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PROPOSING SUSTAINABLE POWER SYSTEMS FOR ENHANCED INTERNATIONAL MONITORING SYSTEMS OPERATIONS

Study Case in Indonesia

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BMKG

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INTRODUCTION
(Background)

CTBTO Relevance

- Continuous station uptime is **critical for treaty verification**
- Self-sustaining power systems reduce risk of outages
- Remote monitoring + predictive maintenance ensure **data quality and resilience**

IMS under CTBTO

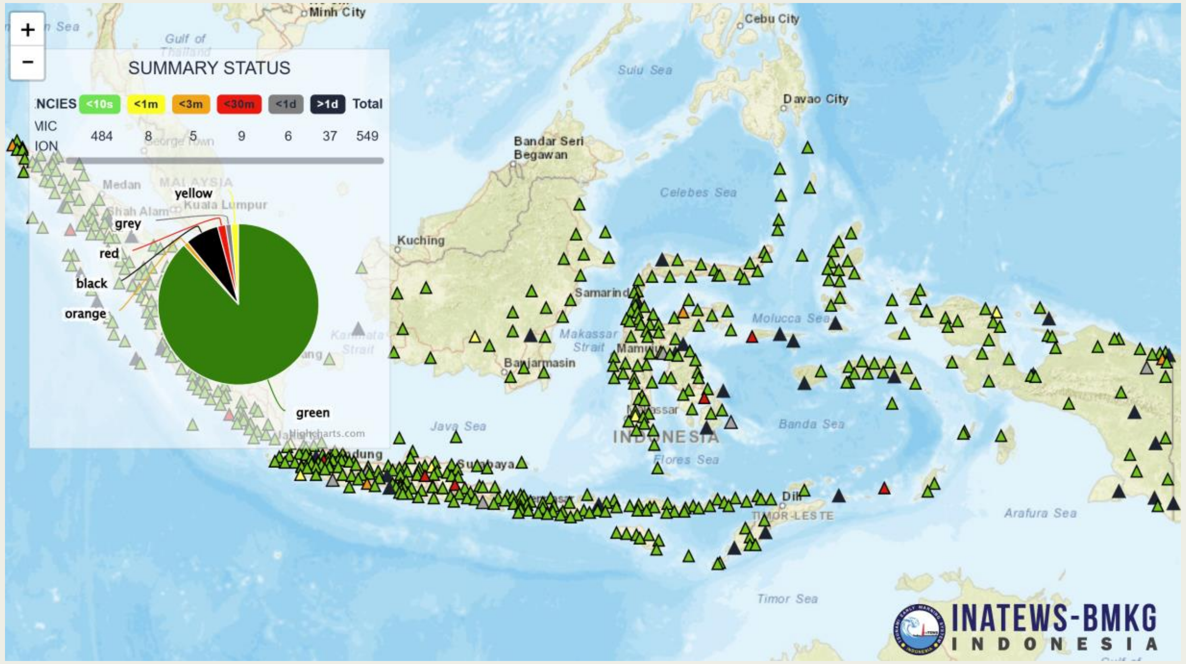
- Global network for nuclear-test-ban verification
- Indonesia: >500 seismic stations (BMKG), 6 auxiliary IMS stations

Maintenance Responsibility

- All seismic & IMS stations are **maintained in-house** by BMKG technicians
- No outsourcing → full reliance on BMKG staff capacity

Operational Challenges

- Wide archipelagic geography → high logistics and travel costs
- Limited number of technicians → stretched across hundreds of stations
- Fiscal constraints (Presidential Instructions /INPRES No.1/2025) → fewer site visits allowed



MAINTENANCE BASED ON MONITORING

POWER SUPPLY

SEISMIC

COMMUNICATION

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INTRODUCTION
(Current Systems)

Deployed Technology

- Solar PV arrays + **Growatt SC4860 MPPT**
- **$LiFePO_4$ batteries** for stable, long-cycle storage
- Connectivity via **Teltonika RUT-955 modem**

Field Proven

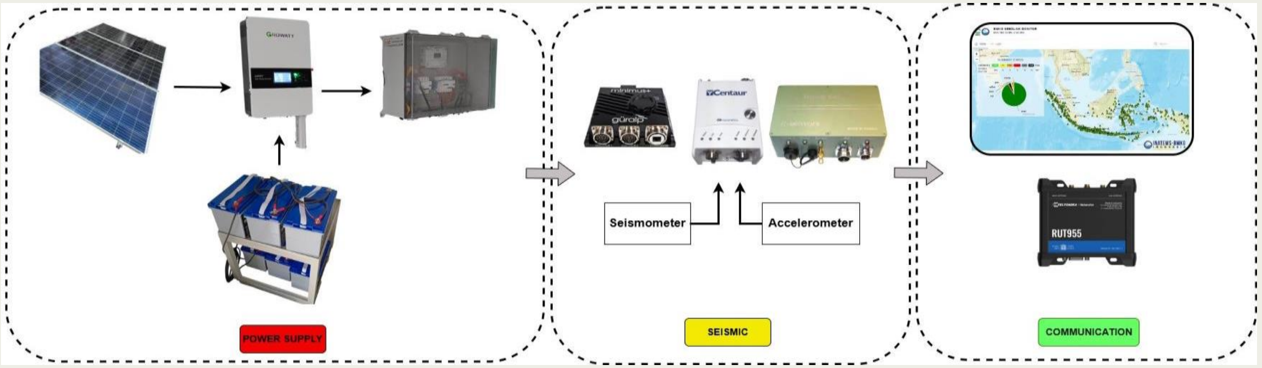
- Successfully implemented at **BMKG stations** (MLJI, PMCI, TRT, ARMI)
- Provides **real-time monitoring** of SoC and charging/discharging

Limitations

- Monitoring **restricted to vendor dashboards** (Growatt/ShinePhone)
- **No MQTT telemetry** → data not integrated with IMS servers
- Maintenance remains **reactive**, not predictive

Key Insight

- Hardware is strong and reliable ✅
- **Bottleneck lies in telemetry & analytics** ❌



Seismological Stations	Power Supply			Seismic			Communication
	Solar Panel	Battery	Solar Charge Controller	Digitizer	Seismometer	Accelerometer	Modem
MLJI	Solar panels 370 WP (3 units)	Haze 12V 70Ah (4 units)	Growatt SC4860	Centaur	Trillium 120Q	Titan	Teltonika RUT-955
PMCI	Solar panels 260 WP (3 units)	LiFePO4 24V 100Ah (6 units)	Growatt SC4860	Centaur	Trillium Horizon	Titan	Teltonika RUT-955 & Cygnus 210
TRT	State electricity company	LiFePO4 12V 100Ah (2 units)	Growatt SC4860	NDAS 8426	R-sensor CME-6211	-	Teltonika RUT-955
ARMI	Solar panels 260 WP (3 units)	LiFePO4 24V 100Ah (6 units)	Growatt SC4860	Minimus+	Guralp 3T 120	Fortis	Teltonika RUT-955

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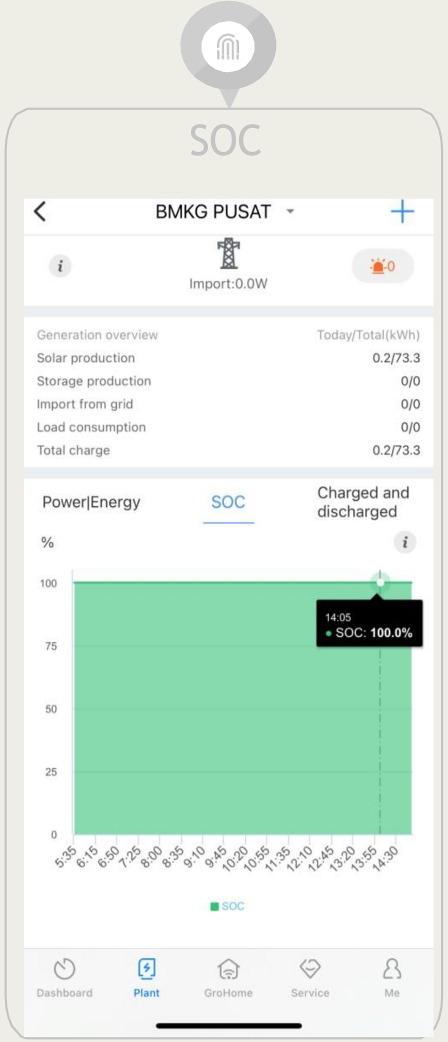
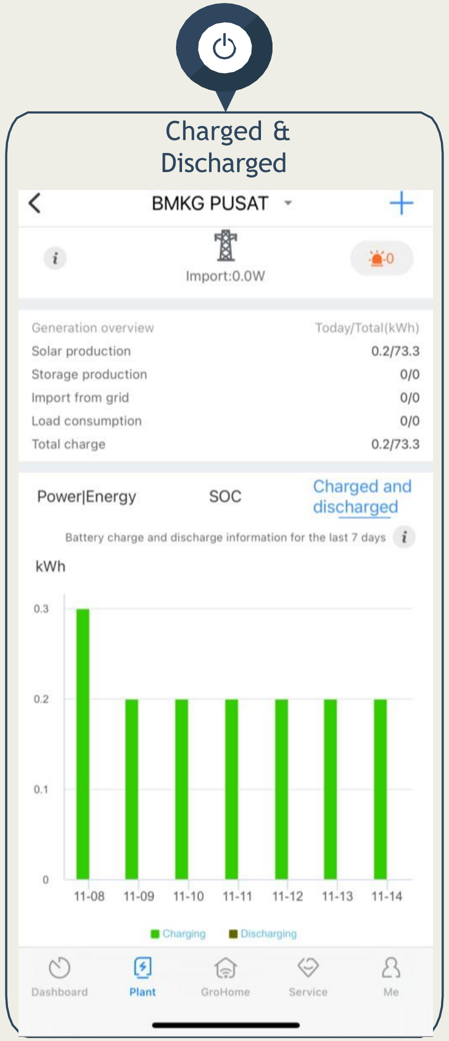
INTRODUCTION
(Identified Challanges)

❌ No MQTT telemetry	Power parameters (voltage, current, SoC, SoH) **locked in vendor dashboards** No integration with **BMKG central servers** for power systems
❌ Reactive maintenance	Failures detected **only after downtime** No predictive tools for **SoH/RUL forecasting**
❌ High costs	Archipelagic geography → **expensive logistics** Limited BMKG technicians stretched across **>500 stations**
❌ Policy pressure	**Presidential Instructions /INPRES No.1/2025** mandates strict expenditure efficiency Fewer site visits allowed → higher risk of undetected failures





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RESEARCH OBJECTIVES

Good Maintenance for Sustainability

Standardize Telemetry

- Adopt **MQTT QoS2** → secure, exactly-once data delivery
- Replace siloed vendor dashboards with

Enable Predictive Maintenance

- Apply **BiLSTM & ensemble AI models for SOH and RUL**
- Transition from **reactive → proactive** station management

Enhance Sustainability (*Triple Bottom Line*)

- **Economic**: lower OPEX, fewer site visits, align with Presidential Instructions (INPRES) No.1/2025
- **Environmental**: maximize battery lifecycle, reduce e-waste, renewable energi
- **Social**: ensure continuous CTBT verification & tsunami early warning reliability

Strategic Impact

- Strengthen **IMS resilience** in Indonesia
- Provide **scalable model** for global IMS operations

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LITERATURE REVIEW

Power Supply in Remote Monitoring	BMKG field tests: PV + $LiFePO_4$ + MPPT **feasible in harsh environments**
	Similar AWS/IoT deployments show same challenges → data often siloed (Ioannou, 2021)
MQTT in IoT Applications	Proven in **environmental monitoring & cloud integration** 【Alves, 2024】
	Lightweight, secure, scalable → ideal for IMS
	QoS2 ensures exactly-once delivery, critical for treaty verification
Predictive Maintenance	**Reactive / scheduled maintenance insufficient** in remote sites 【Afif & Meganendra, 2023】
	BiLSTM & CNN-BiLSTM with attention → **accurate SoH & RUL forecasts** 【Guo, 2022; Zhang, 2022】
	Ensemble deep learning → **robust across variable conditions** 【Ganaie, 2022; Lin, 2023】; **Hybrid CNN–BiLSTM–Attention** models proven accurate for battery SOH & RUL estimation (Zhu et al., 2022)
Sustainability (Triple Bottom Line)	**Economic:** Predictive = lower OPEX, fewer field trips
	Environmental: Extend battery life, reduce e-waste 【Fairuzen, 2021】
	Social: Continuous IMS uptime supports **CTBT verification + tsunami warning** 【Arora, 2024】

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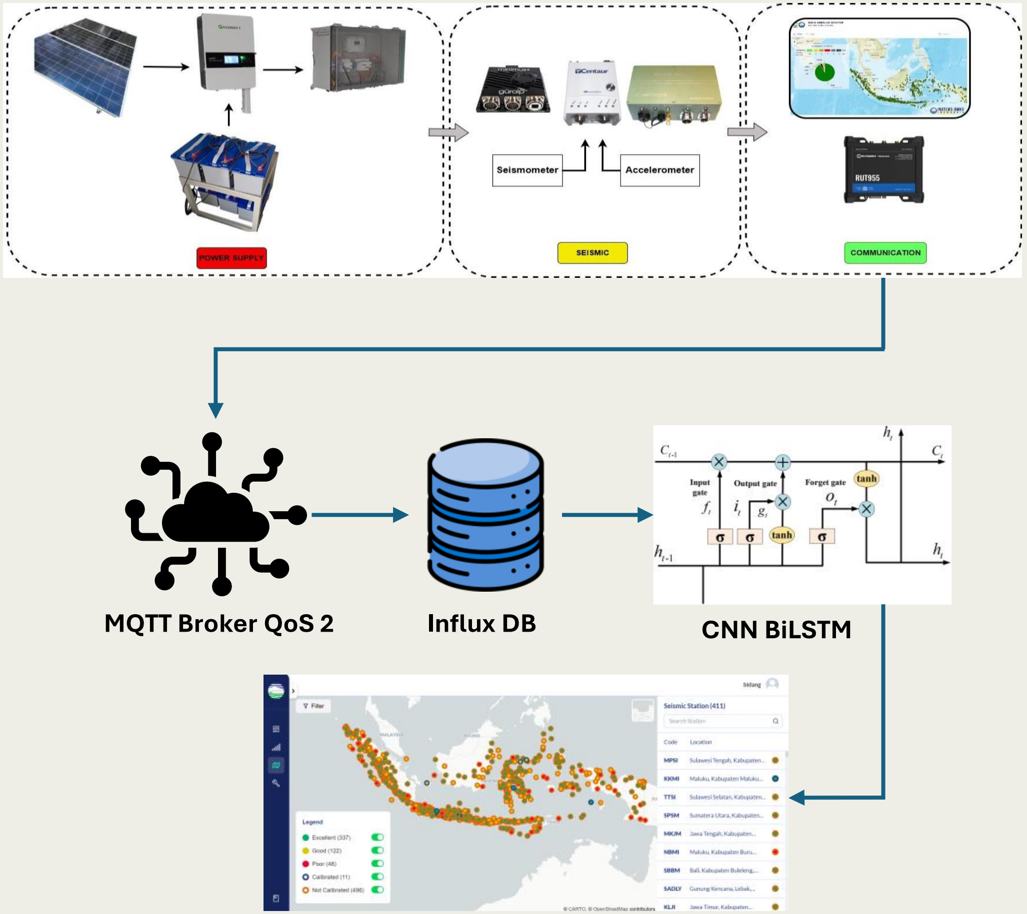
METHODS
(Proposed System Architecture)



Hardware Layer

- Solar PV arrays sized for site load
- **Growatt SC4860 MPPT** → efficient charging + basic monitoring
- **$LiFePO_4$ batteries** → stable, long-cycle energy storage

Connectivity Layer

- **Teltonika RUT-955 Gateway** → cellular/satellite backhaul
- Publishes telemetry via **MQTT (QoS2 + TLS)**

Data & Server Layer

- **IMS Central Server** + Time-Series Database
- Stores multi-site telemetry for trend & fault analysis

Analytics Layer

- **Predictive Maintenance**: BiLSTM + ensemble models
- Continuous estimation of **SoH & RUL**

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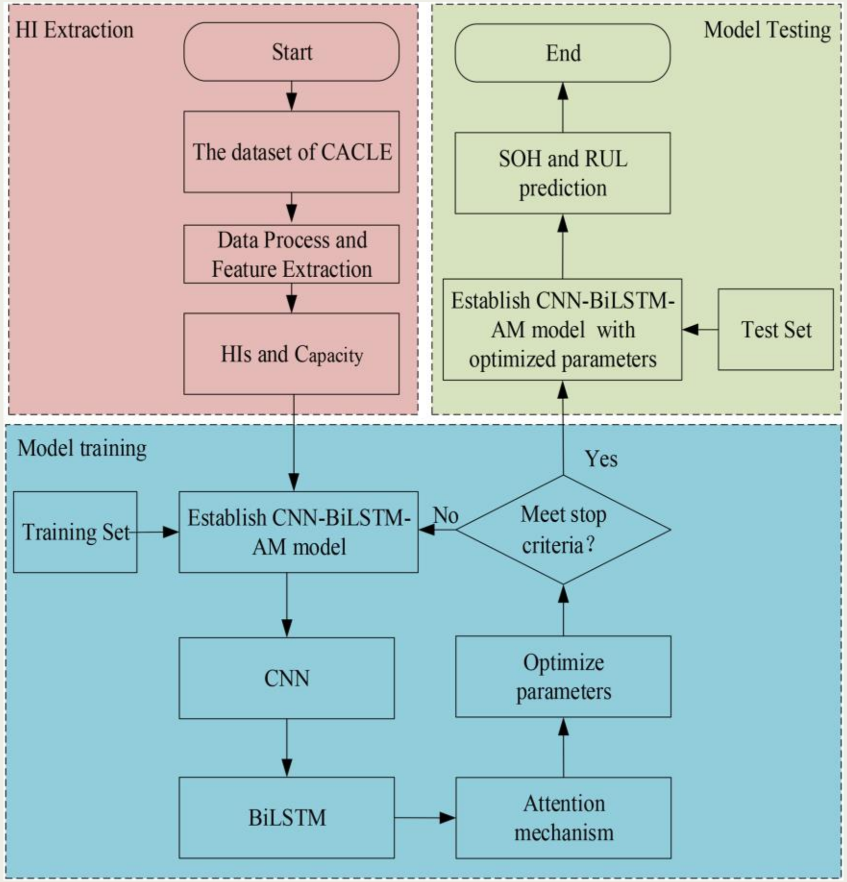
METHODS
(Predictive Maintenance Analytics)



Inputs

- Voltage, Current, Temperature, State of Charge (SoC), Cycle Count

Models

- **BiLSTM** – captures long-term sequential dependencies in battery data
- **CNN–BiLSTM–Attention ensembles** – combine local feature extraction (CNN), temporal context (BiLSTM), and focus on critical patterns (Attention)
- Proven in lithium-ion battery SoH & RUL prediction (Zhu et al., 2022)

Outputs

- Continuous estimation of **State of Health (SoH)**
- Prediction of **Remaining Useful Life (RUL)** until 80% SoH threshold (IEEE standard)

Alerts

- Predictive results published via **MQTT topics** (ims/<site>/alerts)
- Provides **early warnings** → enables proactive interventions before failures

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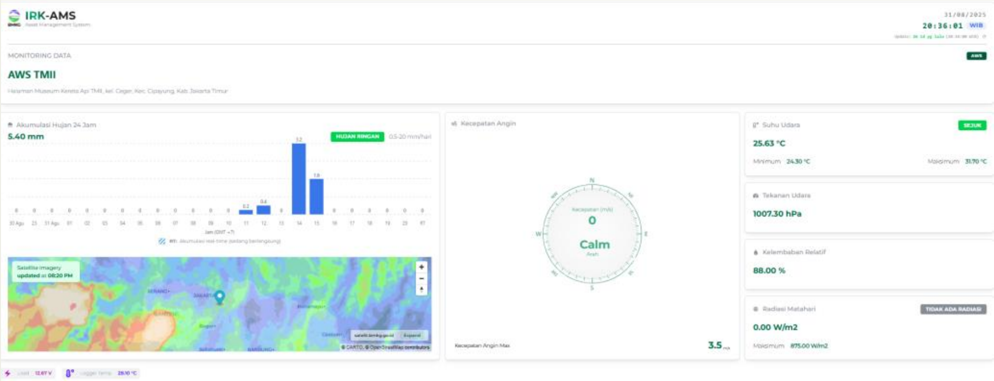
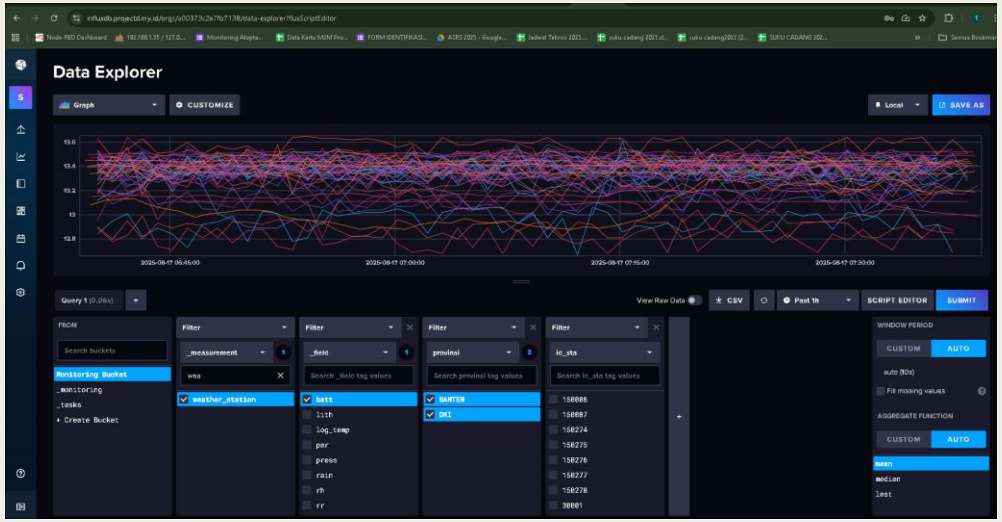
RESULTS AND DISCUSSION
(Field Feasibility)





Implementation Sites (Seismic Stations)

- MLJI (Malang, East Java); PMCI (Mamuju, West Sulawesi); TRT (Pasuruan, East Java) and ARMI (Aru Islands, Maluku)

Status at Seismic Sites

- Deployed: PV + Growatt SC4860 MPPT + $LiFePO_4$ + Teltonika gateway
- Limitation: **No MQTT telemetry, no predictive maintenance** yet
- Further development **constrained by Presidential Instructions (INPRES) No.1/2025 (budget efficiency)**
- Plan: pilot implementation at **BMKG Geophysics sites** in the near term

Experience from AWS (Automatic Weather Stations)

- **MQTT + InfluxDB** successfully deployed for >2 years
- Proven scalability and stability for real-time telemetry
- Next step: integrate **predictive maintenance models** for power systems

Research-backed confidence

- Numerous studies (e.g., Zhu et al., 2022; Guo et al., 2022) show **high accuracy and robustness** of CNN–BiLSTM–Attention models for SoH and RUL prediction
- Strong evidence base → high confidence that **sustainable and reliable IMS power systems** can be achieved

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RESULTS AND DISCUSSION
(Triple Bottom Line Impacts)

Economic 💰

- Reduce costly site visits across Indonesia’s archipelago
- Optimize battery replacement cycles → avoid premature replacements
- Aligns with **Presidential Instructions (INPRES) No.1/2025** on expenditure efficiency

Environmental 🌱

- Transition to **renewable solar energy** reduces fossil fuel reliance
- Predictive replacement **minimizes electronic waste** ($LiFePO_4$ batteries used to full lifespan)
- **Lower carbon** footprint from reduced logistics and transport

Social 👥

- Ensures **continuous IMS uptime** → supports CTBT verification globally
- Reliable seismic stations strengthen **tsunami early warning systems** for local communities
- Builds resilience and public safety through sustainable operations

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CONCLUSION AND FUTURE WORK

Conclusion

- IMS in Indonesia: **proven hardware** (PV + Growatt SC4860 + $LiFePO_4$) but **limited by vendor dashboards** → no MQTT telemetry, no predictive maintenance
- Proposed: **MQTT QoS2 + BiLSTM/ensemble predictive analytics** → shift from **reactive → proactive & sustainable**
- Confidence backed by:
  - ❑ **BMKG AWS experience** (2+ years using MQTT + InfluxDB, next step predictive models)
  - ❑ **Global research** (CNN–BiLSTM–Attention, Zhu 2022; Guo 2022) → high accuracy in SoH & RUL estimation
- **Triple Bottom Line impacts**: lower costs (aligned with Presidential Instructions / INPRES No.1/2025), reduced e-waste & carbon footprint, stronger CTBT verification & tsunami early warning

Future Work

- Pilot deployment at **BMKG Geophysics sites** to validate MQTT + predictive maintenance
- Scale-up integration into **IMS auxiliary stations** for CTBTO verification network
- Extend predictive models with **uncertainty-aware AI** for decision support
- Build a **replicable framework** → scalable across global IMS operations

"With proven hardware, national AWS experience in MQTT, and strong global research on predictive models, we are confident that sustainable, intelligent, and resilient IMS power systems can soon be realized — starting from Indonesia, and potentially scalable for the entire CTBTO network."

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