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Geomagnetically Induced Currents: Assessing the vulnerability of the German power grid

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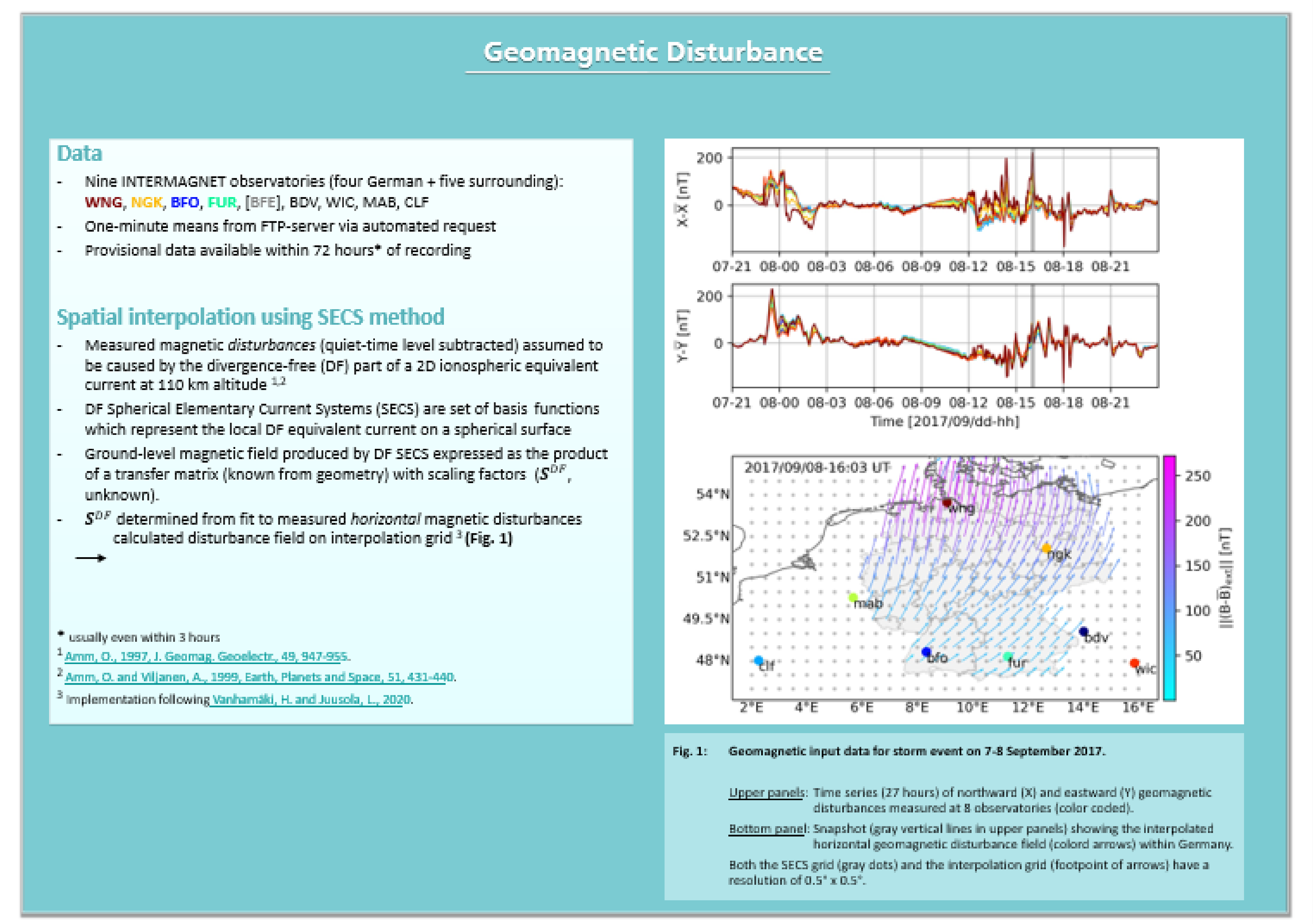
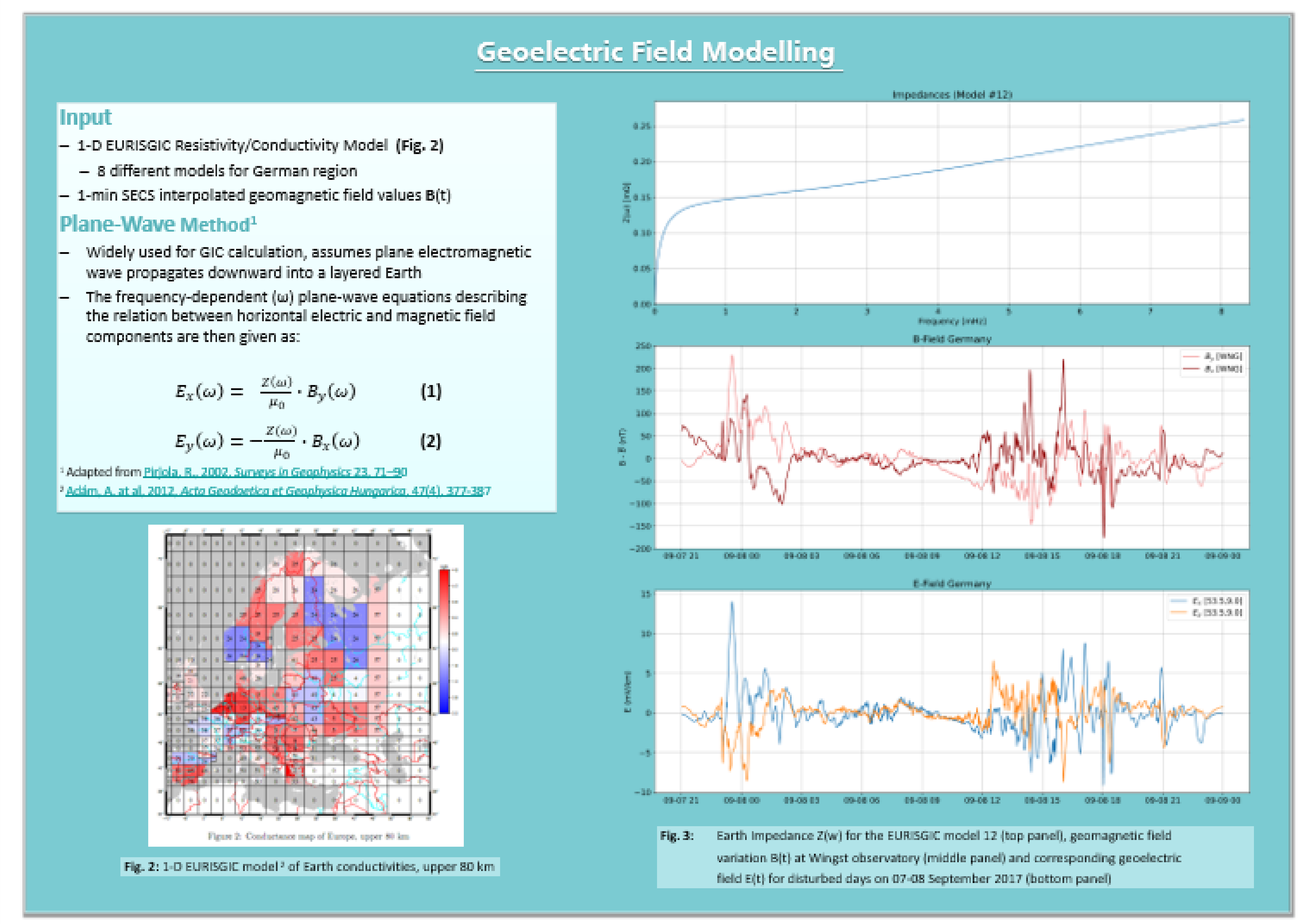
Introduction

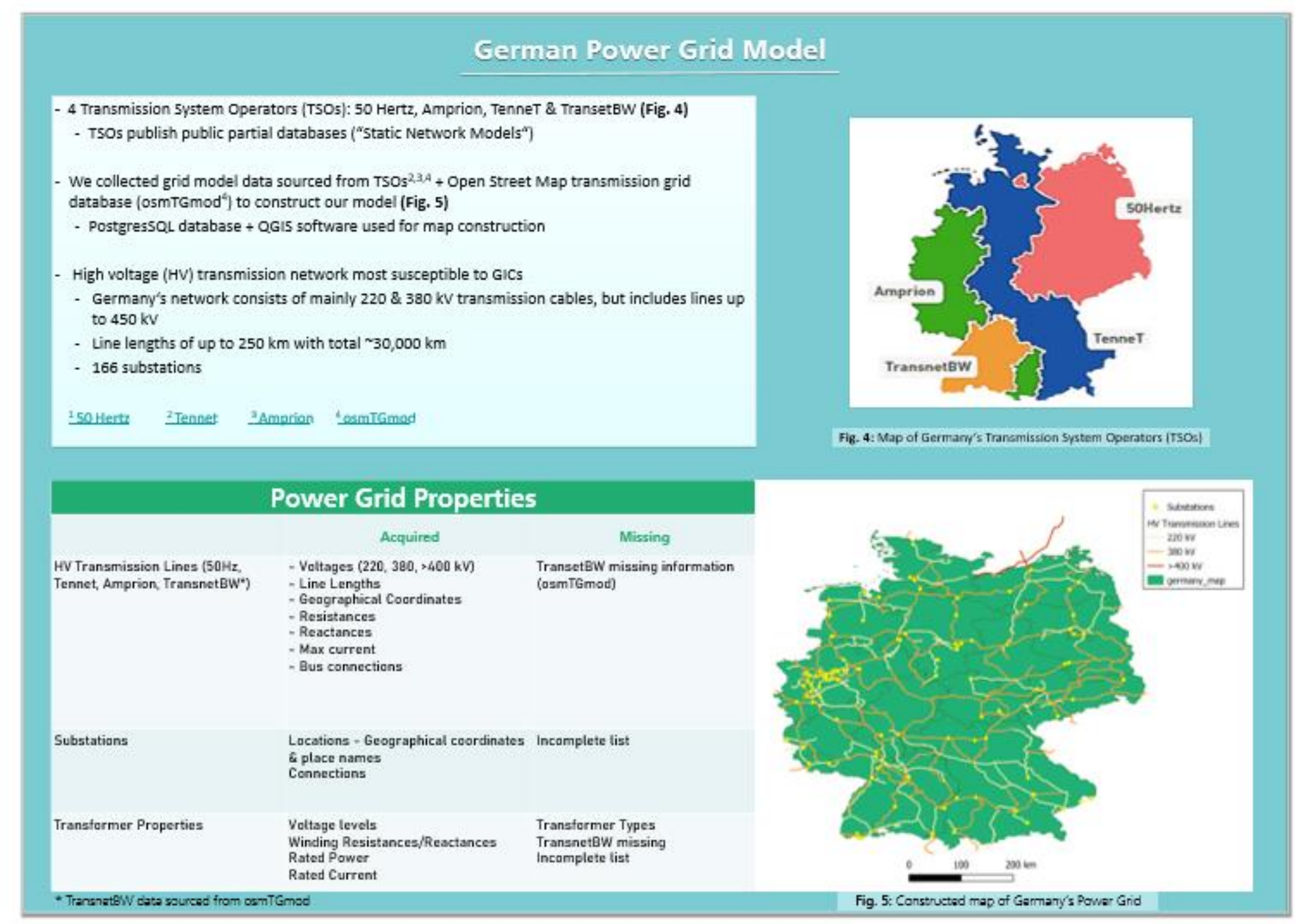
Motivation: Currently there exists no comprehensive research published on the topic of GICs for the region of Germany. Importantly, in recent years there has been increasing evidence that GICs still pose a threat even to mid-latitude countries[1,2], with the potential of long-term damage to power grid components.[3]

Abstract: Here we present current progress, results and challenges for assessing the impact of GICs on the German power network. The primary data source are 1-min magnetic field measurements in the horizontal plane from the four German (incl. neighboring) INTERMAGNET observatories. These are interpolated using the Spherical Elementary Current Systems technique to give maps of magnetic field variability. In order to achieve an accurate calculation of the E-field, information about the conductivity of the sub-surface geology is needed, we outline the availability of data for this purpose for the German geographic region and explore the application of the plane-wave method for calculating geoelectric fields.

The final step in GIC modelling involves constructing a model of the German high-voltage electricity transmission network, information about which is obtainable from several publicly available datasets, including German transmission system operators (TSOs). Here, we present an initial construction of this power network model, including its suitability for our purpose and potential short-comings. We illustrate our approach by the means of case studies focusing on relatively recent, well-studied periods of elevated geomagnetic activity (i.e., the geomagnetic storm from September 2017).







Summary & Outlook

Summary

- Needed geomagnetic input is readily available as 1-min means in near real-time (INTERMAGNET) and is processed with well-established methods (SECS)
- Plane-wave method + EURISGIC 1-D layered earth conductivity model gives initial E-field estimates
- TSOs + osmTGmod provides publicly available but incomplete datasets of HV transmission system

Outlook

- Test 1-sec geomagnetic input and investigate forecasting methods (indices vs. local activity measures)
- Implement 2-D thin-sheet method for E-field modelling (incl. lateral conductivities)
- Try to acquire magnetotelluric survey for Germany – potentially use 3-D Earth conductivity maps instead
- Obtain missing grid information through additional models (e.g., PyPSA European Grid model) & establish collaboration with TSOs.

[1] Bailey, R.L., et al. (2017) *Ann. Geophys.*, 35, 751–761
[2] Blake, S. et al, (2016), *Space Weather*, 14, 1136–1154
[3] Gaunt, C. T.(2014), *J. Space Weather Space Clim.*, 4(27)

Questions?
Comments?
Collaborations?

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Geomagnetic Disturbance

Data

- Nine INTERMAGNET observatories (four German + five surrounding): **WNG**, **NGK**, **BFO**, **FUR**, [BFE], BDV, WIC, MAB, CLF
- One-minute means from FTP-server via automated request
- Provisional data available within 72 hours* of recording

Spatial interpolation using SECS method

- Measured magnetic *disturbances* (quiet-time level subtracted) assumed to be caused by the divergence-free (DF) part of a 2D ionospheric equivalent current at 110 km altitude [1,2]
- DF Spherical Elementary Current Systems (SECS) are set of basis functions which represent the local DF equivalent current on a spherical surface
- Ground-level magnetic field produced by DF SECS expressed as the product of a transfer matrix (known from geometry) with scaling factors ($\boldsymbol{S}^{DF}$, unknown).
- $\boldsymbol{S}^{DF}$ determined from fit to measured *horizontal* magnetic disturbances

→ calculated disturbance field on interpolation grid [3] **(Fig. 1)**

* usually even within 3 hours

[1] Amm, O., 1997, J. Geomag. Geoelectr., 49, 947-955.

[2] Amm, O. and Viljanen, A., 1999, Earth, Planets and Space, 51, 431-440.

[3] Implementation following Vanhamäki, H. and Juusola, L., 2020.

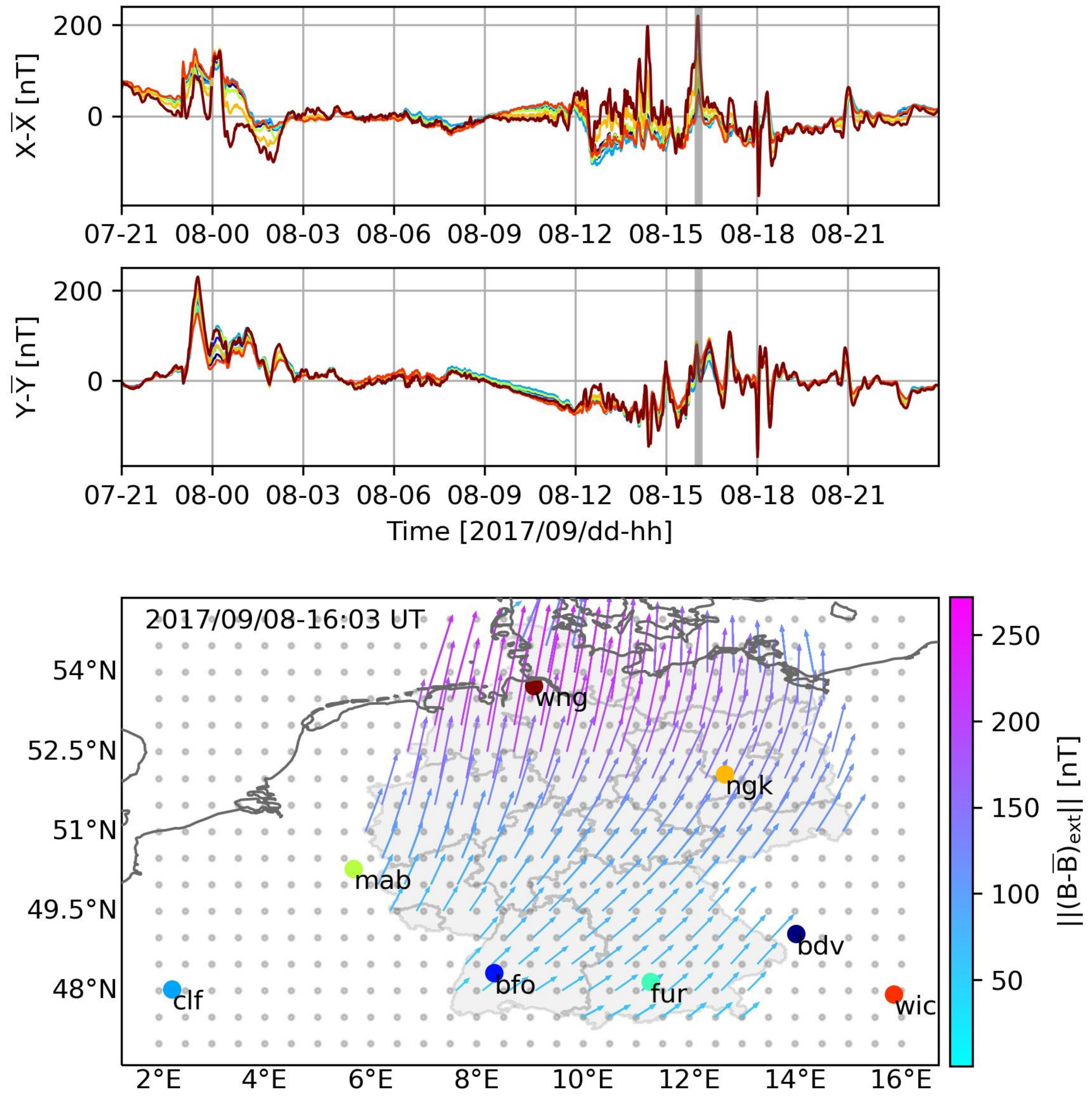

Fig. 1: **Geomagnetic input data for storm event on 7-8 September 2017.**

Upper panels: Time series (27 hours) of northward (X) and eastward (Y) geomagnetic disturbances measured at 8 observatories (color coded).

Bottom panel: Snapshot (gray vertical lines in upper panels) showing the interpolated horizontal geomagnetic disturbance field (colord arrows) within Germany.

Both the SECS grid (gray dots) and the interpolation grid (footpoint of arrows) have a resolution of 0.5° x 0.5°.

Geoelectric Field Modelling

Input

- 1-D EURISGIC Resistivity/Conductivity Model **(Fig. 2)**
  - 8 different models for German region
- 1-min SECS interpolated geomagnetic field values **B**(t)

Plane-Wave Method[1]

- Widely used for GIC calculation, assumes plane electromagnetic wave propagates downward into a layered Earth
- The frequency-dependent (ω) plane-wave equations describing the relation between horizontal electric and magnetic field components are then given as:

$$E_x(\omega) = \frac{Z(\omega)}{\mu_0} \cdot B_y(\omega) \qquad \textbf{(1)}$$

$$E_y(\omega) = -\frac{Z(\omega)}{\mu_0} \cdot B_x(\omega) \qquad \textbf{(2)}$$

[1] Adapted from Pirjola, R., 2002, *Surveys in Geophysics* 23, 71–90

[2] Adám, A. at al, 2012, *Acta Geodaetica et Geophysica Hungarica*, 47(4), 377-387

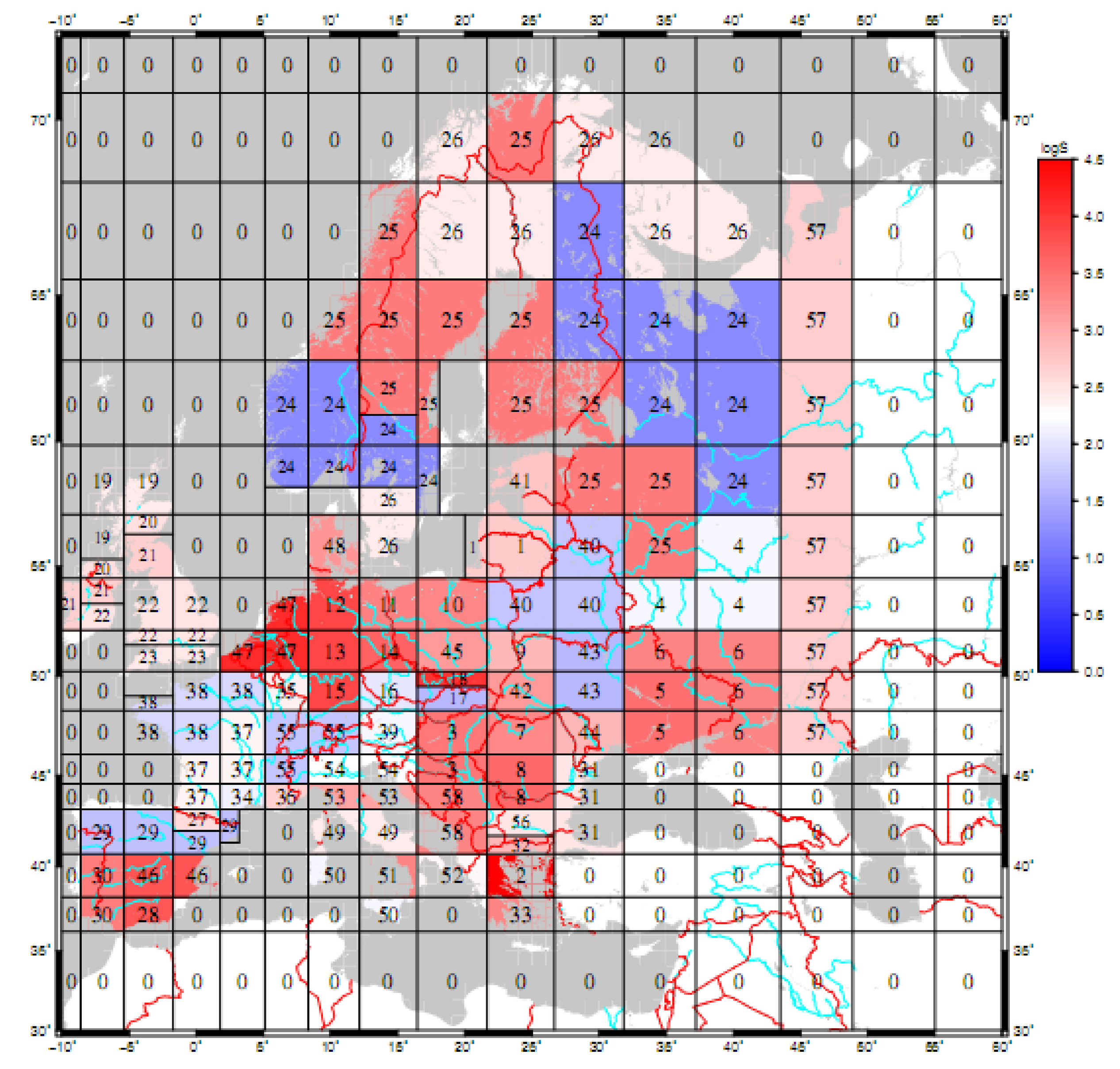

Figure 2: Conductance map of Europe, upper 80 km

Fig. 2: 1-D EURISGIC model[2] of Earth conductivities, upper 80 km

Fig. 3: Earth Impedance Z(w) for the EURISGIC model 12 (top panel), geomagnetic field variation B(t) at Wingst observatory (middle panel) and corresponding geoelectric field E(t) for disturbed days on 07-08 September 2017 (bottom panel)

German Power Grid Model

- 4 Transmission System Operators (TSOs): 50 Hertz, Amprion, TenneT & TransetBW **(Fig. 4)**
  - TSOs publish public partial databases ("Static Network Models")

- We collected grid model data sourced from TSOs[2,3,4] + Open Street Map transmission grid database (osmTGmod[4]) to construct our model **(Fig. 5)**
  - PostgresSQL database + QGIS software used for map construction

- High voltage (HV) transmission network most susceptible to GICs
  - Germany's network consists of mainly 220 & 380 kV transmission cables, but includes lines up to 450 kV
  - Line lengths of up to 250 km with total ~30,000 km
  - 166 substations

[1] 50 Hertz [2] Tennet [3] Amprion [4] osmTGmod

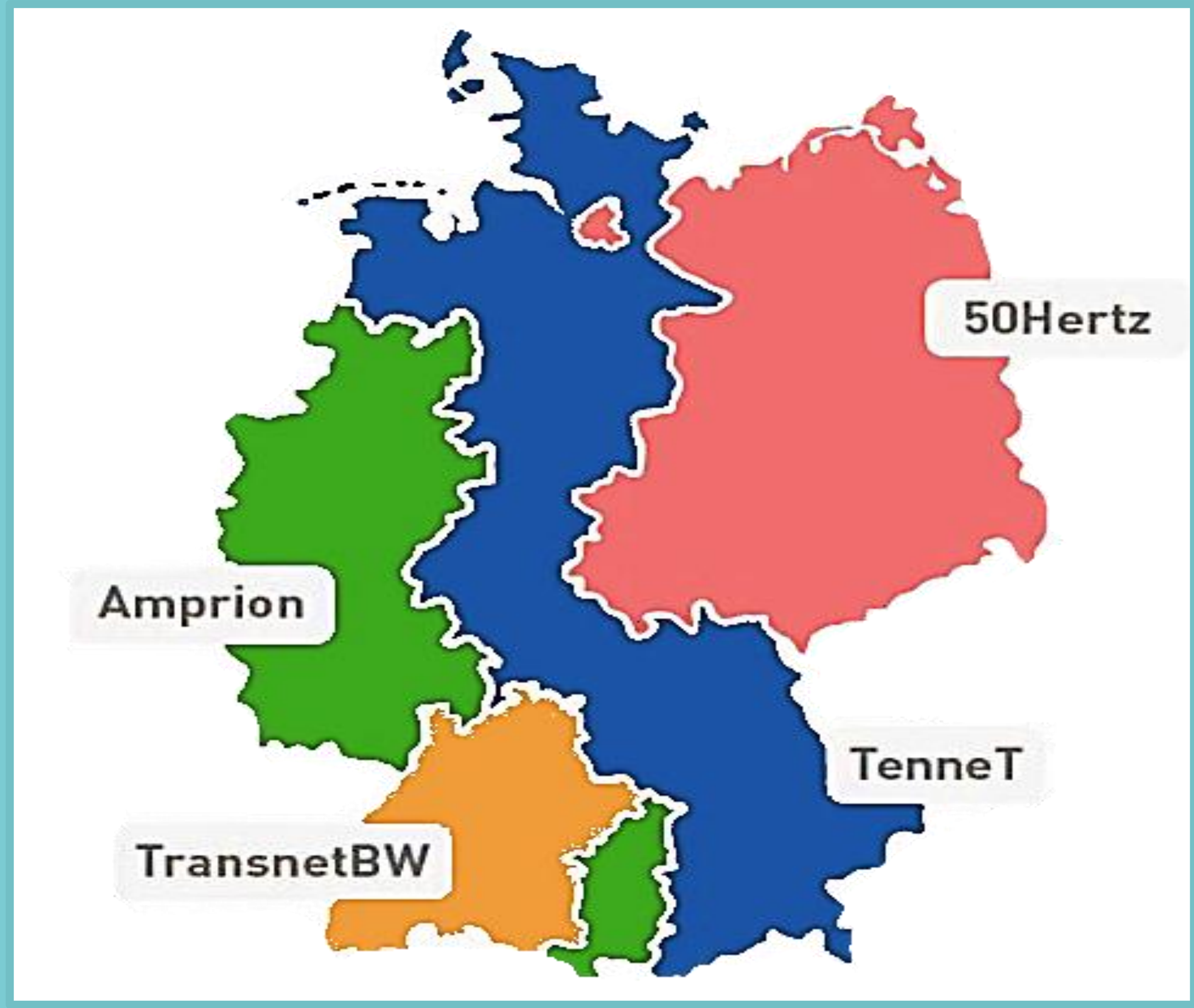

Fig. 4: Map of Germany's Transmission System Operators (TSOs)

Power Grid Properties

	Acquired	Missing
HV Transmission Lines (50Hz, Tennet, Amprion, TransnetBW*)	- Voltages (220, 380, >400 kV) - Line Lengths - Geographical Coordinates - Resistances - Reactances - Max current - Bus connections	TransetBW missing information (osmTGmod)
Substations	Locations - Geographical coordinates & place names Connections	Incomplete list
Transformer Properties	Voltage levels Winding Resistances/Reactances Rated Power Rated Current	Transformer Types TransnetBW missing Incomplete list

* TransnetBW data sourced from osmTGmod

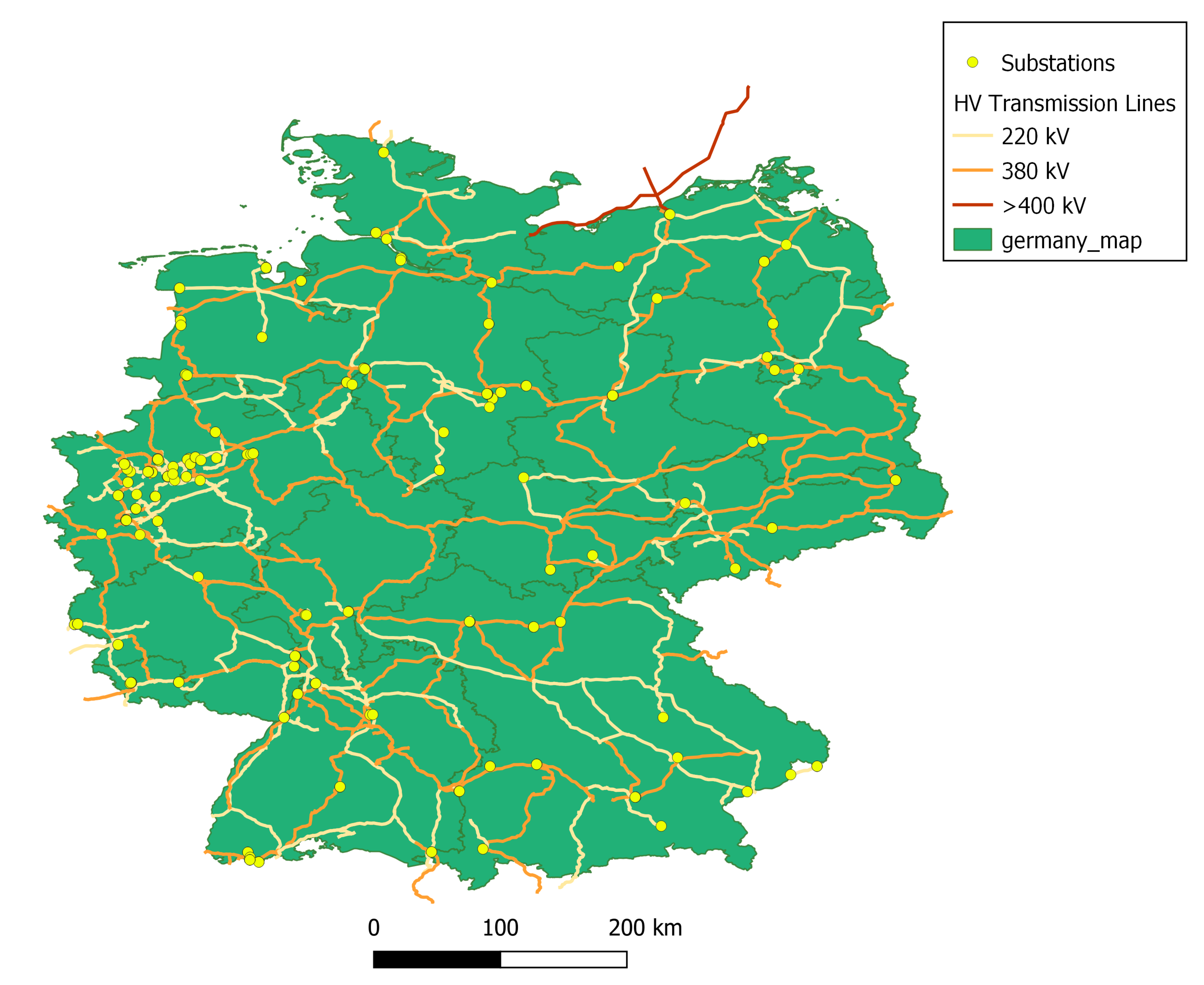

Fig. 5: Constructed map of Germany's Power Grid