Mapping the service areas of Great Britain's electrical infrastructure for whole systems energy decarbonisation

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Aim: To demonstrate the value of electrical infrastructure service areas as fundamental geographical units for aggregating data

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Substation boundary calculation methods

- The distribution level electricity network (132 kV and below) in Great Britain (GB) is operated by 6 Distribution Network Operator (DNO) companies in 14 licence areas. Each organisation has its own data platforms and architecture, although greater standardisation and interoperability will be needed for robust energy systems modelling across the country. An important consideration for any model would be which buildings connect to which pieces of electrical infrastructure (e.g. substations), as the types of buildings connected drive the demand on the substation and influence how this would change in a decarbonised future. This is intrinsically a geographical challenge because it involves drawing a polygon on a map around a point representing the substation, to show the boundary of the area served by it.
- The raw data (e.g. lookups from specific addresses to specific parts of the network) exist in legacy formats, which have been sufficient to meet the operational needs of DNOs. However, increased focus is needed to produce sets of accurate boundaries for bulk download at all voltage levels of the network, particularly for energy systems modelling. As a result, DNOs use geometric techniques and other methods to estimate their substation boundaries. In 2023, the lowest voltage substations with data availability across all DNOs (and monitored power flow data) are primary substations which typically output at 11 kV with a capacity of 2.5 – 30 MVA and provide power for 5,000 – 10,000 dwellings.
- The methods for producing primary substation boundaries vary by DNO; 4 out of 6 companies use Voronoi polygons. In this algorithm, polygons are created from points such that each polygon encompasses the region which is the closest to its corresponding point (edges are part of the lines of equidistance from two points). A Voronoi layer is first made for the smaller secondary substations, which is then aggregated to make the primary substation boundaries based on the upstream connection of each secondary [1]. The remaining DNOs use internal address data to create boundaries based on either postcodes or census output areas. In this work, for the first time, the 14 licence area's 4436 primary substations have been compiled into a single open dataset for GB. We believe that this is a powerful tool for energy systems analysis, as demonstrated by the use cases below, and makes the case for the creation of polygons related to energy infrastructure across the world.

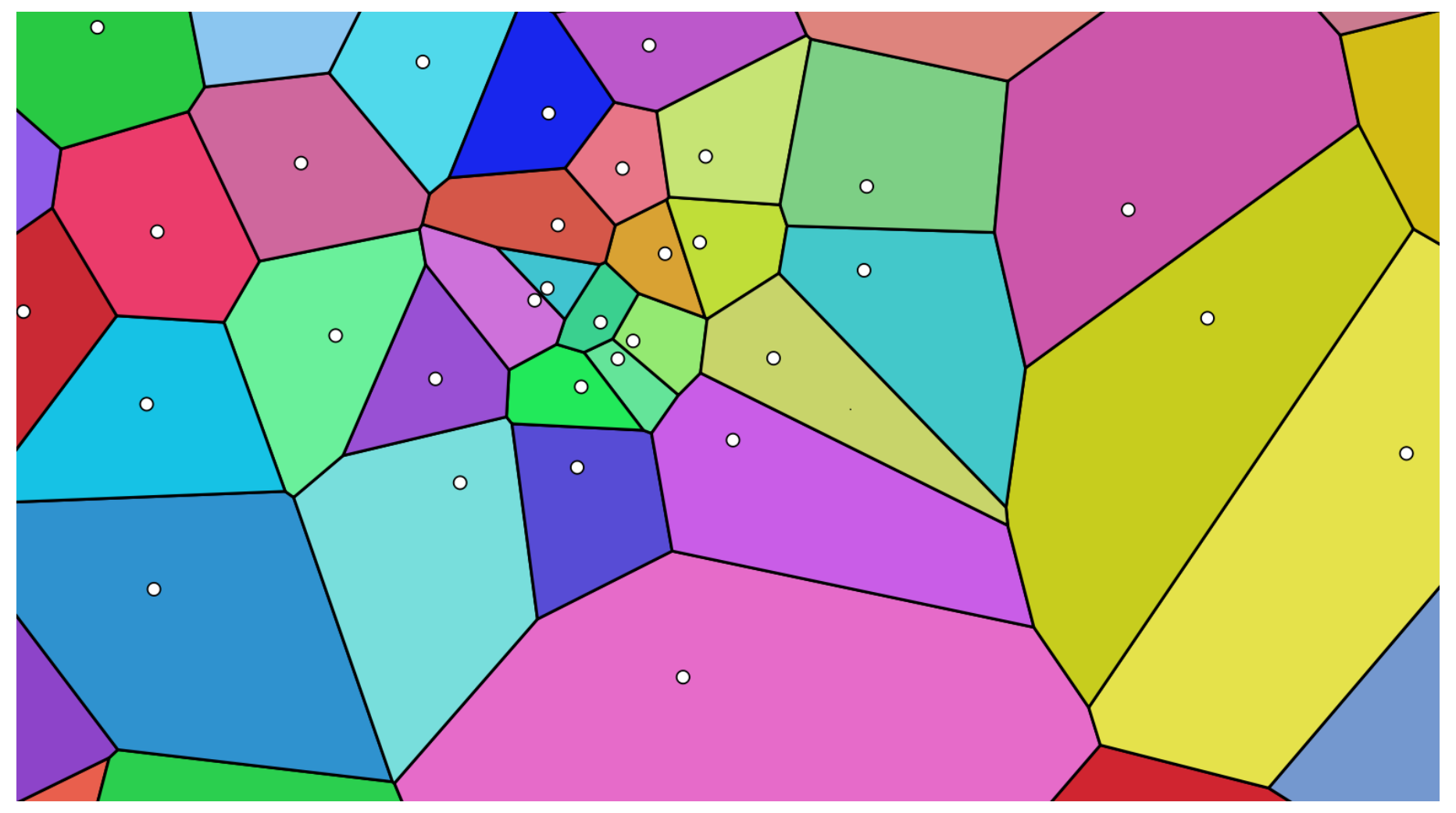


Figure 1 – Example of Voronoi polygons in the 2D plane. Each point represents a substation and each coloured polygon, the region closest to that point [1].

Technical and data challenges of energy decarbonisation

- Direct natural gas combustion is the main heating fuel for 85% of dwellings in GB which is not compatible with the government's 2050 net-zero target [2]. Electric heat pumps (and a decarbonised power grid) are a potential solution with 55-72% of homes expected to use a heat pump by 2050 (up from 2% today) [3]. The technical challenge of providing this energy through the electricity system is demonstrated in Figure 2 which shows the daily GB electricity and gas demand from 2016-23. Were cold weather spikes in demand (such as those in March 2018) to occur in a decarbonised future, it would likely increase the daily electrical demand > 1 TWh (e.g. doubling the demand without even considering the simultaneous electrification of transport), presenting many challenges for the infrastructure [4].
- As well as at a national scale, managing this demand would impact all levels of the electrical network. Substations are limited in their capacity to provide power, so might need costly reinforcement, were other flexibility or low-carbon technology solutions not able to implemented (such as energy storage, time-of-use-tariffs, hydrogen or district heating).
- Open data has recognised value in the energy sector for helping design the future systems and allowing planners to consider these challenges holistically. An important subset of this data landscape is geographical information relating to the areas served by electrical infrastructure, while another component is time-series data of the monitored power flows through the same infrastructure. In combination, these can be used to determine bespoke solutions for different areas based on the underlying data. Ultimately this could lead to a lower cost transition to net-zero, although data gaps exist (e.g. larger areas tend to have much higher granularity time-series data).

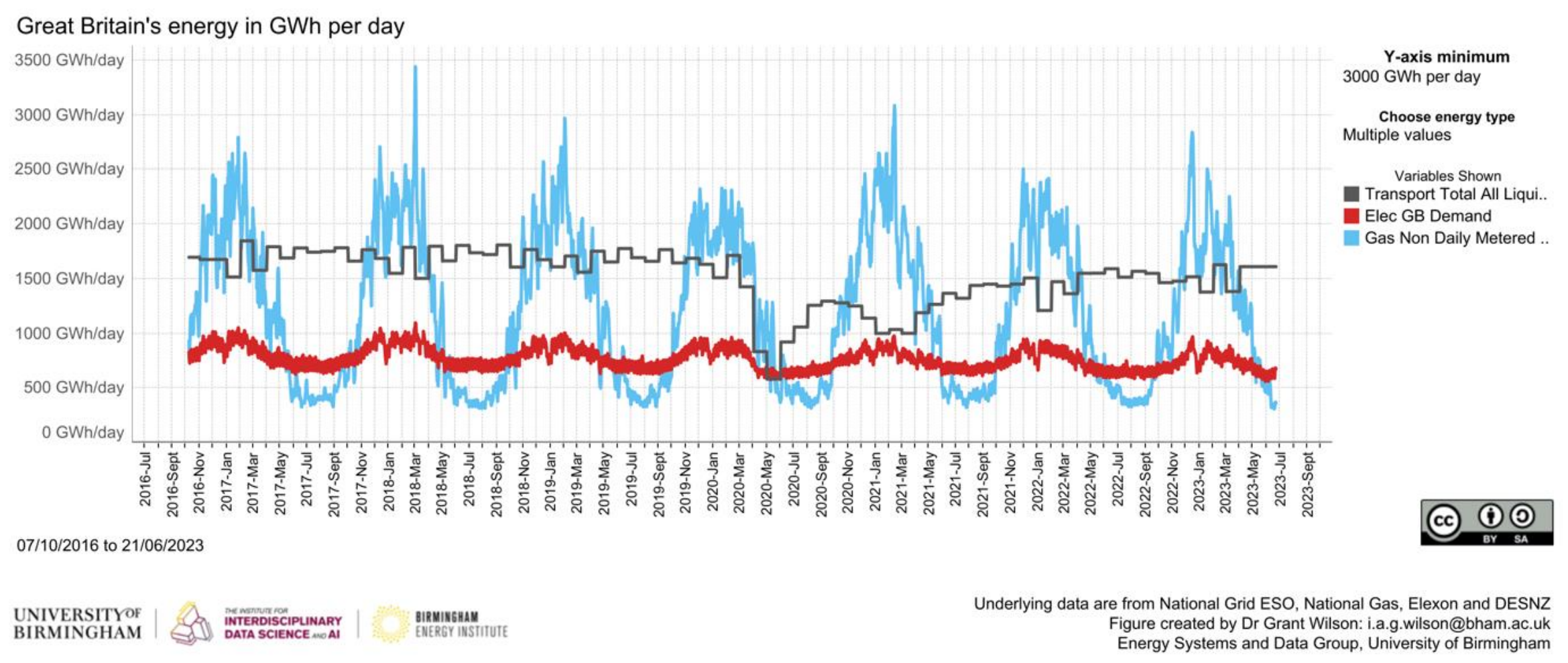


Figure 2 – Multi-vector daily energy demand for GB from 2016-23. Gas is shown in blue, electricity In red and liquid fuels in grey. Data from [4].

Use case 1: Domestic gas usage by primary substation

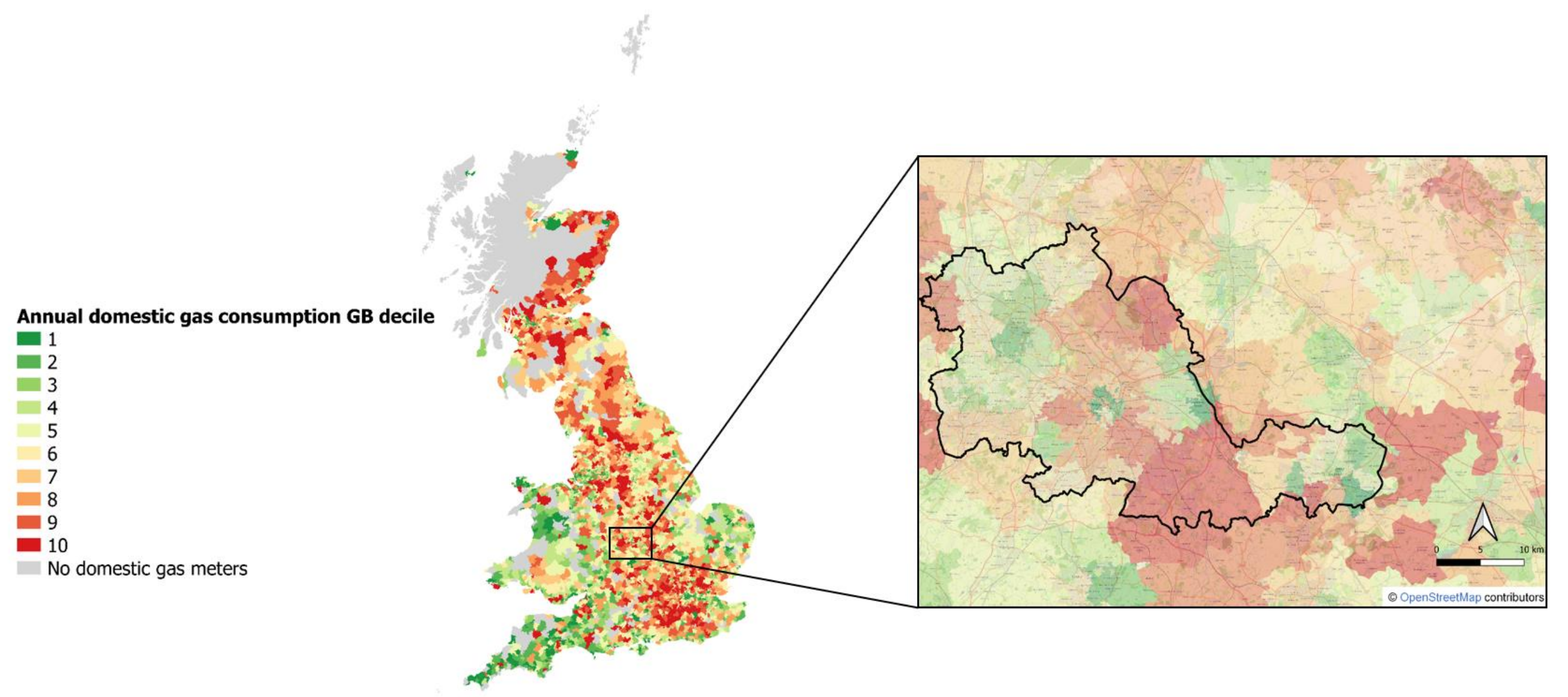
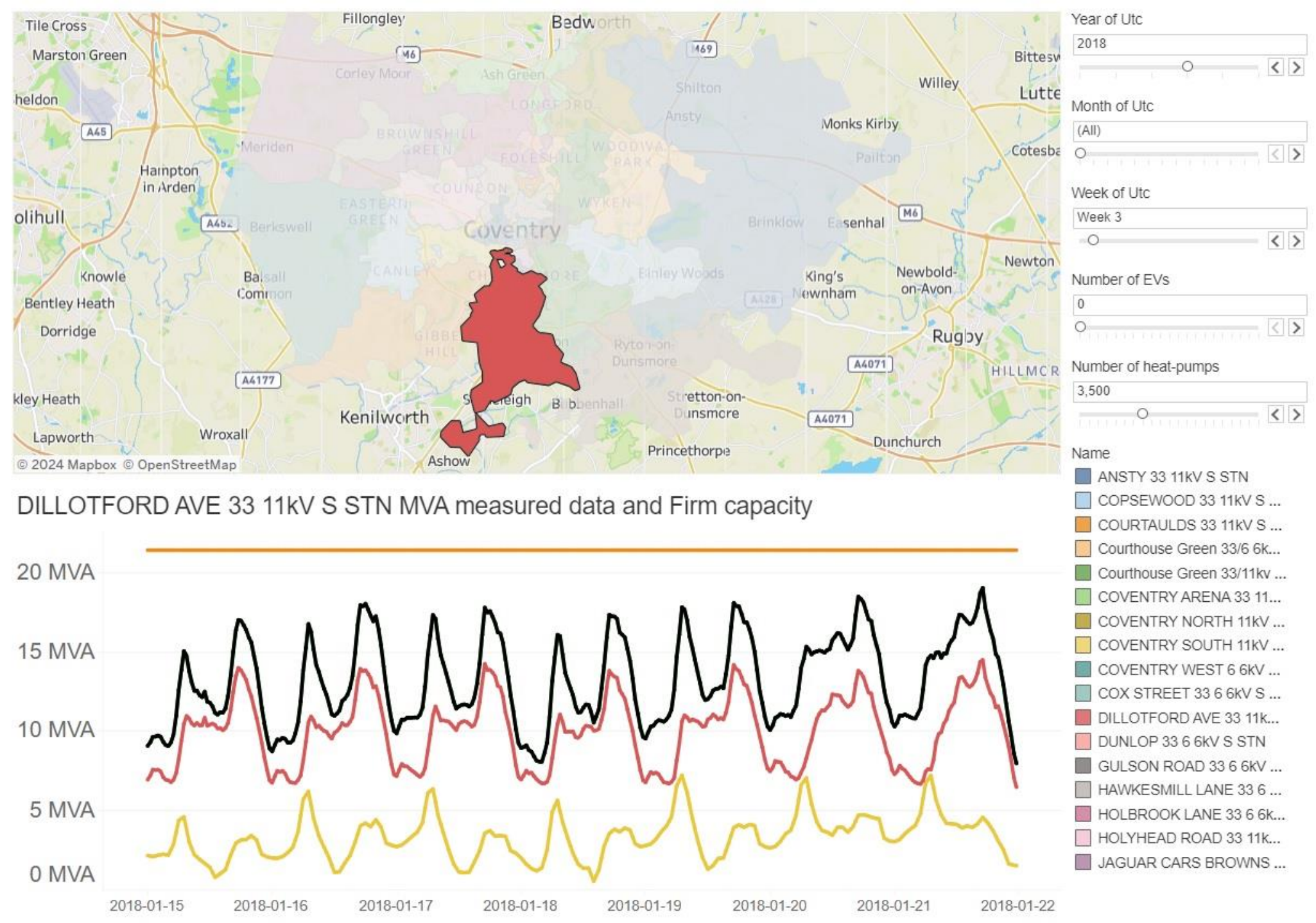


Figure 3 – Gas consumption deciles of GB's primary substations (1 is the least mean consumption decile, 10 is the highest mean consumption decile). The West Midlands has been zoomed in on to show the variation within a single region.

- The UK government's Department for Energy Security and Net Zero (DESNZ) publishes statistics containing the annual domestic consumption of gas and number of domestic gas meters for each postcode [5]. The raw data is obtained from the energy sector and at the time of analysis was available for 2015-20.
- Using the centroids of each postcode to geolocate the data and our GB-wide map of primary substation boundaries, a spatial join was performed to aggregate the gas consumption statistics and meter count to a primary substation level for all of GB. The mean gas consumption per meter was then calculated, so that primary substations could be placed in deciles according to this metric as shown in Figure 3 (with 1 being the least consuming, and 10 the highest).
- Regional trends can be observed, e.g. that the areas with a milder winter climate (such as South West England) consume less domestic gas on average. There are competing factors that influence consumption such as affluence and building fabric efficiency. For example, South East England has large property floor areas, so consumes more than regions with a similar climate.
- The advantage of presenting this data at a geographical resolution related to the energy system is that the impact of heat decarbonisation on electrical infrastructure can be visualised, and ultimately quantitatively considered (e.g. by vector substitution of gas to electricity), to evaluate actions and options at a local level. The challenge is highlighted by the range of mean annual domestic gas consumptions per primary substation which varies from a minimum of 5.1 MWh to a maximum of 28.9 MWh.
- Realistic energy models could build on this foundational work by using weather data to derive sub-annual (e.g. half-hourly) synthetic gas demands and impacts on peak kVA demand under electrified heating scenarios.

Use case 2: Local area energy planning


Year of Utc: 2018
Month of Utc: (All)
Week of Utc: Week 3
Number of EVs: 0
Number of heat-pumps: 3,500

DILLOTFORD AVE 33 11kV S STN MVA measured data and Firm capacity

Figure 4 – Synthetic heat demand from electricity (yellow curve) was added to the baseline half-hourly monitored demand (red curve), to yield an estimated demand (black curve) including added electric vehicles to be compared against the existing firm capacity of the substation (orange line). Data from [7].

- Local area energy planning is a recommended framework for helping communities decarbonise through a holistic and dynamic approach [6]. The principle of using primary substations as fundamental geographic units has been applied in several local area energy projects, notably in the West Midlands Regional Energy Systems Operator (WMRESO) project which ran from 2020-22. An issue throughout this project was that boundaries of different organisations did not align; specifically the gas and electricity networks with those of the municipal authorities and census output areas.
- Part of the project was to design future energy systems for the city of Coventry in 2032 under different localised scenarios, in a similar concept to the Future Energy Scenarios produced by National Grid and the DNOs. These scenarios give projected yearly deployment of low-carbon technologies (such as heat pumps and electric vehicles).
- Figure 4 shows an illustrative tool developed during the WMRESO project which used monitoring data from the primary substations displayed on the map along with user-defined numbers of heat pumps and electric vehicles. Synthetic demand profiles could then be generated, which take account of the additional electrical demand from heat and transport, and then compared to the firm capacity of the substation [7].
- Other datasets that are not directly related to the energy system could also be aggregated to this geography. For example, by using the centroids of census output areas and performing a spatial join, statistics for fuel poverty and deprivation were calculated for each primary substation area. This is important as for a just transition and meaningful local area energy planning, socioeconomic variables need to be considered in addition to the technical design constraints.
- The creation of the boundaries in the dataset from this work would allow this analysis to be conducted in any area of GB which has primary substation monitoring data (almost all primary substations are monitored by DNOs). A fully detailed design would consider all voltages of the network but this is challenging at the lowest voltages.

Acknowledgments and references

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Future work

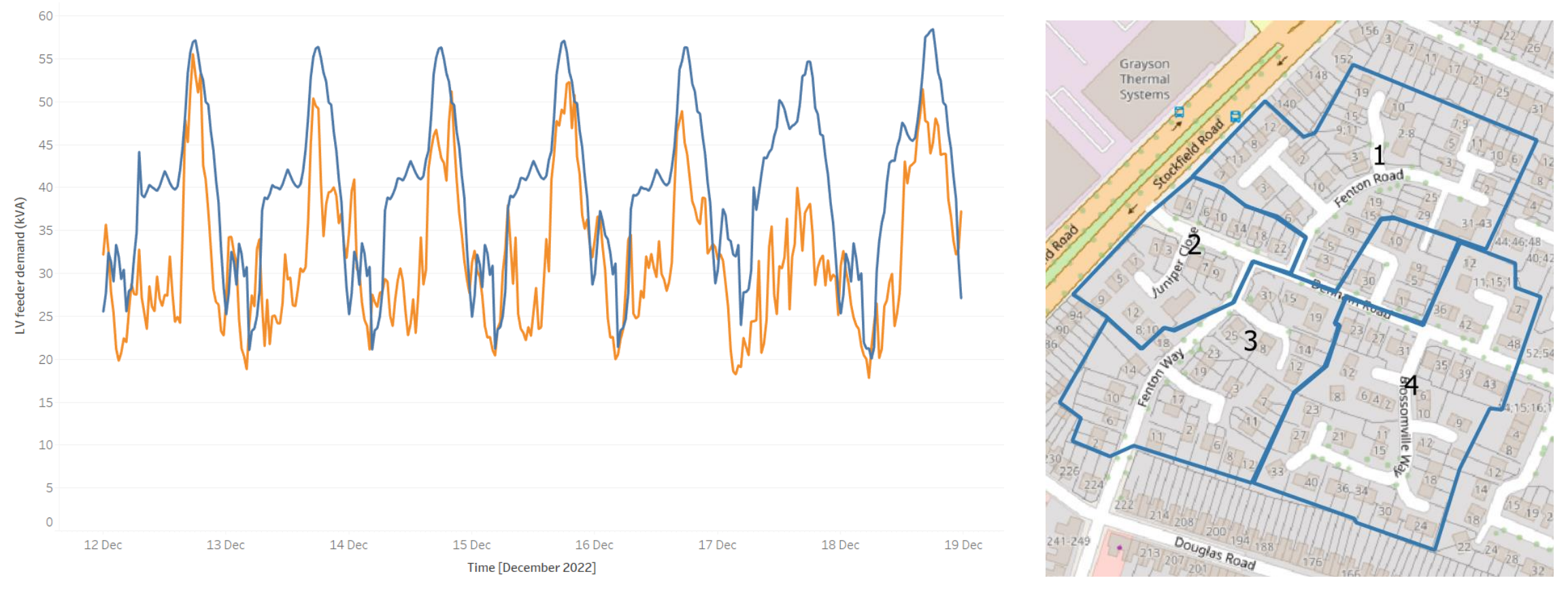

Figure 5 – Synthetic demand calculated from Faraday Tool (blue curve) for area labelled 1 on the map compared with measured demand from the same area (orange curve).

- Secondary or low voltage (LV) networks are where 49% of the reinforcement costs are expected to be required but their geographic boundaries and monitoring data is less available than that of primary substations [8]. However, the data landscape is improving with one DNO, National Grid Electricity Distribution, recently releasing sample LV monitoring data and much sharper LV substation boundaries.
- To demonstrate the art-of-the-possible, legacy maps were observed to draw boundaries for individually feeders from an LV substation. Information on the dwelling archetypes was then inputted into the Centre for Net Zero's Faraday Tool [9] to generate synthetic demands which could be compared to actual monitored power flows (Figure 5). Ultimately, greater availability of LV data would enable digital twins for network planning purposes (where the effect of low-carbon technology on specific houses and on all network voltages can be observed).
- For the primary substation boundaries, we recommend: a consistent methodology across DNO regions, the aggregation of more datasets to this level and a robust governance structure (similar to the Open Geography Portal [10] with periodic updates). The boundaries could also be created for areas served by a common part of other energy infrastructure (e.g. gas or water) and the work replicated by energy organisations (alongside the open modelling community) worldwide.