The problem of resilience in multi-carrier cellular systems: responsibilities and regulation

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***Abstract*— The 'Web-of-Cells' concept allows for decentralised operation and management of a cellular European electricity grid, allowing increased local participation in electricity system management, while maintaining the application of existing network codes and their requirements for security and resilience. This also potentially increases the number and volume of participants in providing ancillary services. However, a further dimension of energy system evolution is the increased coupling of electricity and gas systems, both potentially undergoing significant change in the move towards low-carbon electricity and gases, with deep operational interdependencies which have the potential to create new modes of failure. We identify how system coupling and decentralised, cellular operation will require novel approaches to system planning and operation to manage extreme events. We highlight the new responsibilities that will be required to maintain system resilience. We also discuss the importance of understanding the resilience of the individual energy consumer to the broader nature of resilience in a whole-system context, and how this can be used to inform future regulatory concepts.**

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I. INTRODUCTION

Power system resilience is the ability to limit the extent, severity, and duration of system degradation following an extreme event [1]. An extreme event is one that is characterized by low frequency of occurrence but having significant consequences.

Extreme events can take different forms, including:

- Weather-related events, such as the extreme winter storms affecting the Texan electricity and gas networks in February 2021 [2];
- Wide-scale societal disruption, such as the ongoing COVID-19 pandemic, leading to novel patterns of energy demand and staffing issues for energy utilities [3];
- Common mode failures, such as the French nuclear outages of 2016 due in part to the carbon content of steel used in steam generators across 18 plants [4];
- Coincidence of independent multiple low-probability low-impact events combining to produce a high-impact event, such as the 2008 power cuts in Great Britain following independent outages of the Sizewell B and Longannet power stations within minutes of each other [5];

Resilience is distinct from – but closely linked to - the concepts of security and reliability, dealing with the consequences and outcomes of an event rather than reduction of the probability of it occurring. As an assessed characteristic of an energy system, understanding and capturing resilience is essential to enacting and incentivising prudent investment which improves the response of an energy system to such events.

Multi-carrier energy systems are those which involve more than one means of transporting energy between supply technologies and demand, and with those carriers in some way coupled through conversion technologies. For example, an energy system which has both electricity and gas networks, with electrical power being used to generate hydrogen via electrolysis, would constitute an energy system with two carriers. While coupled electricity and gas networks (either hydrogen or methane) are the most common area of analysis for such systems, other carriers may include water, heat (as in district heating systems) or biofuels, or may include deeper assessment of demand-side behaviors and energy service demands which may be served by multiple carriers. Such interactions between electricity, the fuel chain, and the transport sector are more and more envisaged or already taking place by means of EV (electric vehicles), bio-fuels and hydrogen-based transport [6].

Multi-carrier systems potentially introduce new failure modes to be considered in the evaluation of resilience. In the case of electricity and gas systems coupled through electrolysis, a disruption in the electricity system can cascade and create a shortfall of supply in the gas system. In the case of the Texan blackouts of February 2021, a common causative factor (extreme winter weather conditions) caused disruption in both the power and gas sectors, with the latter exacerbating the impact on electricity production through unavailability of gas supply to electrical generators.

Cellular power/energy systems are those which are composed of independently-operated 'cells', each maintaining their own local balance of energy but with defined boundary interfaces with adjacent cells. Such cellular

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systems permit the exchange of energy or reserves across cell boundaries without any individual cell operator knowing the detailed state of the other cells with which it is interacting – in this manner the operational control of energy balancing actions and actions taken to maintain security are decentralised.

Cellular systems may exist at multiple levels: such as national transmission grids exchanging power within a large synchronous area; Distribution System Operators (DSOs) independently managing the balance of energy within a distribution zone for electricity or gas; microgrids, including combined heat and power (CHP) systems supplying local electrical and/or heat demand. As this illustrates, cellular systems may be hierarchical as well as spatially disaggregated.

In this paper, we first examine the general concept of energy system resilience and disaggregate it into technical and temporal dimensions (section II). For each of these, we qualitatively assess the steps required to extend resilience - as it is understood in the power sector - to the context of multi-carrier cellular energy systems. We then apply this to the specific 'Web of Cells' concept proposed as a future evolved state of the European energy system, within the context of increasing integration of non-electrical energy carriers (section III). Finally, we outline regulatory principles for the design of future energy systems composed of coupled carriers within cellular topologies (section IV).

II. DISAGGREGATING RESILIENCE

The CIGRE Working Group (WG) C4.47 "Power System Resilience" has formulated a definition of resilience that captures and reflects the behaviour and response of a power system exposed to severe stress and extreme events. The CIGRE WG C4.47 defined resilience as "*the ability to limit the extent, severity, and duration of system degradation following an extreme event.*" [1] This definition is achieved through a set of key actionable measures to be taken before *(*anticipation and preparation*)*, during *(*absorption) and after *(*sustainment of critical system operations, rapid recovery and adaptation) the event. These measures can only be achieved by well-planned, executed interventions to preserve and enhance power system resilience at all phases of extreme events.

As a holistic concept, resilience can also be separated into:

- Infrastructure resilience – the physical strength and robustness of the system via long-term planning to withstand the impacts of an event;
- Operational resilience – the short-term strength of the system through active management to ensure uninterpreted supply to customers;
- Organisational resilience – the availability of staff and business continuity measures to ride through an event or crisis.

Temporal components of a resilient system can be disaggregated into the following properties (adapted from [1]):

- Anticipation: the ability to evaluate and monitor the onset of foreseeable scenarios that could have negative outcomes for the system;
- Preparation: the deployment of measures ahead of a foreseen potential system event;
- Absorption: the ability of a system to minimize or entirely avoid the consequences of an extreme event;
- Recovery: in the event of adverse consequences, the ability of the system to return to a stable state which may be ready to manage the next such event;
- Adaptation: the long-term response of the system to evolve and reduce the impact of future events in response to those experienced or avoided.

In each of these cases, the traditional power system paradigm is for a System Operator with monitoring and control capability across the whole spatial area and at several voltage levels to predict, procure and activate the necessary reserve and response services necessary to achieve each of the above components, with any decentralised actions (such as inertial response and demand disconnection) achieved indirectly in response to deviations in system frequency.

Within a cellular paradigm, however, the following additional dimensions should be considered:

- The availability of reserves to be shared between neighbouring cells may be affected by common modes of failure (such as extreme weather events) and the likely dependencies need to be understood;
- If cells represent a smaller operational unit than under the existing paradigm, the available organisational resource may be significantly smaller, with resulting impacts on the extent of planning and management that may be achieved, and the potential for disrupted business activities during extreme events;
- There may be increased communication infrastructure required to enact recovery across a larger number of decentralised service providers;
- Due to the decentralised nature of system operation, the learning from an extreme event and adaptation for future events may not be disseminated across as broad a number of participants;
- The energy service demand characteristics of each cell are likely to be spatially differentiated and existing models based on large-scale aggregated data (such as after-diversity maximum demand) may not be universally applicable.

Extension of the resilience problem to non-electrical energy carriers also requires the operator to understand the couplings and components which have the greatest impact on the response to an extreme event, defined either at a component or system level. Energy supply vulnerability can be used to quantify and prioritise the impact of extreme events and so feed this into system planning and operation [7]. However, in doing so the differential values of lost load (VoLL) need to be considered for each energy carrier – the value to the end consumer of an interrupted supply of gas, for example, may differ significantly from that of electrical energy per unit energy, and this in turn may also be dependent on external factors such as time of day or weather conditions.

Actions and responsibilities for the above dimensions, assessed within the context of multi-carrier cellular energy systems, are described further within Figure 1.

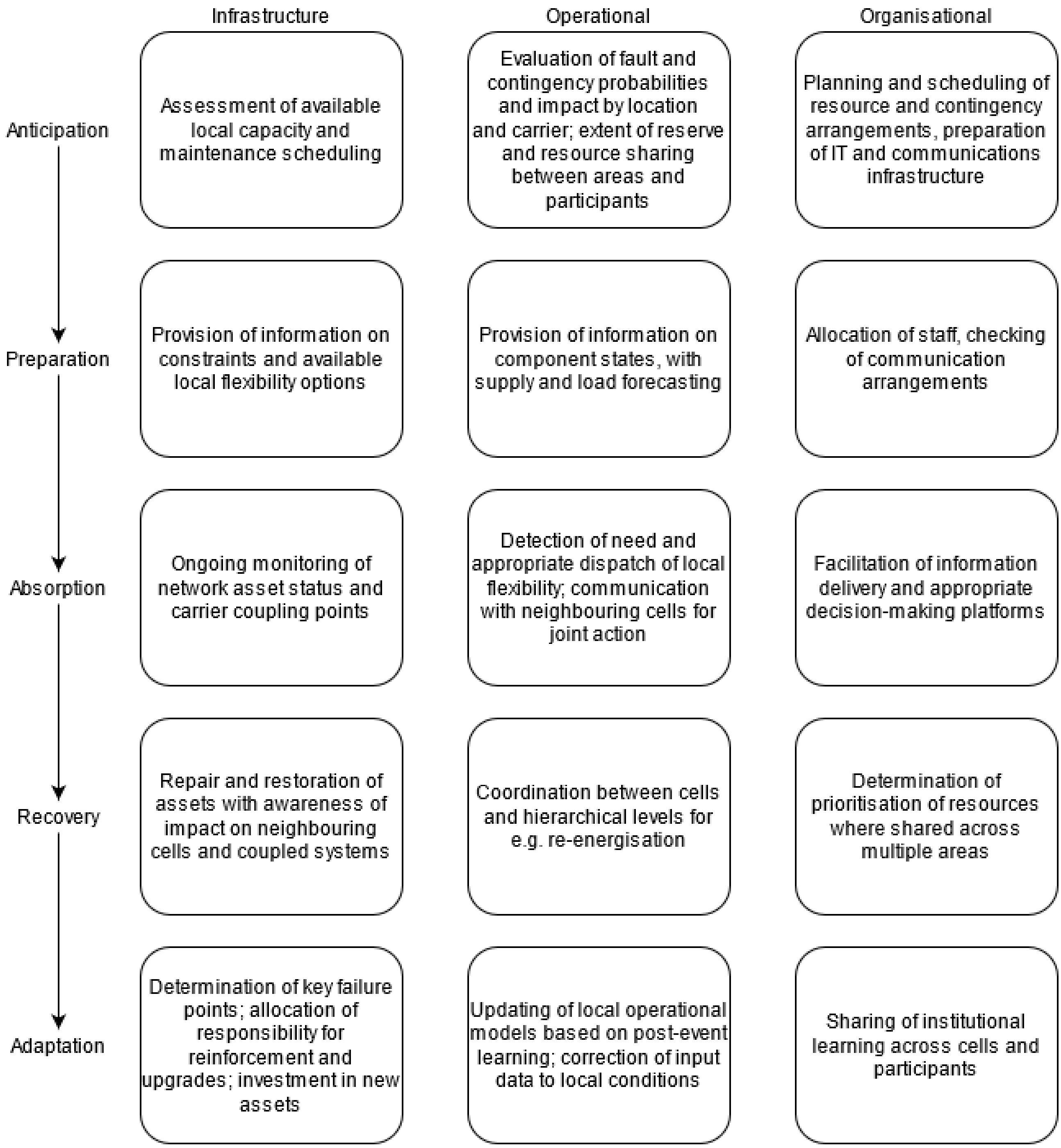

Figure 1 - Disaggregation of the resilience concept within the context of cellular multi-carrier systems

III. The 'Web-of-cells' Concept

A. Overview

In the ELECTRA project, the EU power grid is decomposed into a 'Web of Cells' (WoC) structure, where a cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility available from generators, loads and storage systems. The concept can be summarized as a decentralised control scheme for reserve activations based on local observables, with local collaboration between cells based on local observables (as opposed to global collaboration based on frequency as the global observable).

Control cells are defined as "*A group of interconnected loads, distributed energy resources and storage units within well-defined grid boundaries corresponding to a physical portion of the grid and corresponding to a confined geographical area*." [8] This concept is illustrated in Figure 2.

Within each cell, the total amount of internal flexibility is sufficient to compensate for the cell's generation and load uncertainties in normal operation. Each cell is managed by an automated Cell Controller (CC), under the responsibility of a Cell System Operator (CSO) that supervises its operation and, if required, overrides it. A CSO may oversee one or multiple cells which do not necessarily need to be adjacent.

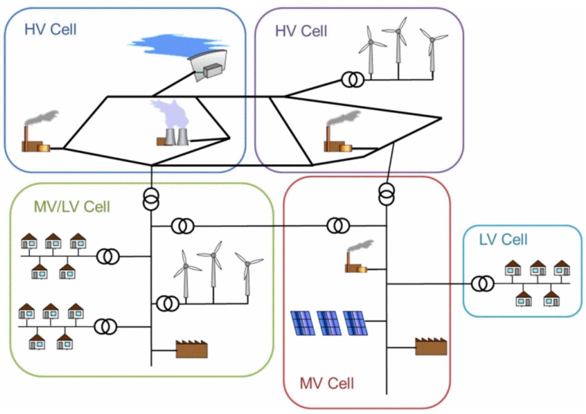

Figure 2 - Schematic illustration of "Web of Cells" architecture (reproduced from [8]*)*

The CSO is responsible for:

- Real-time reserve activation and dispatch within the cell;
- Maintaining an accurate view of the overall cell state, and dispatching local reserves in a secure manner, based on their knowledge of the cell state;
- Containing and restoring system frequency;
- Containing local voltage within secure and stable limits.

The CSO will interface with Balancing Responsible Parties (BRPs) who are responsible for achieving within-market balancing for their individual portfolios, and submit their production schedules to the CSO at market gate closure. On the day of delivery, the CSO takes care of real-time balancing of residual imbalances, and prepares inertia response control, frequency containment control, balancing restoration control and balance steering control. Further details on operational responsibilities are summarized in Table 1.

B. Integration with non-electrical energy carriers

The growing identification of the interdependencies between electricity and other energy carriers has led, in recent years, to the recognition of the need for ‘Energy System Integration’ (ESI) whereby a view of system planning and operation is created which considers all energy interactions. This includes both extant large-scale carriers (such as natural gas, and its associated transmission and distribution), as well as potential new carriers (such as hydrogen and other non-conventional gases), in addition to the inclusion of localised vectors (such as heat networks).

While the majority of such assessment is still in the R&D context, there is a growing recognition by European regulators that the historically separate regulation of energy carriers may not be appropriate under future energy scenarios, and that joint regulation between carriers and sectors may represent a means to a lower-cost energy system in total. This also permits the provision of final demands through different vectors (such as comparing fuel cell to electric vehicles) to be more effectively compared and balanced according to the demands placed on individual carrier infrastructure.

TABLE 1 - CELL OPERATIONAL RESPONSIBILITIES FOR RESERVE ACTIVATION AND DISPATCH

WoC Responsibility	Details
Provision of generation/load forecast information for cell balance setpoints	Generation/load forecasts are made by entities, such as the large-scale Balance Responsible Parties, receiving all necessary information from their large-scale generating and load units, and the aggregators, who collect all necessary information from the small-scale BRPs who themselves are supplied with data by small-scale generating and load units
Provision of information on cell tie-line constraints	CSO responsibility for grid model information
Procurement of flexibilities for the next time-step	CSO responsibility for procurement of balancing and voltage control services
Collection of grid model and grid status information	Can be achieved via direct management of metering infrastructure by the CSO, via a shared data repository, or provision of data via an independent/certified body
Combination of grid model/status and generation/load forecast information	BSPs responsible for providing balancing and voltage control services, may be via an aggregator
Detecting the need for / activating a balancing control service	Allocated under the responsibility of CSOs (current TSOs) based on the cell imbalance observation and event location
Detecting the need for / activating a corrective voltage control service	Allocated under responsibility of CSOs based on the measurements from the metering devices
Decision on adaptation of cell tie-line setpoints	Allocated under the responsibility of CSOs. Neighbouring CSOs require a coordinated decision process whereby the optimal tie-line set-point is determined independently and confirmed between CSOs based on information previously exchanged

In the scenarios prepared for the 2020 ENTSO Ten Year Network Development Plan (TYNDP - [10]), joint scenarios have been created which identify the co-dependency between the gas and electricity sectors and the need for a consistent view between the two sets of regulators. Key elements include:

- Assessment of the impact of power-to-gas (P2G) in terms of increasing utilisation of renewable generation and the injection of green gas;
- Alternative trajectories in the decarbonisation of transport, particularly with respect to peak demand in the two sectors;
- The decarbonisation of the domestic heating sector (conversion of fossil fuel heating to electric heat pump heating or hybrid heat pump heating) increasing electricity consumption and decreasing gas consumption in the residential and commercial sectors;
- Changes to gas-fired power plants fuel consumption due to electricity production from renewable energy sources;

- The growth of the "prosumer" and new patterns of energy consumption and generation at all levels.

The TYNDP identifies a concept labelled as the 'thermal gap' - a demanded volume of electricity which may be supplied by either coal or gas under different market conditions. This creates a potential for dispatch decisions within the WoC concept, which may require knowledge of the status of the gas system (beyond that communicated indirectly by WoC assets).

Secondly, coordination of WoC actors, under scenarios where heat and transport have undergone increased electrification (through heat pumps and EVs respectively) may require improved forecasting methods to understand the major swings in demand out-turn that will become more pronounced and more frequent. The maintenance of system security (with consequently broader impacts resulting from failure) means that WoC actors might be expected to predict and prepare the system to maintain security considering greater detail in the probability of different line flows and potential outages.

Third, the integration of energy carriers by WoC actors will also permit additional future sources of flexibility which encompass interactions with other carriers (e.g. heating, cooling or vehicle-to-grid), and how they might be regulated within the WoC structure.

The regulatory aspects of Energy Systems Integration are only beginning to be explored, but the growth of interest in this area from European regulators (see for example, the British regulator's scoping for a 'smart flexible energy system' [11]) indicates that the WoC concept needs to be introduced with consideration of the mutual visibility and forecasting requirements of actions within other carriers. It should be noted that, at core, the WoC concept is potentially portable to other carriers and extensible to consider multiple vectors in parallel, and that the growth in integrated regulation can be matched by a similar application of parallel carrier-specific cells.

C. *Extension of resilience principles to non-electrical energy carriers*

The above electrical considerations map closely to other energy carriers. The requirement for the instantaneous balance of supply and demand to be maintained may be relaxed for non-electrical carriers; the implicit buffering/storage of e.g. gas and heat systems may reduce the operational complexity. However, the broad principles of managing local balancing remain.

There may, instead, be longer-term considerations to manage, such as the substantial time taken for interruptions in supply to cascade through the different pressure levels of gas networks, and so a longer-term view on control and restoration may be needed than for electrical networks alone. This in turn has implications for the organisational resource required to manage extreme events.

A key organisational aspect will be determining if each energy carrier can be managed independently by a CSO equivalent, or whether a multi-energy CSO role is required to coordinate all of the above responsibilities. As the topology of different energy carriers may not disaggregate to the same arrangement of cells, then the disparities in cell configurations for different carriers will need to be considered and adopted into system management.

IV. Regulatory principles

On the basis of the above assessment, we make the following recommendations for establishing resilient multi-carrier cellular energy systems. As these are a relatively novel area of investigation, these are intended as high-level initial considerations, with the expectation that these will be further developed as the modelling and implementation of such systems evolves.

As the topologies of networks for different energy carriers is likely to vary significantly, assessment will be required of the need for multi-energy cell operators against independent carrier-specific operators acting in tandem. As multi-energy coupling is driven in many cases by the underlying electrification of energy service demands, it may be appropriate for the key coordinating role to lie in the electricity system.

Existing metrics for determining impacts of extreme events and prioritizing preparation and response do not consider the variance in value to the end consumer of different carriers. Any assessment which aims to prioritise the supply of different carriers must correctly assess any differential, also considering that there will be a difference in the extent to which an interruption of supply affects end energy service utilisation.

Organisational resilience is as important as technical or operational considerations, and many of the larger extreme events which may require an operational response can cause wider-spread societal disruption which may impede recovery and adaptation. Organisations should have business continuity arrangements which consider this potential, as well as the means by which carriers may impact each other over longer-term disruptive events. In the case of cellular systems, due to decentralization the organisations involved may be significantly smaller and have a reduced possibility for organisational redundancy, and this capability should be considered when allocating responsibilities.

There is strong institutional knowledge around the nature and frequency of extreme events that may impact energy systems. In introducing new participants to an existing system – either as operators of assets utilising other carriers, or as disaggregated actors within cellular systems – this baseline knowledge can be used to interpret the particular challenges of operating a novel energy system, and it is not necessary to build a working understanding of the resilience of that system from zero. For example, 'war gaming' of known scenarios between cells operators can uncover previously unknown vulnerabilities.

Lastly, multi-carrier and cellular systems strongly imply increased operational complexity, requiring greater data and communications requirements. Mechanisms for data exchange and management will need to be designed rigorously ahead of time. As many of the potential failure modes of carrier-coupled systems will not have been experienced prior to establishing such systems, there is likely a strong role for theoretical research and systems simulation to provide the evidence base needed for designing resilient systems, so wider data availability and openness should be a key principle of system evolution.

REFERENCES

[1] Ciapessoni, E., Cirio, D., Pitto, A., Panteli, M., Van Harte, M., Mak, C. (2019) "Defining power system resilience" *ELECTRA* (306) pp32-34.

[2] Hawker, G., Bell, K. (2021) "Preparing for a resilient energy future: learning from Texas' rolling blackouts" *UK Energy Research Centre*. Online at: https://ukerc.ac.uk/news/preparing-for-a-resilient-energy-future-learning-from-texas-rolling-blackouts/

[3] Panteli, M, Van Harte, M., (2020) "Rethinking power grid resilience: experiences and lessons from the COVID-19 pandemic" *e-CIGRE*. Online at: https://www.cigre.org/article/GB/rethinking-power-grid-resilience-experiences-and-lessons-from-the-covid-19-pandemic

[4] "France's nuclear storm: many power plants down due to quality concerns" Power Magazine, December 1st 2016 issue.

[5] Ofgem (2008) "System Events of 27th May" Online at: https://www.ofgem.gov.uk/sites/default/files/docs/2008/07/national_grid_-_system_events_of_27_may_for_dswg_16_july.pdf

[6] Mancarella, P., Andersson, G., Peças-Lopes, J. A., & Bell, K. R. W. (2016). "Modelling of integrated multi-energy systems: drivers, requirements, and opportunities" *Paper presented at 19th Power Systems Computation Conference, Genoa, Italy*. 10.1109/PSCC.2016.7541031

[7] W. Huang *et al*., "Reliability and Vulnerability Assessment of Multi-Energy Systems: An Energy Hub Based Method," in *IEEE Transactions on Power Systems*, 10.1109/TPWRS.2021.3057724

[8] R. D'hulst *et al*., "Voltage and frequency control for future power systems: the ELECTRA IRP proposal," *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, 2015, pp. 245-250, 10.1109/SEDST.2015.7315215

[9] Di Somma, M., Valenti, M., Ciavarella, R., Graditi, G., Merino, J., Riaño, S., Hawker, G., Carlini, C., Bobinaite, V., Cornez, L., Gatti, A., & Canevese, S. (2018). "Analysis of necessary evolution of the regulatory framework to enable the Web-of-Cells development" *ELECTRA.*

[10] ENTSO-E (2020) "ENTSOs TYNDP 2020 Scenario Report" Online at: https://www.entsos-tyndp2020-scenarios.eu/

[11] HM Government and Ofgem (2017) "Upgrading Our Energy System: Smart Systems and Flexibility Plan" Online at: https://www.ofgem.gov.uk/system/files/docs/2017/07/upgrading_our_energy_system_-_smart_systems_and_flexibility_plan.pdf