infrastructure, with clearer delivery models, cost-recovery mechanisms, and operational incentives to support anticipatory investment and multi-party coordination. Commercially, it identifies misalignments in cross-border pricing, revenue stabilisation mechanisms, and development timelines as key barriers, requiring new market arrangements and coordinated delivery models.

Paper C1-11879. *Offshore Transmission Planning – JWG C1/B4.* This paper synthesises international experience from Joint Working Group C1/B4.49 to provide a holistic view and practical guidance for planning offshore transmission systems in support of large-scale renewable integration, particularly offshore wind. Its key contribution is establishing offshore grids as multi-purpose infrastructure, beyond simple export cables, serving roles such as interconnection between markets, onshore grid reinforcement, and enabling hybrid energy systems. The paper provides a structured analysis of technology choices, system components, and emerging options. It frames offshore grid development as a systems engineering challenge, where topology, protection philosophy, and ancillary service requirements must be integrated early to ensure scalability, reliability, and technical compliance. The paper positions offshore transmission planning as a critical enabler of the energy transition, requiring early standardisation, modularisation, and anticipatory investment to deliver resilient, expandable, and economically efficient offshore grid systems.

Paper C1-12585. *Towards an Efficient, Adequate, Sustainable and Interconnected Mediterranean Power System: Résumé of the Master Plan*. This paper presents a coordinated regional planning framework for the development of the Mediterranean power system, centred on the Med-TSO Mediterranean Master Plan and its associated interconnection programme. Its key contribution is the creation of a structured, corridor-based portfolio of cross-border transmission projects, assessed using harmonised scenarios and a consistent cost-benefit analysis framework aligned with ENTSO-E methodologies, enabling comparison of economic, environmental, and security-of-supply impacts. A central insight is that large-scale interconnection expansion acts as a critical enabler of system efficiency, flexibility, and renewable integration, reducing curtailment, emissions, and system isolation while enhancing security of supply.

Q 1.09 What makes anticipatory investment a strategic necessity in some cases, but a risk in others? How should we think about the trade-offs between speed, cost, and long-term system value when prioritising transmission investment?

Q 1.10 What does good transmission planning look like when uncertainty, interoperability, and future scalability all matter at once?

Q 1.11 How can planners create the right conditions for private capital to support network development without losing sight of whole-system value?

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PS 2: Strategic investment decisions in the context of the energy transition

This preferential subject attracted 41 papers. The topics under discussion in this preferential subject are differentiated according to the following sub-topics:

1. Optimal portfolio mix of transmission, generation, storage and non-wire solutions for ensuring adequacy, resilience and flexibility, and relevant governance framework
2. Investment economics and risk analysis in the new energy landscape
3. Sustainable asset management practices, especially for aging infrastructures

PS 2.1 Optimal portfolio mix of transmission, generation, storage and non-wire solutions for ensuring adequacy, resilience and flexibility, and relevant governance framework

The reviewed body of literature collectively demonstrates a fundamental shift in how power system and grid investments are planned, prioritised, and delivered. Traditional planning approaches largely focused on isolated capacity expansion, least cost optimisation, and siloed generation or transmission studies which are increasingly inadequate in the face of accelerating decarbonisation, climate driven risks, operational complexity, and capital constraints. In response, the papers advocate for holistic, integrated, risk and resilience-based planning frameworks that align long term strategic objectives with near term executable investment decisions.

Paper C1- 10419, *Leveraging Battery Energy Storage in Thermal Power Plants for Enhanced Flexibility, Reliability, and Emergency Backup*: This paper proposes integrating Battery Energy Storage Systems (BESS) with coal-fired plants to address grid stability challenges from high renewable penetration in India. BESS enables steady, efficient thermal operation while providing ramping, peak shifting, and grid support with limited tariff impact. Studies and NTPC pilots show improved efficiency, lower emissions, extended asset life, better use of surplus power, and backup capability. The approach offers a scalable model to convert coal plants into flexible assets supporting renewable integration and system resilience.

Paper C1-10849, *Embedding Grid Security Constraints in Generation Expansion Planning Models: A Real Network Case Study*. This paper proposes a methodology to incorporate the grid stability and operational constraints in the GEP mathematical modelling. The objective is to bridge the gap between economic optimisation and operational security requirements, associated with the generation mix. To this end, the study considers, in the calculation of the optimal generation mix, the constraints related to voltage margins in steady states and frequency stability. The method is tested through simulations conducted on the future New Caledonia power transmission network, which features a high penetration of renewable energy sources.

Paper C1-10952, *Advancement of the Long-Term Transmission Expansion Plan for Achieving Carbon Neutrality by 2050*. This paper outlines approved grid reinforcements in Japan, including central AC

upgrades and a new HVDC subsea link. It explains the evaluation framework, decision-making process, and treatment of uncertainty, offering insights into large-scale transmission planning for decarbonisation.

Paper C1- 11048, *Perspectives on the Application of Storage Systems in the Brazilian Electricity Sector:* This paper examines how energy storage can support Brazil's renewable-rich power system by addressing curtailment, ramping, congestion, and stability challenges. It reviews storage technologies, applications, and the evolving regulatory framework, including the 2026 Capacity Reserve Auction. Case studies from hybrid PV-storage and Cemig's BESS pilots show storage can compete with grid upgrades to improve reliability. The study concludes that with proper regulation and cost declines, storage will be key to enhancing flexibility, resilience, and efficiency in Brazil's power system.

Paper C1-11050, *Structuring the Optimum Viable Portfolio for the Brazilian Electric Power System*. This paper aims to identify optimal, practical solutions to balance the energy trilemma—reliability, emissions reduction, and affordability in Brazil's power system through objective technical analysis. It highlights transmission constraints between renewable-rich regions and load centres as a key challenge. The study proposes methodologies to balance these competing priorities and maximise social welfare across power systems.

Paper C1- 11118, *Market Analysis of Lithium-Ion Batteries for Power System Applications: Strategic Insights and Challenges:* This paper analyses the global lithium-ion battery market for power systems, highlighting strong geographic concentration—dominated by China—and associated supply chain and geopolitical risks. It identifies key vulnerabilities and strategic actions to ensure secure supply, promote competition, and support a resilient battery value chain for the energy transition.

Paper C1-11193, *Integrating Distributed Energy Storage Systems for Resilient, Low-Carbon, and Economically Viable Isolated Power Systems:* This paper evaluates distributed battery energy storage in isolated island systems to improve reliability, reduce fuel use and emissions, and enhance economics. Studies show BESS can cut gas turbine operation, support fast protection and frequency control, and maintain stability. With proper sizing and control, it reduces load shedding and peak investment needs, providing a resilient, low-carbon solution.

Paper C1- 11199, *Development of ESS in the UPS of Russia and Assessment of Their Role in Increasing the Power System Flexibility:* This paper explores how energy storage, pumped hydro and batteries, can address flexibility challenges in Russia's power system. It highlights their complementary roles: pumped hydro for large, long-duration balancing, and batteries for fast, local services. The study proposes a planning framework to evaluate storage as an alternative to generation and grid expansion, concluding that ESS integration is essential for a more flexible, reliable, and cost-effective power system.

Paper C1- 11200, *Energy Storage Systems in Development Plans and Power Markets – GO-15 Vision:* This paper presents the consolidated view of GO15 system operators on how energy storage systems should be integrated into power system development plans and electricity, capacity, and ancillary services markets to support the energy transition. It identifies the main technical and economic drivers for ESS deployment across very large power grids, details priority applications such as power and energy balancing, RES profile smoothing, frequency and voltage control, congestion management and peak shaving, and compares how different GO15 members currently treat ESS in planning, resource adequacy, interconnection studies, flexibility assessments, interconnection standards, and incentive schemes. Building on case studies from CAISO, MISO, ONS, Grid-India and others, the paper outlines minimum technical requirements, cost benchmarks and emerging market mechanisms needed to ensure that PHES and BESS investments are both technically justified and economically viable, and announces a forthcoming GO15 report that will formalize system operators' positions on ESS in development plans and power markets.

Paper C1- 11491, *Shared Storage, Shared Future: Strategic Deployment of District Energy Storage Systems for Power System Flexibility and Decarbonization:* This paper examines district energy storage as shared assets that support decarbonisation, grid flexibility, and local resilience. It shows these systems can reduce costs, curtailment, and congestion while enabling sector coupling. It also highlights technologies, AI control, and new business models, noting regulatory and social barriers. The paper concludes with actions to enable large-scale deployment of district storage in support of EU energy transition goals.

Paper C1- 11808, *Implementing Storage Flexibility: Battery Storage and Photovoltaic Hybrid Systems' Challenges and Opportunities in the Energy Transition:* This paper evaluates hybrid PV-battery systems in Bosnia and Herzegovina under grid constraints. It shows that strict limits make storage uneconomic, while moderate limits can enable profitability, especially with DC coupling and optimized dispatch. Results highlight that viability depends more on grid conditions, curtailment and market design than on technology maturity.

Paper C1-11830, *Strategically planning a Transmission Network – the Challenge of the Energy Transition in the North of Scotland*. . Strategic planning requires assessing future network needs based on both the connection pipeline and longer-term user behaviour, including location and market participation. As power flows between generation, storage, and demand become more dynamic, purely deterministic approaches are insufficient. A 'proxy probabilistic' NoS model, combining security-constrained DC optimal power flow, year-round hourly simulation, and targeted scenario analysis, provides a more realistic view of system evolution and emerging thermal constraints within the NoS. This is aligned to the broader shift toward GB-wide strategic and spatial planning, where flexible user needs, reduced zonal rigidity, and uncertainty in asset timing and location drive a wide range of possible futures and heightened investment uncertainty.

Paper C1- 11970, *Optimal Power Supply Strategy for a Near Shore Archipelago in NEOM*: This paper provide insight in the integrated system and optimal network configuration on a group of islands. Pioneer case of applying meshed MVDC to near-shore archipelago is presented. The process to select between different topologies and technologies were comprehensively presented as a worthy lesson to other cases.

Paper C1- 12014, *Strategic Allocation of Lines, Capacity, and Grid-Forming Inverters to Improve Fault Tolerance in Renewable-Rich Network:* This paper proposes a method to improve fault tolerance in inverter-dominated grids by optimising transmission expansion and the placement and capability of grid-forming batteries. It finds that increasing grid-forming inverters at former generator nodes, with modest reinforcement and ~3 p.u. overcurrent capability, provides a cost-optimal way to enhance fault response and grid resilience.

Paper C1- 12496, *Design of an integrated electricity fuelled energy system and the systemic roles of hydrogen:* This paper highlights hydrogen's role in achieving a carbon-free energy system in the Netherlands by 2050. It shows hydrogen is essential for hard-to-electrify sectors, long-duration storage, and reducing grid expansion needs. Despite costs and inefficiencies, it is critical due to limited alternatives, with system integration and regional planning key to deployment.

Paper C1- 12517, *Scheduling Strategy for Movable Electricity-Hydrogen Supplier Powered by Impulsive Wave Energy:* This paper presents a movable wave-powered electricity-hydrogen system for remote microgrids, integrating batteries, electrolysis, fuel cells, and heat recovery to improve resilience and efficiency. It uses optimized energy management to handle variability and reduce infrastructure needs, achieving up to 38.8% higher revenue than stationary systems.

Paper C1- 12552, *Transmission Clusters in Northern Ireland – Optimising the Connection of New Renewable Generation:* This paper presents a model of clustering generation to optimise connection timelines, network reinforcement, and reduce whole-system costs, while sharing risk between

developers and the electricity consumer. This approach will be key to decarbonise the power system in Northern Ireland, and could be replicated elsewhere. The key aim of this policy is to deliver infrastructure ahead of need, with costs initially borne by the network owner. Upon connection, generators will pay this development cost back in proportion to their use of the capacity created. This paper details the design of this Policy, and an example of its implementation.

Q 2.01 Should system operators prioritize grid expansion or flexible resources (storage, demand response, HVDC controllability) to reduce curtailment?

Q 2.02 Are we still planning "networks," or are we now planning socio-technical systems where assets, markets, climate, and human capabilities are inseparable?

Q 2.03 Is "least-cost" optimisation still a meaningful concept in power system planning, or should resilience and flexibility be treated as co-equal objectives even when they increase system costs? How should planners value resilience investments when their long-term benefits are uncertain?

Q 2.04 Can a single optimisation framework realistically balance adequacy, resilience, flexibility, and decarbonisation, or do these objectives inevitably require political and governance trade-offs outside the model?

Q 2.05 Is energy storage becoming the default solution because it is genuinely optimal, or because it conveniently postpones harder decisions on transmission and market reform?

PS 2.2 Investment economics and risk analysis in the new energy landscape

The papers in this section highlight a clear shift toward risk informed, resilience oriented and investment ready power system planning across local, national and cross border contexts. They show how co optimising cost, flexibility and resilience, under climate, market and policy uncertainty, requires advanced technical economic methods alongside credible governance and financing frameworks. Key themes include de risking investment in emerging markets, improved load forecasting and capacity assessment methodologies, risk based asset portfolio management, and the growing role of digitalisation, flexibility and hydrogen. Large scale interconnections and policy instruments such as CBAM(Carbon Border Adjustment Mechanism), further underscore the need for coordinated regional planning and transparent decision making. Overall, the papers demonstrate that achieving decarbonisation and resilience depends as much on institutional alignment and investment structures as on technical innovation.

Paper C1- 10169, *A Framework for Co-optimizing Cost and Resilience in Stand-Alone Power Systems for Green Hydrogen Production*. This paper presents a techno-economic optimisation framework for least-cost, resilient green hydrogen systems using solar, wind, and battery storage. A case study in Egypt shows that PV-led systems with wind and storage can deliver reliable, cost-competitive hydrogen, with viability strongly influenced by battery sizing and financing conditions.

Paper C1- 10417, *Balancing Risk and Reward: Investment Strategies for Emerging Economies in the Renewable Energy Transition:* This article argues that balancing investment risk and reward requires an integrated approach combining strong legal frameworks, effective financial instruments, and consistent policy implementation. Case studies from India, Brazil, and South Africa show that improving off-taker reliability, adopting blended-finance structures, and maintaining stable regulation can substantially reduce investment risk.

Paper C1- 10424, *OSOWOG (One Sun One World One Grid) : Innovative investments favouring Net Zero Carbon energy exchanges among interconnected continents:* OSOWOG enables economic and environmental gains by pooling renewable resources across regions, but requires complex, high-uncertainty investment decisions. This paper proposes a Strategic Investment Decision Framework (SIDF) to guide structured, practical planning for intercontinental and regional grid interconnections.

Paper C1-10669, *Integrating rooftop solar into load forecasting: A South African emerging methodology*. This paper proposes a methodology to incorporate behind-the-meter rooftop PV impacts into South Africa's demand forecasts. It shows PV adoption reduces and reshapes demand, effects missed by traditional methods. The framework isolates PV impacts and enables accurate forecasting from national to substation level, improving planning alignment with actual system behaviour.

Paper C1- 10732, *An Approach for Justifying and Prioritizing Adaptation Investments for Climate Resilience:* This paper proposes a framework to prioritise climate resilience investments in power systems under uncertainty, combining risk and cost-benefit analysis with sensitivity testing. A case study shows decisions, especially pole replacement are robust across scenarios, providing practical guidance for cost-effective resilience planning.

Paper C1- 10953, *Projects for Digital Flexibilities to Optimize the Existing and Future Physical Infrastructure in Japan and France:* Integrating large amounts of PV and wind power creates growing congestion challenges, especially in local grids. Although congestion is only beginning to appear in both countries, significant new infrastructure would eventually be required; an approach that is costly, slow, and burdensome for society. To address this, Japan's Connect & Manage system and France's NAZA mechanism were developed to increase renewable hosting capacity while minimizing grid reinforcements. By using automated curtailment and other flexibility measures, these systems allow more renewable energy to connect at lower overall cost.

Paper C1-11116, *The novel Italian approach for the Target Capacity Assessment: main results and relevant sensitivity analyses*. This paper presents the novel approach developed and outlines the methodological enhancements introduced in the 2025 Target Capacity Report, along with the findings derived from applying this updated framework to the Italian power system under the latest reference scenarios and their relevant sensitivities, which is a heuristic-based method designed to identify economically efficient additional transmission capacity: specifically, it evaluates capacity increases where the overall system benefits surpass the associated investment costs. The purpose of the study is to facilitate the development of an efficient and economical transmission system, by supporting the definition of the output-based regulatory scheme rewarding the increases in transmission capacities.

Paper C1- 11337, *Mitigating Curtailment Risks in Korea's Renewable Future: Grid Simulation with Offshore Wind AEP and Transmission Scenarios:*

Paper C1- 11473, *Review and Analysis on Outlook of Bi-directional Hydrogen Energy Storage in New Power System in China:* This paper evaluates hydrogen energy storage in China's power system, finding that bi-directional use is limited by high costs and low efficiency. It concludes hydrogen will mainly play a one-directional role, supporting industrial decarbonisation and transport rather than large-scale power system storage.

Paper C1- 11743, *Electricity at EU borders under CBAM: Assessing future costs and strategic implications for Bosnia and Herzegovina:* This paper assesses the implications of the Carbon Border Adjustment Mechanism (CBAM) for Bosnia and Herzegovina (BiH), a non-EU country bordering the EU and currently the only net exporter of electricity in the Western Balkans, with generation still predominantly coal-based. It proposes a replicable, phased approach to CBAM implementation that progresses toward full Emissions Trading System (ETS) compliance by 2030, centred on an aggregate,

National Energy and Climate Plan based emissions factor. The proposed modelling framework contributes to the broader discussion on carbon pricing and investment risk, offering quantified insights to support both EU and non-EU jurisdictions in navigating carbon regulation while advancing their climate commitments.

Paper C1- 11783, *Methodological Approach to Economic Assessment of UHVDC Cross Border Interconnection for Renewable Energy Trading:* This study provides a quantitative assessment of the net socio-economic gains achieved when renewable energy is delivered via an Ultra-High Voltage Direct Current cross-border transmission network (UHVDC-CBT). It (i) introduces a structured, life-cycle-based integrated evaluation framework, and (ii) strengthens practical applicability by using the Weighted Average Cost of Capital (WACC) instead of conventional overnight cost assumptions. The proposed methodology offers a rigorous approach for determining the economic feasibility of UHVDC-CBT interconnections and delivers evidence that can inform future policy formulation and investment decisions.

Paper C1- 11818, *Unlocking Investment in Power System Resilience: A Review of current Practices and Recommendations:* Embedding resilience into investment decision-making requires a holistic, multi-dimensional approach that integrates technical modelling, economic analysis, stakeholder engagement, regulatory alignment, and organisational culture change. This paper advances a structured, evidence-based transformation of how resilience investments in power infrastructure are assessed and prioritised, with sufficient flexibility to be adapted to the needs of different network operators and stakeholder contexts. The proposed recommendations support the development of a proof-of-concept framework, capable of institutionalising resilience-oriented investment practices, while also informing the evolution of business-as-usual practices across the global power sector.

Paper C1- 11996, *Risk-Informed Decisions for Asset Portfolio under Rapid Grid Expansions:* This paper propose an innovative methodology derived from existing standards and recommendations for prioritization of TSO's infrastructure projects based on different risk matrices which are made comparable using the concept of value unit. Risk methods in asset management have traditionally focused on asset-condition assessments to guide renewal strategies, and TenneT Germany initially applied a business-value framework built for this purpose. This paper shows how the framework was expanded to evaluate a broader set of capacity-related risks arising from the energy transition and grid-expansion projects.

Paper C1- 12054, *Private Capital for HVDC Interconnectors in Europe: Techno-Economic and Policy Insights:* This paper analyses the role of private capital and alternative development models in accelerating interconnector development, illustrated through the Apollo-Link HVDC project between Spain and Italy. A conceptual framework distinguishes interconnector development models by actor type and financing structure, highlighting the growing relevance of privately initiated, off-balance-sheet projects. It shows that privately initiated, off-balance-sheet projects can complement traditional planning processes and help close delivery gaps. The findings highlight the value of diversified financing models and transparent analytical frameworks in aligning private investment with European system objectives, thereby strengthening the resilience and efficiency of Europe’s future power system.

Q 2.06 Is centralised, government-led grid planning more effective than market-driven, decentralised models for future grid needs?

Q 2.07 Should grid planning include mandatory resilience criteria for extreme weather, cyber threats, and geopolitical risks?

Q 2.08 When does hydrogen provide unique system value that batteries, transmission expansion, or demand response cannot substitute?

PS 2.3 Sustainable asset management practices, especially for aging infrastructures

The papers in PS 2.3 examine how power system owners and planners are adapting asset management practices to manage aging power infrastructure sustainably under increasing climate, operational, and investment pressures. They emphasise a move from siloed, asset-by-asset renewal approaches, toward integrated, risk-informed asset management, combining asset condition, load growth, and climate risk to guide investment prioritisation and resilience planning, and regional approaches to infrastructure modernisation and cross-border coordination. Key themes include optimising existing assets through enhanced utilisation and digital tools, coordinating regional infrastructure modernisation, and addressing critical skills and capability gaps required to support data-driven and resilient grid operations. Together, the papers demonstrate that sustainable management of aging infrastructure depends not only on technical solutions, but on integrated planning, digitalisation, regional cooperation, and workforce readiness to deliver resilient and future-ready power systems.
This topic covers methods, frameworks, and regional strategies for planning future-ready grids. It focuses on transmission upgrades, cross-border interconnections, prioritisation of infrastructure investments, integration of new renewable clusters, and advanced modelling tools for system stability and security.

Paper C1-10105 *A Holistic Framework for Integrated Grid Planning: Balancing Load Growth, Aging Infrastructure, and Climate-Driven Risk*. This paper outlines the methodology, process design, and implementation of PG&E's (Pacific Gas and Electric Company), IGP framework. The primary objective of the IGP framework is to establish a risk-informed, data-driven, and capital-efficient investment plan that aligns long-term system needs with near-term operational priorities. The framework attempts to address traditional fragmentation in utility's investment planning practices by integrating asset condition assessments, asset intervention eligibility and benefit estimation, risk modelling, investment bundling, and capacity/load forecasting into a single decision-support platform.

Paper C1- 10187, *A Framework to Enhance Grid Resilience for Long-Term Planning of Transmission Systems*. This paper proposes an integrated planning framework for TSOs to align resource adequacy and system resilience investments. It supports optimal generation–transmission portfolios and risk-informed decisions under uncertainty, enhancing resilience to extreme weather and ensuring reliable service continuity

Paper C1- 10732, *An Approach for Justifying and Prioritizing Adaptation Investments for Climate Resilience:* This paper proposes a framework to prioritise climate resilience investments in power systems under uncertainty, combining risk and cost-benefit analysis with sensitivity testing. A case study shows that investments—especially pole replacement—remain effective across varied conditions, providing practical guidance for robust, cost-effective resilience planning.

Paper C1- 11792, *Western Balkan Action Plan for Power Grids: Advancing Grid Modernisation and Integration through Coordinated Regional Planning and EU Funding Support:* The WB region faces a critical decade requiring rapid upgrades in infrastructure, regulation, and capacity to support the energy transition. Power grids are both the key bottleneck and opportunity; without major modernisation, renewables and market integration will stall. The paper outlines a coordinated regional action plan, requiring strong collaboration across utilities, regulators, governments, and partners.

Paper C1- 11794, *Criteria, Methodology and Selection of Priority Electricity Infrastructure Projects in Southeast Europe:* The overall objective of the paper is to introduce criteria and methodology to select the priority energy infrastructure projects in Southeast Europe until 2050. The final target is to enhance market integration, security of supply, sustainability and competition of the electricity markets. The authors have developed a project-assessment methodology which was used to evaluate the impact of the proposed projects on regional level. A standardised, model-based assessment combining monetised and non-monetised indicators can prioritise regional projects that maximise welfare and resilience.

Paper C1-11880, *Enhancing Power System Utilisation: Tools and Insights from Norway*. Norway's TSO has over 30 years' experience enhancing transmission capacity and utilisation in response to rising demand and system changes. Measures include temperature uprating of lines and system protection schemes beyond N-1 limits. A comprehensive toolbox, covering assets, operations and planning, and customer flexibility; integrates physical, operational, and market solutions to maximise grid use.

Paper C1-12553, *Improved transformer condition monitoring and improved assessment of the impact of small-scale generation:* This paper introduces two complementary methods for strategic investment: enhanced transformer thermal analysis using IEC 60076-7 and advanced modelling of unmeasurable small-scale generation (SSG). The findings show that conservative planning can unnecessarily limit renewable connections. Together, these approaches improve asset utilisation, defer capital spend, and accelerate renewable integration while maintaining system security.

Paper C1-12579, *A Planning-oriented Contingency Analysis Tool for Custom Power System Models Beyond Native Capabilities of Widely Adopted Power System Software*: This paper introduces a Python-based Contingency Analysis Tool (CAT) developed to address the limitations of widely used power system software platforms such as Siemens PSS®E, PowerWorld, and DIgSILENT PowerFactory, when incorporating custom models not natively supported. The CAT directly addresses the challenge of integrating emerging technologies, such as the Modular Static Synchronous Series Compensator (M-SSSC), into grid planning and security assessments. It enables contingency analysis using custom, user-defined models that are not supported by industry-standard tools such as PSS®E, thereby allowing planners to assess scenarios that would otherwise be impractical or impossible to evaluate. In addition, the CAT offers targeted monitoring of selected system elements, giving users enhanced control and visibility over simulation outcomes.

Paper C1-12586, *Upskilling needs for the Energy System to support the Energy Transition in Europe with a focus on digital skills ETIP SNET WG4 – Digitalisation of the Electricity:* This paper analyses workforce upskilling needs in Europe's electricity sector amid digitalisation and the energy transition. It finds critical gaps in advanced skills, AI, data, cybersecurity, and digital platforms alongside the need for systems thinking and digital leadership to manage increasingly complex, integrated energy systems.

Q 2.09 How should TSOs/DSOs prioritise investments among aging infrastructure upgrades, new transmission corridors, and digitalisation?

Q 2.10 What infrastructure innovations could overcome the key barriers of distance, intermittency, and stability in cross-continental energy flows?

Q 2.11 Can integrated planning frameworks realistically replace today's siloed asset, system, and investment planning processes, or do they risk becoming overly complex "super-models" that are difficult to govern and trust?

Q 2.12 How far should operational security constraints (voltage, frequency, fault tolerance) be embedded in long-term generation and transmission expansion models?

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PS 3: Planning the cyber-physical system

The subject of PS3 is "Planning the cyber-physical system" and it covers three themes:

- Impact of digitalisation on power system planning: role of AI, digital twins, big data
- Integration of physical, cyber and electrical security with asset management techniques

- Case studies of successful applications of modelling and digital tools in power system planning

There are in total of 9 papers in PS3. This is not a large number compared to the total number of papers in SC1, but the accepted papers are interesting and present valuable results from the authors' work.
Below, individual papers are assigned to the topics mentioned, briefly summarized, and questions for the authors are formulated.

PS 3.1 Impact of digitalisation on power system planning: role of AI, digital twins, big data

3 papers discuss issues related to theme 1. Each of the presented papers uses tools and techniques classified in the area of AI support power system planning task.

Paper 11496 - *Enhancing the planning of power systems through Artificial Intelligence in real multi scenarios within a decarbonization context* - explores the use of artificial intelligence in the context of energy transition and the growing share of renewable energy sources. It was presented the AIDA (Artificial Intelligence Dynamic Assessment) tool, which is designed to support power system stability analysis by automating and optimizing the scenario selection and dynamic simulation process. This automates the process and increases computational efficiency in identifying operational risks. Thanks to the use of AI algorithms, it was possible to significantly reduce the number of analyzed cases while maintaining high accuracy of results.

The research presented in paper 11972 - *Machine Learning-Based Uncertainty Quantification in Capacity Expansion Models* - focuses on Capacity Expansion Models (CEMs), which are used to determine the optimal structure of the future energy system, including the optimal level of investment in generation sources, energy storage, and transmission infrastructure. The authors analyze the possibility of using machine learning models as surrogate models for complex CEM optimization models. Such surrogate models allow for rapid approximation of the results of computationally expensive simulations and enable extensive scenario analysis. The authors utilize Bayesian Neural Networks (BNNs) and transfer learning techniques, which allow for the use of data from simplified simulations to train models for more complex scenarios.

Paper 12582 - *Data-driven distribution network expansion planning for hosting new green investments* - proposes a modular framework for multi-year distribution network planning integrating an efficient Mixed-Integer Linear Programming (MILP) optimization engine with high-performance computing modules, including a Fixed-Point Iteration (FPI) power flow engine, pre-trained AI analytics for forecasting, and Dynamic Time Warping (DTW) for scenario clustering. The research focuses on the problem of optimal design and expansion of transmission infrastructure in conditions of increasing variability of electricity production and changing structure of the power system. The authors showed that the use of modern optimization methods can significantly improve the efficiency of the energy infrastructure planning process, and a properly designed transmission network can significantly increase the flexibility of the power system and enable the integration of a larger number of renewable energy sources.

Q 3.01 How significant was the reduction in the number of scenarios after using AI methods compared to the traditional approach?

Q 3.02 Which optimization algorithms proved most effective in the analyzed transmission grid development planning problem?

PS 3.2 Integration of physical, cyber and electrical security with asset management techniques

3 papers can be classified under this theme. Their content highlights the use of AI tools in network asset management to improve power system (here often referred to as Cyber-Physical Power System) resilience and security.

Paper 10744 - *Revolutionizing IBR Asset Management, Plant Model Development and Testing, and Compliance Across the Asset Lifecycle* - presents a framework for managing IBR assets, as a versioned digital engineering. The lifecycle of these assets is at the core of this management. The framework begins with the automated download of IBR installation artifact files to create a living profile of the IBR installation expressed as structured, machine-readable objects. The framework integrates automated testing of model quality and performance across multiple simulation domains, supported by a human-assisted engineering review layer. These actions are necessary for formal reasons and to adapt to changing standards and manufacturers' offers.

The research object of paper 10954 - *MESH: A Cyber-Physical Energy Architecture for Sustainable and Resilient Infrastructure* - is a new cyber-physical energy system architecture called MESH (Machine-learning Energy System Holistic). This concept concerns the integration of physical electricity flows and cyber-based control intelligence. MESH itself represents a target state for a decentralized, autonomous, and cooperative energy-management system. One of the key elements of MESH architecture is the concept of shifting computing loads between data centers based on energy conditions. This concept aims to challenge the current understanding of demand management, which is treated as constant.

The authors of paper 11843 - *Cyber-Flexible Security Planning for Renewable-Rich Power Systems Under Adversarial Attacks* - focus on analyzing the impact of cyberattacks on the operational security of the Cyber-Physical Power System (CPPS) and on developing planning methods to increase the system's resilience to such threats. The paper specifically analyzes attacks manipulating load data and data of energy production from wind farms. An important element is also the concept of Cyber-Flexible Security Services (CFSS), i.e. security services provided by appropriately selected generating units or other system resources, whose task is to maintain the required system security margins in the event of cyber disruptions. The issues addressed fit into the novel Cyber-Resilient Infrastructure Security Planning (CRISP) framework.

Q 3.03 Will extending the Cyber-Physical Power System with new architecture and resource management (e.g., MESH, CFSS) improve security and resilience in real-world power systems, or is this still a conceptual issue?

PS 3.3 Case studies of successful applications of modelling and digital tools in power system planning

Theme 3 includes 3 papers. The authors of these papers describe selected practical applications of AI tools and the integration of advanced models for specific applications.

Paper 12061 - *Cyber-Physical Integration of System Integrity Protection Schemes in Thailand: From Simulation to Real-Time Operation* - presents a practical application of cyber-physical system planning in Thailand's transmission network, demonstrating how simulation-based studies are translated into real-time System Integrity Protection Schemes (SIPS) implementation. Specifically, the authors analyze the process of designing, testing, and implementing a SIPS, encompassing both the simulation environment and implementation in a real system. These actions are aimed at increasing the operational resilience of the power system. Based on the analyses carried out, special protection systems were designed and implemented to respond to specific emergency scenarios. The results confirm that modelling-based cyber-physical SIPS planning is practical, scalable, and field-proven.

Paper 12131 - *Comparative Analysis of AI Tools for Empowering Prosumagers in Cyber-physical Electricity Market: A planning oriented perspective for cyber physical power systems (CPPS)* - proposes an integrated, planning-oriented framework for cyber-physical energy systems with active prosumer participation. This approach identifies seven planning dimensions and then combines them with seven categories of artificial intelligence and digital tools, creating a structured 7x7 model. This model is complemented by eight planning-oriented evaluation criteria that emphasize specific features of the planning process. The proposed framework provides a qualitative planning perspective that guides the positioning of AI capabilities in the long-term development of CPPS, under conditions of active participation by energy market participants, through the selection of advanced and modern analytical tools and automated decision-making systems.

The main goal of paper 12551 - *Clustering-Based Selection of Representative Hours for security and resilience analysis-mainland European use case* - is to develop a methodology and implement it for selecting representative power system operating hours, which can be used in further analyses of system security and resilience. The undertaken actions support planning for future power system structures and complexity. The authors demonstrate that appropriate selection of representative hours can significantly reduce the number of analyzed cases while maintaining high-quality results. The clustering approach used has the features of modern AI tools.

Q 3.04 How can the impact of specific AI technologies on energy system efficiency be quantitatively assessed?