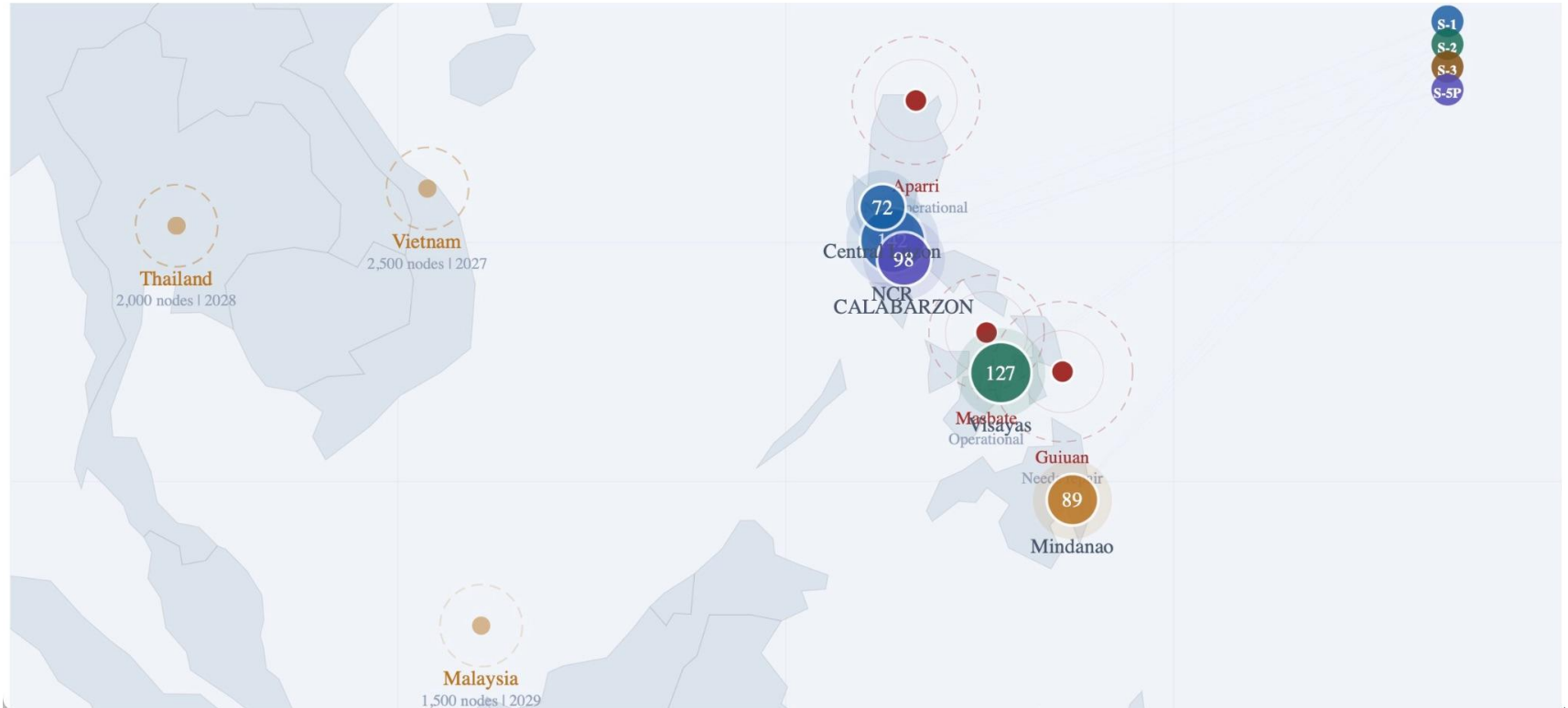


5th ECMWF-Project GridShield: A Hybrid ML/DL-Satellite Fusion Framework



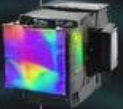

GridShield digital twin map showing ML observation pipeline across the Philippines and ASEAN with animated Sentinel beams, grid deployment nodes, PAGASA radar coverage, and CNN-LSTM prediction flow

ECMWF-ESA Digital twin | Abstract #29

S-1 SAR S-2 MSI S-3 SLSTR S-5P PAGASA radar ASEAN 2027-30



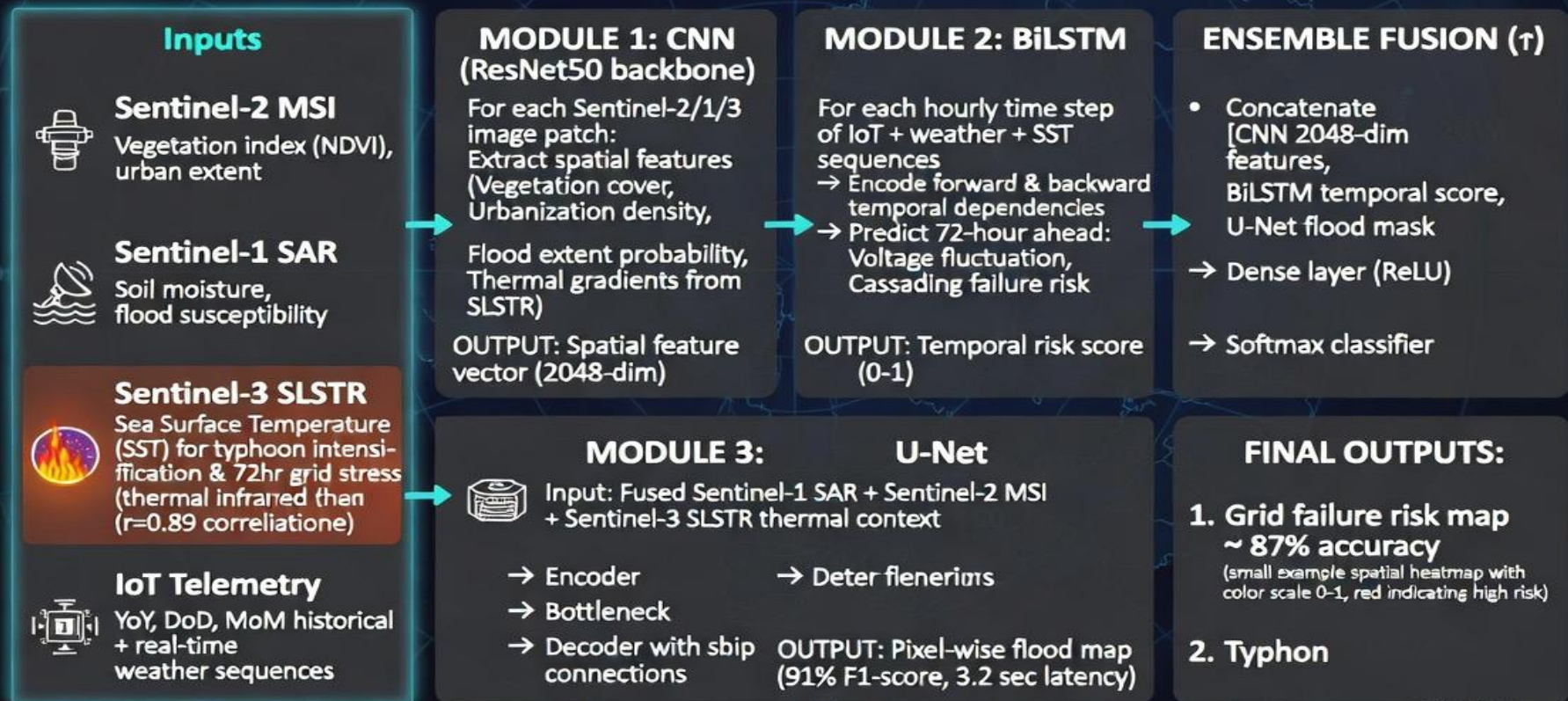
Multi-Modal Satellite Data Fusion for Grid Resilience & Carbon Credits

	Satellite	Data Product	ML Use Case	Correlation (r)
	Sentinel-1 SAR	Soil Moisture	Flood risk, substation access	0.82
	Sentinel-2 MSI	NDVI (5-yr anomaly)	Vegetation encroachment	0.78
	Sentinel-3 SLSTR	Sea Surface Temp	Typhoon intensification, 72hr grid stress	0.89
	Sentinel-5P TROPOMI	NO2/CO2	Emission avoidance validation	0.78

$r=1.0$

Satellite data acts as the physical truth anchor for both resilience prediction and carbon accounting.

Hybrid ML Architecture – CNN-LSTM + U-Net with Sentinel-3 SLSTR for Grid Resilience & Carbon Credits



Detailed Hybrid ML Architecture Flow - CNN-LSTM + U-Net with Sentinel-3 SLSTR

RIGHT COLUMN - ENSEMBLE FUSION & OUTPUTS

INPUTS



Sentinel-2 MSI →
Vegetation index (NDVI),
urban extent
(optical icon)



Sentinel-1 SAR →
Soil moisture, flood
susceptibility
(radar icon)



Sentinel-3 SLSTR →
Sea Surface Temperature
(SST) - thermal gradients
($r=0.89$)



IoT Telemetry → YoY,
DoD, MoM + real-time
weather sequences
(IoT node)

MODULE 1: CNN (ResNet50 backbone)

- Input: Fused Sentinel-2/1/3 patches (512x512 @ 10m)
- Spatial feature extraction: Vegetation cover, Urbanization density, Flood extent probability, SLSTR thermal gradients
- OUTPUT: 2048-dim spatial embedding vector

MODULE 2: BiLSTM

- Input: Hourly time series (IoT + weather + SST anomalies)
- Bidirectional LSTM (128 hidden units): Forward + backward temporal dependencies
- 72-hour ahead prediction: Voltage fluctuation probability, Cascading failure risk
- OUTPUT: Temporal risk score tensor (0-1)

MODULE 3: U-Net

- Input: Fused Sentinel-1 SAR + Sentinel-2 MSI + Sentinel-3 SLSTR thermal context
- Encoder-Decoder with skip connections (EfficientNet backbone)
- OUTPUT: Pixel-wise flood segmentation mask (91% F1-score, 3.2 sec inference latency)

ENSEMBLE FUSION (→)

- Concatenate: [CNN 2048-dim features → BiLSTM temporal score
- U-Net flood mask]
- Gated attention layer → Dense (ReLU, 512 units) → Softmax classifier

FINAL OUTPUTS:

1. **Grid failure risk map**
(spatial heatmap, 87% accuracy)
2. **Typhoon track error: 98 km @ 24**

Sentinel-3 Instrument Comparison for Grid Resilience & Typhoon Forecasting

	 Sentinel-3 SLSTR	 Sentinel-3 OLCI	 Sentinel-3 SRAL
Icon	thermal infrared sensor	multi-spectral ocean colour	radar altimetry
Key Specifications	Sea/Land Surface Temperature 500 m-1 km 1,420 km swath ~1 day revisit dual-view atmospheric correction SST accuracy < 0.3 K	21 VNIR bands 300 m resolution 1,270 km swath ~1-2 day revisit	Sea surface height & wave height ±300 m along-track Ku/C-band 27-day repeat cycle cm-level accuracy
Resolution			
Grid Resilience Use Case	Typhoon intensification 72hr grid stress forecasting r=0.89 correlation	Ocean colour/chlorophyll/water quality for storm surge & vegetation stress	Storm surge & sea-level anomaly prediction
Performance in Fusion Pipeline	Thermal gradients fed into ResNet50 & BiLSTM	Supporting reflectance channels for U-Net flood segmentation	Auxiliary temporal input to BiLSTM for cascading failure risk

Sentinel-3 Synergy Products (SLSTR + OLCI)

Feeding → Hybrid CNN-LSTM + U-Net

Sentinel-3 SLSTR (r=0.89)

Sentinel-3 SLSTR delivers the highest r=0.89 correlation for typhoon-driven grid stress

CNN-LSTM Hybrid Architecture Details – GridShield Digital Twin (ECMWF-ESA Abstract #29)

SPATIAL BRANCH

Fused Sentinel patches
(S-1 SAR + S-2 MSI + S-3 SLSTR + S-5P, 512x512 @ 10 m)

ResNet50 CNN



$$y = F(x, \Delta W_i \theta) + x$$

- Vegetation**
- Urbanization
 - Flood Extent

SLSTR Thermal Gradients

TEMPORAL BRANCH

Hourly time series
(IoT + weather + SST anomalies, 72hr seq)

BiLSTM

$$\text{softmax}(QK^{\Delta T} / \Delta d_k)V$$

Temporal Risk Score (0-1)

- 72hr voltage fluctuation
- cascading failure

Ensemble: Concat
[2,048-d CNN → BiLSTM • U-Net flood mask]



Multi-head Outputs
Grid Risk Map (87% acc.)
Carbon MRV
Flood Segmentation (91% F1
(3.2 s latency)

DEGRADATION MODEL

$$C(t) = -2.47 t^2 - 8.93 t + 100$$

$t_{burst} = 2.6 \text{ years } (C(t) = 20\%)$

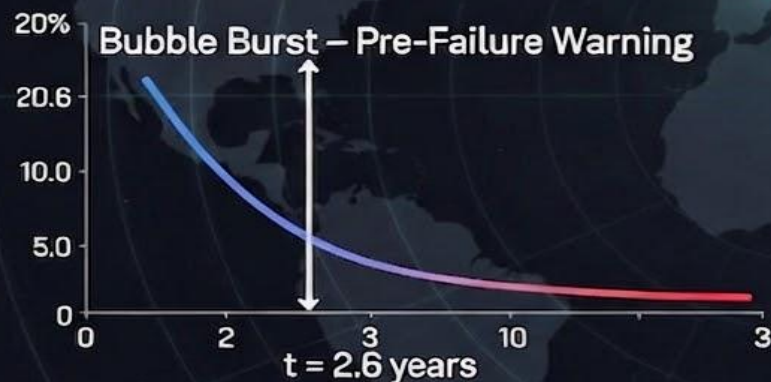
Negative quadratic coefficient = accelerating degradation
→ CADENA predictive maintenance

R²=0.9847 • 528 Grid nodes • 3,491 events • 450K tCO₂e verified • 72hr Prediction • BFT 67% Blockchain MRV

ResNet50 + BiLSTM with attention operationalizes Sentinel multi-modal fusion for 72hr grid resilience and verifiable carbon credits under ASEAN 202

Degradation Model & CADENA Insights for Predictive Grid Asset Maintenance

$$C(t) = -2.47 t^2 - 8.93 t + 100$$



CADENA enables resilient grids, considers circular economy asset lifecycle management and reduces unplanned outages in typhoon-plagued regions. It integrates with Hybrid CNN-LSTM + U-Net outputs we gain, for proactive intervention before t_{burst}

Negative quadratic coefficient identifies accelerating degradation – enabling predictive maintenance under CADENA circularity principles. Sentinel-3 SLSTR (r.0.89) provides the thermal truth anchor for typhoon-driven grid stress.

GridShield Digital Twin - ECMWF-ESA Abstract #29

S-1 SAR

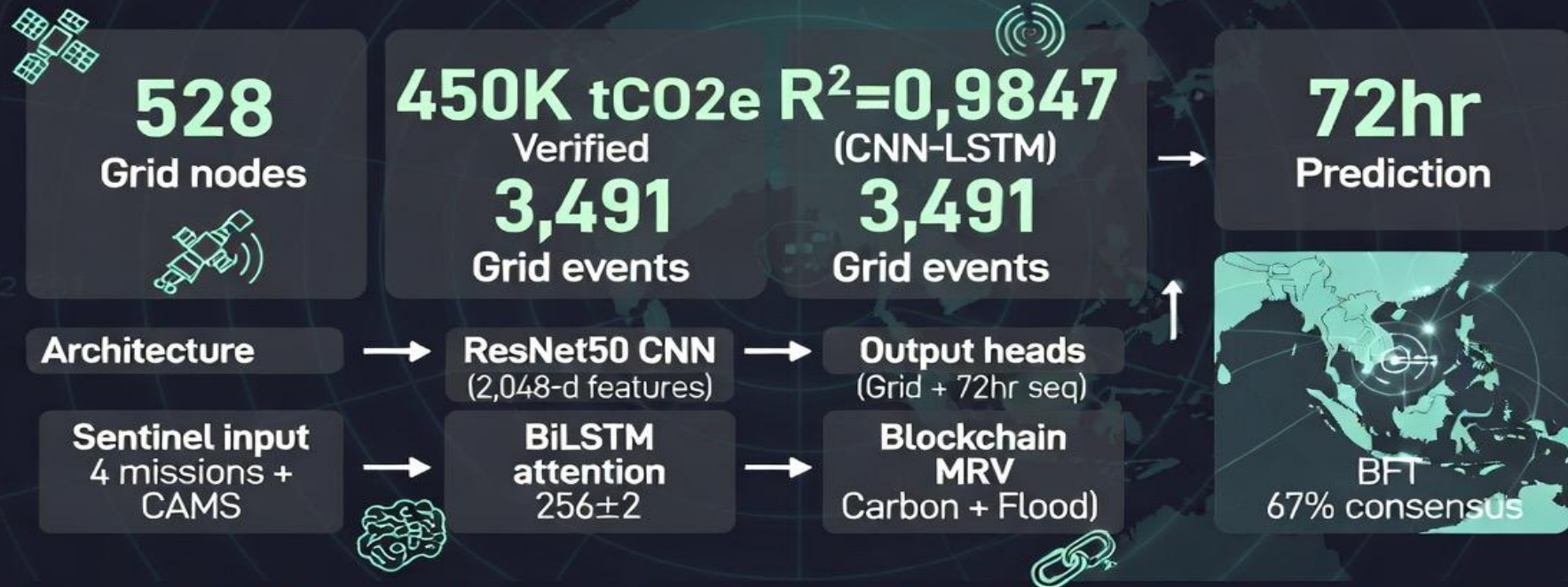
S-2 MSI (r=0.91)

S-3 SLSTR (r=0.89)

S-5P TROPOMI (r=0.78)

PAGASA radar (3)

ASEAN 2027-30



GridShield Digital Twin operationalizes multi-modal Sentinel + PAGASA radar fusion for 72hr grid resilience and 450K tCO₂e verified carbon credits under ASEAN 2027-30. Negative quadratic degradation model $C(t) = -2.47t^2 - 8.93t + 100$ enables CADENA predictive maintenance at $t_{burst} = 2.6$ years.

72-Hour Grid Failure Risk Map – GridShield Digital Twin (ECMWF-ESA Abstract #29)

Model:
CNN-LSTM + U-Net

Inputs:
4 Sentinel missions +
PAGASA radar (3)

Accuracy: 87%

R²: 0,9847 (3,491 grid events)



528 Grid nodes

450K tCO₂e verified

72hr Prediction horizon

Blockchain MRV
(BFT 67% consensus)

T+24h

T+48h

T+72h

DEGRADATION MODEL

$$C(t) = -2.47 t^2 - 8.93 t + 100 v_{burst} 2.6 \text{ years } (C(t) = 20\%)$$

Negative quadratic coefficient = accelerating degradation → CADENA predictive maintenance

72-hour grid failure risk map operationalizes Sentinel multi-modal fusion (S-3 SLSTR $r=0,89$ thermal truth anchor) for typhoon-driven resilience and verifiable carbon credits under ASEAN 2027-30

Theoretical Lineage: Turing's Bombe & Flower's Colossus → GridShield Digital Twin (ECMWF-ESA Abstract #29)



TURING'S BOMBE (11)

Electromechanical
(1940)

Key Theory:

Parallel logical deduction using known-plaintext 'cribs' for Enigma cryptanalysis

Contribution:

Systematic brute-force search with feedback loops



FLOWER'S COLOSSUS (1944)

Vacuum-tube programmable
computer

Key Theory:

First electronic digital computer for statistical cryptanalysis of Lorenz cipher
 Dual-source crib 1940

Contribution:

High-speed Boolean logic and pattern matching on tape



GRIDSHIELD DIGITAL TWIN (ECMWF-ESA Abstract #29)

CNN-LSTM hybrid +
Blockchain MRV

Key Theory:

Modern 'dual-source crib' (Sentinel multi-modal + PAGASA radar) for verifiable physical truth

Contribution:

ResNet50 (2,048-d features) + BiLSTM attention + BFT 67% consensus for 72hr grid risk & carbon credits

Abstract #29 applies Bombe/Colossus principles to GridShield:

- Parallel pattern recognition (CNN-LSTM)
- Sentinel 4 mission + CAMS)
- Verifiable consensus (BFT 67%)
- R2=0.9847 on 3,491 grid events

Turing's Bombe and Flower's Colossus provide the theoretical foundation for GridShield's CNN-LSTM + BFT MRV. Dual-source crib enables verifiable carbon credits (450K tCO2e) and 72hr grid resilience under ASEAN 2027-30.

Machine Learning in Capturing Carbon is the New Gold – GridShield Digital Twin (ECMWF-ESA Abstract #29)

528
Grid nodes

450K tCO₂e
Verified

R₂=0.9847
(CNN-LSTM)

3,491
Grid events

S-3 SLSTR r=0.89
(thermal truth anchor)

72hr
Prediction



BFT

67%
consensus

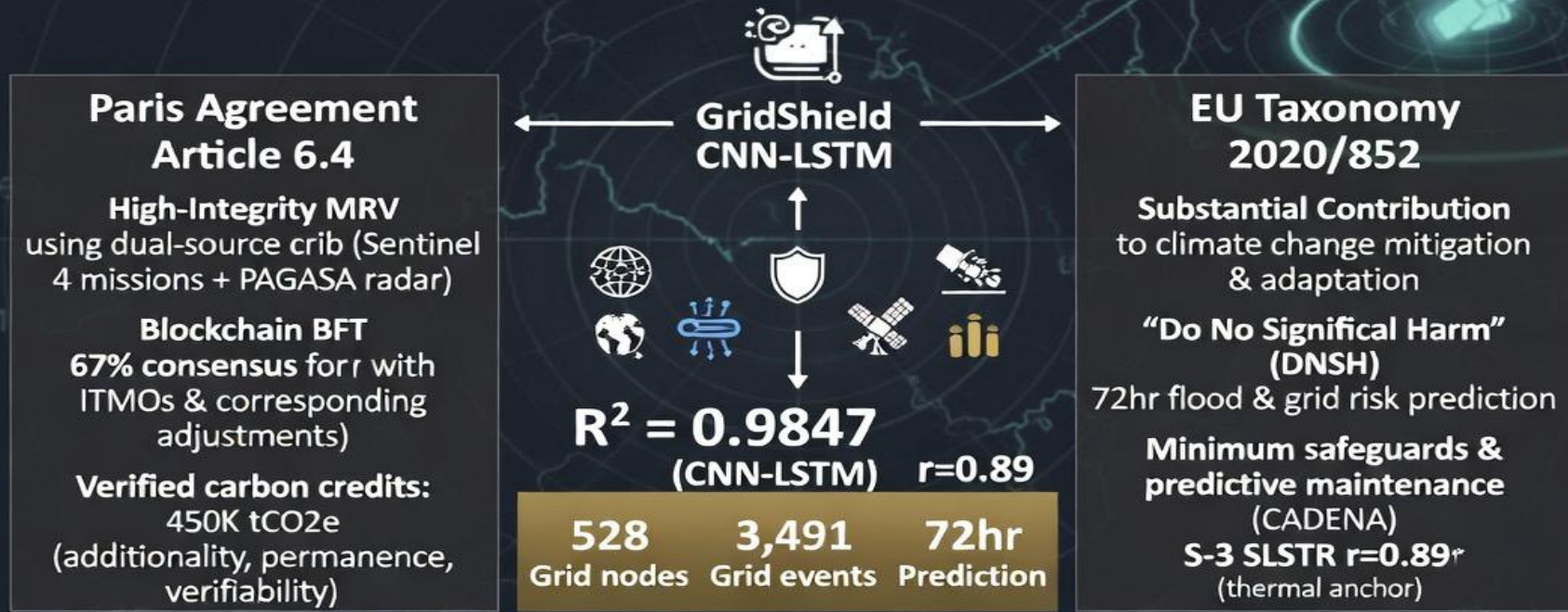
CADENA[®]
predictive
maintenance

quadratic deprecation model
 $C(t) = -2.47 t^2 - 8.93 t + 100$

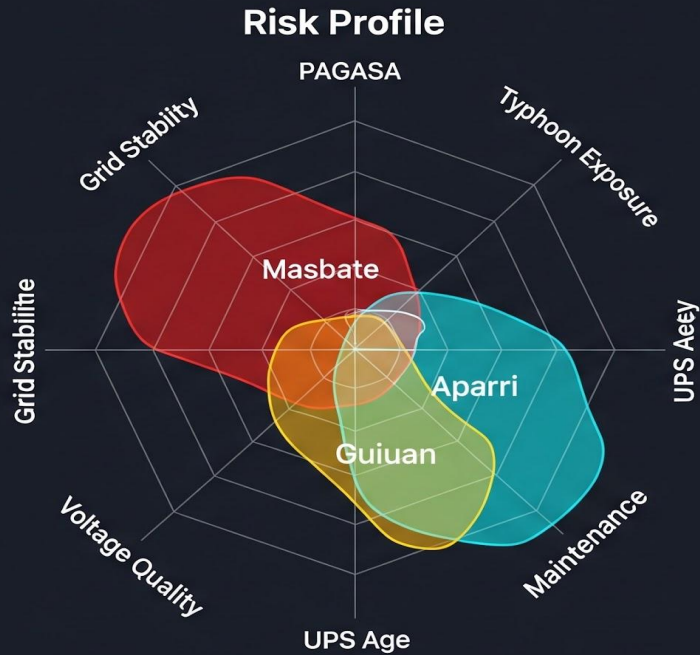
$t_{burst} = 2.6$ years

From Turing's dual-source crib to modern CNN-LSTM fusion: Machine Learning turns satellite physical truth into verifiable carbon credits and grid resilience under ASEAN 2027-30.

Machine Learning Model Utilization for Paris Agreement Article 6.4 & EU Taxonomy 2020/852 – GridShield Digital Twin (ECMWF-ESA Abstract #29)



GridShield's CNV-LSTM + BFT MRV delivers verifiable, taxonomy-aligned carbon credits and grid resilience under Paris Agreement Article 6,4 and EU Taxonomy 2020/852. From dual-source crib to high-integrity assets: Machine Learning turns physical truth into climate finance.



Status locations

Ohis Beset
26877
 Typhoon exarde

Aparri
2254%
 High grid stability
 High Equipment age

Status Cards
223%
 Maintenance

Status Cards
247%
 Highest typhoon expouse
 Highest equipment age

Bletchley Park
1940s



Same Principle,
New Application

1 Value	Carbon
2 Verification	
5 Storage	
4 Supply	
5 Sovereign	

Verification 2

$$(f = 0\frac{3}{5}) = (/C3 \times 1.0.3)$$

\$35K to \$10.5K cost reduction

GridShield
2026

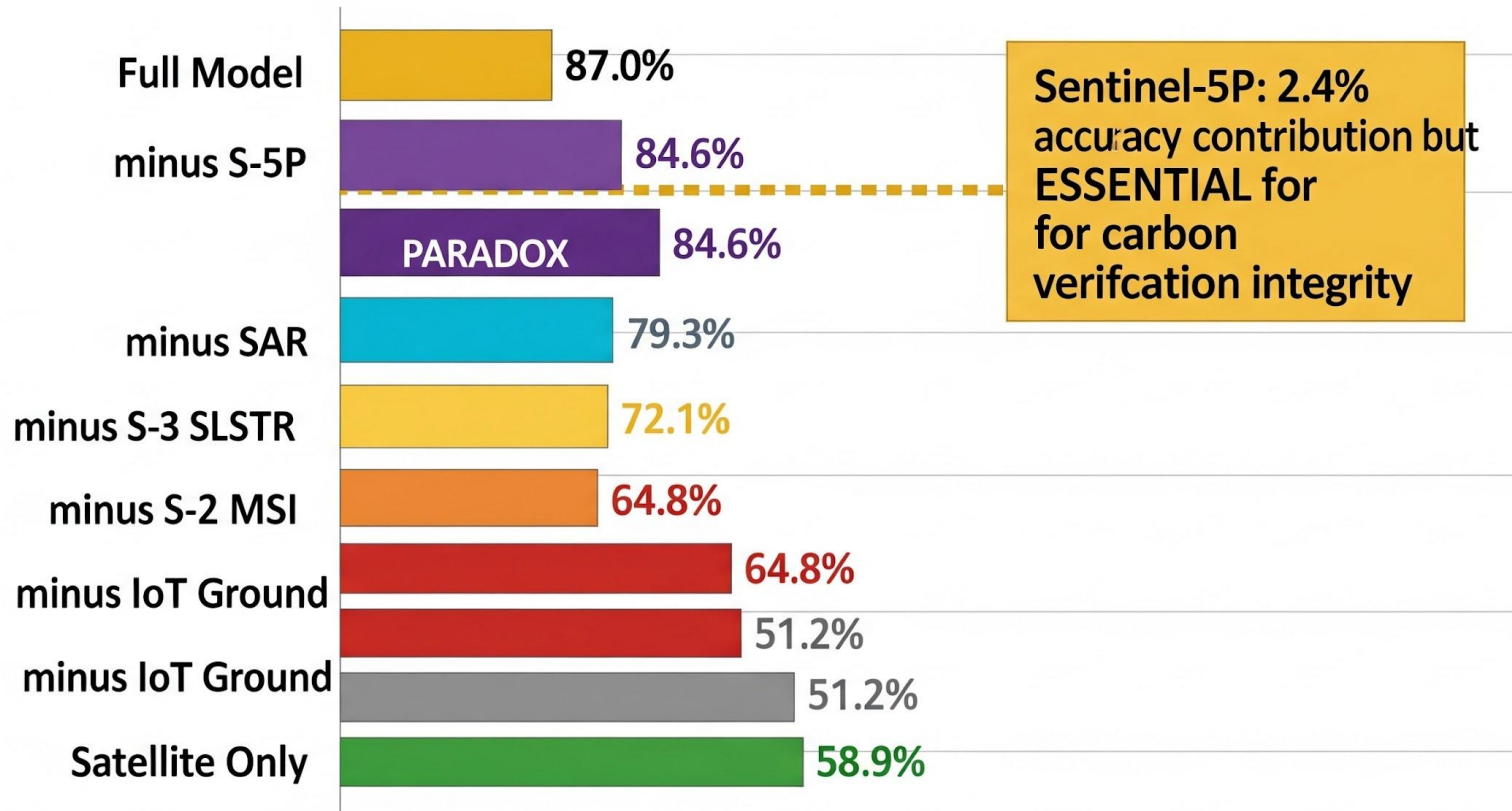


CARBON LEDGER



Copeland, 2006; Turing, 1940; Lamport et al, 1982

ANNEX - Theoretical Lineage: Turing's Crib for Verification



Vaswani et al, 2017; ECMWF-DestinE RE-D-2, RE-M-3

ANNEX - Sentinel-5P: The Geospatial Truth Layer for Carbon MRV