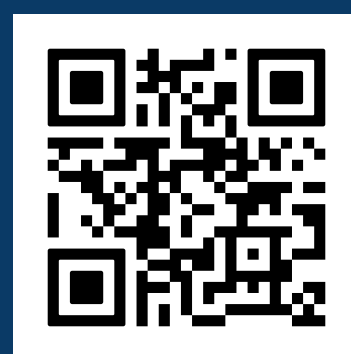




Abstract

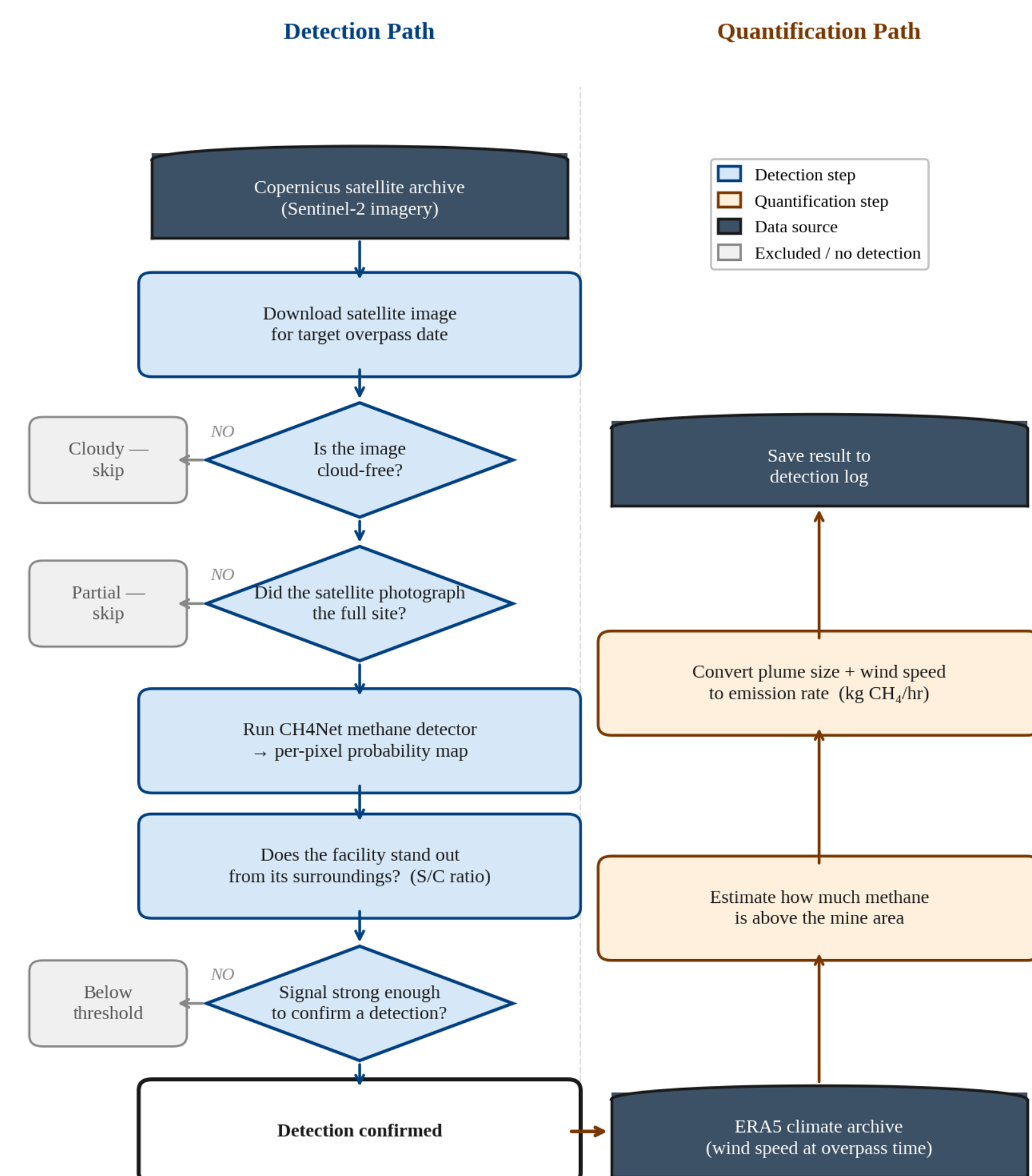
Industrial emissions are a major contributor to environmental and climate-related challenges, accounting for 55% of greenhouse gas emissions in EU production activities in 2023 [2]. This project explores the use of satellite imagery as an alternative data source for industrial emissions monitoring and economic activity analysis, leveraging near real-time Earth observation data to enable timely assessments with minimal reporting lag. Using Sentinel-2 imagery, the proposed pipeline consists of: **(a)** region-of-interest (ROI) exploration of different locations, **(b)** statistically calibrated methane plume detection using a retrained CH₄Net, **(c)** methane quantification over the Bełchatów coal mine in Poland, and **(d)** assessment of the financial exposure associated with these emissions under carbon-price and market stress scenarios.

I. Introduction

Facility-level methane emissions are a critical, unpriced liability in the European coal sector. While independent monitoring is essential to quantify this transition risk, current optical satellite pipelines fail on European terrain. State-of-the-art detectors like CH₄Net, optimized for arid landscapes, suffer a severe domain shift, yielding 48% false-positive rates over temperate, heterogeneous coal mines. For financial and regulatory applications, reliable statistical false-positive control is essential.

This project bridges this gap by developing an operational pipeline specifically tailored to European coal terrain. We retrain the core detection engine and adapt the retrieval methodology to successfully handle continuous, year-round emitters and complex local landscapes. The framework provides supervisors with an independent means of monitoring emissions without relying on operator self-reporting. It demonstrates how satellite observations can be used to estimate carbon-cost exposures for transition-risk stress testing.

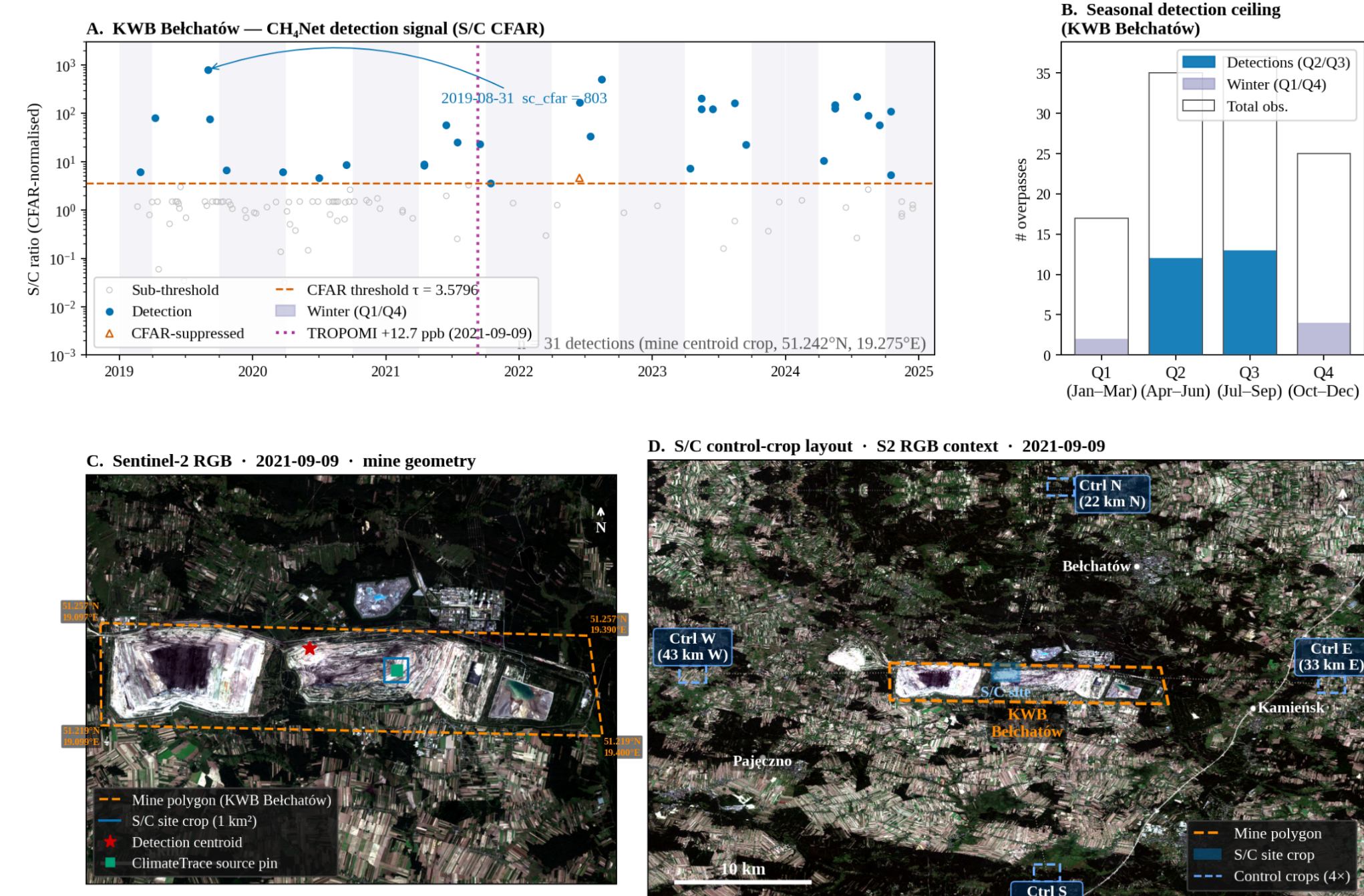
II. Methodology



III. Detection at KWB Bełchatów

We fine-tuned the 12-band CH₄Net U-Net CNN on a European-specific dataset 14 TROPOMI confirmed real crops, 51 synthetic injections, and 22 verified negatives to mitigate surface artifacts. After filtering cloudy and partial observations, the model generates a per-pixel probability map. The facility's signal is then divided by the mean of four spatially offset control crops to yield the Signal-to-Control (S/C) ratio, actively normalizing the measurement against the local background.

Applying this calibrated pipeline across 8 candidate facilities, we selected KWB Bełchatów as the primary case study due to persistent multi-year detections, facility scale, and alignment with Climate TRACE.



Detection Record (2019–2025):

- ▶ **A. Conformal Thresholding:** 30 cloud-free overpasses clear the calibrated CFAR threshold ($\tau = 3.58$).
- ▶ **B. Seasonal Limits:** Detections cluster in Q2/Q3. Winter (Q1/Q4) is structurally unobservable due to clouds and low SWIR sensitivity.
- ▶ **C. Facility Geometry:** Retrieval is executed strictly within the mine boundary, excluding the adjacent power station.
- ▶ **D. In-Scene Backgrounding:** Background reflectance is estimated dynamically using spatially offset control crops.

IV. Wind Estimation

Wind speed is essential for methane quantification because plume transport and dispersion directly affect emissions estimates. ERA5 Copernicus wind data were aligned with the selected ROI, Varon et al. [3] and are used to convert methane enhancement into emissions flux estimates.

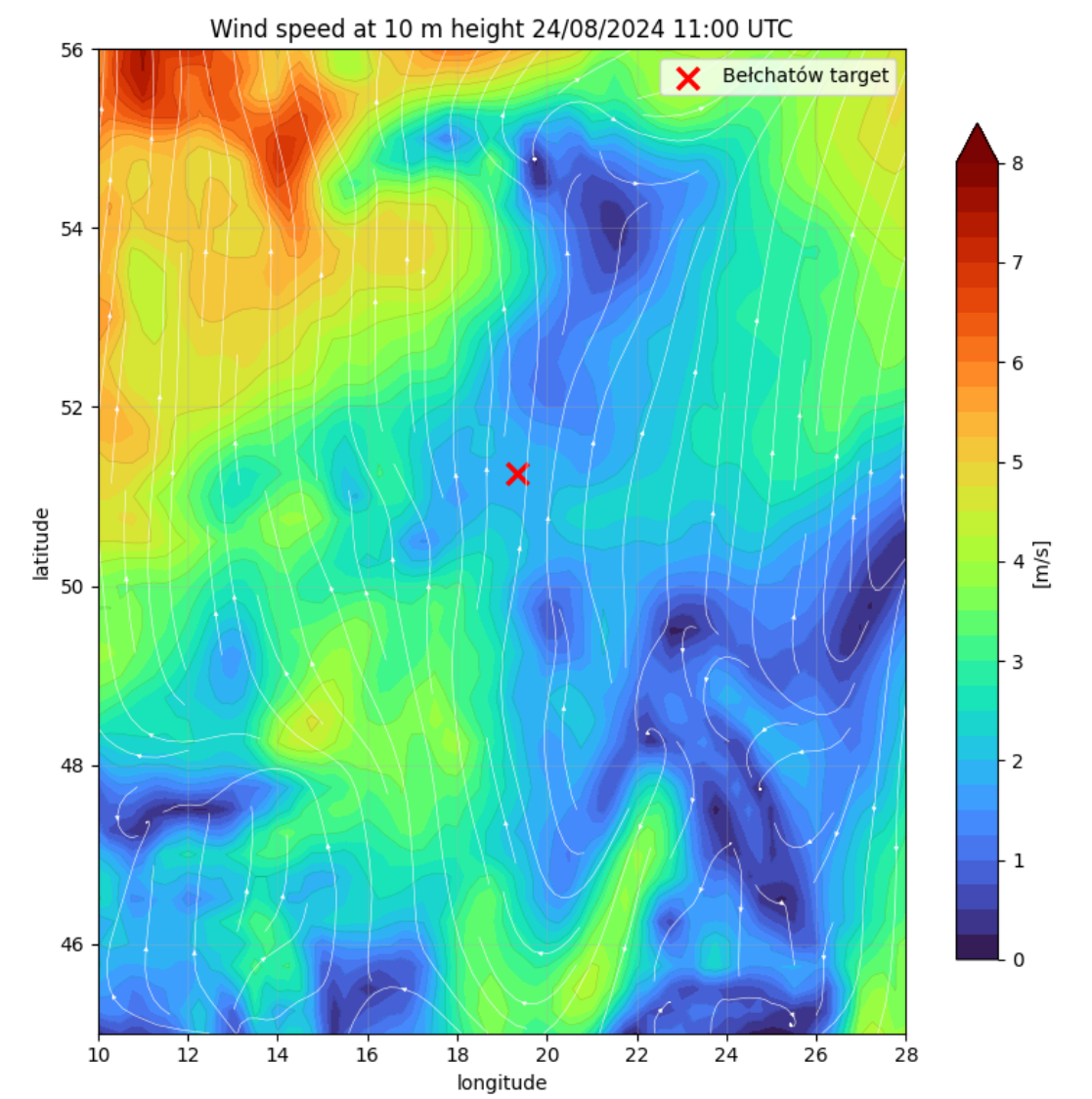


Figure: ERA5 10 m wind field over the Bełchatów ROI. Wind-speed magnitude and streamlines are used to estimate plume transport near the industrial source during the Sentinel-2 overpass.

$$Q = \frac{IME \cdot U_{\text{eff}}}{L}$$
$$U_{\text{eff}} = 0.33 U_{10} + 0.45$$

V. Methane Quantification

We utilize the Sentinel-2 MBSP retrieval framework of Varon et al. [3], adapted for continuous emitters. To avoid suppressing persistent methane signals through bitemporal differencing at year-round sites, we use **in-scene background normalization** rather than reference-scene subtraction.

$$\Delta R_{\text{MBSP}} = \frac{c B_{12} - B_{11}}{B_{11}}, \quad \Delta \Omega = k \Delta R_{\text{MBSP}}$$

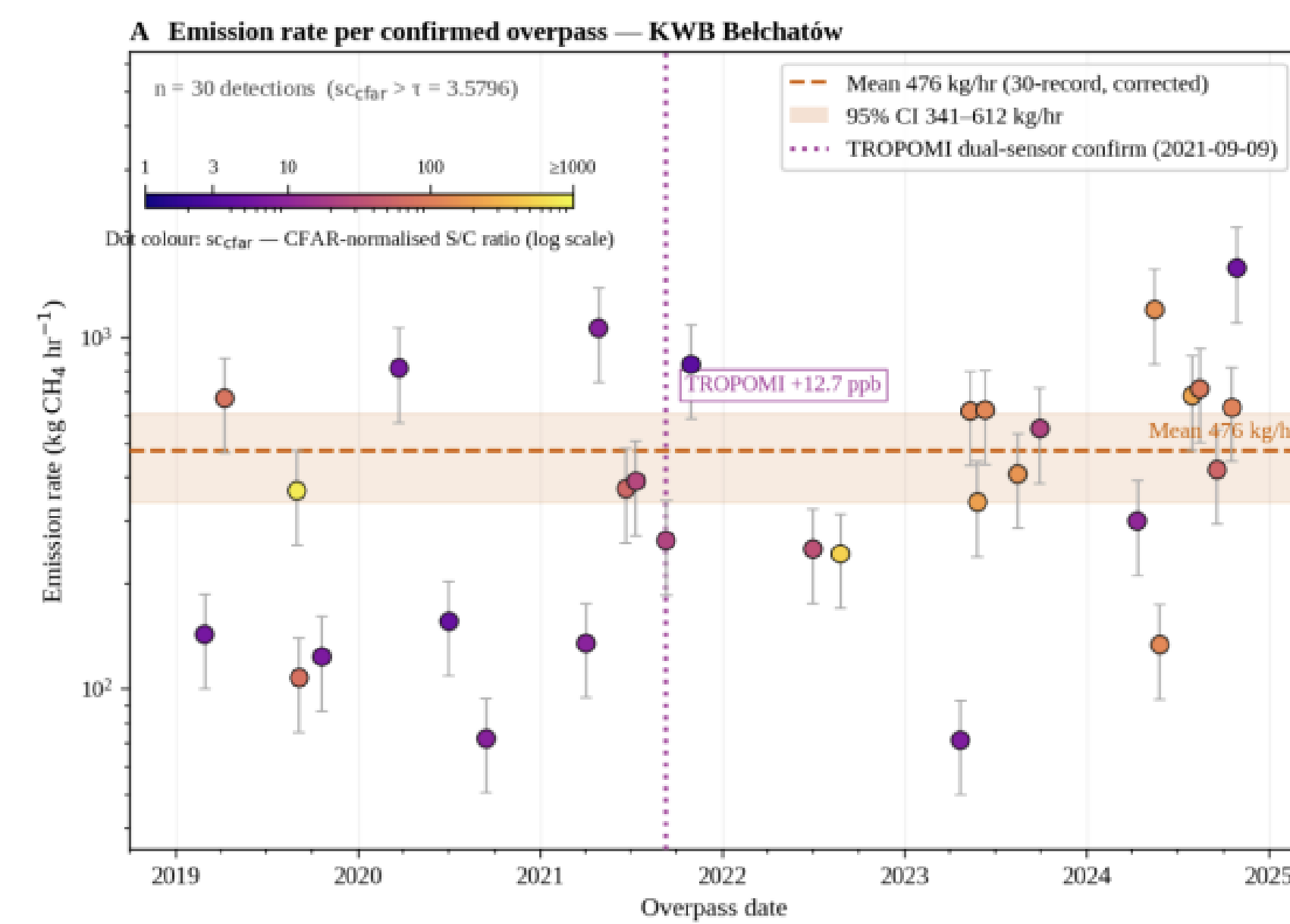
We derive a scene-specific scaling factor c by fitting background reflectance on in-scene non-plume pixels, then compute column enhancements $\Delta \Omega$ across the Bełchatów OSM mine polygon. Source rates Q are derived using wind-aligned IME inversion.

Pseudo-Code Methane Emission Quantification

- 1: Given target ROI, Sentinel-2 B11/B12, ERA5 wind, pixel size s
- 2: Select Sentinel-2 tile and clip to ROI
- 3: Load u_{10}, v_{10} and compute $U_{10} = \sqrt{u_{10}^2 + v_{10}^2}$
- 4: Compute $U_{\text{eff}} = 0.33 U_{10} + 0.45$
- 5: Fit $c = \Sigma(B_{11} B_{12}) / \Sigma(B_{12}^2)$
- 6: Compute $\Delta R_{\text{MBSP}} = (c B_{12} - B_{11}) / B_{11}$
- 7: Convert $\Delta \Omega = k \Delta R_{\text{MBSP}}$
- 8: Define plume mask $P = \Delta \Omega > q_{95}(\Delta \Omega)$
- 9: Smooth P using a 3×3 median filter
- 10: Compute $A_p = \Sigma_{p \in P} s^2$ and $L = \sqrt{A_p}$
- 11: Compute $IME = \Sigma_{p \in P} \Delta \Omega(p) s^2$
- 12: Estimate source rate $Q = IME \cdot U_{\text{eff}} / L$
- 13: Report Q in kg/s, t/h, and annualized t/year

Where:

B_{11}, B_{12} : Sentinel-2 SWIR bands
 ΔR_{MBSP} : reflectance signal
 $\Delta \Omega$: CH₄ enhancement
 IME : integrated methane enhancement
 c : band scaling factor
 k : CH₄ conversion factor
 P : plume mask
 Q : methane source rate



Key results ($n = 30$, 2019–2025): mean 476 kg CH₄/hr (95% CI: 341–612); range 72–1,578 kg/hr; annualised estimate **4,174 t CH₄/yr** (95% CI: [2,987–5,360] t/yr); recovery ratio **14.1%** of the Climate TRACE 2024 inventory — consistent with published Sentinel-2 ranges for single-overpass SWIR sensing at temperate latitudes.

Operational use cases. The pipeline supports institutional applications such as: (i) **MRV validation** under EU Methane Regulation 2024/1787, where the $\leq 10\%$ FPR guarantee makes estimates suitable for compliance-oriented monitoring workflows; (ii) **portfolio screening**, providing an independent top-down remote sensing signal of methane exposure and transition risk beyond operator self-disclosures and annual reporting.

Uncertainty decomposition. Carbon-price trajectory dominates total variance (76.9%); ERA5 wind bias and plume spatial extent together contribute only $\sim 11\%$, meaning improved satellite precision would not materially reduce the dominant source of exposure uncertainty.

VI. Economic Analysis Assessment

We map the Bełchatów methane estimates into transition-risk exposure under explicit policy assumptions. The issuer is **PGE Polska Grupa Energetyczna S.A.** (WSE:PGE; Moody's Baa1, Fitch BBB), the state-controlled utility that operates Bełchatów through its GiEK subsidiary. PGE already holds €2.54B in CO₂ allowances on its balance sheet (end-2024).

Implied annual carbon-cost exposure. Converting 4,174 t CH₄/yr via IPCC AR5 GWP100 (factor 28) gives 116,872 t CO₂e/yr. EUA price sensitivity:

Table: Carbon-Cost Exposure by EUA Price Case

Case	€/tCO ₂ e	Mean	CI Lower	CI Upper
Low	50	€5.84 M	€4.18 M	€7.50 M
Central	70	€8.18 M	€5.85 M	€10.51 M
Upper	95	€11.10 M	€7.94 M	€14.25 M

The central case adds approximately 0.3% to PGE's existing €2.54B allowance book under GWP100, rising to 1.0% under GWP20. The exposure is entirely unpriced and unaudited without independent monitoring.

Monte Carlo Climate VaR (10,000 simulations, seed 42) [4]. Carbon-price trajectory dominates the variance (76.9%); satellite measurement uncertainties together contribute only $\sim 11\%$.

Table: Climate VaR Summary

Risk metric	GWP100 (€M)	GWP20 (€M)
Mean expected liability	7.51	22.25
Median	6.93	20.54
Climate VaR 95	13.46	39.89
Climate VaR 99	17.77	52.69
99% Expected Shortfall	20.22	59.95

Credit-spread and equity stress on a hypothetical €10M PGE position. P&L scales linearly with position size.

Table: Stress Scenarios

Tier	ΔEq.	ΔSpr.	Equity P&L	Bond P&L
Mild	−3%	+15 bp	−€300 K	−€75 K
Moderate	−7%	+35 bp	−€700 K	−€175 K
Severe	−10%	+50 bp	−€1.00 M	−€250 K

Illustrative scenario analysis. Position sizes are hypothetical and carbon-cost figures are exposure proxies, not booked liabilities. Results are conditional on regulatory adoption of a methane pricing framework comparable to the EU ETS.

Future Work

- ▶ Extend CH₄Net training coverage to complex, industrial-fringe terrain to recover valid sub-threshold methane plumes that are currently suppressed by the inflated CFAR gate.
- ▶ Grow the conformal calibration set from $n = 35$ toward $n \geq 40$ with broader Atlantic and Continental ecoregion coverage, tightening the bootstrap confidence interval on τ for continent-scale deployment.
- ▶ Fuse Sentinel-2 with TROPOMI and Sentinel-2C to extend winter (Q1/Q4) coverage and tighten the annualised emission uncertainty band without new model development.

References

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- [2] Eurostat. Industrial emission statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_emission_statistics. 2026.
- [3] Varon et al. High-frequency monitoring of anomalous methane point sources with multispectral Sentinel-2 satellite observations. *Atmos. Meas. Tech.*, 14:2771–2785, 2021.
- [4] Desnos et al. From climate stress testing to climate value-at-risk: A stochastic approach. *SSRN*, 2023.