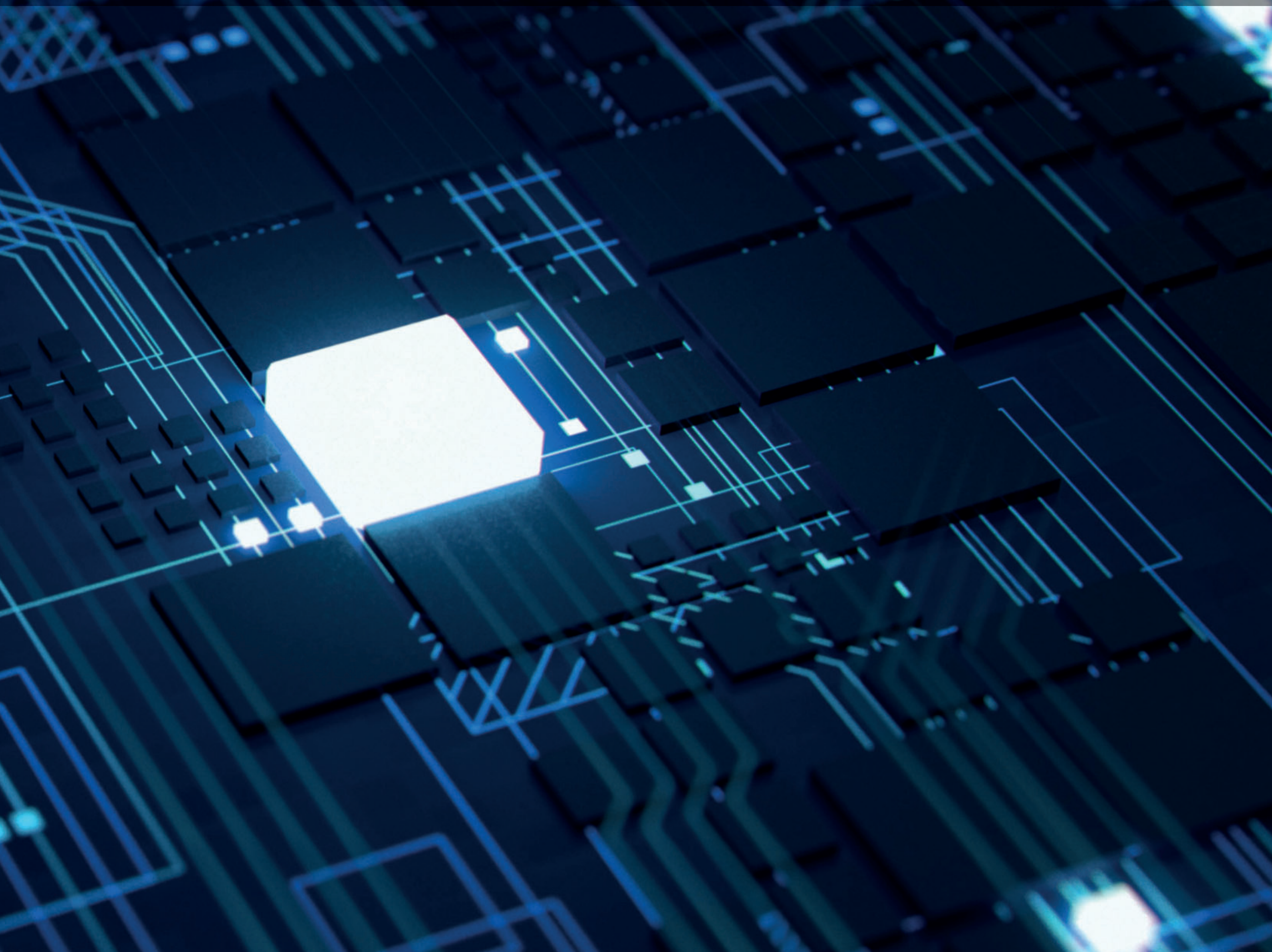
ELECTRA

European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids



Deliverable 12.3

Final Report on project results

Executive summary

The ELECTRA Integrated Research Programme (IRP) on smart grids, brings together 21 European partners of the EERA Joint Programme on Smart Grids to reinforce and accelerate Europe's research cooperation in this area and to drive a closer integration of the research programmes of the participating organizations and of the related national programmes.

Focused on the medium - to long-term evolution of the power system, ELECTRA IRP adopted an holistic approach including both Research Technical Development (RTD) and Coordination Support Actions (CSA).

The joint **RTD activity** allowed to develop a distributed control scheme for balancing (frequency) and voltage control in the power system of 2030+. The new grid control scheme proposed and developed within the project, called **"*Web-of-Cells*" (WoC), i**s designed to enable the local control of the grid. In fact, over the course of the project, the importance and the need for a more distributed control became evident through studies, simulations and experimental validation as well as by discussion with key experts.

According to the WoC concept the power system is split into control cells. A cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate the cell generation and load uncertainties in normal operation.

On a conceptual level, supported by simulations and lab-scale validation, it has been proven that the WoC concept is in principle feasible and allows to provide real-time frequency (balancing) and voltage services in the future power system. This includes the underlying control functions supporting the six ELECTRA use cases, the observability functions in the power system, as well as the control room visualization and most important the integration in future markets and regulation.

ELECTRA R&D was efficiently supported and complemented by specific **CSA activities**. Namely, ELECTRA coordinated with the most relevant smart grids initiatives across Europe, interacted with grid stakeholders at national and EU level, and strongly supported the European participation to Mission Innovation with reference to the Innovation Challenge #1 (IC#1) on smart grids.

Relevant results also include the mapping of existing research infrastructures, the update of a dedicated database and also recommendations for the coordinated development of European smart grids research infrastructures.

Moreover, an effective researcher exchange programme to better support international cooperation in research and innovation has been developed and fully implemented.

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1 Introduction

The development and deployment of renewable energy sources is widely recognized as a major priority, as European countries look to move towards a more sustainable model of energy provision. Renewable energy sources (RES) account for an ever-greater proportion of our overall energy supply, and are set to rise further in future in line with EU strategy. Thus, **grid integration of RES** is a top priority R&D topic and a highly active area of research, with many different European initiatives, programmes and projects dedicated to investigating innovative solutions towards a smarter grid.

In particular, the ELECTRA IRP was focused on the medium- to long-term evolution of the power system, and consisted of two key dimensions: pursuing specific research investigations including laboratory scale implementation and validation, and helping to coordinate EU research under key R&D topics more effectively. A holistic approach incorporating Coordination Support Actions (**CSA**) and Research Technical Development (**RTD**) activity has been used by ELECTRA to achieve these goals.

The IRP work package structure reported in **Figure 1** is instrumental in addressing several burning technical questions, including the following:

- Available Scenarios:
  What will the future power system look like?
- Interoperable system:
  How can different concepts be translated into technical specifications?
- System visualization:
  What needs to be observed?
- Improved flexibility:
  What kind of flexibility will be available?
- Experimental validation:
  How can new decentralized control concepts be evaluated at laboratory scale levels?
- Future operator's needs:
  How can the operational decisions in future control rooms be supported?

All the above questions have been addressed in the light of the new grid control architecture that has been proposed and developed within the project called “**Web-of-Cells**” (WoC).

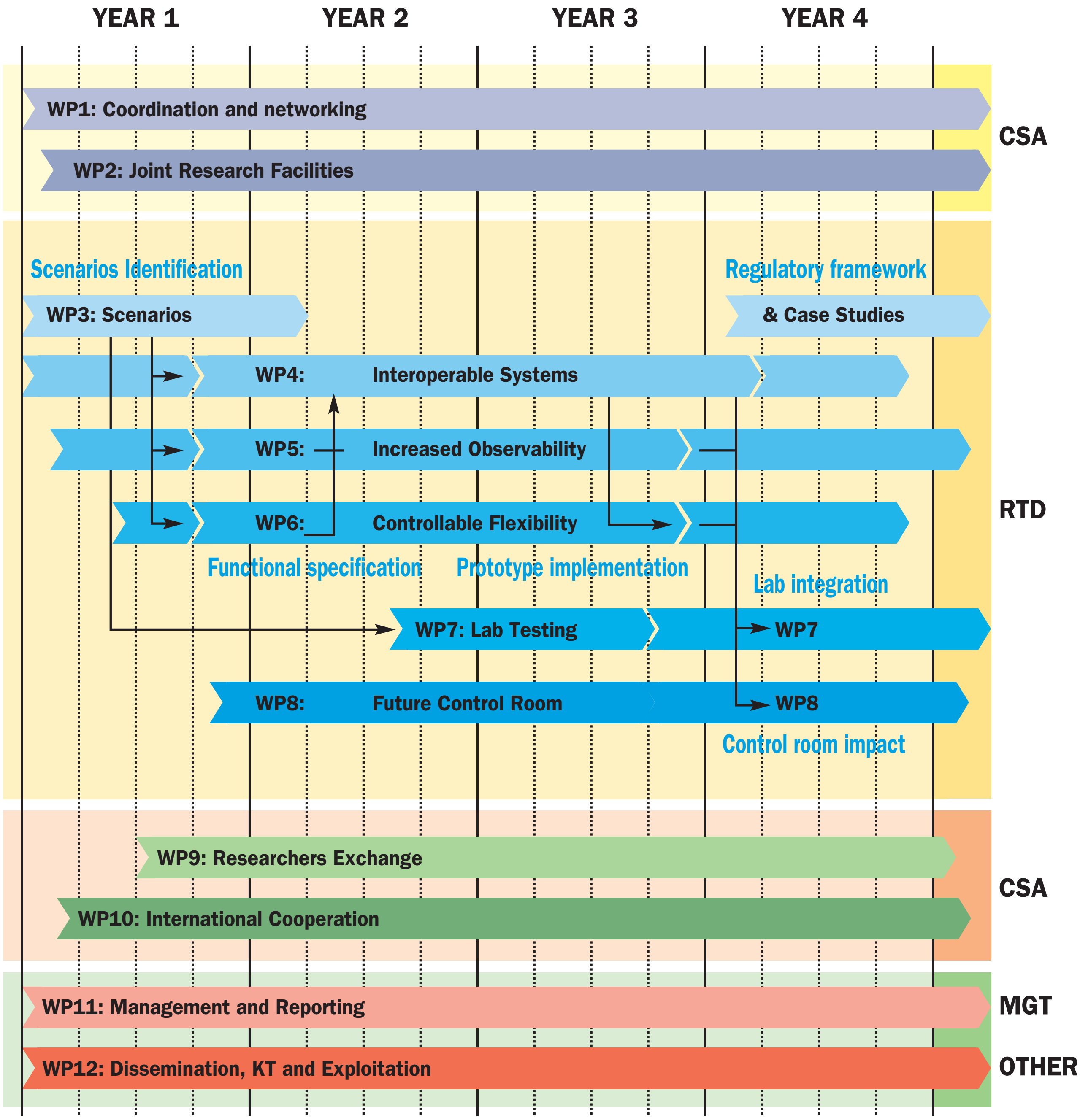


Figure 1 | **Gantt chart of the ELECTRA IRP**

2 The Web-of-Cells concept

A new approach to the power grid control

2.1 Background

A distributed control scheme for balance and voltage control for the future (2030+) power system has been developed within the Integrated Research Program (IRP) ELECTRA. Based on a number of widely accepted trends regarding the 2030+ power system, a new control architecture for reserves activation that better addresses the fundamental changes of the future power system is proposed. The focus is on a control architecture related to the **real-time reserves activation** by the system operators. The aim is to correct real-time imbalances (thus frequency deviations), caused by residual imbalances left over by the Balancing Responsible Parties (BRPs) as a result of forecast errors or incidents, as well as to regulate voltages. To emphasize: the scope of the ELECTRA IRP is the control that takes place **after**

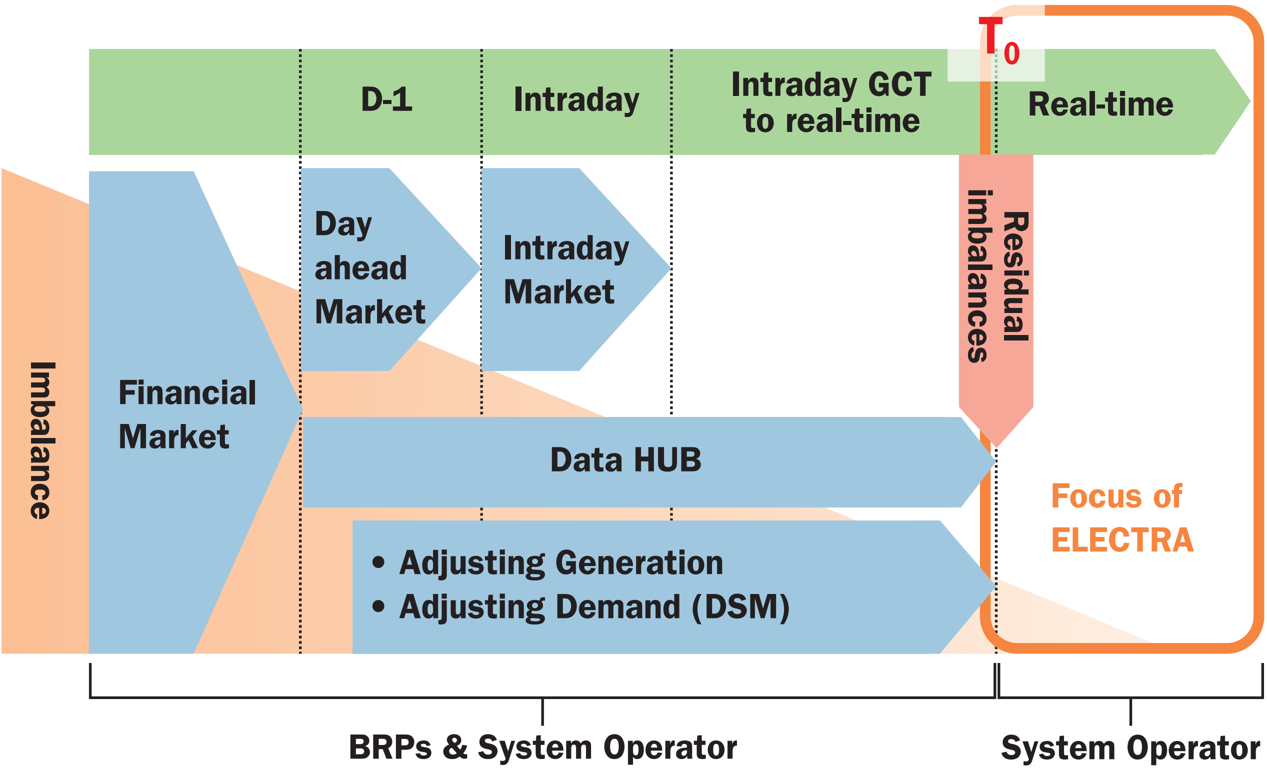


Figure 2 | ELECTRA focus of balancing procedures

the market parties ended their market-balancing activities (T_0) and it addresses real-time deviations from the scheduled balance resulting from forecast errors (in load or generation) or incidents (**Figure 2**), in order to ensure voltage and frequency (balancing) control in the future power system. It is expected that due to the forthcoming changes, the future frequency and voltage control can no longer be effectively managed in a Transmission System Operator (TSO) centred manner. Instead, a new approach is required, that leverages innovative monitoring systems based on a fully instrumented network, and autonomous distributed control functions. In order to regain reliable control over the power grid, distributed generators and loads should and will be controlled to manage the continuous stream of imbalances as perceived system-wide by the TSO's today.

Maintaining the present centralised detection and activation paradigm requires a lot of detailed local information to be collected, aggregated and communicated from all Low Voltage (LV) and Medium Voltage (MV) networks to the High Voltage (HV) grid, to allow the TSO to detect local problems, and to determine a secure and optimal reserves activation action using distributed (flexible) resources. For these reasons, ELECTRA IRP proposes a distributed control approach, the so-called Web-of-Cells (WoC) concept [1] [2], which is described in this document. Since the ELECTRA IRP is targeting the time horizon 2030+ the WoC proof of concept validation was performed mainly by simulations and lab-based experiments.

2.2 The ELECTRA key assumptions

ELECTRA analysed control solutions are not related to a specific scenario, but instead related to a number of clear and indisputable trends, that fit multiple future scenarios. Main aspects of these trends are the following:

Generation will shift from classical dispatchable units to intermittent renewables*:* The European Commission's Reference Scenario 2016 [3] foresees that electricity coming from Renewable Energy Sources (RES) will increase, as a share of net power generation, from around 20% in 2010 to 42% in 2030 (see **Figure 3**). Variable RES (solar and wind) are expected to reach around 19% of total net electricity generation in 2020, 25% in 2030 and 36% in 2050. This will result in:

- Paradigm shift from generation following load to load following generation.
- Increased need for balancing reserves activations.

Generation will shift from relatively few large units to many smaller units: electricity generation is shifting from a few large central power plants to many smaller units connected mainly at the distribution level. In addition to the smaller units, there will still remain large central power generators, being increasingly more of a RES nature (e.g., large on-shore and off-shore wind-power plants, hydro-electric power plants, and marine energy parks).

- There will be more locations – and chances – where deviations compared to what was forecasted and planned, and incidents (like generation outages) can happen, but each individual incident will have a smaller – local – impact.

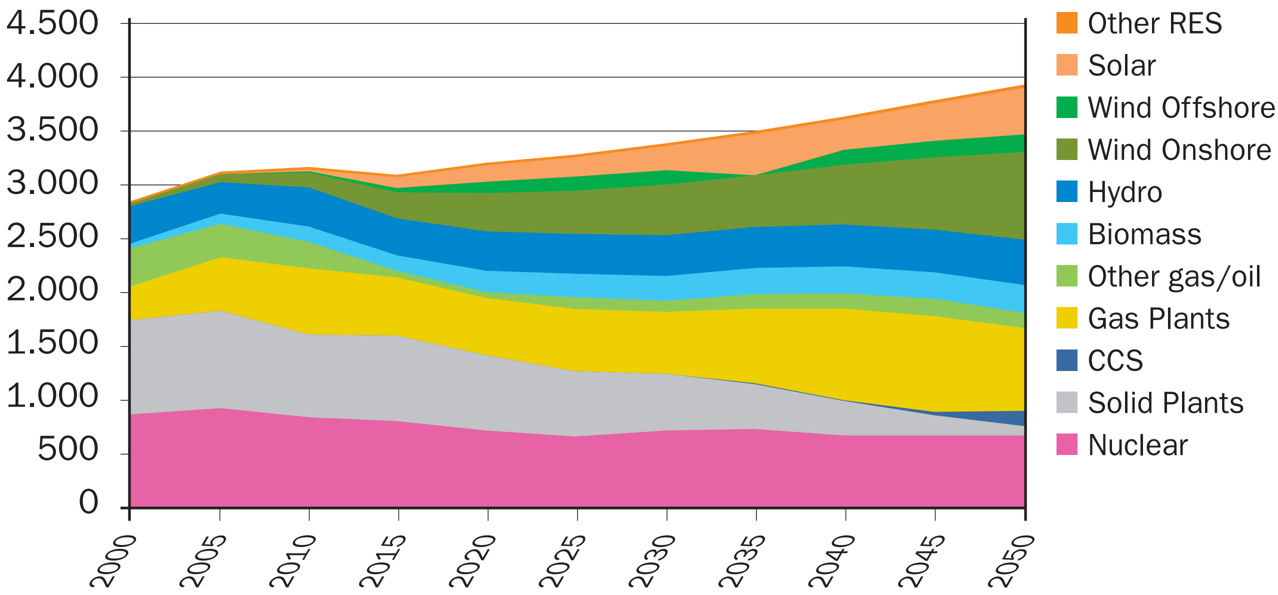


Figure 3 | Electricity generation per plant type [3]

- Local – i.e., distribution system level - incidents may have a local impact that goes unnoticed at a system global level.
- There will be a shift from synchronous generators to power electronics interfaced generation reducing the power system inertia and causing a higher Rate-Of-Change-Of-Frequency (ROCOF), more spurious tripping of protection relays, and short activation times for frequency containment reserves.
- Since the power system production portfolio is subjected to changes throughout the day (renewable generators are weather and time dependent), power system time constants and response times will constantly change.

Generation will substantially shift from central transmission system connected generation to decentralized distribution system connected generation:

- More injection at LV and MV distribution grid increases the risk of local voltage problems and congestions (especially given the expected increase in electricity consumption).
- Resources that can help to address voltage and balancing problems (i.e. by providing ancillary services), will move, to a large extent, from transmission system level (HV) to distribution system level (MV/LV).
- A central system operator at transmission level no longer has the system overview to effectively dispatch reserves, so coordination between operators of different voltage levels will be essential.
- The distribution and availability of resources (production as well as storage) may vary significantly from different geographical locations.

Electricity consumption will increase significantly: due to the Greenhouse Gas (GHG) emission reduction targets, there is a drive towards the electrification of transport and heating/cooling, resulting in an expected increase of the electricity consumption. As a result, grids will be used closer to their limits. Besides, a large fraction of the increased load will be actively controlled and/or responding to market signals, making – local – consumption forecasting even more challenging.

Electrical storage will be a cost-effective solution for offering ancillary services: according to the recommendations for a European Energy Storage Technology Development Roadmap [4], prices of (electrical) storage are projected to drop, making distributed storage a competitive solution compared to traditional resources for reserve services. Furthermore, the energy storage roadmap claims that distributed storage located at a utility substation on the distribution grid has a much higher value than central storage because it offers to defer distribution networks upgrades and circuit stability control. Such storage devices are well suited to deal with continuous, small up and down fluctuations caused by intermittency and forecasting errors. Moreover, they have a large flexibility range in both power flow directions and usually a fast reaction time.

Ubiquitous sensors will vastly increase the power system observability: with the proliferation of distributed generation, the decline of sensors and innovative solutions costs over the next few years, the inclusion of sensing and monitoring systems is starting to make compelling economic sense. This is essential for providing grid operators with a holistic view of the grid and its critical components [5] and will result in many more measurement points at all voltage levels, such as Phasor Measurement Units (PMU's), smart metering infrastructure and other power and voltage measurement systems.

Large amounts of fast reacting distributed resources could offer reserves capacity: vast amounts of controllable loads, local storage and converter-coupled energy sources will be available at all voltage levels (especially at the low voltage levels), providing very fast reaction and ramp times. These distributed resources can offer their flexibility capability as a service (e.g. balance restoration, frequency containment, congestion management) to grid operators and market parties [6].

- There will be a large number of distributed resources with a large variety (production as well as consumption and storage resources), that will be able to provide Frequency Containment Reserves (FCR) (possibly imposed participation through regulation) and/or Balance Restoration Reserves (BRR).
- In future, local reserves will not be more expensive than central ones. A lot of related functionalities, such as voltage and frequency support, are already mandatory now (e.g., PV inverters). Even in presence of a market for related services a lot of flexibility will be available resulting in low prices.
- In future, local reserves activations might be (almost) cost free (e.g., shifting consumption).

Developments in information and communication technologies will support the pathway towards more decentralized or distributed managed power systems: the developments of Information and Communication Technologies (ICT) and their massive introduction in the power system in the last decades completely changed the monitoring, operating and planning methods. Without the availability of data and information exchange, even liberalisation of the energy sector would not have been possible. Currently also the last mile of the power system is about to be covered by ICT, supporting also the massive integration of small-scale generation, prosumers, storage, e-mobility and demand response. This will be additionally supported considering the progress and developments concerning Internet of Things (IoT) as well as big data technologies. IoT can lead to a completely rethinking of LV grid operation use cases. The amount of IoT-ready devices (sensors, meters, inverters, home management systems, etc.) in LV grids is surging. These appliances can be used for additional services like forecasts of load, generation and flexibility requests.

> *In short, ELECTRA foresees **a decentralized managed future**, with a high share of renewable resources providing flexibility at distribution system level and the possibility of local sensing, monitoring and control.*

2.3 The Web-of-Cells architecture

Cell-based architecture for decentralized balancing and voltage control

The foreseen massive availability of flexible energy resources, mainly connected to the grid at distribution system level, leads to the idea that a decentralized or distributed control concept, aimed to solve local problems locally, will best address the fundamental changes in the future power system. For this reason, ELECTRA proposes a new cell-based distributed control framework named WoC. In this view the power system is split into control cells.

> *An ELECTRA cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate the cell generation and load uncertainties in normal operation.*

In line with the above definition:

- an ELECTRA cell is connected to one or more neighbouring cells via one or more physical tie-lines,
- there is no restriction in how cells are interconnected,
- an ELECTRA cell can span over more voltage levels,
- it is not required that a cell is self-sufficient (capable to balance internal generation and load), but this case is possible.

Considering the ownership and the responsibility of tie-lines between cells, these are always assigned to one of the linked cells. In this way the physical boundaries of a cell may also include some tie-lines.

Each cell is managed by a so-called Cell Controller (CC). The CC is under the responsibility of a Cell System Operator (CSO) role that supervises its operation and, if needed, is able to override it. A CSO (present DSO/TSO) can operate multiple cells (also non-adjacent), each one having its own CC. The CC includes functions and services conventionally provided by DNOs, DSOs, and TSOs or by new network operators. Roles and responsibilities are detailed and the functions required for the CC are summarized below. It is anticipated that the CC will provide autonomous control of balance/frequency and voltage. This could radically change the present paradigm, involving a central TSO control room/centre, to instead require significantly reduced manual operator interaction for real-time control.

The cell definition includes as a special case a cell that has only one connection point with the rest of the system and with enough resources to be self-sufficient. This type of cells is able to operate both in grid-connected and in island mode.

Web-of-Cells operation modes and related functions

In order to maintain frequency (balancing) and voltage control in the future power system, the WoC control scheme introduces six high-level use cases to be implemented in each cell, which are:

- Balance Restoration Control (BRC)
- Adaptive Frequency Containment Control (aFCC)
- Inertia Response Power Control (IRPC),
- Balance Steering Control (BSC),
- Primary Voltage Control (PVC) and
- Post Primary Voltage Control (PPVC).

These use cases are characterized by three fundamental characteristics:

- Solving local problems at cell level,
- Responsibilization with local neighbour-to-neighbour collaboration, and
- Ensuring that only local reserves providing resources, where activation does not cause local grid problems, will be used.

Cells are treated as 'physical clusters' with characteristics of a Virtual Power Plant (VPP) responsible for matching their actual net active power import/export profile to the forecasted profile (which relates to system balance). This is the responsibility of the **Balance Restoration Control (BRC)** functionality. The system balance (as well as frequency) is restored according to a bottom-up approach based on local observables. The cell power exchange set-points correspond to a system balance and if each cell adheres to its set-points, the system balance is kept. The proposed BRC shows resemblance to the present Frequency Restoration Control (FRC) responsible for restoring the system balance, in a centralised manner. In contrast to FRC, which is a secondary control and takes over from Frequency Containment Control (FCC), in the ELECTRA WoC concept the BRC runs at the same timescale as FCC and therefore contributes to frequency containment as well as balance/frequency restoration. Deviations observed by a cell can be caused by the cell itself, but also by neighbouring cells, so there is a level of local collaborative balance (and frequency) restoration.

For **Frequency Containment Control (FCC)** an adaptive functionality is proposed. It ensures that each cell adapts the amount of provided active power versus frequency (dP/df) droop in response to real-time frequency and tie-line deviations from their nominal values. The output of the FCC functionality is as a multiplication coefficient used to modify the nominal Cell Power Frequency Characteristic (CPFC). The latter parameter is specified by a set-point received from a system-level process. A cell level *frequency droop parameter determination* function receives the cell's CPFC set point (cell's contribution to the system NPFC – Network Power Frequency Characteristics) for the next time step. The *merit order decision* function ranks the available frequency droop devices based on cost and location. This is done based on availability and cost information received from the devices, load and generation forecasts of all busses, and a local grid model. Location information is important to ensure that the power activations of the frequency droop devices will not cause local grid problems. The resulting ordered list is sent to the f*requency droop parameter determination* function determining the requested active power droop setting for each frequency droop device. Each of these receives its droop setting for the next time period and will continuously monitor the frequency deviation and consequently modify its active power output in accordance to its droop setting. This droop setting is continuously adapted by the adaptive CPFC determination function by means of a scaling factor determined based on the cell's imbalance state. Based on frequency and cell imbalance error signals, this function will calculate a scaling factor to achieve that most FCC activations are done in cells actually causing the deviation. This should mitigate cell imbalances (with subsequent BRC activations) in cells that otherwise would be in balance because of a blind reaction on a global observable (frequency deviation). This is the adaptive aspect.

As mentioned above, more and more grid integrated electricity generation is going to be converter based. All PV power plants as well as a high share of wind power plants already use converters as grid interfaces. Hence, the presence of synchronous generators providing inertia through their rotating mass is expected to decline. Based on the actual energy mix the available inertia can vary wildly. For that reason, ELECTRA IRP has introduced an **Inertia Response Power Control (IRPC)** functionality, which ensures that additional synthetic inertia is supplied (by managing suitable flexible resources), to complement the physical inertia of the system. A cell level *ROCOF (df/dt) droop slope determination function* receives a cell's moment of inertia set point (cell's contribution to the system inertia) for the next time period. A *merit order decision function* ranks the available ROCOF droop devices based on cost and location. This is done based on availability and cost information received from them, load and generation forecasts of all buses (nodes), and a local grid model. As already remarked for FCC, location information is important to ensure that power activations of the ROCOF droop devices will not cause local grid problems. The resulting list is sent to the *ROCOF droop slope determination* function that defines the requested droop slope setting for each ROCOF droop device that will receive its droop setting for the next time period. It will then continuously monitor the ROCOF and modify its power output in accordance to its droop

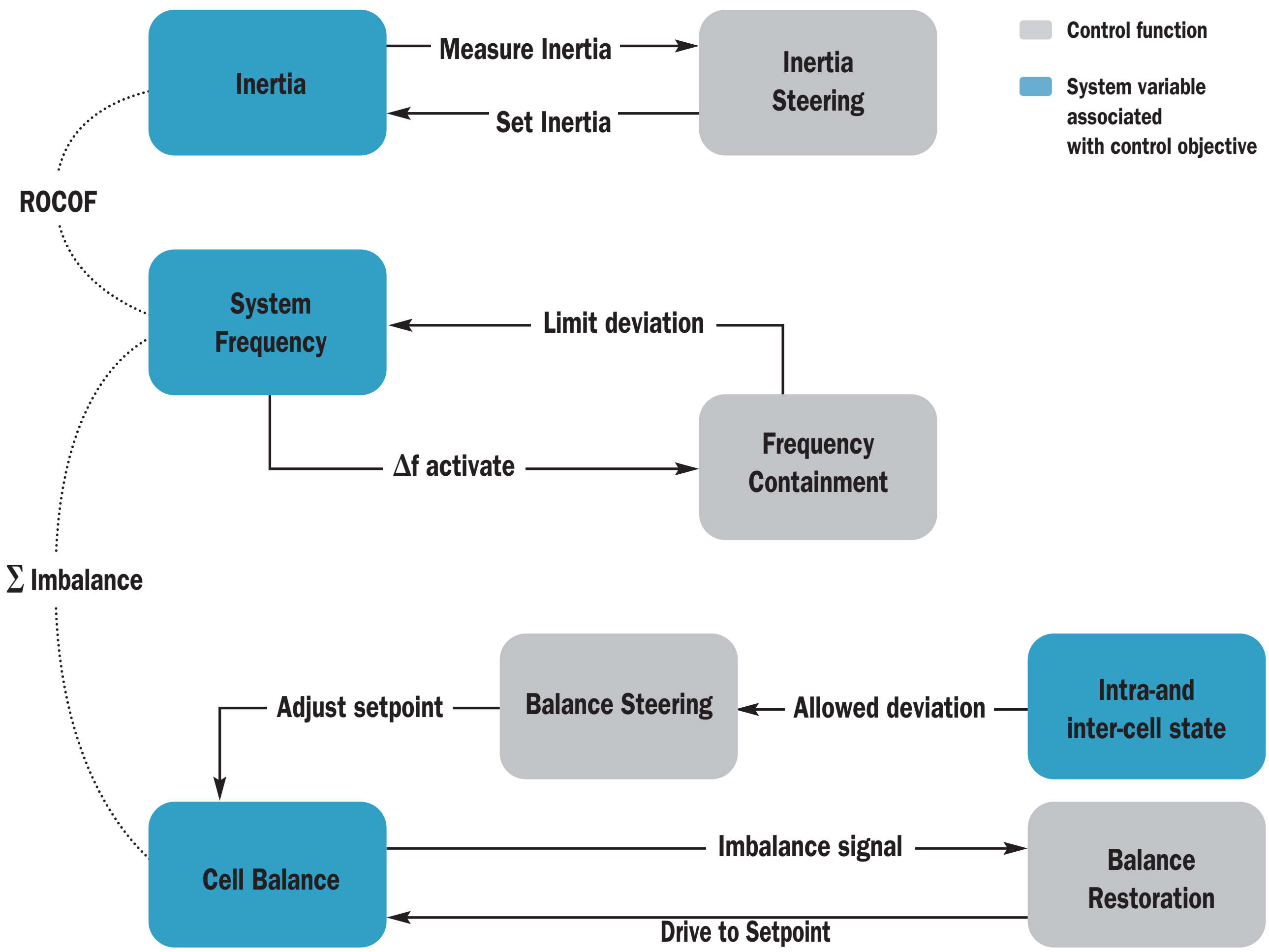


Figure 4 | WoC balance control functions

setting. No dead band will be used so that an action is taken even on the slightest ROCOF values. This choice is made to reap the side-effect of limiting the frequency fluctuation also during normal operation; i.e. the frequency fluctuation due to small variations of load and generation. A dead band combined with a low amount of inertia provided by synchronous generators could result in high frequency fluctuation and so in the tripping some of the connected generation.

To complete the Balance/Frequency Control related functionalities a **Balance Steering Control (BSC)** is introduced. The BSC tries to counteract the excessive amount of bottom-up BRC activations based on local observables and losing the benefits of imbalance netting. BSC implements a distributed/decentralized coordination scheme where neighbouring cells mutually agree on changing their tie-line active power flow set points and this way reduce the amount of BRC reserves that have been activated in each cell. This can be considered as an implementation of a localized imbalance netting mechanism. Specifically, this use case will implement a corrective BSC functionality, which determines new set-points for the BRC controller, thereby causing the deactivation of resources previously activated by BRC.

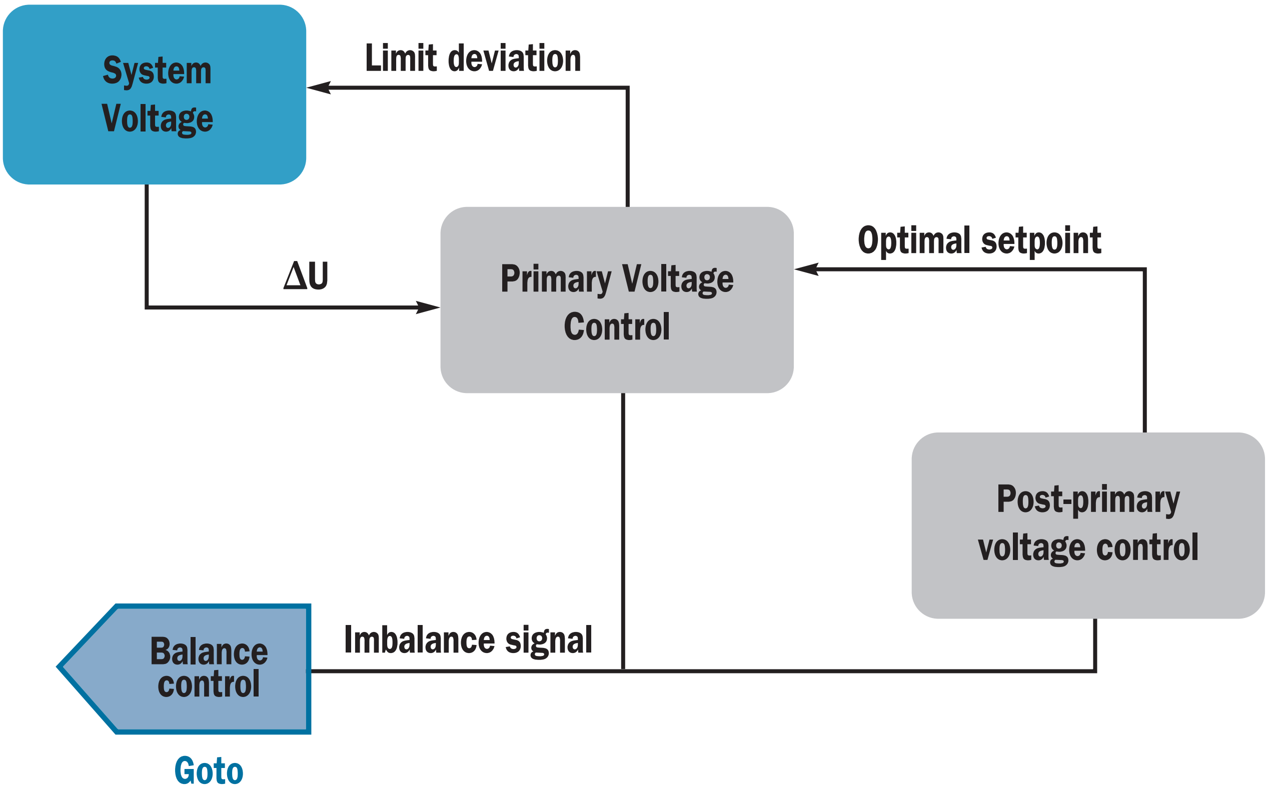


Figure 5 | WoC voltage control functions

Voltage control functions (see **Figure 5**) are active at all voltage levels in a very dynamic manner: not only to correct voltage deviations that cause voltage limit violations, but to minimize power-flow losses too. The **Primary Voltage Control (PVC)** functionality, as it is already in use today, will be present at all voltage levels. Even at LV and MV level it could influence a cell's balance.

Additionally, ELECTRA proposes a **Post-Primary Voltage Control (PPVC)** functionality determining set-points for all resources able to contribute to voltage control (and loss minimization): like PVC (automated voltage regulation)-resources, Q-controllable resources, tap-changing transformers, capacitor banks. The cell central PPVC function is activated either by means of a system level trigger (proactive set-point recalculation), or when one of the pilot nodes reports a voltage violation (i.e. a voltage deviation outside the limits: corrective set-point recalculation). ELECTRA assumes there is no constant requests by the PPVC function of all pilot node voltages, but that pilot nodes autonomously monitor their local voltage and send a signal when they detect a violation. On receipt of the activation trigger (timer or voltage violation error), the PPVC function will send a trigger signal to the *PPVC set-point providing function* to initiate the calculation of new set-points. As input for this set-point calculation, information is collected from the (voltage) *reserves information provider* function (availability of voltage reserves), the *tie-line power flow set-point provider* function (reactive power-flow profile set-point at the cell tie-lines), and the *load & generation forecast providing* function (load and generation forecasts). For implementing this functionality, a local grid model is assumed to be available. Based on all this information, the *PPVC set-point providing* function performs an Optimal Power Flow (OPF) to calculate voltage set-point settings keeping all nodes within the limits according to valid standards and minimizing power flow losses in the cell. The *PPVC controlling* function then sends the calculated set-points to the PVC droop nodes, controllable Q nodes, capacitor banks and On-load-tap-changer-transformers (OLTCs).

In course of the development and validation activities two different kind of functions have been distinguished:

- In focus functions of the specific use case functionality: mainly at cell and inter-cell level. These are functions related to the observables (input for detecting if a corrective action is needed) or actuations (e.g. activating power to realize the correction): mainly at device and flexibility resource level.
- Supportive functions that are needed for testing and validation, but are not part of the control loop itself and can be emulated (e.g. using a database or file read access of previously stored values). Examples are functions that provide load and generation forecasts.

As already mentioned above some of these functions are used for several use cases. **Table 1** gives an overview of all use case and the related control, observer and actuator functions. More details on the related control function are presented in ELECTRA Deliverables D6.3 and simulation results in D6.4.

Cells cooperation and interconnected operating modes

For the further analysis and evaluation of cells cooperation and interconnected operating modes a selection has been made addressing mainly the combination of balancing and frequency control (i.e., IRPC and FCC; FCC and BRC; FCC, BRC and BSC), as well as voltage control (i.e., PVC and PPVC) use cases taking the laboratory capabilities of the ELECTRA partners and the stakeholders feedback (i.e., CIRED Workshop 2016) into account.

The analytical and experimental assessments in the work undertaken have demonstrated the suitability of the proposed control approaches for the dynamically changing power system of the future. The experimental evaluation was an important step towards proving the ability of the proposed controls to perform under almost the real-world conditions implemented in the laboratories. While the simulations already highlighted the benefits of these controls over state-of-the-art, it remained unclear whether these fundamentally new approaches would perform satisfactorily outside idealised simulated conditions. Therefore, the conducted experiments where imperative to highlight the real-world applicability of the proposed controls. The resilience of the proposed controllers to communications asynchronicity, finite measurement and control step resolution, various noise sources, parameter uncertainties, and other factors not explicitly incorporated in the mathematical model were tested in the process as well. The deployment of the controllers on dedicated hardware enabled rapid prototyping, allowing an efficient iterative development process by feeding back experiences

ELECTRA Use Case	Related WoC control (c), observer (o) and actuator (a) functions	Related WoC control functions - supportive
Balance Restoration Control (BRC)	• Merit Order Collection (c) • Merit Order Decision (c) • Imbalance Determination (c) • Imbalance Correction (c) • Tie-line Active Power Observation (o) • Tie-line Active Power Set-point Provider (a)	• Reserves Information Provider • Load & Generator Forecaster • DER - Controllable P device
Adaptive Frequency Containment Control (aFCC)	• Frequency Drop Parameter Determination (c) • Merit Order Collection (c) • Merit Decision (c) • Adaptive CPFC Determination (c) • Frequency Observation (o) • (BRC) Imbalance Determination (c)	• Cell CPFC Set-point Provider • Reserves Information Provider • Load & Generator Forecaster • DER - ROCOF droop device
Inertia Response Power Control (IRPC)	• Merit Order Collection (c) • Merit Order Decision (c) • df/dt Drop Slope Determination (c) • (BRC) Imbalance Determination (c)	• Cell Inertia Set-point Provider • Reserves Information Provider • Load & Generator Forecaster • DER - ROCOF droop device
Balance Steering Control (BSC)	• Tie-line Limit Calculation (c) • Cell Set-point Adjusting (c) • Tie-line Active Power Observation (o) • Imbalance Determination (BRC) (c)	• Tie-line Active Power Flow Set-point provider
Primary Voltage Control (PVC)	• DER - AVR device (a)	
Post Primary Voltage Control (PPVC)	• PPVC Controlling (c) • PPVC Set-point Providing (c) • Voltage Pilot Nodes (o) • DER - AVR Device (a) • DER - Controllabe Q Device (a) • Capacitor banks (a) • OLTC (a)	• Reserves Information Provider • Load & Generator Forecaster • Tie-Line Power Flow Set-point Provider

Table 1 I ELECTRA Web-of-Cells use cases and the related control, observer and actuator functions

made under real conditions into the theoretical method.

The following observations have been made:

Balancing and frequency control with focus on FCC and BRC use case combination: with the development of the balancing control functions (FCC and BRC) and their validation in a laboratory environment, the promise of the WoC concept has been delivered, i.e., the ability of a more decentralized and distributed operation of power systems has been proven. Furthermore, the developed controls in essence work towards the objective of solving local problems locally. Beginning with the speculation of advantages of more local control, this exercise has proven some merits of prioritizing of local response to a local imbalance, such as improved dynamic response, robust reserve activations and reducing the divergence from planned system conditions and hence minimizing the operational implications of the disturbance. In addition, the developed controls support enhanced scalability in the future grid, given the autonomy of the approaches.

Balancing and frequency control with focus on FCC, BRC, and BSC use case combination: investigating the results from the BSC perspective one realises that this use case manages an effective negotiation and, in addition, the system is benefited from the imbalance netting effect of two adjacent cells without jeopardising the stability in all simulation scenarios as well as in the experimental implementation. The negotiation is always successful even in the case of unequal imbalances or exhaustion of one tie-line's capacity. Moreover, in all implemented scenarios the BRC controller deactivates the output power of the reserves, thus benefiting from imbalance netting exploitation.
In all cases, the frequency stability is maintained, and overall, the frequency dynamics are limited proving that the combination of the proposed controllers is secure for the system operation. This is true even in the case of significant time delays such as in the experimental implementation. The only issue identified during the tests was the unsuccessful restoration of the power of each individual tie-line. However, this issue is related to the absence of a voltage control strategy from the scenario that would control the power flow on the grid lines. This controller was deemed out of scope for this combination of the use cases and, therefore, is a potential scenario for further analysis.

In terms of FCC and BRC, effectively in all scenarios the two controllers were capable of identifying the location of imbalances and acting towards successful frequency containment and frequency/balance restoration respectively. The presence of adaptive FCC always slightly worsens the dynamic frequency deviation. This could be attributed to the non-optimized design of the fuzzy controllers used for the adaptive functionality. Otherwise, the controller effectively modifies the droop slope of all FCC reserves in order to increase the contribution of the faulty cell and decrease that of its neighbours.

Balancing and frequency control with focus on IRPC and FCC use case combination: The ability of FCC to improve short-term frequency stability of the investigated networks has been shown. Implementations of FCC in simulation and hardware platforms showed improvements of frequency nadir and steady state frequency deviation after a disturbance. In addition, the ability of an adaptive FCC to improve frequency stability metrics was proven. The higher frequency deviation in case of an adaptive FCC was found to be rather small, but with the advantage of less FCC contribution from reserves, which are located in cells, where no disturbance has happened.

The ability of IRPC to improve ROCOF/inertia time constant has been presented through simulations. In experimental validation the positive impact of IRPC was not obvious. Reason for this is the chosen droop slope and dead band. These parameters are very important and need to be designed according to the ability of the chosen devices and the power system requirements.

Anyway, in a future power system with reduced inertia, a contribution from other Distributed Energy Resources (DER) is needed. Other implementations to provide inertia, like virtual synchronous machines, need to be understood, integrated and validated in further investigations.

If the overall system inertia is very small, distributed devices need to provide more inertia by activation of IRPC reserves. Therefore, more balancing energy is needed from distributed resources and the peak power injection needs to be higher.

The reduction of system inertia could have negative impact on mechanical generators (wind turbines) or life-cycle of batteries. For this reason, overall system inertia should remain over a minimum in order to guarantee power system stability. Investigations in ELECTRA showed that the combination of FCC and IRPC and their distributed reserves contribute sufficiently to balancing control and improve the short-term frequency stability of a future power system.

Balancing and frequency control with focus on PVC and PPVC use case combination: From the realized experiments on the PVC and PPVC combination with several generation and load scenarios as well as cell configurations some general remarks can be highlighted. The implementation of a PVC/PPVC scheme in the WoC is advantageous from the perspective of the power losses reduction if compared with traditional planning schemes as it is based on the use of optimal power flows due to the observability capacities of the WoC. It also shows a faster recovery in case of an unexpected event as the system is able to restore the voltages to the optimal values in very short time frames. Additionally, it is beneficial in terms of a reduction in the number of activations of the PPVC. From the voltage control perspective, there is no real-time coordination between the neighbouring cells but only common agreements in terms of reactive power exchanges in the tie-lines. That means that, while ensuring enough reactive power reserves within the cell to reach an optimal power flow solution in the system, it is going to work properly. However, the possible conflicts between voltage and frequency controllers has not been explored and remains as future work to be accomplished.

2.4 Cell System Operator role and responsibilities

Within the WoC framework, each cell is managed by an automated Cell Controller (CC), which is constituted of a set of algorithms for voltage and frequency control. The CC is under the responsibility of a Cell System Operator (CSO) that supervises its operation and, if required, overrides it. The CSO role can be interpreted by the traditional DSOs or TSOs (distribution or transmission ‘Cell Operators’) or by new types system operators, that can be defined by regulation authorities.

A CSO can be responsible for many cells, that do not necessarily need to be adjacent, and oversees their CCs. This allows control to be undertaken remotely in order to increase flexibility and redundancy ,and could lead to optimal (financially and technically) solutions to the integrated grid. This does not change the real physical structure of cells and its physical constituents.

A 3-cell example is shown in **Figure 6**.

Each CSO is responsible for establishing and maintaining automatic control mechanisms as well as procuring sufficient reserves, contributing to a stable and secure system operation.

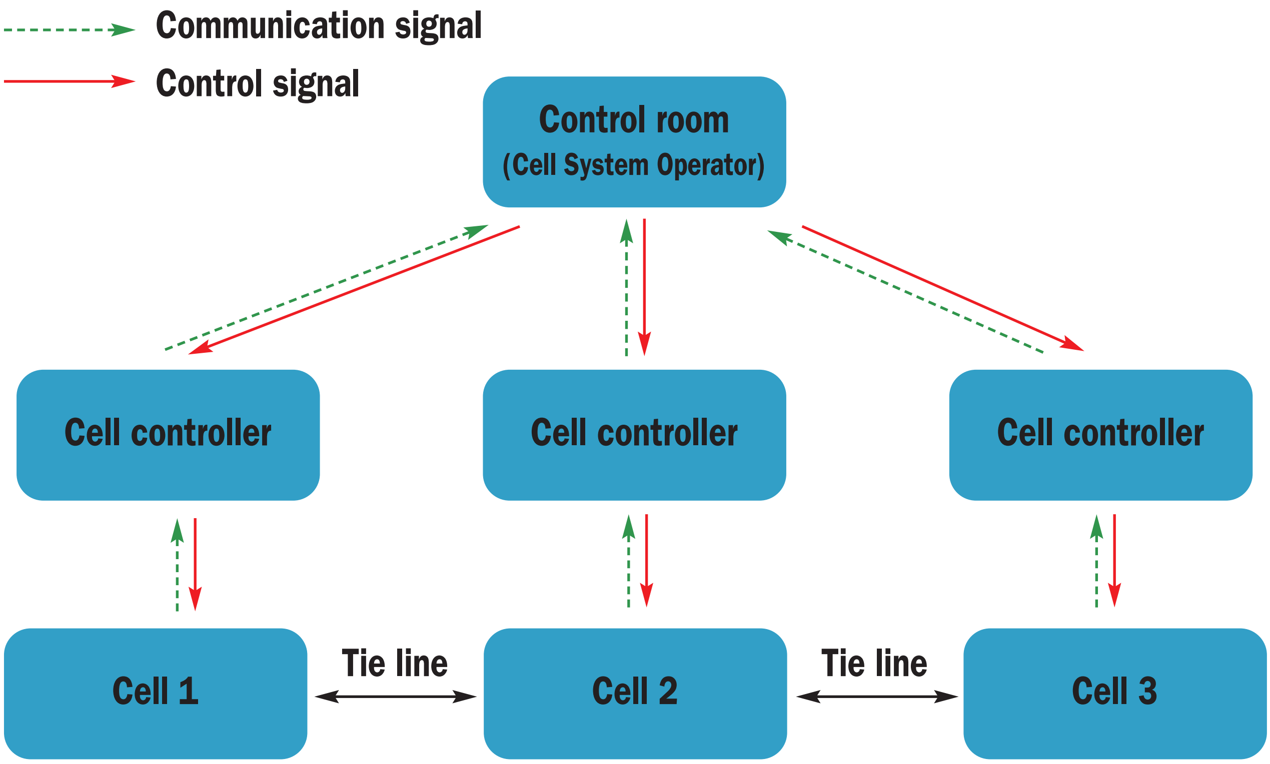


Figure 6 | A 3-cell example highlighting interactions between Cells, Cell Controllers and Cell System Operator

This is done by:

- Contribution to containing and restoring system frequency and a secured power exchange by maintaining the cell balance under operating schedules by timely activation of local reserves (by means of IRPC, BRC, FCC, BSC mechanisms).
- Containing, stabilizing and restoring local voltage within safe boundaries (by means of PPVC mechanism).
- Operating in real-time the state of a cell. A CSO has the role of monitoring the system and its interconnections (tie-lines), to initiate control actions in response to critical events in order to maintain secure and stable operation. Further, it is the CSO's responsibility to co-ordinate with neighbouring operators regarding control actions that affect them as well (mainly by means of BSC mechanism).

Each CSO supervises and operates the cells under its responsibility from a control room.

Within an increasingly complex control environment, operators have to focus on more strategic decisions. Their role is to maintain the situational awareness in terms of the overall stability and operation of the network. When corrective actions are automatically undertaken by CC, the operators need to ensure that the predicted final state of operation is acceptable and stable. If the automated and autonomous systems are unable to ensure a stable system then the operators need tools that alert them to this situation, and to intervene to solve it.

They also need tools to reduce their workload, given the complexity of the WoC, particularly in emergency situations.

One of the key actives of ELECTRA has been to develop and demonstrate decision support prototypes for system operator control room functions in the Web-of-Cells (WoC) framework. Control rooms need to show to the operator both the options for risk mitigation and the consequences of each set of suggested preventive and corrective actions. In addition, they must recognise the increased level of complexity and autonomy within the WoC, leading to a new set of decision support and Situational Awareness (SA) tools that reflect the new operational environment. Given the expected degree of automation, availability of market mechanisms and variety of contributing controls to voltage and frequency management, the decision support tools need to be goal-oriented, that is able to make independent assessments of the decisions that need to be taken in reaction to any control and information signals received.

The operators are responsible for online supervision of the network. Highly automated systems bear the risk of the “out-of-the-loop” syndrome, where the operators are detached from the state of the system and are unable to grasp the decision making process.

Hence, Decision Support Systems (DSSs) need to provide condensed situational awareness of the operational conditions and control trajectories in real time, as the automatic systems will take the majority of control decisions. The operator will be alerted to situations when the automatic systems cannot manage the contingencies/deviations. The operator will intervene and take control using their knowledge obtained by training and experience, as well as the recommendations from decision support functions. Improved decision support can guarantee timely operator intervention and flexibility towards rapid recovery of the power system. If a decision needs to be made by the operator, the DSS will prioritise alternative solutions to a problem. This allows a control decision to be taken quickly. Moreover, the DSS is able to apply the optimal solution if there is no response from the human operator within a certain time.

Decision support features have been created that are capable of exposing and characterising the threats to the power system and the vulnerabilities to which it is exposed. Advanced features that reveal congestion issues and reveal rising threat levels have been incorporated as well. The operator can access to mitigating actions that can reduce to a minimum the risks for the system using the resources available in real time. Compared with the current range of emerging tools, this work addressed the significant complication introduced by the increasing adoption of decentralised technologies and growing volumes of data. These software applications are designed to show both the options for risk mitigation to the operator and also the consequences of each set of actions.

Moreover, a design exercise has been undertaken to specify how the decision support systems will be integrated, combined and coordinated to allow the operator to improve their decision making. The high-level integration of the developed decision support systems is illustrated in **Figure 7**, and this includes support for transient stability, voltage control and frequency control. Each decision support system operates independently based on the network situation and provides available actions associated with outcomes. Moreover, the

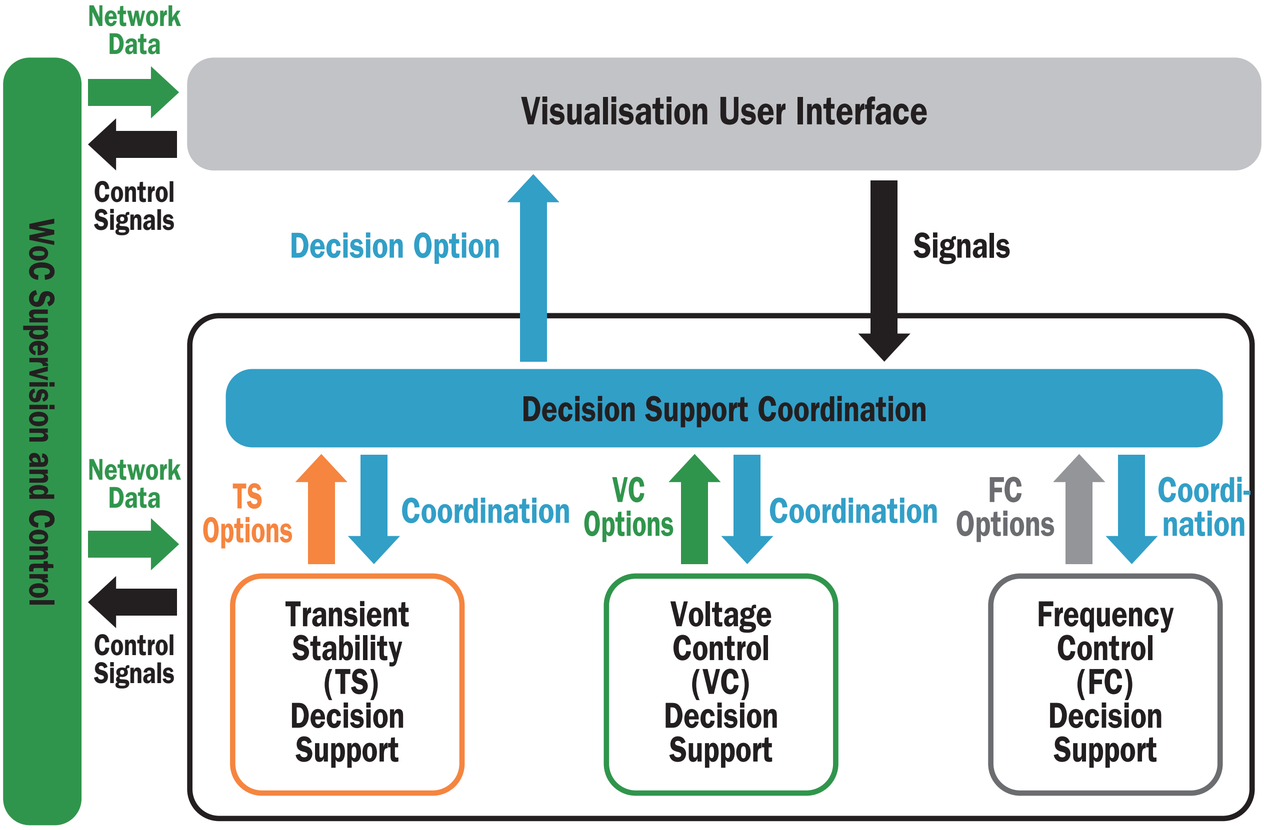


Figure 7 | Integration of Different Decision Support Functions

decision support functions may need to interact with each other in order to mitigate any conflict that may occur, such as transient stability and voltage control decision support. Once decision options are relayed to the user interface, the operator can either take the best action or override the action and finally control signals are sent to the network environment. If there is no response from the operator within the defined time period, the decision support can automatically send the best action to the network environment.

2.5 WoC market integration

Market roles

The **Cell System Operator (CSO)** is responsible for the procurement of capacity reserves in the appropriate markets of balancing and voltage control services. The CSO will buy inertia capacity, balancing capacity and reactive power products from Balance Service Providers (BSPs), and will activate them in real-time when necessary (cell imbalance or voltage problem; see **Figure 8**).

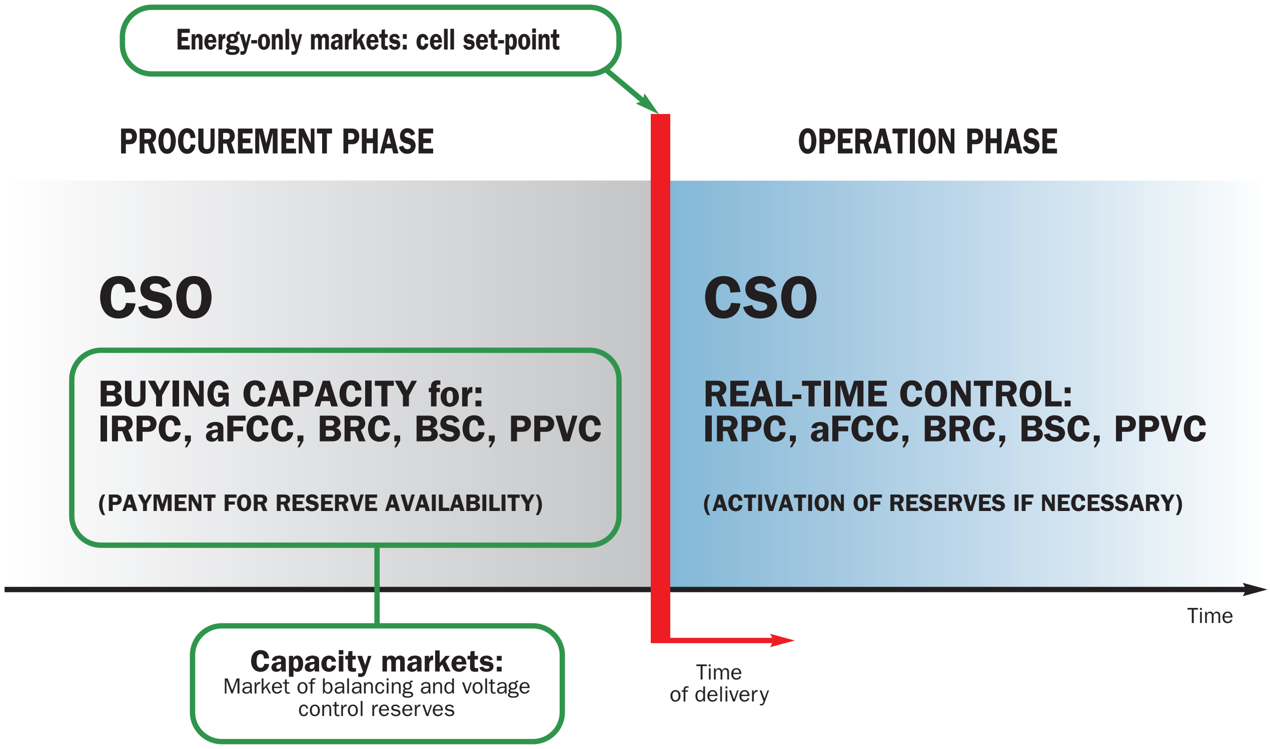


Figure 8 | WoC procurement and real-time operation phase

Each CSO procures balancing services via an organised marketplace (exchange, where harmonized trading rules are applied), using a common platform developed at the WoC level, and which employs an auction as a mechanism for efficient allocation of resources and efficient pricing of inertia, balancing and voltage control services. The auction is cleared based on price of bids submitted by the BSPs to the capacity markets open separately for each cell by the corresponding CSO. A Market Clearing Price (MCP) for all BSPs in the cell is established. Based on the MCP, the CSO will remunerate BSPs for availability of capacity for inertia, balancing capacity, and reactive power capacity, and for their utilization in real-time if needed.

The CSO must also generate the necessary information for establishing the set-points of the cells in the energy-only markets (day-ahead and intraday), and to calculate the needed reserves (inertia, balancing capacity and reactive power) for the cell. In addition to the cell tie-lines constraints, this information includes the cell generation and load forecasts/schedules provided to the CSO by BRPs and Aggregators.

After receiving energy schedules, the CSO aggregates the BRPs production, consumption, tie-lines power flows and trade energy schedules at cell level and derives the net position of the cell.

During the real-time operation of the cell, the CSO activates the balancing energy, inertia and reactive power reserves, if needed. The CSO recovers the cost of these services provision from the BRPs who were in imbalance during the particular market time unit, i.e. the CSO sells the procured balancing and voltage control products to the BRPs who are in imbalance. The CSO settles these individual imbalances with the BRPs by applying imbalance prices to their imbalance positions. The BRP's imbalance is the quarter-hourly (15 min) difference between the BRP's total injections and off-takes. The total imbalance in the cell is the sum of all BRP imbalances.

In relation to the market for balancing and voltage control products, the CSO is responsible for the preparation of market regulations to the BSPs and the BRPs. Market regulations are established to regulate the rights and obligations of the BSPs and the BRPs in the market, and to ensure that the market for balancing and voltage control products will function properly and that settlement will be performed correctly.

A **Balance and Voltage Control Service Provider (BSP)** is an actor selling balancing and voltage control products to the CSO in the procurement phase of capacity markets. Balancing and voltage control products are provided by the BSPs to the CSO by bidding in an organized market. There is no contract or obligation for the BSPs to offer in the market, inertia, capacity for inertia, reactive power, balancing capacity, and balancing energy for upward or downward regulation; the BSPs voluntarily participate in the market and bid a volume and price at which would wish to sell to the CSO. Through this bidding process, the BSPs establish the supply curves of the capacity markets.

Besides, balancing and voltage control products can be acquired by the CSOs in the bilateral market, when the BSPs and the CSO negotiate a contract regarding the offered balancing and voltage control product (its quantity and quality) and its price. Bilateral contracts are valuable since they protect the BSPs and the CSOs against price uncertainty and make revenue and payment streams more predictable.

BSPs are compensated for availability of balancing capacity, and for the utilization, when necessary, of that capacity by the CSO during the real-time operation of the cell (actual delivery of electricity).

The rights and responsibilities of the BSP in the market for balancing and voltage control products are the following:

- The BSP qualifies for providing bids for balancing energy or balancing capacity which are procured and activated by the CSO.
- Each BSP participating in the procurement process for balancing capacity submits and have the right to update its balancing capacity bids before the Gate Closure Time (GCT) of the bidding process.
- Each BSP with a contract for balancing capacity submits to its CSO the balancing energy bids corresponding to the volume, products, and other requirements set out in the balancing capacity contract.
- Any BSP has the right to submit to the CSO the balancing energy bids from the standard products for which it has passed the prequalification process.

The distributed generation and renewable energy sources (producers-consumers-prosumers) usually do not have the minimum participation size to enter as individuals in the markets for provision of ancillary services. Sometimes, the distributed generation units do not even have enough control capabilities to be able to adapt their operating mode according to the needs.

An **Aggregator** is an entity, which gathers the flexibility by forming Virtual Power Plants (VPPs), that will enable the participation of those smaller units in the balancing and voltage control services markets. It is a type of BSP. The same concept can be used also for the Aggregator as a type of BRP.

A **BRP** is an actor with a valid balance agreement with the CSO, and manages a balance obligation on its own behalf as a producer (conventional or RES-based), consumer or trader of electricity, or on the behalf of other producers, consumers or traders of electricity.

During the stage of balance planning the BRPs are obliged to provide to the CSO the planned energy production, consumption and trade schedules (separately) for every Schedule Time Unit (STU) within the day of delivery. Moreover, energy schedules for import and export shall be notified to the CSO separately too as the trade directions (into the cell and from the cell) are understood to be equivalent to production and consumption, respectively.

The BRP is responsible for its imbalances. Imbalance means an energy volume calculated for the BRP and representing the difference between the allocated volume attributed to that BRP and the final position of that BRP within a given imbalance settlement period (assumed to be 15 min in the WoC). An imbalance indicates the size and the direction of the settlement between the BRP and CSO. An imbalance can be positive meaning that the BRP is in surplus of electricity, or negative meaning that the BRP is in shortage of electricity.

The rights and responsibilities of the BRPs in the market for frequency and voltage control products are the following:

- In real-time, each BRP strives to be balanced or help the power system to be balanced.
- Each BRP is financially responsible for the imbalances to be settled with the CSO.
- Prior to the intraday gate closure time, each BRP may change the schedules required to calculate its position.
- After the intraday gate closure time, each BRP may change the internal commercial schedules required to calculate its position.

The **Market Operator (MO)** is the entity responsible to favour the transparent operation of the market and to bring together all the interests of multiple actors buying and selling products in a non-discriminatory way. The MO provides the results of the energy-only markets (bilateral, day ahead and intraday markets) to each CSO – such as production and consumption volumes of the cell, tie-lines power flows and electricity prices – who then estimates the total balance in the cell and based on the estimations, necessary “set-points” are set for each cell.

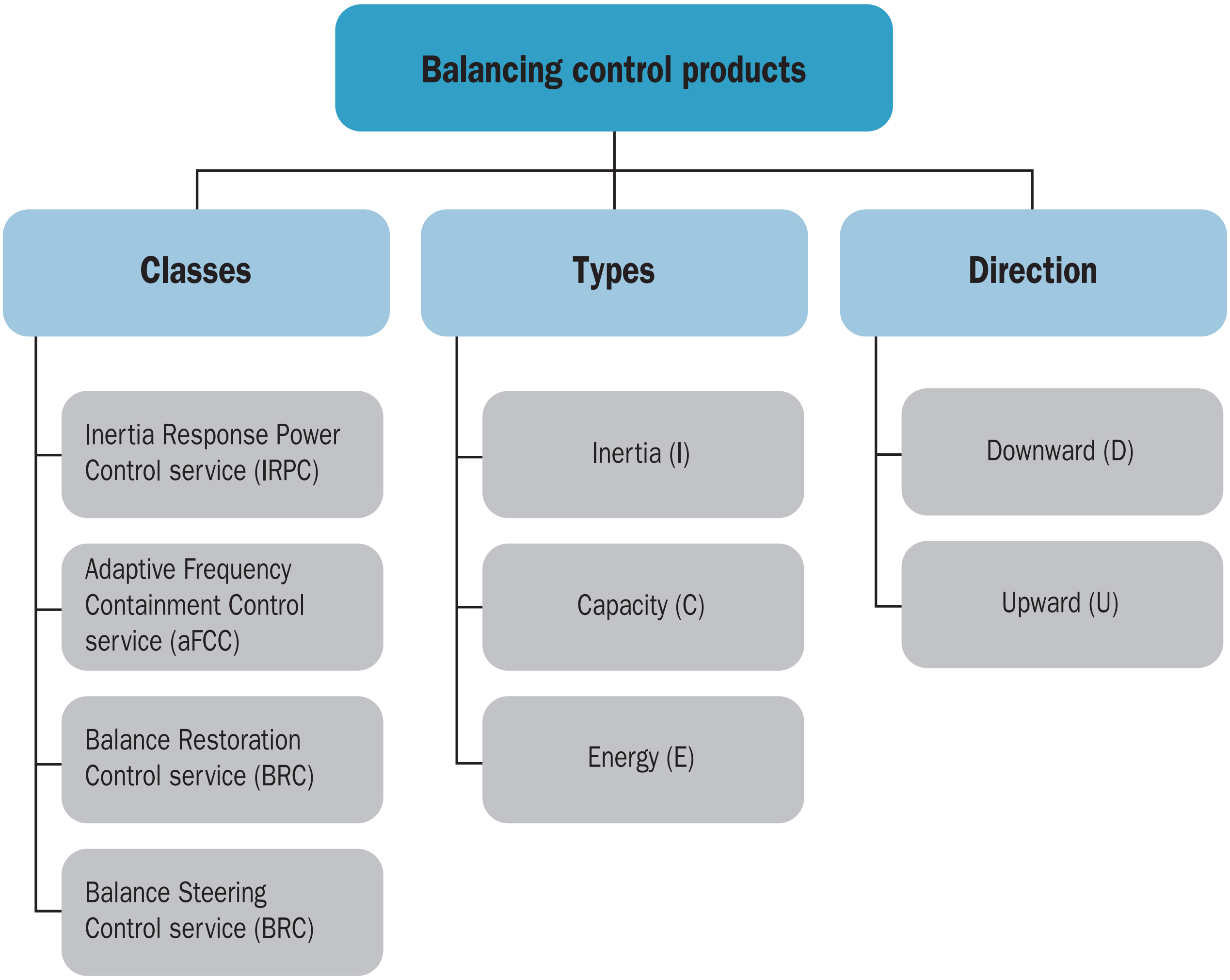


Figure 9 | Categorization of balancing control products

Products and related market design elements

Within the WoC control architecture the market is an *exchange*, as the type of organized marketplace where the CSO and the Balance and Voltage Control Service Providers (BSPs) meet to trade balancing and voltage control products, in a voluntary, non-discriminatory and transparent way. *Uniform auction* is the proposed instrument to promote competition in the procurement of balancing and voltage control products; the CSO collects all the bids from the BSPs, creates an aggregate supply curve for the balancing and voltage control products, and match it with the requested volume of these products. The CSO establishes the Market-Clearing Price (MCP). Win the BSPs whose bids offer lower or equal price to the MCP. All winners receive the same price ("pay-as-clear"), independently on their bids and offers.

New kinds of balancing and voltage control products are developed and traded in the market (see **Figure 9** and **Figure 10**).

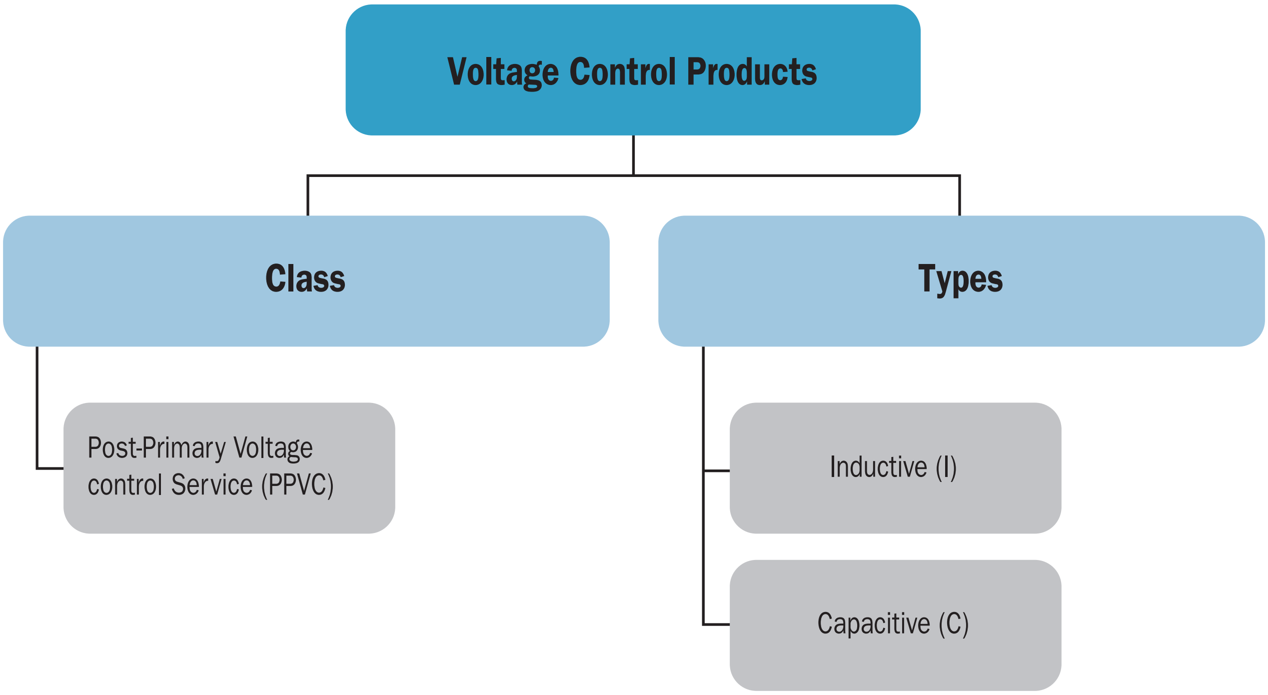


Figure 10 | Categorization of voltage control products

The classes of **balancing control products** are the services for *IRPC, FCC*, *BRC* and *BSC*. For these services four types of balancing products are traded:

- Capacity for inertia means a volume of reserve capacity that the BSP has agreed to hold and in respect to which the BSP has agreed to submit bids for a corresponding volume of inertia to the CSO for the duration of the contract.
- Inertia means inertia used by the CSO and provided by the BSPs.
- Balancing energy means energy provided by the BSPs, either injected or withdrawn, used by the CSO to perform balancing (to compensate for unforeseen imbalances and to guarantee the stability of the power system).
- Balancing capacity means a volume of reserve capacity that the BSP has agreed to hold and in respect to which the BSP has agreed to submit bids for a corresponding volume of balancing energy to the CSO for the duration of the contract. Balancing capacity is procured by the CSO ahead of real-time with the purpose to hedge the CSO against the risk of not having enough balancing energy bids by the BSPs in real-time.

Two directions of balancing products (except inertia) are available:

- Upward regulation means an increase in generation (or decrease in consumption).
- Downward regulation means a decrease in generation (or increase in consumption).

Two classes of voltage control service are developed within the WoC power grid structure,

Characteristic	IRPC	aFCC	BRC	BSC	PPVC
Ramping	> 1MW•s/s	> 1 MW/s	> 10 MW/min	> 10 MW/min	> 5 MVA/min
Full Activation time	< 1 s	2-5 s	2-5 s	10-30 s	>30 s
Minimum and Maximum quantity	< 1MW•s	< 1 MW	1-5 MW	1-5 MW	5-10 MVA
Preparation period	< 1 s	< 5 s	< 1 min	< 1 min	< 5 min
Deactivation period	<20 s	10-30 s	10-30 s	10-30 s	10-30 s
Minimum and Maximum duration of delivery period	15-60 min				
Mode of activation	Merit order	Merit order	Merit order	Merit order	Optimal power flow calculation

Table 2 I Minimum requirements for standardized control products

however, only one class is developed as a product for trading purposes. This is:

- Post-Primary Voltage Control (PPVC) service is the commitment to keep or bring the voltage levels in the nodes of the cell back to the safe-band values, while optimizing the power flows in order to minimize the losses in the network. Each cell is responsible for its own voltage control.

Two types of **voltage control products** are developed: consumption and injection of reactive power:

- Inductive reactive power is used when voltage is too high to compensate the capacitive reactive power.
- Capacitive reactive power is used when voltage is too low to compensate inductive reactive power.

Standard balancing and voltage control products are traded in the WoC power grid structure with the minimum requirements shown in **Table 2**.

A set of general, balance planning, product provision and imbalance settlement **market design elements** is considered within the WoC power grid structure.

General elements: within the WoC the Bid Time Unit (BTU), which is the main time unit in the market for balancing and voltage control products dividing the balance responsibility between the CSO and the BSPs, is linked to Schedule Time Unit (STU), dividing responsibility between the CSO and the BRPs, and Imbalance Settlement Period (ISP), the period for which imbalance of the BRP is calculated. It is expected that linking the BTU to STU and ISP will improve operational and price efficiency. Moreover, to improve balance planning accuracy, availability of balancing resources and price efficiency, a short BTU, STU and ISP (of 15 minutes) instead of long (of 60 minutes) is proposed.

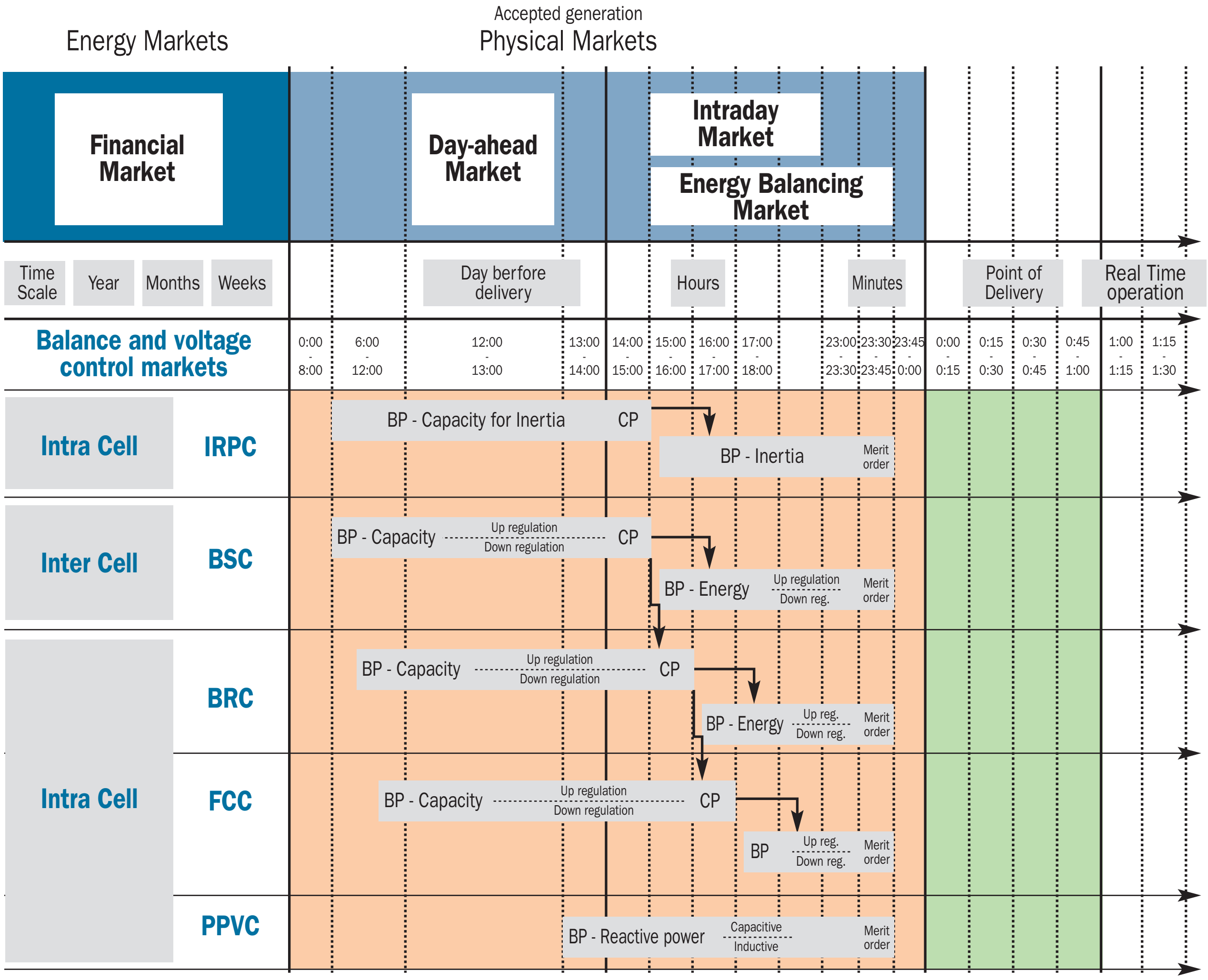
With the purpose to develop a transparent market for balancing and voltage control products, publication of information is of high importance. A high-level framework of a transparent market for balancing and voltage control products is proposed. It is developed in a way to assure horizontal and vertical transparency of the market for balancing and voltage control products.

Balance planning elements: within the WoC, producers, consumers and traders of electricity have a balance obligation. Electricity produced from RES participate fully in the balancing mechanisms. This means that they have the same responsibilities as other type generators, and are allowed to provide balancing resources subject to common rules. With the purpose to assure very accurate accounting of imbalance, a unit-by-unit balancing scheme is applied for large units, but a portfolio balancing scheme allowing aggregations of units is used in case small-scale RES.

The BRPs submit separate energy schedules for production, consumption and trade (import and export) during the predefined time periods. The Initial Gate Closure Time (IGCT) at which the BRPs must submit general initial energy schedule to the CSO is related to the time period from the day-ahead (DA) market closure to the intraday (ID) market opening. The particular time should be selected to allow the BRPs to have sufficient time to prepare the initial energy schedules and the CSOs to have enough time to aggregate them and take decision regarding volume of balancing and voltage control product is required for the cell.

Balance and voltage control products provision elements: The CSO procures the balancing and voltage control products in the organized market, which is an auction-based exchange. The market considers a uniform pricing rule for balancing and voltage control product price setting. Under the uniform pricing rule, the BSPs who won the auction are paid a single price, which is the Market-Clearing Price (MCP) regardless of their bids. Cascading procurement principle, which is expected that will increase price efficiency in the market for balancing and voltage control products, is implemented. The implementation of the principle means that any surplus of high-quality balancing product is by the auctioneer (CSO), automatically transferred to the market for lower-quality balancing product and so on. Balancing and voltage control products are procured on commercial basis and the BSPs are remunerated for the provision of these products. The CSOs pay the BSPs for the inertia capacity and balancing capacity availability and for their utilization, if the IRPC, FCC, BRC and BSC services are activated in real-time. PPVC service is paid if reactive power is used in real-time. Each CSO shall use cost-effective balancing energy bids available for delivery in its cell based on the merit order list. Inertia is activated based on a merit order list principle, and reactive power based on an Optimal Power Flow (OPF) calculation (for which a merit order list could be considered as well).

Imbalance settlement elements: within the WoC power grid structure's imbalance settlement model, each CSO calculates the final position, allocated volume and imbalance for each BRP, for each ISP and in each imbalance cell. Final position of the BRP is calculated using the approach that the BRP has three final positions – production, trade, and consumption. The WoC power grid structure supports the single pricing mechanism for imbalance price setting because it assumes that there should be no imbalance pricing asymmetries, meaning that there should be no different prices paid for being positive or negative imbalance within a given settlement period. For the reason of transparency, clearness and simplicity, the balance



BP: Bidding process; CP: Clearing process

Figure 11 | Timing of submarkets for balancing/voltage control

incentivizing components that sometimes are added to the regulation prices to punish the BRP imbalances in the same direction as the system imbalance or to incentivize all BRPs to keep their balance, are not foreseen within the WoC. It is expected that the single pricing will lead to the lowest actual imbalance cost and will result in the highest cost allocation efficiency. It will not discriminate against small market actors. However, this mechanism could give weaker incentives for balance planning accuracy. An imbalance price is calculated based on the MCP of upward and downward regulation.

Market sequence organisation

The market for balancing and voltage control products is a constituent part of the wholesale electricity market. In addition to the capacity markets for the procurement of reserves (balancing and voltage control services) to be activated if necessary in each cell during the real-time operation by the CSO, the set-points of all cells will be established through energy-only markets.

In a day-ahead market (DA), which is established at WoC level, electricity is traded one day before the actual delivery. The cell has to be in balance at the end of the DA market (i.e., scheduled generation in the cell shall be equal to the forecasted demand in the cell plus net export to another cell). Electricity is traded both the day-ahead bilaterally (OTC trading) and on the day-ahead power exchange, as it is today.

In the intra-day market (ID), which is established at the WoC level, electricity is traded on the delivery day itself. The ID market enables market actors to correct for shifts in their DA nominations due to better wind forecasts, unexpected power plant outages, etc. This is a continuous market, and trading takes place every day until one hour before delivery.

The MO provides the results of the energy-only markets (bilateral, DA and ID markets) to each CSO – such as production and consumption volumes of the cell, tie-lines power flows and electricity prices – who then estimates the total balance in the cell and based on the estimations, necessary “set-points” are set for each cell.

In the energy balancing markets, energy bids are collected in merit order list at the regional level between neighbouring cells, which enables CSOs to correct possible power system imbalances before RT, closer to defined “set-points” after ID market closure; collection of energy bids is accepted until 15 min. before the production hour.

The CSOs maintain the system balance by activating balancing capacity. The balancing capacity market is not part of the pure energy-only market, since balancing capacity delivers both energy services (i.e., generating electric energy when activated) and capacity services (i.e., reserving generation capacity). The CSO is the single buyer of balancing capacity and contracts different types of balancing capacity.

In the market for balancing and voltage control products, capacity for inertia, balancing capacity, inertia, balancing energy and reactive power is traded between the BSPs and CSOs at the intra-cell and inter-cell levels and settlements between the CSOs and the BRPs are carried out. As such, the market for balancing and voltage control products is split into a procurement side (i.e., procurement and activation of balancing and inertia capacities (if necessary, in real-time), as well as reactive power by the CSOs) and a settlement side (i.e., financial settlement of the BRP imbalances by the CSOs).

At the procurement side of the market for balancing and voltage control products the BSPs sell IRPC, FCC, BRC, BSC and PPVC services and the CSOs procure them. Each balancing and voltage control product is traded in a separate sub-market. The sub-markets for inertia capacity, inertia, balancing capacity and balancing energy for upward and downward regulation, inductive and capacitive reactive power are established too. For each balancing product there are established two main types of sub-markets: balancing capacity (the BSPs are compensated for availability of reserves) and balancing energy (the BSPs are compensated for the actual delivery of electricity (i.e. utilization of balancing capacity), or inertia capacity and inertia. In the sub-market for voltage control products reactive power is traded. Since voltage is a very local problem, therefore it is solved locally by local voltage service providers. It is expected

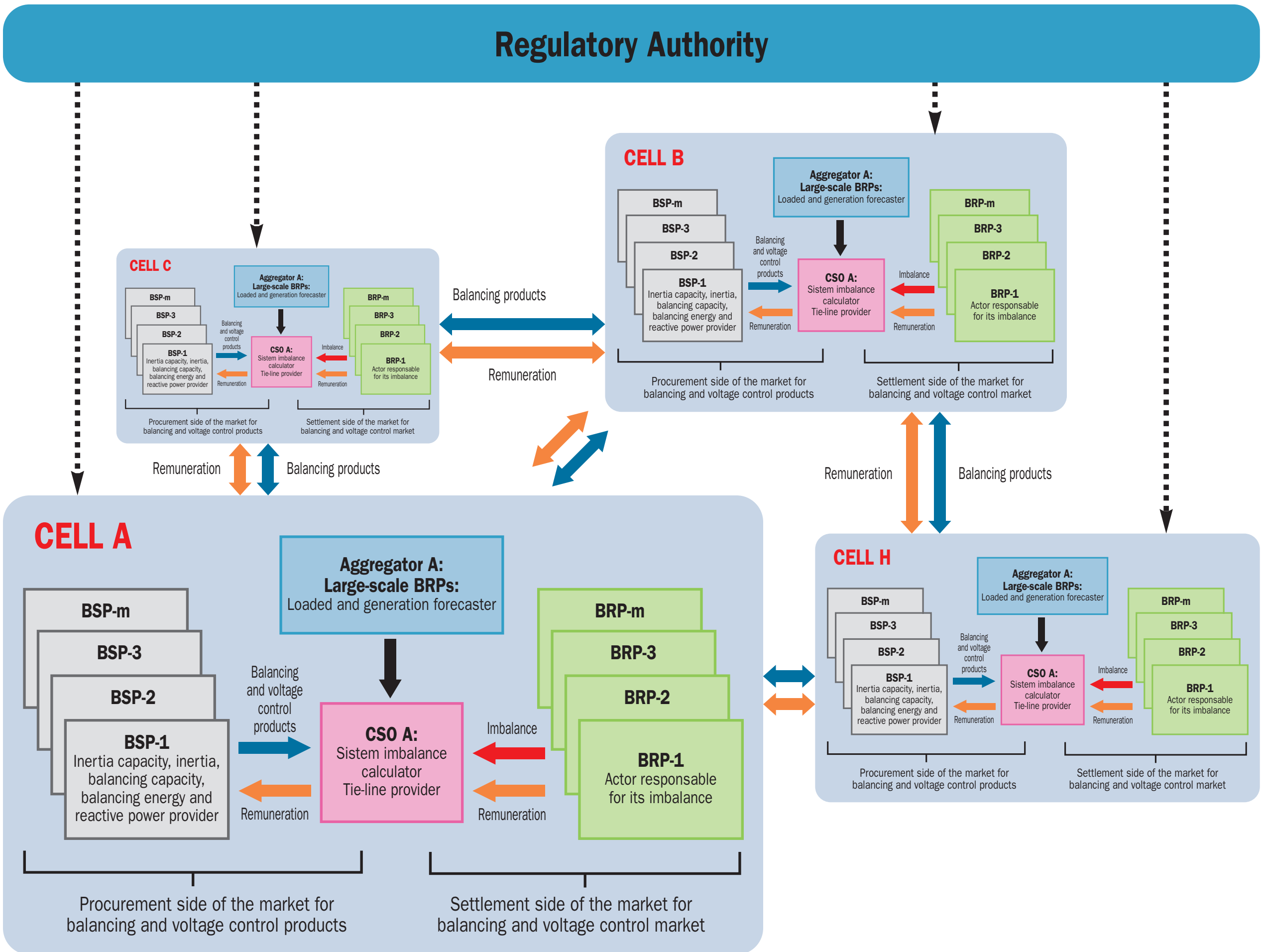


Figure 12 | Interactions of the market actors for balancing and voltage control services

that at least several voltage control service providers capable to locally solve voltage problems will be available in future.

The CSO has the responsibility to balance the cell (stick to the cell set-point) by using available resources to maintain the frequency and voltage and to secure a stable operation. The CSO will compensate cell imbalances in real-time by activating balancing capacities, which are contracted ahead of time from the market actors who provide balancing and voltage control products (BSPs). At the settlement side, the CSOs sell balancing and voltage control products to the BRPs who are in imbalance, and the BRPs pay for the provision of products. The BRP's imbalance is the quarter-hourly (15 min.) difference between the BRP's total injections and off-takes. The total imbalance in the cell is the sum of all BRP imbalances.

The timing of sub-markets for balancing and voltage control products is organized in a way that initially, the BSPs decide on in which sub-market – inertia capacity or balancing capacity – they take part in.

Those BSPs who decide to participate in the sub-market for inertia capacity and whose bids are accepted for a particular market time unit, are not allowed participating in other sub-markets for this market time unit. The same is valid for the BSPs who bid the balancing capacity. Those BSPs who decided to participate in the sub-market for balancing capacity for a particular service and whose bids are accepted for a particular market time unit, are not allowed participating in other sub-markets, except in the sub-market for balancing energy. Moreover, those BSPs whose bids of higher quality balancing capacity are rejected by the market can bid the sub-market for lower-quality balancing capacity or bid the sub-market for voltage control services, if they satisfy bidding requirements. The sub-markets for inertia capacity and balancing capacity are organized earlier than sub-markets for inertia and balancing energy, since inertia and balancing energy bids are submitted to the market by the BSPs who won inertia capacity and balancing capacity auction and thus have the obligation to keep the inertia capacity or balancing capacity for the particular market time unit. Thus, a clear interrelationship of the timing of sub-markets is established. The timing of sub-markets for reactive power is organized in a way that merit order is established. According to the current specification of PPVC, no merit order function is considered. Activation is based on real-time OPF which considers as an initial assumption that all resources have the same price (market-resulting merit order list could be considered as well, if necessary).

In the market, the balancing and voltage control products are traded between the BSPs and CSOs at intra-cell and inter-cell levels, and settlements are carried out between the CSOs and the BRPs. The interactions between these market actors split the market into a procurement side and a settlement side are seen in **Figure 12**.

2.6 Outlook

As planned, the technology readiness level (TRL) of ELECTRA IRP outcomes reaches 3 to 4, being TRL4 “Prototype or component validation under laboratory conditions”. TRL5 and beyond are for pre-commercialization and testing of prototypes under real or field conditions, and are clearly beyond the ELECTRA scope. The developments around the WoC concept within ELECTRA were focusing on flexible (aggregate) resource level, cell level and inter-cell level. The physical, single device level was not in scope of the research, considering the long-term research perspective (2030+) as well as the conceptual RTD work performed. Nevertheless, it was requested to partly address the device level, when setting up the test cases and performing the individual lab-scale experiments.

For increasing the TRL of the WoC concept and enabling the implementation and application in real networks, effort on device level as well as on the actual communication interfaces and protocols is requested, in order to ensure the provision of the required flexibility for the different use cases and underlying functionalities in real environment. This includes flexible and adaptive set of active grid components capable of efficiently delivering the quality of supply specified by grid rules and/or grid codes, irrespective of size or position (central or regional). Before applying the WoC in real networks, it is needed to further detail and refine the concepts as well as to analyse and verify them, taking into consideration the implementation of the functionalities (algorithms) at device level in particular. Since corresponding proof of concept tests have been carried out with some limitations, further research and development on higher TRL levels is necessary, including more concrete rules for defining cells and corresponding test networks and benchmark criteria.

The WoC concept as well as the related control function are addressing the power system 2030+. One important assumption of ELECTRA is that developments in information and communication technologies support the pathway towards more decentralized managed power systems. The analysis of communication standards in light of the ELECTRA use cases gave very good results putting in evidence that the information exchange needed by the ELECTRA use cases are completely covered by the existing standards. Since there was again no focus on device level, before implementing and applying the WoC concept in present networks these issues need to be clarified as it is true for any remotely-controlled device going to be integrated in the real system.

Another important aspect in terms of WoC application is the issue of integrating the concept in the processes as well as the control room functionalities of power system operators. ELECTRA IRP developed a high-level design of an overarching architecture for future control room functionality in a WoC context. In order to demonstrate an integrated decision support system, a design for the combination and co-ordination of the developed decision support tools has been created, including how they react to decision points and events. This decision support system blueprint for different control functionalities can fully support the control of the WoC concept, and allows the human operator to benefit from improved information and automated decision making under complex WoC scenarios. In addition, a number of visualisation prototypes have been developed for different decision support control functions. These provide operators with key information, and provide situational awareness during events. They also allow operators to access network data and to alter or add control actions if necessary. For an implementation of the WoC in real grids, these prototypes need to be further refined, commercialised and integrated in actual SCADA systems presently in use.

The increase of the ELECTRA WoC concept TRL, including the clarification of the above mentioned issues at device level, are a key requirement for performing detailed scalability analysis of the related technologies in the existing grid supporting the provision of a detailed implementation migration plan in the future.

From a regulatory perspective, the management of BSC requires the definition of competitive and non-discriminatory mechanisms for tie-line constraint calculation, information exchange, activation and deactivation. Currently, there is no mechanism analogous to BSC, active within the same time frames as that defined in the WoC concept. The same applies also for the IRPC: new procedures and rules are needed. An evolution of the Coordinated Balancing Area (CoBA) between neighbouring TSOs would be necessary. A set of standard products for imbalance netting will require a definition, based on sound economic principles, in order to ensure harmonisation within and across CoBAs.

The analysis of the Market Design Initiative of the Winter Package and ENTSO-E Network Codes for market design show that the WoC concept should respect the high-level EU regulations, which are related to the general principles regarding the operation of wholesale electricity markets, including market for system balancing products.

3 Coordination and support actions

3.1 Introduction

The ELECTRA Coordination and support actions **(CSA)** activity is manifold and encompasses:

i) the **Coordination and Networking** with national and European projects and initiatives; EERA JP on Smart Grids (JP SG), other EERA JPs and IRPs, relevant European and national projects and initiatives and grid stakeholders, such as the ENTSO-E, EDSO4SG, EASE and the new ETIP SNET.

ii) the identification and use of smart grids **Research Infrastructures**;

iii) the establishment and management of a **Researcher Exchange Programme;**

iv) specific activities towards **International Cooperation** and in support to Mission Innovation.

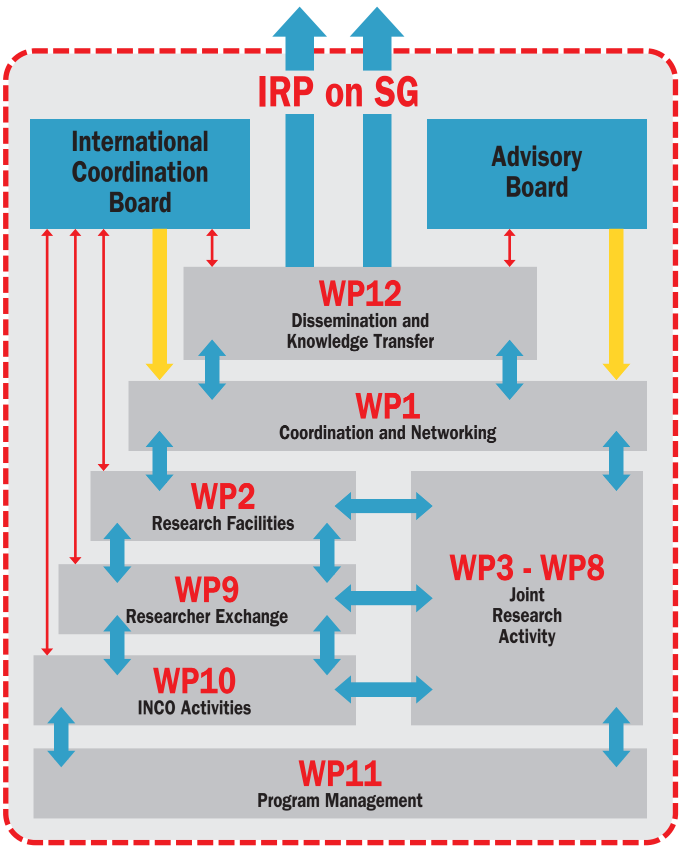


Figure 13 | Interconnections of CSA work packages

In particular, ELECTRA boosted the extensive coordination of the ELECTRA IRP with the EERA JP on Smart Grids (JP SG), other EERA JPs and IRPs, relevant European and national projects and initiatives and grid stakeholders, such as the ENTSO-E, EDSO4SG, EASE and the new ETIP SNET.

ELECTRA CSA activity also allowed to identify some of the most relevant European Research Infrastructures and to promote their effective use to validate with a system perspective new solutions and technologies in regard to future decentralized grid controls, power system testing, grid flexibility and advanced DER interoperability.

Moreover, ELECTRA developed a suitable mobility scheme to operate an efficient programme of researcher exchanges to achieve the training of researchers, and especially early career researchers.

And finally, the ELECTRA consortium devoted a significant effort to promote a broad and efficient collaboration with extra-European research institutions and international organisations, as foreseen by the Mission Innovation global initiative.

3.2 Coordination and Networking

The smart grids area is very broad and, moreover, practically every single European country has important ongoing R&D activities in this strategic energy field. These are some of the main reasons why R&D activities in the field of smart grids need better coordination both at National and at European level.

Starting from this situation the ELECTRA IRP and its related EERA Joint Programme on Smart Grids (JP SG) aim to improve this ineffective approach, leading to common European objectives, maximizing synergies and identifying research priorities.

In particular ELECTRA IRP enabled coordination and networking activity with several linked EERA JPs and other IRPs, grid stakeholders, such as ENTSO-E, EDSO4SG, the ETIP SNET members, national and European projects, and others initiatives as for example ERA-Net Smart Grids Plus and IEA ISGAN. Information, feedback and suggestions provided by these different parties have been extremely useful for both the research and coordination and support action (CSA) activities performed in the ELECTRA IRP.

The main instruments that have been used to ensure coordination and networking of ELECTRA IRP with external key groups and EU grid stakeholders are technical meetings and workshops where the exchange of information and sharing of strategy, priorities and results, as well as knowledge and lessons learnt about reciprocal R&D efforts were strongly promoted.

The main achievements of the coordination and networking activity certainly include:

- Effective interaction with the major smart grids R&D initiatives in Europe by sharing results and discussing different approaches and open research issues.

- Feedback and suggestions on the proposed Web-of-Cells concept as well as indications about its further consolidation and development from EU grid stakeholders.
- Contributions to the ENTSO-e roadmaps and Implementation Plans under public consultation thus highlighting several low TRL R&D topics deserving further attention.
- Indications about system operators main strategy for grid modernization thus collecting specific information about their view on R&D topics and related priority.
- Close contacts and connections with relevant ongoing projects and initiatives at European and national level by organising joint technical workshops with selected projects.

In fact, during the course of the activity the ELECTRA IRP succeeded:

- To reinforce the coordination with some of the more closely related **EERA JPs** (as **Smart Cities, Wind, Energy Storage**) by several means as invitation of EERA JP Coordinators and WP leaders to reciprocal Steering Committee meetings and workshops in order to identify areas where technical cooperation may be more productive.
- To improve the coordination with the other IRPs by participating to specific coordination meetings organized under the supervision of the European Commission. Main goal was to exchange the experiences in order to compare and analyse the different approaches used to general organizational tasks, as for example common scheme for knowledge transfer, conditions for researcher exchange and KPIs.
- To reinforce coordination with **EU grid stakeholders** to include industrial perspectives into the ELECTRA research priorities. ELECTRA participants interacted with the EDSO and ENTSO-E R&D Committees by presenting and discussing ongoing activities and future plan. Moreover, sent comments and suggestions to strategic documents under public consultation as for example the ENTSO-E's R&D Implementation Plan 2016-2018. This contribution has been then acknowledged by ENTSO-E and the comments circulated to the involved TSO members.
- Support to the **ERA-Net Smart Grids Plus** initiative by providing inputs about R&D topics priority through replies to questionnaires and dedicated contributions to ERA-Net Smart Grids Plus scoping workshops held at the European Utility Week 2016 in Barcelona and 2017 in Amsterdam. In both events, important stakeholder associations met to identify the key smart grids challenges in view of the future calls for R&D projects.
- To efficiently interact with some selected **EU projects** on smart grids and to organize joint workshops on commonly agreed R&D topics, as for example with: EvolvDSO, IDE4L, GRID4EU, and ERIGRID. Those EU projects also agreed to share their approach and results and to contribute to workshops where the ELECTRA activity and the Web-of-Cells concept was presented and discussed.

Moreover ELECTRA members strongly coordinated their activity with **Mission Innovation** - a global initiative that currently involves 22 countries and the European Union that have committed to seek to double their governments' clean energy R&D investments over five years in transformative clean energy technologies. And in particular with its **Innovation Challenge #1 on smart grids**. Europe is very well represented in MI IC#1 by 9 countries and the European Union. Apart from Sweden all the others are also ELECTRA members. By means of MI IC#1 the interaction with representatives from Ministries and funding Agencies in the involved countries has been dramatically enhanced in order to share information on main goals and strategy at National level, R&D priorities, and ongoing projects with the aim to leverage possible synergies and to help defining priority funding allocation.

Finally, ELECTRA members fully engaged in discussions and consultations with representatives from European grid stakeholders and the European Commission. In fact, the European Commission started an informal consultation process with the interested grid stakeholders to set governance principles of the European Technology and Innovation Platform (**ETIP**) “Smarter energy grids and storage for a more integrated energy system”. The replies to these consultations always included the contributions from EERA JP SG and ELECTRA.

3.3 The future of European Smart Grids research infrastructures

A Powerful European Research Infrastructure is necessary to reach consensus on harmonized solutions that allow collaboration on the technical level and thereby accelerate the development and implementation of smart grids. To support the transformation process of the power system envisaged in the ELECTRA IRP, key smart grid technologies on both the transmission system level and the distribution system level must be researched, tested and demonstrated in appropriate Research Infrastructures (RIs). Such laboratory and field environments need to allow the set-up of real-scale smart distribution grid sections. The grid connection guidelines for generators of the power system are being continuously updated to ensure interoperability and provision of system relevant ancillary services. The applicability of the new properties and services as well as of resulting connection rules have to be researched and demonstrated under future scenarios that should be set up in testing environments.

For this purpose, it is necessary to provide appropriate research infrastructure for the investigations on the integration of power technologies with ICT, adaptive control strategies and contingency management as well as protection aspects.

For ensuring the reliability of existing equipment, for further development of equipment functionalities or for testing new methodologies in research projects: Researchers and developers in the Smart Grid and DER field need laboratories and testing facilities for experiments, demonstration pilots or their daily business.

For connecting existing labs with researchers and customers, a Database of DER and Smart Grid Research Infrastructure was developed – free accessible via http://infrastructure.der-lab.net/. Maintained by DERlab since 2012, the database contains details on Smart Grid and DER laboratories, testing facilities and similar competencies, clustering all relevant information and the labs’ profiles systematically.

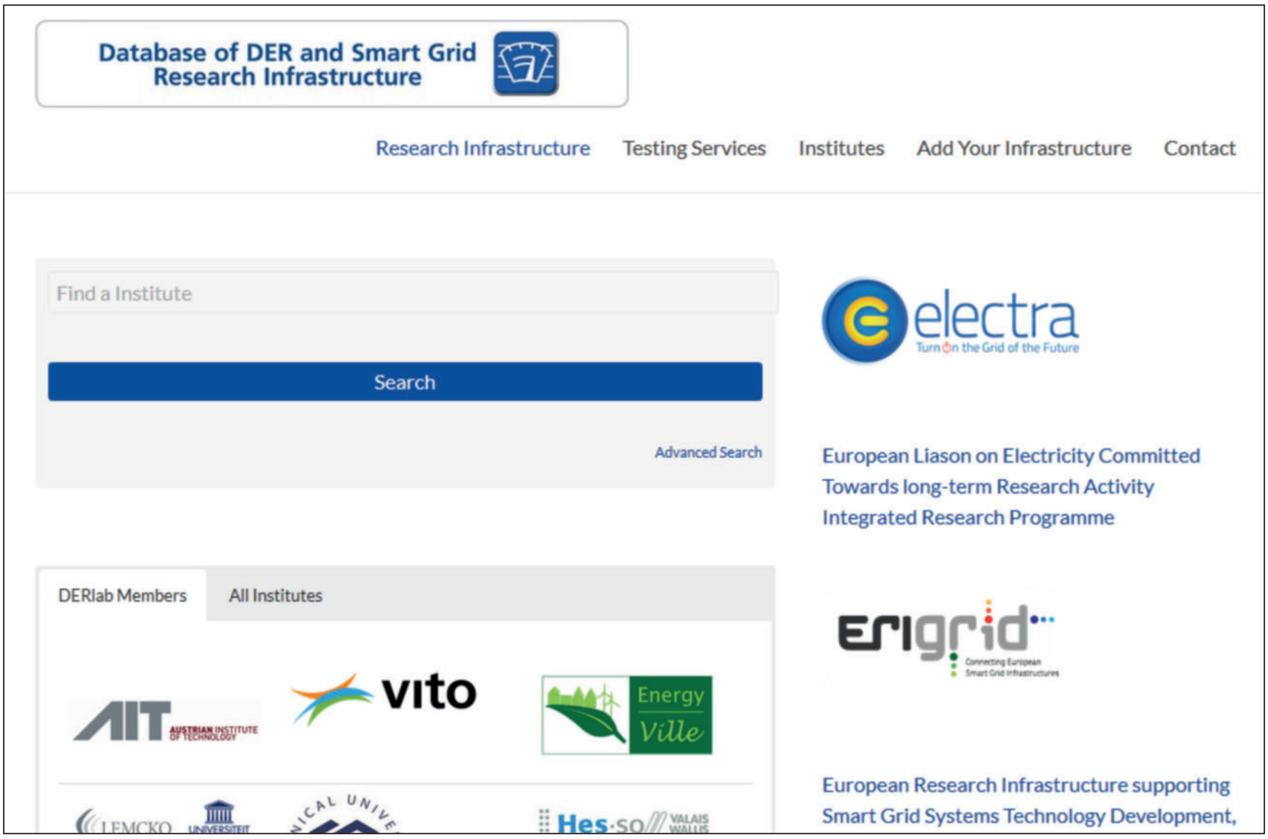


Figure 14 | Database of DER and Smart Grid Research Infrastructure

In September 2016, the database version 2.0 was launched, appearing in a completely renewed design and offering new extensive search and filtering options. Currently, the directory includes more than 50 institutes from Europe and the USA, presenting more than 200 labs, testing capabilities and services. Each institute has the chance to present all relevant information about their facilities in order to inform their customers on the most important details, such as:

- Static and mobile equipment of the facility
- Power range
- Simulation and optimisation tools
- Offered testing services within the laboratory
- Quality management and standards compliance of the offered testing services

Examples of RIs listed in the database cover a broad range from photovoltaic system labs, power hardware in the loop (PHIL) simulation environments or Microgrid configurations.

For offering an up-to-date overview on the existing research infrastructure, DERlab aims at constantly expanding its database, encouraging all institutes active in the field of DER and Smart Grids, to submit information on their laboratories and facilities – they will be a gainful extension to the current content. Adding infrastructure to the database is very easy and free:

An embedded online form on http://infrastructure.der-lab.net/add-your-ri-database/ allows new entries and updates.

Institutes with facilities in the DERlab database clearly benefit from DERlab's core business: Its network and dissemination activities:

- The database is accessed by our broad international network, which coincides with the institutes' targeted customers
- Institutes gain visibility in the field of DER and Smart Grids
- With the enhanced search functions in the database, possible new customers can easily find the services offered by the institute

Following the increasing level of complexity of system operation & management in the European electricity system, there is an urgent need for increased flexibility and full implementation of Smart Grid solutions such as information and communication technology and power electronic-based grid components.

The emphasis of this further development of the European smart grid research infrastructure, is clearly laid on the systems level, as smart grid demonstration projects cannot cover the required tasks, such as the investigation of severe grid disturbances and the preparation of fundamentally new control concepts.

While testing of individual components is covered to a certain extent by current research infrastructure, system testing still needs further development. In this context, some fundamental gaps have been identified:

- Research infrastructures implementing a multi-domain RI for analysing and validating Smart Grid concepts at the system level are missing today; capabilities of existing RIs are mainly focusing on the component level and hence system integration topics are not addressed in a holistic manner.
- A holistic framework (including analysis and evaluation criteria) for the validation and the corresponding research infrastructure with proper methods, protocols, and tools needs to be developed.

To resolve these gaps, the key needs to be met by future research infrastructures will relate to systematically combine power system simulation with control systems emulation and full-scale hardware testing of components. For this purpose combined hard- and software testing solutions such as e.g. power hardware in the loop (PHIL) and control hardware in the loop (CHIL) approaches will have to be developed and implemented in RIs. Accordingly, recommendations for the coordinated development of European Smart Grid research infrastructure were elaborated, covering technical aspects and also addressing potential opportunities for funding of these structures.

3.4 The Researcher Exchange Programme

Effective coordination and support action requires the commitment and dedication of people working to develop better, deeper understanding and shared research goals, and the ELECTRA project has facilitated this for smart grid research through the creation and operation of a new researcher exchange programme, "ELECTRA REX". This programme provided funding for researchers to work together in another's facilities over a number of weeks, enabling collaboration beyond mere participation in meetings that sees cooperation in research deliberation, debate, development, modelling, simulation, analysis and experimental work. The resultant value from the mobility experience has been reportedly felt by the participating individuals themselves, their organisations, the ELECTRA project and wider EERA Joint Programme in Smart Grids, and ultimately the wider research community who have benefited from the advancement and dissemination of the web of cells concept.

A new seven stage methodology was developed for the ELECTRA REX programme, and initiated by a sequence of multiple calls for applications. Three exchange "products" (see **Figure 15**) were designed to support the ambition of the programme: ELECTRA exchanges to encourage deeper cooperation across the project and JP team; European exchanges to stimulate wider involvement from the research community in new decentralised smart grid controls; Global exchanges to establish new cooperations in shared research challenges across the globe. Each of these exchange opportunities were offered for between 2 weeks and 12 weeks (with co-funding encouraged for those at the upper end of the scale), and made available to PhD students and staff from both research and industrial organisations. The scheme offered funding for travel, subsistence, dissemination, and some laboratory costs.

The deliverables designed for these exchanges target quality dissemination and insightful feedback, and the scheme has been recognised by other groups as providing an exemplar to be followed.

The ELECTRA REX programme has supported a total of 40 exchanges, involving researchers from Europe, North America, South America, Asia and Australasia. Of those who have participated in the exchanges, 63% have been early career researchers, many of whom have benefited from the inclusion of training during the period of exchange. 28% of the exchanges were conducted by female researchers. Over 4 person-years of exchange have been managed

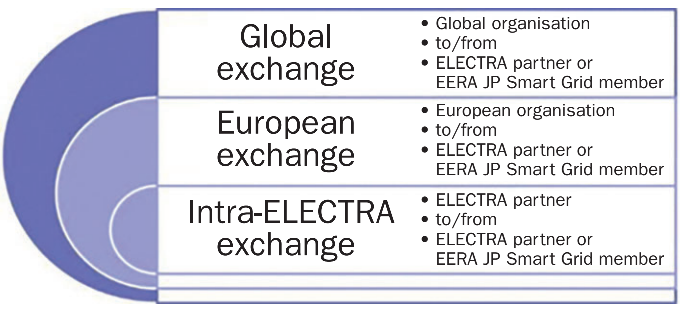


Figure 15 | ELECTRA REX mobility "products"

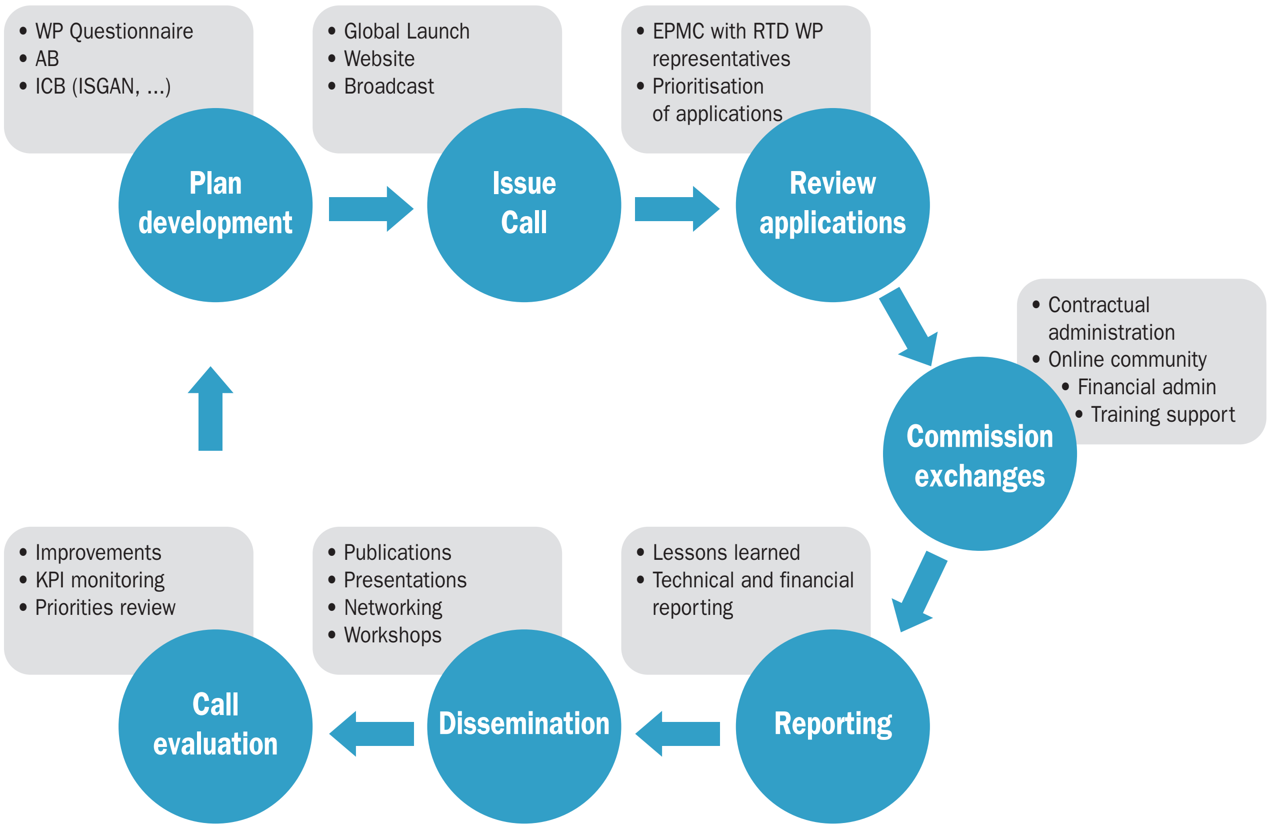


Figure 16 | Seven stage methodology for managing ELECTRA REX

by the programme, and its dissemination efforts have included 4 international ELECTRA REX workshops, and a significant number of high quality co-authored publications.

The ELECTRA REX programme has been recognised for having developed good practice. The inclusion of post-exchange questionnaires and wider mobility survey have supported the project's assessment of good and best practice, and provided a useful assessment of the scheme's learning. As a result, the ELECTRA REX model has now been adopted by others, including by EERA for their cross energy domain mobility programme.

The developed mobility scheme

The ELECTRA REX methodology is based on the operation of multiple calls for applications, and management through a seven stage cycle. This methodology is illustrated in **Figure 16**. This process permitted multiple calls to be managed at different stages, thus enabling new calls to be issued on a regular basis.

Each individual call for applications is developed in accordance with priority topics for collaboration, however applications in other areas were also considered. In each case a public forum at conference or project event was used for the global launch of the call – the first being at IRED'14 in Kyoto. The online portal for applications supported efficient handling of the submission and review process, the latter being commenced soon after

Figure 17 | ELECTRA REX researchers participating in ELECTRA REX Workshop 2

deadline to enable rapid turn-around. An Exchange Programme Management Committee gave the programme oversight and was responsible for the independent reviews, and operated under the direction of the Exchange Coordinator, Professor Graeme Burt.

In each case of a successful applicant, a three-way contract was established between the co-ordinator, host and home institutions, and this commissioning stage ensured adequate institution support to the applicant and focussed the team's attention on the common mobility deliverables: home and host questionnaires, abstract for web dissemination, and joint publication. These outputs not only supported effective reporting and dissemination of the results of the exchange, but also provided feedback that was valuable in drawing out lessons learned and making further improvements to the benefit of the subsequent calls and their applicants.

The experience of mobility

A wealth of experience has been gained through the operation of the ELECTRA REX programme, to the benefit of the researchers, the participating organisations, and the wider smart grid research community. The 40 exchanges conducted under ELECTRA REX are documented on the project web page through short abstracts, and these are complemented by the co-authored papers that have been published.

This experience has further been shared through a series of four international ELECTRA REX workshops that have been organised to share mobility experience and results to wide

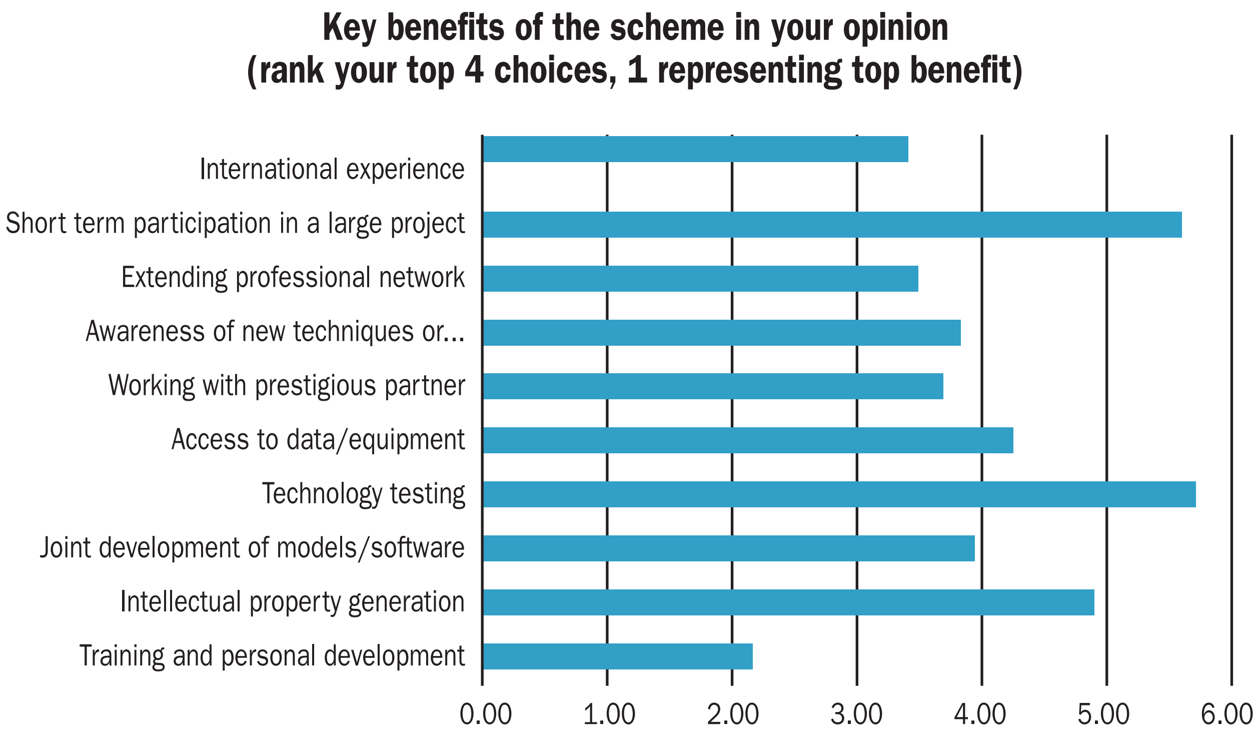


Figure 18 | Example from the analysis of mobility survey results

ranging audiences. These took the form of special sessions at the following:

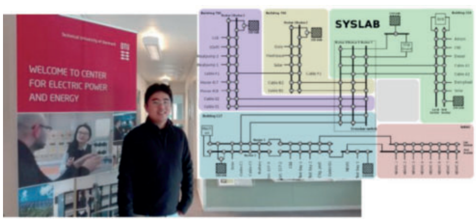
1. Special papers session at EDST'15, 8th-11th September 2015, in Vienna, Austria.
2. Special papers session at IEEE PES Innovative Smart Grid Technologies, Europe (ISGT Europe) 2016, in Ljubljana, Slovenia.
3. Presentation session and discussion forum at the First European Energy Research Alliance Conference, 2016, in Birmingham, UK. This was conducted in partnership with the EERA Mobility Task Force.
4. Special papers session at IEEE PES Innovative Smart Grid Technologies, Europe (ISGT Europe) 2017, in Turin, Italy.

The EDST and ISGT hosted workshops gave opportunity for the exchange researchers' peer-reviewed and co-authored papers to be presented, as well as sharing their personal experience of mobility. For example, five of the recipients of Call 2/3 exchanges had their papers successfully accepted for presentation at ISGT Europe 2016, and each of them presented at the ELECTRA REX special session (**Figure 17**). These events proved successful, reaching out to new and different audiences, as well as enabling an exchange of individuals' experiences.

The ELECTRA REX team have actively sought feedback from recipients of mobility awards through the exchange questionnaires, feedback sessions, and from a survey developed and used in cooperation with the EERA Mobility Task Force. The latter provided useful insight as to the broader experience of mobility from over 70 respondents from 16 countries. **Figure 18** shows one example from the analysis of reported mobility schemes, that shows training and personal development to be by far the top ranking reported benefit of mobility, while the next most valuable being highlighted were international experience and professional networking. It is perhaps telling that a high ranking benefit reported in private has been the opportunity to extract oneself from daily management tasks and obtain valuable focussed thinking time!

Invaluable results from mobility

The ELECTRA REX programme has delivered significant value into the research achievements of the ELECTRA project, which have been reported and disseminated in abstracts on the project web page, workshop presentations at international conference, and quality peer-reviewed publications. In many cases, research work has been completed that would otherwise have been impossible to complete in home organisations.



Example exchange by Diego Issicaba, INESC P&D (Brasil) to DTU (Denmark)
This exchange gave opportunity for Belief-Desire-Intention (BDI) agents to be modelled to operate on DTU's Syslab experimental network in order to provide experimental validation of the agent control scheme operating under the web of cells philosophy. The experiments demonstrated a group of cells negotiating to control tieline power flows, and being resilient to equipment failures. The impact of the exchange was to see realised one of the earliest validation experiments associated with the web of cells concept.

Example exchange by Efren Guillo-Sansano, USTRATH (UK) to Florida State University (USA)
This exchange provided an opportunity for early stage evaluation of decentralised control algorithms for the web of cells concept. By using the FSU cyber-physical systems testbed, a fast integration of the prototype controllers was realised as controller hardware in the loop, and early feedback provided of the effectiveness of the controller performance under frequency events. This proved to be highly valuable in informing the later implementation of a distributed frequency control scenario in a WoC architecture on an innovative Power Hardware in the Loop validation platform at Strathclyde.

Wider impact from the mobility programme

The ELECTRA REX programme has brought further benefit beyond the limits of the funded groups and ELECTRA project.

The successful operation of the REX programme has benefited the wider EERA community. Scheme experiences and results have been disseminated at the First EERA Conference in 2016, where it was presented as one of the Alliance's success stories (**Figure 19**), and summarized in the EERA Mobility Task Force Report.

Figure 19 | ELECTRA REX presented as one of the "EERA Success Story" flyers

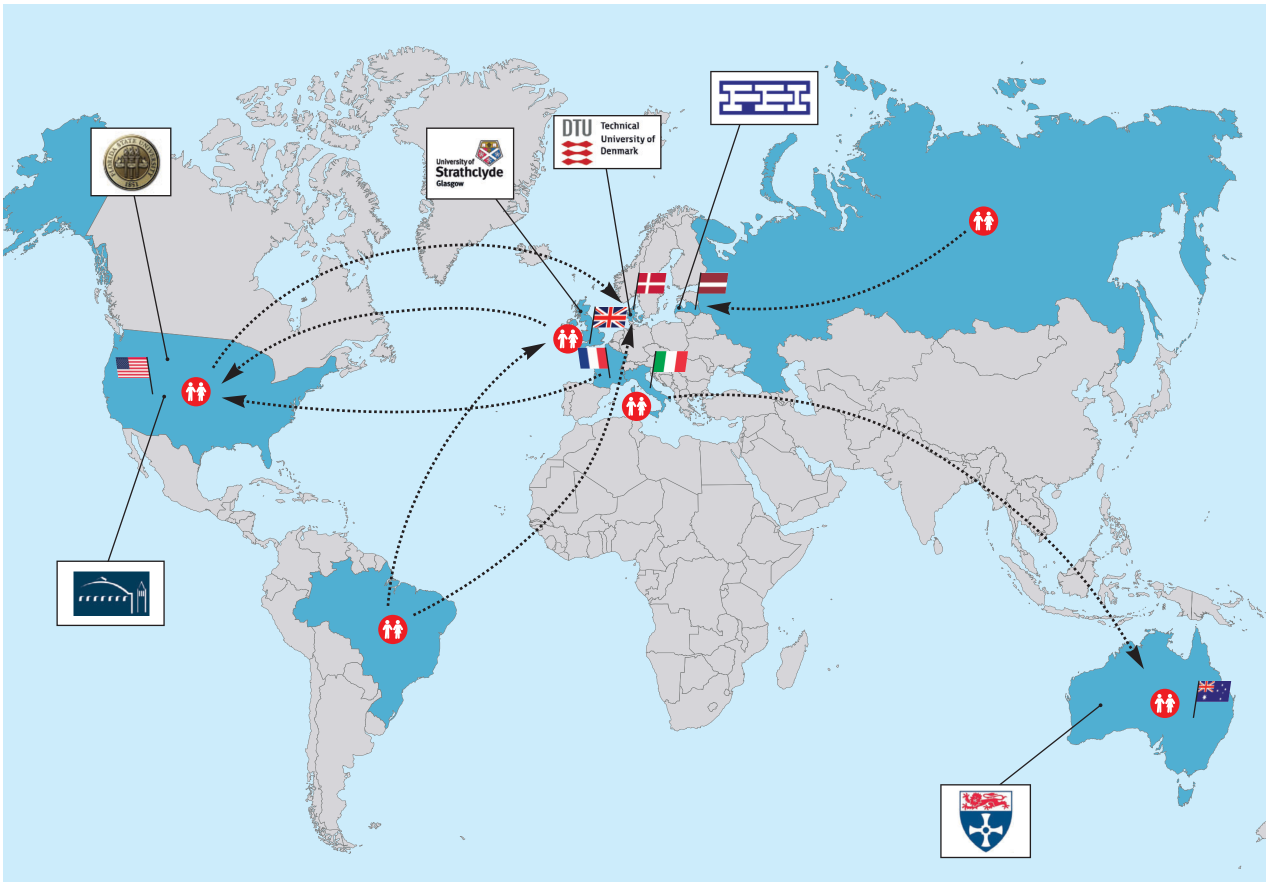


Figure 20 | REX Call 3 global exchanges

The ELECTRA REX methodology and structures have subsequently been adopted as the basis of the EERA Mobility Programme, for use by the other Joint Programmes. The model has further factored in EERA strategy discussions, coordination meetings with other Joint Programme and IRP leads, and is also being used as the basis of CSA actions within other proposals.

The ELECTRA REX Global exchange offer has played a major part in supporting the EERA Joint Programme's international coordination (INCO) effort. The provision of mobility support is attractive to international teams, and a total of 13 Global exchanges were conducted over the project duration (e.g. REX Call 3 is illustrated in **Figure 20**). These encompassed exchanges between ELECTRA/EERA collaborators and research teams in North America, South America, Russia, Asia, and Australasia. In each case, co-authored papers have been produced, and in some instances new project collaborations commenced that will long-outlast the ELECTRA project and continue to support the EERA Joint Programme's INCO activities.

3.5 International Cooperation and Mission Innovation

We understand and value the importance of International Cooperation (INCO) since by sharing information and lesson learnt, by exchanging strategic views and approaches, and planning effective INCO (lab-to-lab cooperation, joint R&D activity, etc.) we can all gain benefits and then advance faster towards smart grids RD&D.

It is evident that there is a need for a common forum of smart grids practitioners to discuss issues of mutual interest, to promote information sharing first and then practical cooperation internationally in order to accelerate the development and deployment of smart grids. Therefore, a strategy on how to engage with extra European research organizations, funding agencies and key international initiatives and platforms as IEA ISGAN and Mission Innovation (MI) Innovation Challenge #1 Smart Grids, in order to leverage synergy and available results and achievements from these important platforms, was very much needed for ELECTRA and we are still very determined on this.

The smart grids field has always been fairly international, but in practical work the international aspect has become much more important than ever before. In fact, globalization means global challenges, but also global opportunities, more open markets and convergence on interoperable technical solutions for the evolving energy systems worldwide.

The present practices could differ from country to country and there is a need to share best practices. We all know that grid problems can be approached from different angles and there seldom is a unique best solution to a problem. The challenge is to make these different approaches converge to such an extent that sufficient comparability can be achieved. To ensure that this global framework is consistent with the European strategy it was important that EU projects as the ELECTRA IRP offer their knowledge and expertise to possibly influence this development. This acted as a basis for future INCO activities, establishing long-term relationships, fostering closer interaction with extra-EU institutes and joint research initiatives on selected smart grids topics of mutual interest.

In particular, the ELECTRA activity on International Cooperation in the smart grids field focused on:

- The identification of potential INCO partners as research organisations/programmes;
- The definition of R&D topics of mutual interest for INCO activities;
- The coordination of the selected R&D topics with both the IRP and the EERA JP SG;
- The coordination and contribution to the major worldwide initiatives such as ISGAN and Mission Innovation, Innovation Challenge #1.

The present section provides a summary of the INCO activities carried out within ELECTRA, including the synergies with Mission Innovation (MI) and the Researchers Exchanges (REX) programme developed by ELECTRA.

Several Smart Grids topics have been identified as of common interest for the ELECTRA IRP and other countries outside Europe, creating a list of topics to be commonly addressed. The list has been defined through a questionnaire developed by ELECTRA and series of meetings, workshops and conferences with the Advisory Board (AB) and International Coordination Board (ICB) members, research centres and other institutions.

To perform this task ELECTRA partners shared and leveraged their own contacts and bilateral agreements, but the support provided by IEA ISGAN and Mission Innovation (MI) allowed ELECTRA to establish contacts, find topics of common interest and share results with additional new actors.

The International Smart Grids Action Network (ISGAN) aims to improve the understanding of smart grid technologies, practices and systems and to promote adoption of related enabling government policies. ISGAN is a Clean Energy Ministerial (CEM) initiative on smart grids organised as a IEA (International Energy Agency) Technology Collaboration Programme (TCP), with the participation of 25 Countries that have agreed to collaborate on advancing clean energy technologies, following the CEM high-level attention and commitment to concrete steps that accelerate the global transition to clean energy.

The link with ISGAN was promoted and facilitated by the many ELECTRA partners having an active role in the ExCo or directly in the activities (Annexes) launched by this initiative, including RSE, AIT, DERLab, TECNALIA, but also DTU, SINTEF, and VTT.

In developing activities within ISGAN, ELECTRA partners contributed to different international events to facilitate dynamic knowledge sharing on smart grids strategies, projects and programs, organised periodic meetings to focus on the actions to be made, monitored the activities progress and contributed to the identification of action priorities at international level to promote the development of smart grids.

On the other hand, Mission Innovation (MI) is a global initiative that currently involves 22 countries and the European Union to dramatically accelerate global clean energy innovation. As part of the initiative, participating countries have committed to seek to double their governments' clean energy R&D investments over five years. These additional resources are intended to dramatically accelerate the availability of the advanced technologies for a future global energy mix that is clean, affordable and reliable. Mission Innovation was announced on November 30th, 2015 as world leaders met in Paris to undertake ambitious efforts to fight climate changes and, at the end of 2016, seven Innovation Challenges have been agreed upon and launched.

The first of the seven innovation challenges (IC#1) focusses on smart grids and is co-led by China, India and Italy. IC#1 aims to enable future grids that are powered by affordable, reliable, decentralised renewable electricity systems.

IC#1 is co-led by China, India and Italy and involves the following countries: Australia, Brazil, Canada, Denmark, the European Union, Finland, France, Germany, Indonesia, Mexico, Norway, Saudi Arabia, Republic of Korea, Sweden, the Netherlands, the United Kingdom, and the United States [6]. Among the countries involved in IC#1, eight are also represented in the ELECTRA IRP.

The presence of a very significant number of European countries in ELECTRA and IC#1 allowed to leverage on common aspects and experiences gained in the ELECTRA period, especially in the INCO framework. Currently, IC#1 can count on 18 countries and the European Union represented by the European Commission (EC) and 8 of them are also involved in the ELECTRA IRP, highlighting the existing strong link between the two.

Synergies between WP10 and IC#1

As a global initiative, since the very beginning ELECTRA partner considered IC#1 as a way to implement INCO activities in the smart grids field; in fact, the involvement of several countries either in ELECTRA and IC#1 allows to leverage on experiences and lessons learnt and make them available outside the European boundaries, remarking the key role played by Europe in smart grids.

The practical activities of IC#1 have been launched in January 2017. It is noteworthy to highlight that the methodologies and the experiences gained within ELECTRA put the basis for the activities carried out in IC#1. As an example, the questionnaire developed by ELECTRA for the identification of potential joint R&D activities in the smart grids field was the methodology adopted also within IC#1. Moreover, starting from the ELECTRA experience, IC#1 defined a set of KPIs to periodically monitor how the Challenge activity is progressing. IC#1 is the first Challenge who developed a set of KPIs, stimulating the interest of the MI Secretariat, that is interested in sharing this as an input to MI at large, in standardizing metrics across the Challenges and in increasing their international exposure.

First results of IC#1 and ELECTRA team contributions

In the first semester of 2017, IC#1 made a survey to identify the most important RD&D

MISSION INNOVATION
Accelerating the Clean Energy Revolution

IC#1 Top 10 Priorities

	Smart Grid Tasks	Category	Further Details
10	Improve storage integration at all time scales (in operation for system services but also when performing planning studies as an additional degree of freedom) as a source of flexibility	R, D, M, C	Integration of storage in network management
9	Use of demand response for system services with well-defined interactions among market players and network operators (and TSO-DSO exchange of information)	R, D, M	Grid observability, demand response
8	Developing regional electricity highways with both AC and DC technologies	R	New materials and technologies, grid controllability, flexible grid use
7	New planning tools able to account for the full complexity of electricity networks (distributed and intermittent generation, variable and controllable loads, power electronics, storage)	R, D, M	Optimal grid design New planning approaches and tools
6	Identify and support improvements of suitable flexibility options (RES generation, flexible thermal power generation, load, network, storage, integration with other energy network) to ensure adequacy and security	R, D, M	Storage integration, demand response, flexible grid use, interaction with non-electrical energy networks, flexible thermal power generation; Active demand response to automation and control of MV network, flexible decentralised thermal power generation
5	Study and demonstrate new grid architectures both at transmission and distribution level as a source of flexibility	R, D, M	Optimal grid design, flexible grid use
4	Optimising the existing assets and the network capacity making use of new technologies	R, D	Smart asset management, new materials and technologies
3	Improve the accuracy of the generation forecast	R, D, M	RES forecast; DSO integration of small DER, monitoring and control of LV network, automation and control of MV network
2	Optimization of the energy system	R, D, M	Integration with other energy networks
1	New materials and technologies to increase the flexibility of the grid	R, C	New materials and technologies

priorities in the national strategies of IC#1 member countries. The main aim was to agree and then launch IC#1 activities related to the topics that gathered more interest. Each member country and EC was asked to choose and rank, according to the view of its nation, the ten most relevant “Smart Grid Challenges” among the 44 proposed. The main reference for the elaboration of a questionnaire developed by ELECTRA was the “Final 10-year ETIP SNET R&I roadmap covering 2017-26” released by ETIP SNET on December 2016.

Figure 21 | First IC#1 deep-dive workshop in Beijing on June 6th, 2017: IC#1 "Beijing Consensus" signature by Ministers from co-leading countries (left) and panel session 1 with representatives from IEA, EC, US DoE and the Swedish Smart Grid Forum (right)

Fifteen countries replied to **this questionnaire** and averaging all the responses the top ten relevant challenges were selected. ELECTRA partners were instrumental to the identification of the smart grids priorities to be further analysed in the next years as a practical example of international cooperation among the interested countries and also volunteered to draft the Programme of Work for some of the selected joint R&D tasks and to lead them. Being RSE together with US DOE/PNL leading the Tasks on "New grid architectures" that includes specific work on the Web-of-Cells and related concepts.

The activity and related actions to be performed have been agreed during web-meetings and dedicated calls; however, in several occasions national and general workshops have been organized.

The first IC#1 deep-dive workshop was held in early June 2017 in Beijing. With the presence of representatives from 12 member countries, the European Commission, the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and Austria as an observer this workshop was a great success. In fact, it enabled experts from around the world who are active contributors in the smart grids area to discuss and exchange in-depth experiences and insights on smart grids development in future energy systems, sharing best practices, addressing common issues and focusing on future work thus exploring a new frontier in collaboration. It is noteworthy to highlight that IC#1 was the very first Challenge to organize a dedicated workshop, highlighting the positive collaborating environment existing among the involved members.

After a 2-day closed-door meeting, on June 6th IC#1 organized a public event at the China National Convention Center as side event of CEM8 (Clean Energy Ministerial) and MI-2 (Second Mission Innovation Ministerial) that was attended by more than 150 delegates from about 20 countries and international organizations as IEA, IRENA, WEF, universities, research institutes and enterprises.

This one full day public event also included three panel discussions focusing on strategies and plans, R&D challenges and business opportunities for smart grids providing to worldwide representatives from governments, funding agencies, business leaders and experts with the opportunity to bring their knowledge and perspective on the importance of public investment for innovation and the ways that the public and private sectors can engage more productively. For what concerns with the industry sector, this event allowed the participants to share their innovative smart grids and clean energy technologies, products, and business models and to express their strong interest and willingness to support possible research and other activities.

A second IC#1 deep-dive workshop was held in November 2017 in New Delhi. This workshop included a two-day closed door technical brainstorming session on the ongoing IC#1 activities, whereas the third day was organized as an open public event. A technical expo was also organized on the third day to showcase some of the national & bilateral research development & demonstration programmes on smart grids supported by Government of India along with industry participation. The main deliverables and outcomes from the second IC#1 workshop are reported in the following:

- New Delhi Declaration on IC#1 present and future strategy and specific activity agreed, signed and released thus further consolidating the IC#1 team;
- Official release of IC#1 Country Report 2017 (CR2017);
- Agreement on the first R&D Tasks to be launched by early 2018 with the definition of involved countries as leaders and contributors;
- Bilateral collaboration agreements officially signed (India with UK, US, Italy).

In particular, the IC#1 CR2017 includes contributions from 14 countries (4 continents) with leading role in smart grids; 7 out of the 14 contributions are from European countries and 6 of them from ELECTRA members counties: Italy, Denmark, Finland, France, Germany, and Norway. The collection and incorporation of those contributions was made possible thanks to the active role of ELECTRA partners as RSE, DTU, VTT, SINTEF that also fully engaged with colleagues from Sweden whose important contribution was also secured.

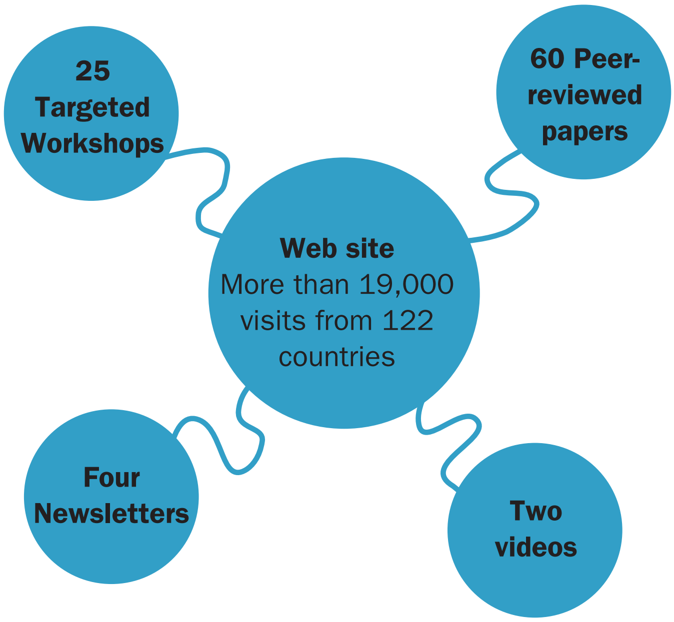
Finally, it is important to highlight that till now the ELECTRA website has been used as the only repository for all the public documents released by IC#1; this is the case for example for the 1st and 2nd deep-dive workshop agenda and documents, but also for the CR2017 released in November 2017 with more than 110 downloads. Moreover, the ELECTRA website provides IC#1 also with reserved areas for co-leads and for members where relevant information (country representatives name and affiliation, mailing list, etc.) and working documents are stored.

4 Dissemination and exploitation of project results

Dissemination activities have the main objective to communicate project results to the scientific community, industrial users and other stakeholders. In this framework, the key target group is constituted by the TSOs and the DSOs, as well as the related European and national organizations such as ENTSO-E and EDSO4SG, and other initiatives such as ETIP SNET and ISGAN.

To this purpose the following dissemination tools and channels are used:

- Workshops targeted to specific audience groups.
- Presentations of posters and paper to Conferences.
- Publications of peer reviewed papers in Conference Proceedings and scientific journals.
- Project web-site.
- On-line news letters.
- Videos on social networks.



Twenty-five workshops were organized all over the world (Japan, China, India, Brazil, Canada, ten European Countries) and were addressed to:

- obtain feedback on project results by EU grid stakeholders, such as ETP WG1 and EDSO4SG. Round tables were also organized at CIRED 2016 and 2017 and on-line questionnaire were set-up.
- Exchange of technical information and share views on research perspectives and priorities with other FP 7th EU projects (EvolvDSO, Grid4EU, IDE4L, DISCERN).

Deal on specific topics such as research infrastructure (side event at IRED 2016 in cooperation with ISGAN).

- Establish stable relationships with B.R.I.C.S. countries. Namely a smart grids workshop has been organized in Florianopolis, Brazil with INESC P&D Brazil. Moreover two deep-dive workshop of Mission Innovation IC#1 Smart Grids were held in Beijing and New Delhi, respectively.
- Reinforce cooperation with EERA by thematic workshops and round tables periodically organized in correspondence of EERA JP Smart Grids General Assembly (Bilbao 2015, Nicosia 2016, Trondheim 2016, Kassel 2017).

Four Researchers Exchange Workshops were organized in the frame of International Conferences in order to allow early carrier researchers to communicate technical results and share their experience of exchange working in leading smart grid organisations.

Policy makers were approached in events such as Innogrid2020+, where the ELECTRA Coordinator participated to the panel session "*Prosumers empowerment and active system management*".

Finally a two days Final Event was organized in San Donato Milanese with the purpose to convince potentially stakeholders of the merits of the work and of its potential for further developments. The Final event included two sessions dedicated to the presentation of RTD and CSA results, respectively. Moreover two round tables with stakeholders participation and a poster session dedicated to Researchers Exchange were organized. A booklet illustrating results has also been issued.

Sixty peer-reviewed papers have been generated by Electra researchers. **Thirty-nine** have been published in Conference Proceedings and **twenty-one** in scientific Journals. Eight papers are currently under review in scientific journals, while seven papers have been accepted for presentations at International Conferences.

Two videos are available on You Tube. The first video (https://youtu.be/Qcwz_uSdstM) deals with ELECTRA objectives and results, while the second (https://youtu.be/pkRexl_CRyc) presents the Web-of-Cells concept.

Four on–line news letters have been issued, reaching more than 200 recipients, each.

All the project events have been announced and publicized on the ELECTRA web-site, where relevant documents/presentations have been uploaded and are available for download.

Similarly, details and summary of peer-reviewed papers have been uploaded on the website.

Finally news and relevant documents, such as country reports, of Mission Innovation IC#1 are hosted in a dedicated slot of ELECTRA web-site.

ELECTRA generated thirty-two **foreground assets**. Most of them are related to the WoC concept, such as control functions and simulation models developed in various environments (Matlab Simulink, DIgSILENT). Since the RTD activity was on a conceptual level followed by experimental laboratory validation, the developed assets are at Technology Readiness Level (TRL) of 3 and 4. On the contrary, results from the CSA activity, such as the REX methodology and scheme for researcher mobility, questionnaire for R&D priorities, Data base of DER and Smart grid infrastructure (*http://infrastructure.der-lab.net/*), can be considered as ”ready for use and implementation”, although they should be customized, depending on their specific use.

These assets have been transferred in the recently developed *EERA Intellectual Property (IP) repository* and will be made available (*free access*) through the **web-based IP showcase** (*http://app.eera-set.eu/ecm/showcase*).

This will allow:

- to make available results generated by ELECTRA to other users;
- put the basis for new projects aimed to bring to maturity the WoC concept.

5 Conclusions and the way forward

The ELECTRA project has developed a new grid control architecture, called “Web-of-Cells” (WoC); a new concept for voltage and balancing control of future power systems with very high penetration of variable renewable energy sources. The WoC was initially proposed and then studied and consolidated by means of a coordinated set of activities that benefitted from the large expertise available within the ELECTRA consortium and the inputs from key grid stakeholders.

By simulations and lab-scale extensive validations, it has been proven that the WoC concept is in principle feasible and allows to provide real-time frequency (balancing) and voltage services in the future power systems. This includes the underlying control and observability functions supporting the six ELECTRA use cases, as well as the control room new functionalities and equally important the integration of the WoC concept in the future markets and regulatory frameworks. Based on these very promising results, an exploitation plan articulated in three sequential phases has been defined in order to further develop the WoC concept and bring it beyond TRL 4 “Technology validated at laboratory level” up to the prototype level, by 2030.

In the first phase (2018-2021), specific aspects of the WoC concept will be investigated in the frame of national and international projects undertaken by ELECTRA partners. Activities performed in these projects will provide important elements for further development and consolidation of this control architecture. In this timeframe, the European Energy Research Alliance Joint Program (EERA JP) on Smart Grids will have a very important and leading role in promoting coordination and synergies among R&D projects and providing a common understanding of their results. The second phase (2021-2026) will be aimed at systematically investigating the WoC concept and to consolidate its maturity by means of a project that will allow an extensive scalability analysis of the WoC concept and will support the provision of a detailed migration plan for the progressive deployment of the concept in real networks. This will require effort on device level implementation as well as on the communication interfaces and protocols. Grid operators will be directly involved in the project to take into account all constraints and necessary steps to be performed in order to obtain a realistic plan to implement and demonstrate WoC concept in a real grid portion. Again, the members of the EERA JP Smart Grids will have a key role in forming the core of the project consortium and then launching such a project and in disseminating its results. In the third phase the WoC control concept will be implemented and demonstrated by grid operators in a real environment. It will represent a fundamental step to realize, by 2030, the complete migration of the WoC concept from R&D organizations to industry, in view of system prototype development and demonstration.

The new grid architecture based upon the WoC concept and the new advanced algorithms for voltage and frequency control are all set to promote further collaborations at the European level, and also more widely within international initiatives. Indeed, the feedback and indications provided by different parties during meetings and technical workshops organized by the ELECTRA team during project execution were extremely useful for the research activities performed in the ELECTRA technical work packages.

The ELECTRA technical activity was suitably complemented by specific Coordination and Support Actions (CSA) and the synergy created between those types of activity resulted to be very effective in supporting the overall achievement of the project's main results.

The ELECTRA CSA activity encompassed the Coordination and Networking with national and European projects and initiatives, the identification and use of smart grids Research Infrastructures, the establishment and management of a Researcher Exchange Programme, and specific activities towards International Cooperation and in support to Mission Innovation.

In particular, the ELECTRA IRP allowed to identify key European Research Infrastructures and to promote their effective use to validate with a system perspective new solutions and technologies in regard to future decentralized grid controls, power system testing, grid flexibility and advanced DER interoperability.

Moreover, ELECTRA developed a suitable mobility scheme to operate an efficient programme of managed researcher exchanges to achieve the training of researchers, and especially early career researchers, by providing them with the opportunity to work in some of the best existing smart grids laboratories in Europe and elsewhere, thus contributing to the establishment of a deeper culture of awareness and cooperation amongst European and international smart grids researchers.

And finally, the ELECTRA consortium devoted a significant effort to promote a broad and efficient collaboration with extra-European research institutions and international organisations to disseminate the European vision on the smart grids field, as well as to highlight its approach, best practices and main results outside the continental boundaries as foreseen by the Mission Innovation global initiative.

We wish to thank all the people, stakeholders, researchers, policy makers, EC Officers that have actively supported us in these years: we hope to continue our fruitful collaboration and to be able in the near future to discuss with you the progresses of the WoC concept towards its grid implementation !

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Public deliverables list

(available at: www.electrairp.eu)

DEL. NO.	DELIVERABLE NAME
D1.3	Report on National fundings and strategy in the smart grids area (in collaboration with EERA Secretariat)
D2.1	European smart grid research infrastructure database
D3.1	Specification of Smart Grids high level functional architecture for frequency and voltage control
D3.2	Market design supporting the Web-of-Cells control architecture
D3.3	Analysis of necessary evolution of the regulatory framework to enable the Web-of-Cells development
D4.1	Description of security concerns and proposed solutions for the frequency and voltage control system & Maturity model for smart grid risk assessment
D4.2	Description of the detailed Functional Architecture of the Frequency and Voltage control solution (functional and information layer)
D4.3	Existing standards and Gap analysis for the pro-posed frequency and voltage control solutions
D4.4	ELECTRA Web-of-Cells Cyber Security Analysis Report
D5.1	Adaptive assessment of future scenarios and mapping of observability needs
D5.2	Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes
D5.3	The Web of Cells control architecture for operating future power systems
D5.4	Functional description of the monitoring and observability detailed concepts for the Pan-European Control Schemes
D5.5	Observables for the Web-of-Cells concept

DEL. NO.	DELIVERABLE NAME
D6.1	Functional specification of the control functions for the control of flexibility across the different control boundaries
D6.2	Impact of network disturbances on the proposed voltage and frequency control solution
D6.3	Core functions of Web-of-Cells control scheme
D6.4	Simulations based evaluation of the ELECTRA WoC solutions for voltage and balancing control – stand-alone use case simulation results
D7.1	Report on the evaluation and validation of the ELECTRA WoC control
D7.2	Lessons learned from the ELECTRA WoC control concept evaluation and recommendations for further testing and validation of 2030 integrated frequency and voltage control approaches
D8.1	Demonstration of visualization techniques for the control room engineer in 2030
D8.2	Demonstration of decision support for real time operation encompassing the identification of key threats and vulnerabilities and the provision of assessed interventions
D8.3	Recommendations on future development of decisions support system
D9.1	Exchange programme procedures and documentation
D9.4	Final report on exchange programme outputs on the IRP website
D10.3	List of mutually interesting R&D topics and prioritization by country of R&D topics to be jointly addressed – Final Report
D10.4	Final Report on Joint Collaborative projects launched and being launched with extra EU countries, and on synergies with Mission Innovation IC#1 on Smart Grids
D12.4	Plan for the use and exploitation of the foreground

Acronyms

AB	Advisory Board
aFCC	Adaptive Frequency Containment Control
BP	Bidding Process
BRC	Balance Restoration Control
BRP	Balancing Responsible Party
BRR	Balance Restoration Services
BSC	Balance Steering Control
BSP	Balance and Voltage Service Providers
BTU	Bid Time Unit
CC	Cell Controller
CHP	Combined Heat and Power
CP	Clearing Process
CPFC	Cell Power Frequency Characteristics
CSA	Coordination Support Actions
CSO	Cell System Operator
CoBA	Coordinated Balancing Area
DA	Day Ahead
DNO	Distribution Network Operator
DSO	Distribution System Operator
EDSO4SG	European Distribution System Operators' Association for Smart Grids
EERA	European Energy Research Alliance
ELECTRA	European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids
ENTSOE	European Network of Transmission System Operators for Electricity
ESI	Energy system integration
ETIP - SNET	European Technology & Innovation Platform - Smart Networks for Energy Transition
FCR	Frequency Containment Reserves
FRC	Frequency Restoration Control
GCT	Gate Closure Time
GHG	Greenhouse Gas
HV	High Voltage
ICB	International Coordination Board
ICT	Information and Communication Technologies

IEA	International Energy Agency
INCO	International Cooperation
IRP	Integrated Research Programme
ISGAN	International Smart Grid Action Network
ID	Intra Day
IoT	Internet of Things
IRP	Integrated Research Program
IRPC	Inertia Response Power Control
ISP	Imbalance Settlement Period
JP SG	Joint Programme on Smart Grids
KPI	Key Performance Indicator
NIST	National Institute of Standards and Technology
LV	Low Voltage
MI	Mission Innovation
MCP	Market Clearing Price
MO	Market Operator
MV	Medium Voltage
OLTC	On-load-tap-changer-transformers
OTC	Over the Counter
PMU	Phasor Measurement Units
PPVC	Post Primary Voltage Control
PV	Photovoltaic
PVC	Primary Voltage Control
RES	Renewable Energy Sources
REX	Researches Exchange
ROCOF	Rate-Of-Change-Of-Frequency
SA	Situational Awareness
STU	Schedule Time Unit
TRL	Technology Readiness Level
TSO	Transmission System Operator
VPP	Virtual Power Plant
WoC	Web-of-Cells

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