Title	Geospatial Visualisation Techniques for Transmission System Needs Identification: A Case Study with High Shares of Distributed Energy Resources
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Publication date	2020-09-03
Publication information	Daly, Pádraig, Jeff Kelliher, and Paul Cuffe. “Geospatial Visualisation Techniques for Transmission System Needs Identification: A Case Study with High Shares of Distributed Energy Resources,” 2020.
Conference details	The 48th CIGRE Session, Virtual Conference, 24 August - 3 September 2020
Item record/more information	http://hdl.handle.net/10197/12143

Geospatial Visualisation Techniques for Transmission System Needs Identification: A Case Study with High Shares of Distributed Energy Resources

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SUMMARY

This paper presents the principles of a mapping and network visualisation tool in development at the transmission system operator (TSO) of Ireland. Employing a set of Python packages, its intention is to aid planning engineers to explore, understand and communicate power system analysis results by providing more meaningful network diagrams.

In order to illustrate the guiding design philosophy, the business process of scenario-based network investment needs identification is used. This process involves building alternative, multi-decadal pathways for the electricity system, which generates a significant volume of data and hence sense-making burden. Given that data-visualisation choices can obfuscate or mislead, how such data is represented can have a bearing on whether actionable insights are garnered. While planning knowledge guides the visual communication, the principles presented should prove useful to the synthesis of any power system subject matter and visualisation; graphic design could be effectively employed when communicating key messages to decision-makers, as ultimately the most important aspects of any analysis must be *shown*.

A significant topic in its own right, the application of visualisation techniques in the field of power systems is low compared to other scientific fields. The paper thus proceeds with a treatment of the extant forms of visualisation currently employed by the power systems community. Rationale and notes on the selection of geographic maps and information dashboards as means for visualising power system data – including the multi-dimensional data of distributed energy resources – are then provided.

KEYWORDS

Distributed energy resources (DER) – Power system planning – Python programming language – Visualisation.

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1. INTRODUCTION

This paper presents the design principles of a visualisation tool under development by the transmission system operator (TSO) of Ireland, employing the use case of network investment needs identification. Rationale for developing such a tool include:
Open-source and flexibility: employing HoloViz[1] [1], the tool is designed so that it can visualise power system data/simulation results independent of the commercial power system software package used, in order to cater for teams across the TSO.
Communication and reporting: the tool can create geographic maps that are accessible for a number of stakeholders. Techniques are employed so that members of governance committees and readers of public-facing TSO planning reports can readily understand the information. While commercial power system software packages do offer to some extent the possibility for geo-aware single-line-diagram-based visualisation, such data is linked to a simulation case and hence to a single system snapshot. In contrast, using the HoloViews [3], GeoViews and Panel libraries[2], the tool presented can:

- summarise thousands of snapshots;
- create an interactive dashboard, with the Panel library. This allows for inputs to be juxtaposed with the outputs of power system analysis, which assists the investigation of relationships within the dataset, e.g. between the unit commitment and economic dispatch (dispatch) and a network investment need (need).

Large data set exploration: the relatively high level of uncertainty in the investment planning timeframe calls for multiple scenarios and solutions to be analysed [4]. The ability to explore this data is key to fully exploiting future scenarios and hence better avoids captured decisions.

1.1 Literature review
A map is an intuitive way to represent a power transmission system, which has both a geographic and an electrical structure [5]. However, it can be challenging to draw intuitive networks diagrams for displaying power system data, which can be large, complex and multi-facetted [6]. This impedes sense making for operators and planners. Indeed, creating meaningful and attractive choropleth maps is known as a challenging problem in general [7], and the particularities introduced in the power system context have not been exhaustively studied. Various examples exist that describe the augmentation of power system diagrams with colour maps, symbols, animations and other visual devices to portray relevant data (voltages, loadings, outages, fault propagation etc.) [8–10]. Some authors have noted the lack of a “best practise” for the design of power system control room overview displays, with excessive clutter and overuse of colour cited as recurring problems [11]. The work of [12] aside, there seems to be a research gap surrounding visualising power system data connected with expansion/scenario/investment planning.

Work in [13] uses flow fields to visualise aggregate power flows in large networks. Work in [14] proposes automated techniques for positioning nodes in a network one-line diagram, seeking to maximise visual neatness and logical clarity without unduly distorting geographic positioning accuracy (see also [15]). The authors of [14] make a compelling case for

[1] HoloViz is a set of open-source Python [2] packages for coherent data analysis and visualisation.
[2] HoloViews, GeoViews and Panel are some of the libraries provided in the HoloViz ecosystem. HoloViews provides a set of data structures paired with a separate plotting system to render data; GeoViews extends HoloViews for geographic representations; Panel allows for such plots to be laid out and connected with widgets to create custom inerative web apps and dashboards. Where the dataset to be plotted has more than 1e5 or 1e6 points, the Datashader library can be employed to pre-render the data in Python, before displaying it in the web browser.

well-designed network diagrams: *"Diagrams for electric power networks aid system analysis; they complement numerical data with a visual context."*

For certain analysis tasks, it may be appropriate to abandon the network's geographic representation altogether, in favour of a diagram that better emphasises its electrical structure [16] or connectivity [17]. There are a number of existing algorithms for laying out arbitrary networks in a clean way, and these have been successively applied to creating non-geographic layouts of electrical power systems [18]. For instance, if the prevailing power flow disposition of a system is of interest, it may be insightful to use a Sugiyama graph layout [19], which positions nodes such that power flows uniformly from the top to the bottom of the diagram, as in [20].

2. CASE STUDY

The first step of the TSO of Ireland's grid development framework involves assessing how the transmission network performs against its planning reliability criteria [21] under credible future pathways for the electricity system. The outcome of this screening study is a set of scenario-based needs, shown at network-element and area levels. The presented tool plays a key role in showing the scale of needs, in delineating the boundary of the need areas, and in confirming the causal factors of each need. While scenario-based needs identification is the chosen use case, the visualisation tool's application can be beneficial in many aspects of power system planning.

Given the uncertainty and hence potential margin for error in the planning timeframe, multiple future scenarios are designed and employed. These scenarios [22] should reflect Government policy, stakeholder feedback, and market/technology trends across the electricity and energy sectors. For example, factors such as the rate of decarbonisation, distributed energy resources (DER) uptake and demand growth are coherently varied across scenarios. Such range facilitates planners to test the performance of solution options against different future outcomes.

Once the scenario portfolios are designed, hourly-resolution dispatch modelling of these portfolios is conducted. These schedules are used to initialise a myriad of simulated network performance tests, e.g. ac contingency analysis. To get a feel for a typical dataset arising: a power flow simulation is conducted for a set of more probable N–1 contingencies (~800 events, including circuits, generators, loads and interconnectors) as well as for the intact network case, for each schedule time-period (8,760 hours) in the study years (3) of each scenario (3). In comparison to employing merit-order dispatch for a small selection of envelope demand cases, e.g. winter peak and summer valley, time-series power flow simulation provides a more detailed comparison of scenarios, by determining the timing and frequency-of-occurrence of thermal loading or voltage issues. Such data can be used to gauge the credibility of an issue.

For each contingency, any transmission network element (~400 circuits and 250 substations) that performs outside of the relevant planning reliability criteria is recorded as a violation. As in [23], violations for circuit thermal loading, substation low and high-voltage range and step are considered here. For each element in each scenario-year time-series power flow simulation, the following is recorded: the number of violations, the worst-case violation magnitude, the contingency that results in the worst-case violation magnitude, any other contingencies that cause a violation, and the hour of the dispatch for which the worst-case violation magnitude occurs. Knowledge of the dispatches (both demand and supply sides) and the contingencies that influence a violation allows for these elements to be coherently grouped into network areas that contain a need arising from the same set of circumstances, while also capturing that the scale, prevalence and timing of a violation changes depending on the scenario. This area-derivation process facilitates more detailed, local solution-optioneering studies.

3. GEOSPATIAL VISUALISATION OF SIMULATION RESULTS

An illustrative example of a map employed for needs communication is shown in Figure 1, which is an ensemble of the worst-case thermal-loading violations across simulated network performance tests for Coordinated Action, which is the TSO's most decentralised scenario (see [22], [23] for details).

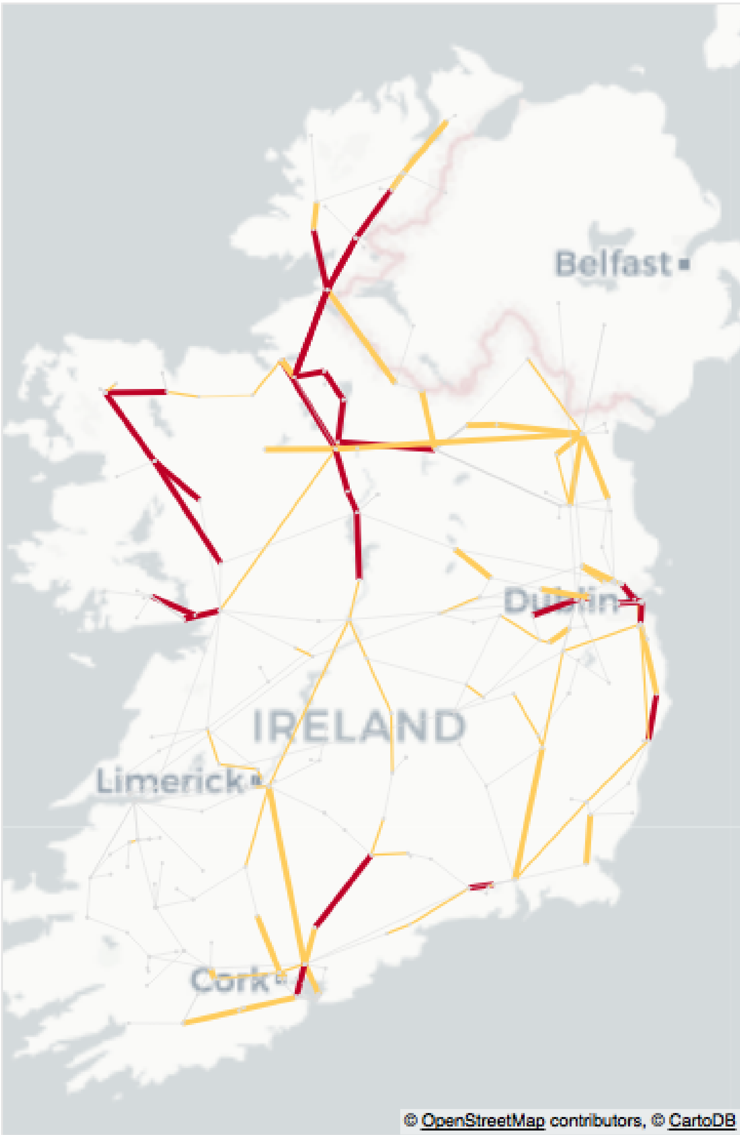


Figure 1: Geographic map superimposed with an ensemble of worst-case thermal loading simulation results.

In Figure 1, any circuit not grey in colour indicates a planning-criteria violation. Given the negative connotation, colours associated with positive outcomes, e.g. green, should be avoided. Given that the map is for communication purposes, the data is categorised to improve understanding, using subject matter knowledge in order to inform the visualisation.

3.1 Thermal-loading violations

To legibly display continuous numerical data on a choropleth mapping, it is often helpful to first bin the data into a small number of categories. Different methods exist for selecting suitable break points between classes in empirical data sets [24]. For instance, it is often desirable that each class contains a similar number of data points. Indeed, some authors have suggested that specifying appropriate class breakpoints is among the most important problems facing the designer of a choropleth mapping [7], [25]. For the present purposes, prior expert knowledge about the severity and relative frequency of prospective circuit overloads is used to define different categories of severity: these breakpoints are not derived empirically. However, it is desirable to show two dimensions of potential overloading for a circuit: the *frequency* that such problems manifest across the planning scenarios, and the *extent* of the overload that occurs. As shown in Figure 2, a design decision was taken to encode the former dimension using two distinct line thicknesses, with the overload extent encoded using two categorical colourings. Due to its intuitive association with problematic or dangerous conditions, a red hue is deemed suitable for emphasising circuits overloading in simulations. The ColorBrewer [26] catalogue of colour maps provides a five-class perceptually linear progression of yellow-orange-red tones (YlOrRd), and the second and fifth entries of this were selected, as shown in Figure 2. The darker shade clearly flags those circuits that experience heavier overloading. Likewise, circuits experiencing such effects at a "*Common*" frequency are drawn with a line thickness three times thicker than the "*Rare*" class, to add significant visual weight and draw attention to these elements of the diagram.

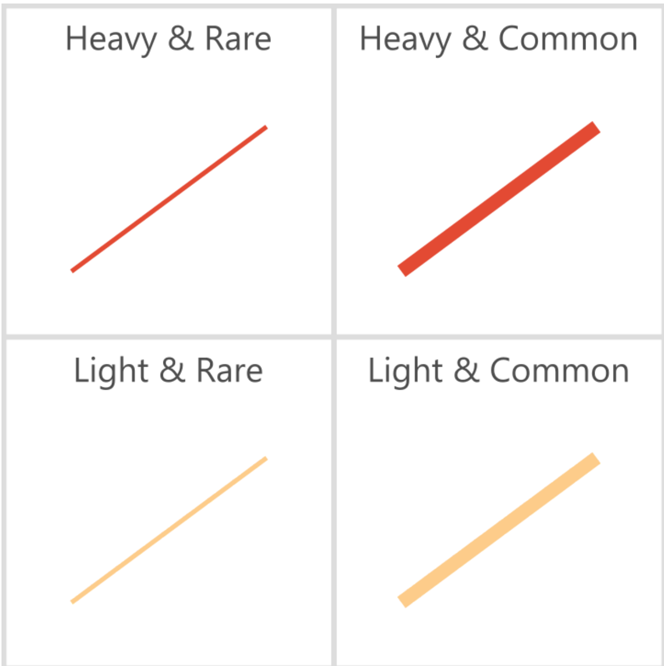


Figure 2: Thermal-loading violation categories.

The thermal-loading violation magnitude breakpoints were selected as:

Light overloading: >110% <=150%: a breach that could be – if not already – solved by uprating the existing circuit if the circuit is an overhead line. If the line is already uprated, a solution equivalent to a new local circuit may be required. Flexible ac transmission systems (FACTS)-based solutions may allow for a rebalancing of local power flows across a set of circuits, reducing the new-build requirement. The planning criteria threshold for N-1 performance tests is 110%. Modelling any circuit emergency ratings is also important in order to prevent false-positive violations occurring.

Heavy overloading: >= 150%: a breach that a local solution may not fully alleviate. Such magnitudes point to portfolio changes beyond that of typical load growth or the connection of a nearby generator; instead pointing to changes of a scale that create an inter-regional power transfer deficit.

The thermal-loading violation frequency-of-occurrence breakpoints were selected as:
Rare: >5 <= 100: These conditions – depending on the scale of the violation consequence – may not warrant an investment case, instead are best dealt with via redispatching in the operational timeframe given their low probability. In a given study year, breaches occurring for less than 5 times are deemed outliers.
Common: > 100: breaches that occur often enough in the time-series simulation to be diagnosed with certainty as a frequent violation. Some frequency-of-occurrence values can reach into the thousands for a study year; such breaches, if unaddressed, could cause significant congestion redispatch costs.

3.2 Voltage violations
The inclusion of voltage violations is ongoing. For steady-state analysis, four main types of voltage violations are typically appraised under the planning criteria: range and step violations in both the high and low directions. Assuming thermal-loading violations have not caused them, a range violation indicates a lack of local voltage control capability; a step violation can indicate a lack of system strength or an overdependence on a single source of reactive power.

The multiplicity of violation types at a given substation creates visualisation challenges: a symbol for each violation type leads to the possibility of four symbols being superimposed on a single node. Instead, as shown in Figure 3, a composite marker symbol is designed, under the following principles:

- Directionality of the voltage issues must be intuitively understood. This is encoded with arrow tips. Further, higher weighting is given to voltage violations occurring in both directions, as it denotes the potential need for leading and lagging reactive power provision. This is encoded by a larger marker size.
- A voltage step issue tends to be of a higher order than a voltage range issue, as it indicates a more vulnerable part of the network. This is encoded with a darker hue.

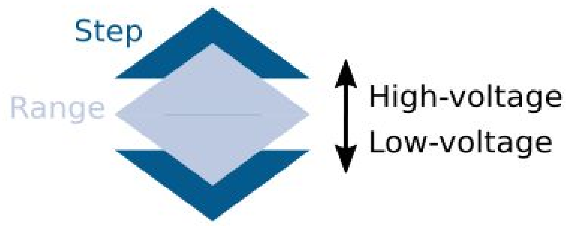
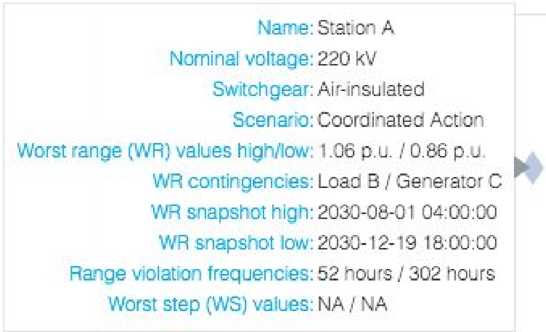


Figure 3: Voltage violation categories.

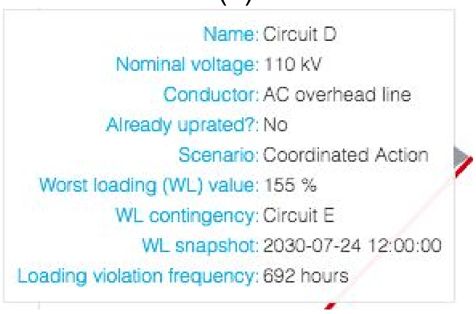
Given that a voltage violation at a load bus indicates the possibility of a security-of-supply issue and given that the planning criteria does not prescribe load-shedding to resolve N-1 issues, just one instance of a voltage violation has the potential to degrade system reliability, particularly if the violation occurs in the vicinity of a critical load centre. As a consequence, it is intended that all voltage violations be shown. Thus, while frequency is included as part of the hover tool parameters (see Figure 4), it is not included in the visual design for the voltage symbol.

3.3 Display mechanisms for supplemental information
Due to the use of the extension to the Bokeh plotting library [27], additional information can be revealed via user interaction. For example, when the cursor is placed over a station or circuit on a map such as Figure 1, tabular data of the form shown in Figure 4 is displayed.

Such functionality adds value by supplying a richer understanding of the data, without distracting from the primary message of the map.



(a)



(b)

Figure 4: Annotation revealed when the cursor is placed on a given (a) station and (b) circuit.

Figure 1 can be further complimented by a visual representation of the dispatches associated with each planning-criteria violation. When a station or circuit in Figure 1 is selected via tapping a touchpad or left clicking a mouse, an adjacent plot showing the hour of the relevant dispatch can be reactively updated. Figure 5 shows the design of this dispatch representation, which is a bar plot displaying two values for each category shown: the dispatched quantity (coloured fill) and the installed capacity (bar edge). The dispatch quantities are annotated on the bar plot itself, which quickens the comprehension of information by removing the need to compare against a horizontal axis. The supply categories chosen are those that have distinct availability time-series and an appreciable impact on needs. Other categories, e.g. ocean generation or storage in this case, may not be of sufficient scale to warrant inclusion. The dispatch representation could be further improved by breaking the dispatch data into a regional level and creating multiple plots suitably located around Figure 1. For Ireland, North-West, South-West, South-East and Dublin (and surrounds) provide quasi-aware transmission-network groupings.

Interactive annotations, including any explanatory text to guide the user, are often overlooked as an effective way to provide key information without cluttering the visual [28].

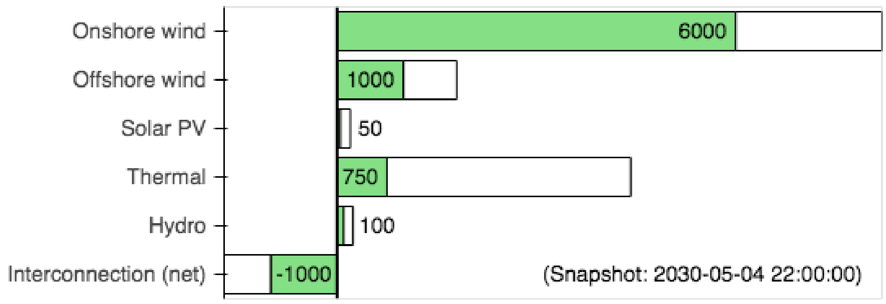


Figure 5: Horizontal bar plot employed for representing the dispatch.

4. DISTRIBUTED ENERGY RESOURCES

DER is an umbrella term for a source or sink of power located on the distribution system, typically small in scale, including: distributed generation, e.g. solar photovoltaics (PV) and combined heat and power (CHP); energy storage, e.g. thermal and battery; electric vehicles (EVs); demand-side management [29]. Traditionally, this heterogeneous resource mix was deemed non-dispatchable, although aggregator participation in the energy or system services markets may change this.

A TSO planning engineer is likely to have approximate data about DER, due to heretofore-low uptake and hence historical data, or due to a lack of metering or telemetry. There is also significant uncertainty with regard to future population, technology, location and behavioural aspects. Given such uncertainty, different assumptions should be taken across any future scenarios employed. For example, taking EVs as a candidate DER technology, varying:

- the levels of consumer adoption and participation (the latter via applications);
- the available tariff structures, e.g. time-of-use or dynamic, and hence impact on the temporal component of charging demand;
- the technology efficiency gains;
- the nodal/spatial allocation of charging demand.

Irrespective of the sophistication level employed, a planner should understand how changes in such assumptions affect their simulation results. Discussion and convergence, if possible, of DER assumptions with the distribution system operator (DSO) is preferable.

Given the multi-dimensional nature of the data, a dashboard could be an effective tool for a planner to explore how DER assumptions impact upon system performance. As defined by [30], a dashboard is *"a visual display of the most important information needed to achieve one or more objectives, consolidated and arranged on a single screen so the information can be monitored at a glance."*

Figure 6 shows a dashboard for EVs. Selecting a scenario and entering a snapshot time stamp updates the data in the adjacent plots. The line plot shows the hourly variation of EV demand across the day. For the chosen snapshot (hour), the left-hand map portrays the spatial distribution of EV demand across transmission nodes (although modelled at the distribution level in power flow, EV demand has been mapped to the nearest transmission station). The right-hand map portrays any simulated voltage violations at these transmission nodes for the same hour. By moving the "Hour of Day" slider, a planner can change the hour and hence system EV demand-level examined, and consequently can see the change in nodal demand and the occurrence of low-voltage range violations (the data similarly updates if the “Scenario” or “Snapshot Selection” year, month or day is changed).

As recommended by [16], due to *“[the possibility that the] interpolation process can create artefacts … [and that] voltage is only meaningfully defined for each bus,”* we avoid the use of interpolation techniques to convert voltage values into a continuous heat map overlaid across the system. For nodal EV demand, a perceptually linear colour map is applied at each transmission node. For low-voltage range violations, a binary system is employed, showing only transmission nodes with EV demand that exhibit that violation for the selected snapshot.

Widgets to include other DER technologies could increase the dashboard’s scope. Additional information can be added to the dashboard, e.g. text and tables describing underlying assumptions. However, care is needed to ensure that additional information does not clutter and thereby weaken the visual communication.

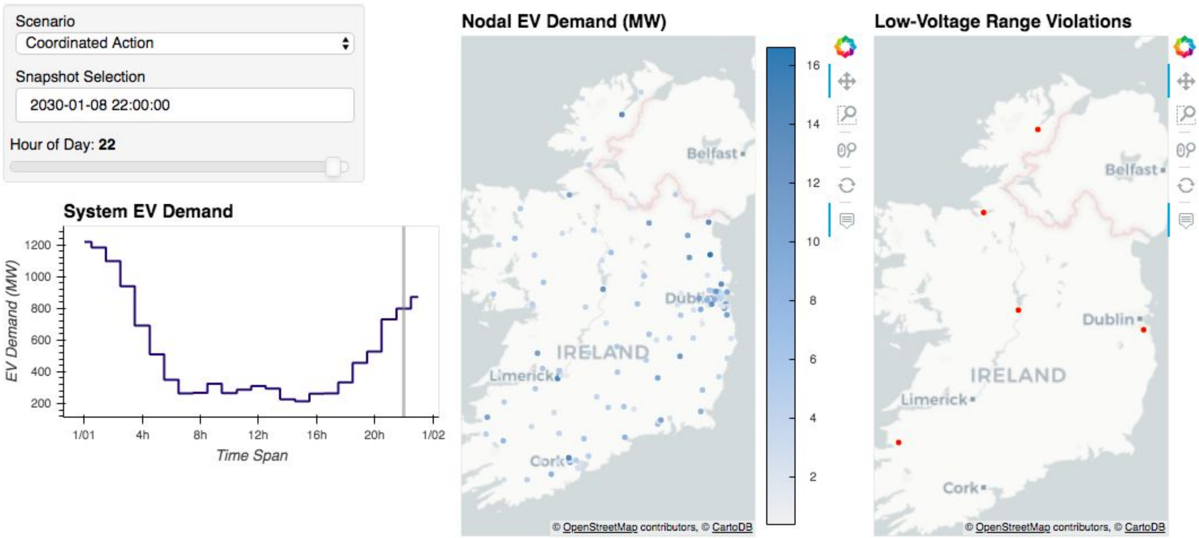


Figure 6: Dashboard of EV data and their impact on low-voltage range violations.

5. CONCLUDING REMARKS AND FUTURE DIRECTION

Open-source software enhancements [1] have lowered the barriers to producing quantitative maps and information dashboards, which, if encoded meaningfully and selected effectively, can be cogent forms exploring, understanding and communicating the outcomes of power system analysis. However, poor visualisation choices can lead to incorrect conclusions, ultimately undermining decision-making. In order to redress this, and given that engineers typically receive no training in graphic design or visualisation theory, an overview of the principles applied to a network visualisation tool is presented.

Scope for future work includes object-orientated programming development, the extension of the tool to display other data, e.g. variable renewable energy source locations, and network assumptions (reinforcements, maintenance). Future visual design additions include representing power-flow directionality on geographic maps, laying out the network to improve graphic clarity, and linking with other databases and simulation types (dynamics).

ACKNOWLEDGEMENT

This work has emanated from research conducted with the financial support of Science Foundation Ireland under the SFI Strategic Partnership Programme Grant Number SFI/15/SPP/E3125. The opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Science Foundation Ireland.

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