Real-Time Wave Energy Forecasting with Physics-Informed Kolmogorov-Arnold Networks (PIKAN)

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Background

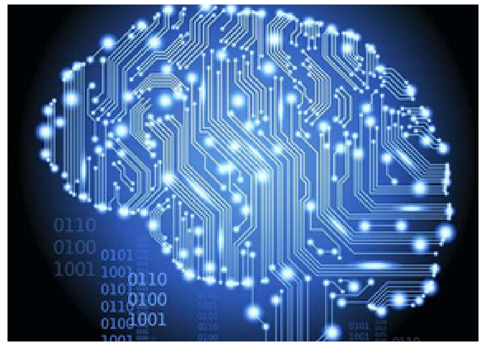
- ICT drives 4IR innovation across AI, IoT, big data, and automation.
- Marine forecasting is still computationally heavy when using CFD or spectral models within ASEAN
- Embedding physics-informed AI within IoT devices can enable real-time, low-latency prediction.

Problem:

- Existing models (CFD, LSTM) are either too slow or “black-box.”
- No lab-scale ICT testbed for marine forecasting exists in Brunei or the ASEAN region.
- Lack of physics-consistent forecasts limits safe and efficient wave-energy operations.

Goal:

- Develop a real-time, low-cost, physics-informed ICT system deployable on embedded hardware (e.g., Raspberry Pi).
- Aligned with the ASEAN Digital Economy Framework Agreement (DEFA) by demonstrating IoT & AI digital services that contribute to ASEAN’s US$1-2 trillion digital economy by 2030.



Targets

- Build a smart IoT-enabled wave tank for real-time monitoring.
- Integrate ESP32 with sensors → Raspberry Pi → Cloud (ThingSpeak).
- Train and benchmark AI models (LSTM, PINN, PIKAN).
- Deploy PIKAN for sub-second wave prediction and visualization.
- Support Wawasan Brunei 2035 & UN SDGs 7 & 13. Also aligns with DEFA (digital innovation), the ASEAN Renewable Energy Long-Term Roadmap (energy transition) and the ASEAN Climate Change Strategic Action Plan 2025-2030 (climate resilience).

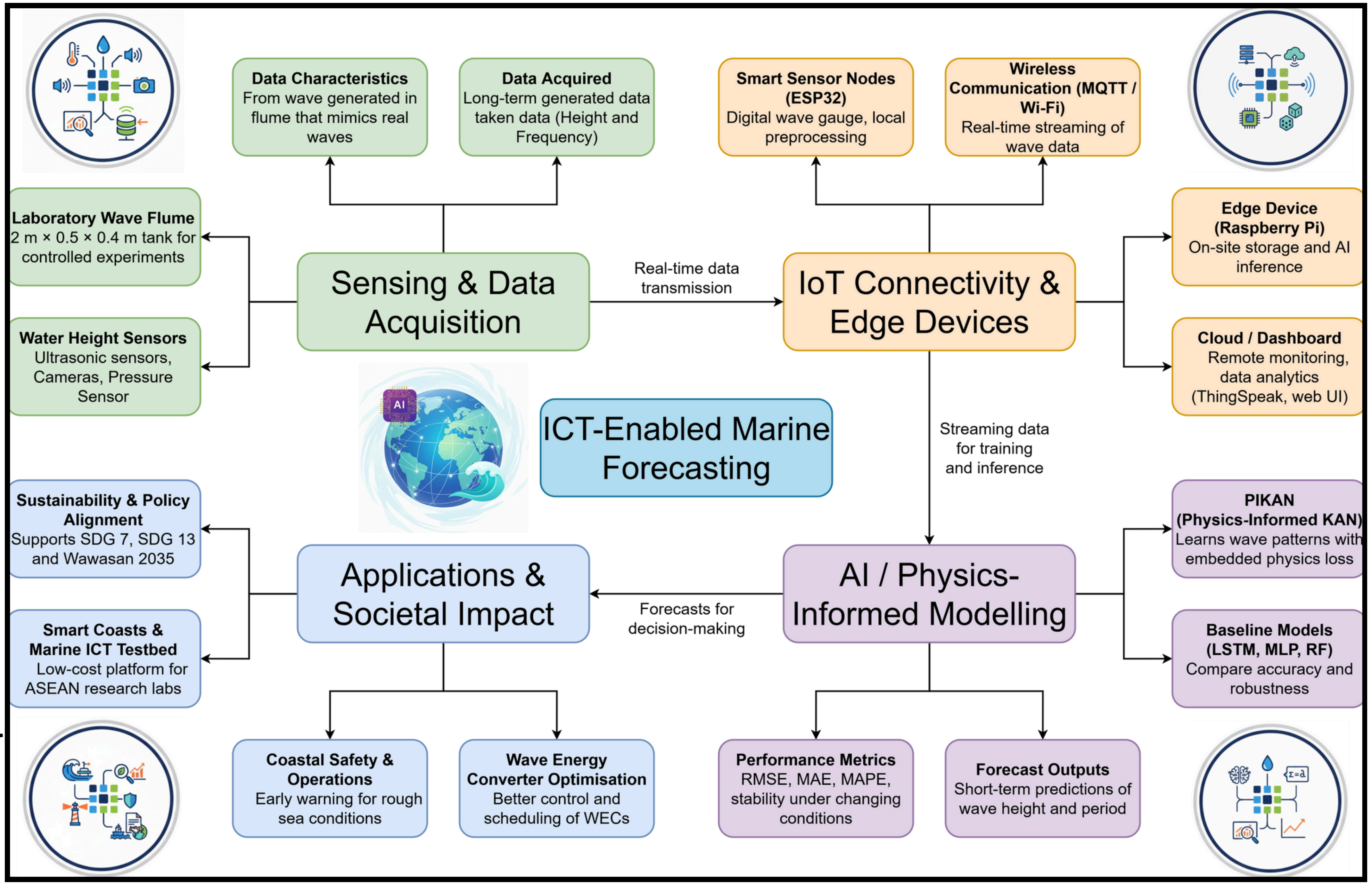


Figure 1: ICT-AI-IoT integration concept for real-time marine forecasting and decision support.

Proposed Method (1/3): System Architecture

- IoT Integration:
  Sensors → ESP32 (Data Acquisition) → Raspberry Pi (Edge AI) → Cloud Dashboard.
- Communication: Wifiprotocol for real-time streaming.
- Visualization: Web dashboard for live monitoring and data analytics.
- Edge-AI Inference: Local forecasting to minimize latency.

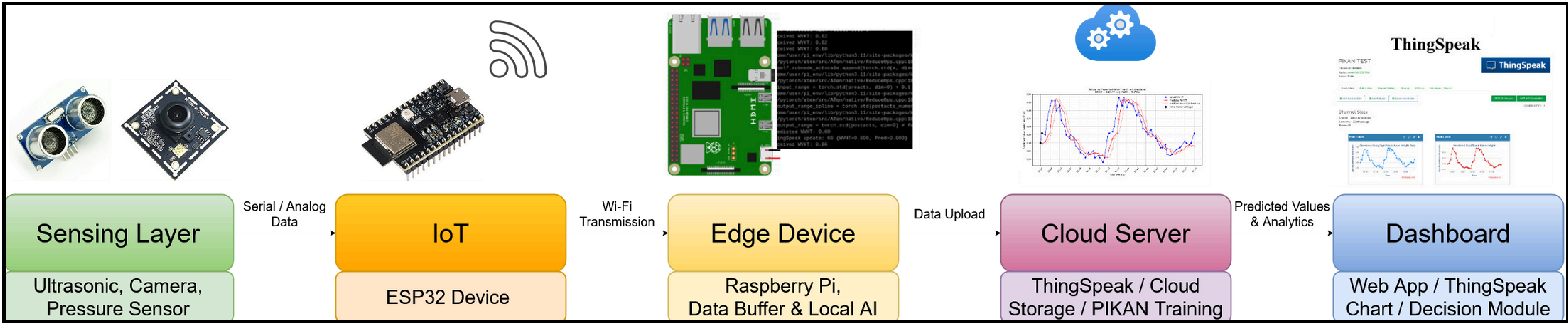


Figure 2: IoT-AI system architecture showing real-time data flow from marine sensors to cloud-based physics-informed modelling and dashboard.

Proposed Method (2/3): AI Modelling

- Model Core: Physics-Informed Kolmogorov–Arnold Network (PIKAN).
- Combines KAN's interpretable spline transformations with physics residual loss.
- Training Data: Local tank data (or available buoy data if needed).
- Comparative Models: MLP, LSTM, PINN, RF, GBR.
- Optimization: Minimize RMSE + physics-loss for stable forecasts.

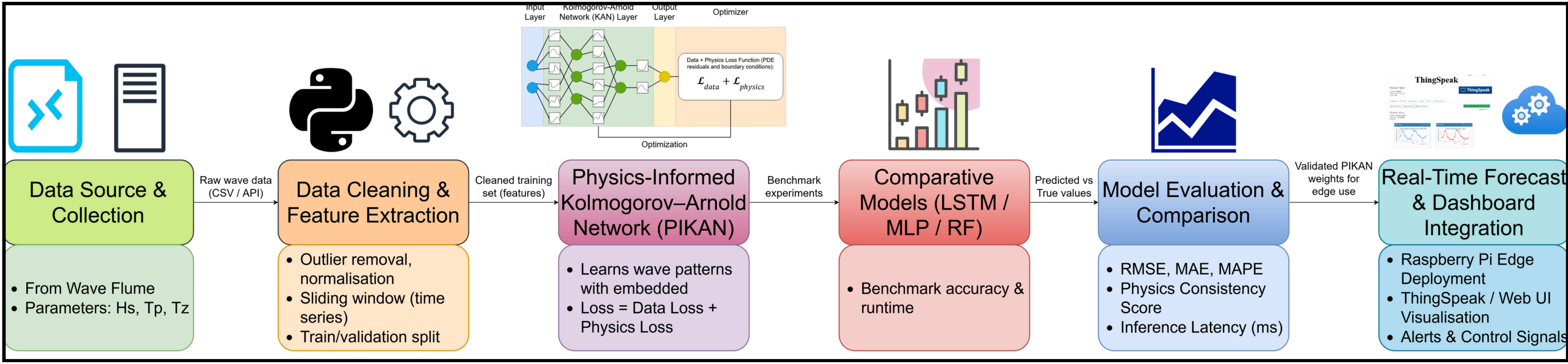


Figure 3: Workflow of the Physics-Informed Kolmogorov-Arnold Network (PIKAN) training and inference process, integrating raw marine data, AI modelling, and real-time deployment.

Proposed Method (3/3): Experimental Platform

- Wave Tank: 2.0 m × 0.5 m × 0.4 m with 0.26 m working depth.
- Wave Generator: Stepper-driven paddle, programmable via Arduino.
- Absorptive Beach: 1:8 slope to suppress >90% reflections.
- Instrumentation: Ultrasonic, and Camera sensor
- Manufacturability: Low-cost hybrid acrylic–steel frame for scalability. Steel used are hollow SS303 40mm X 40mm X 3.2mm

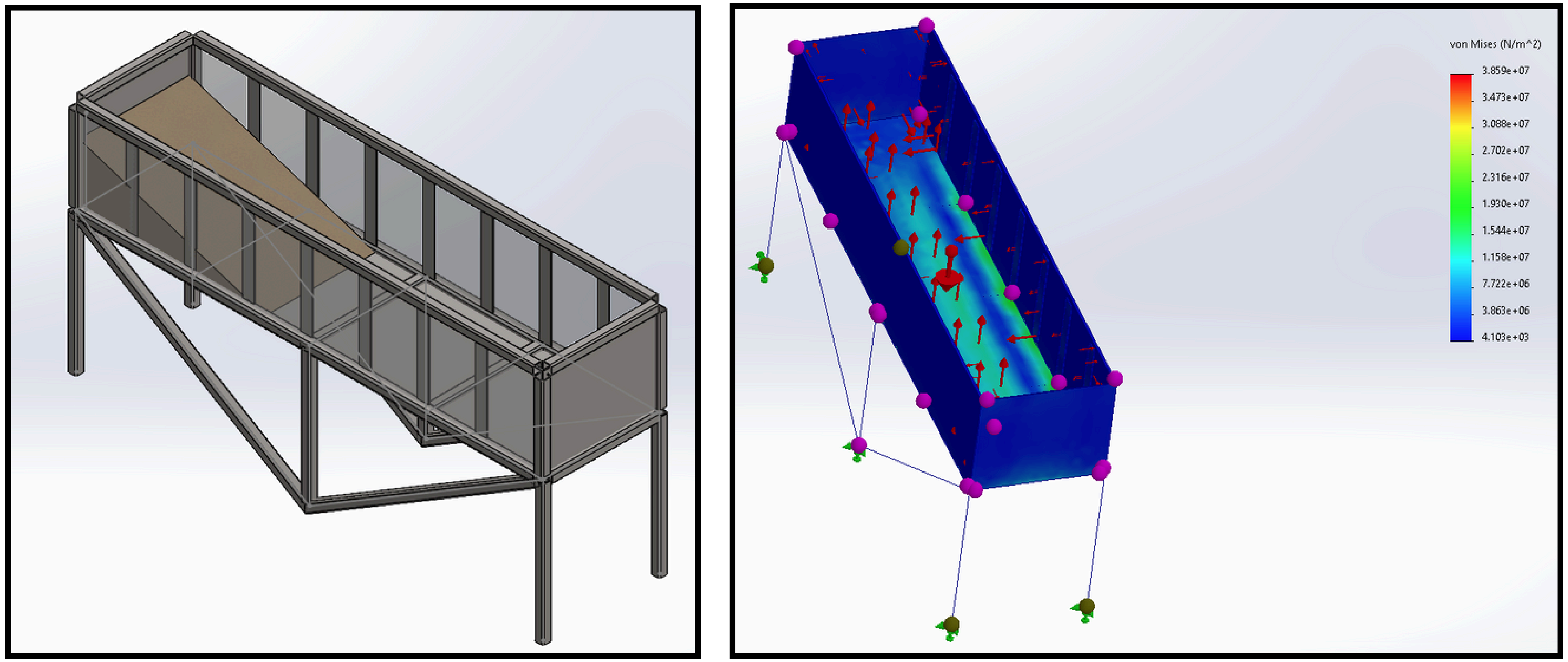
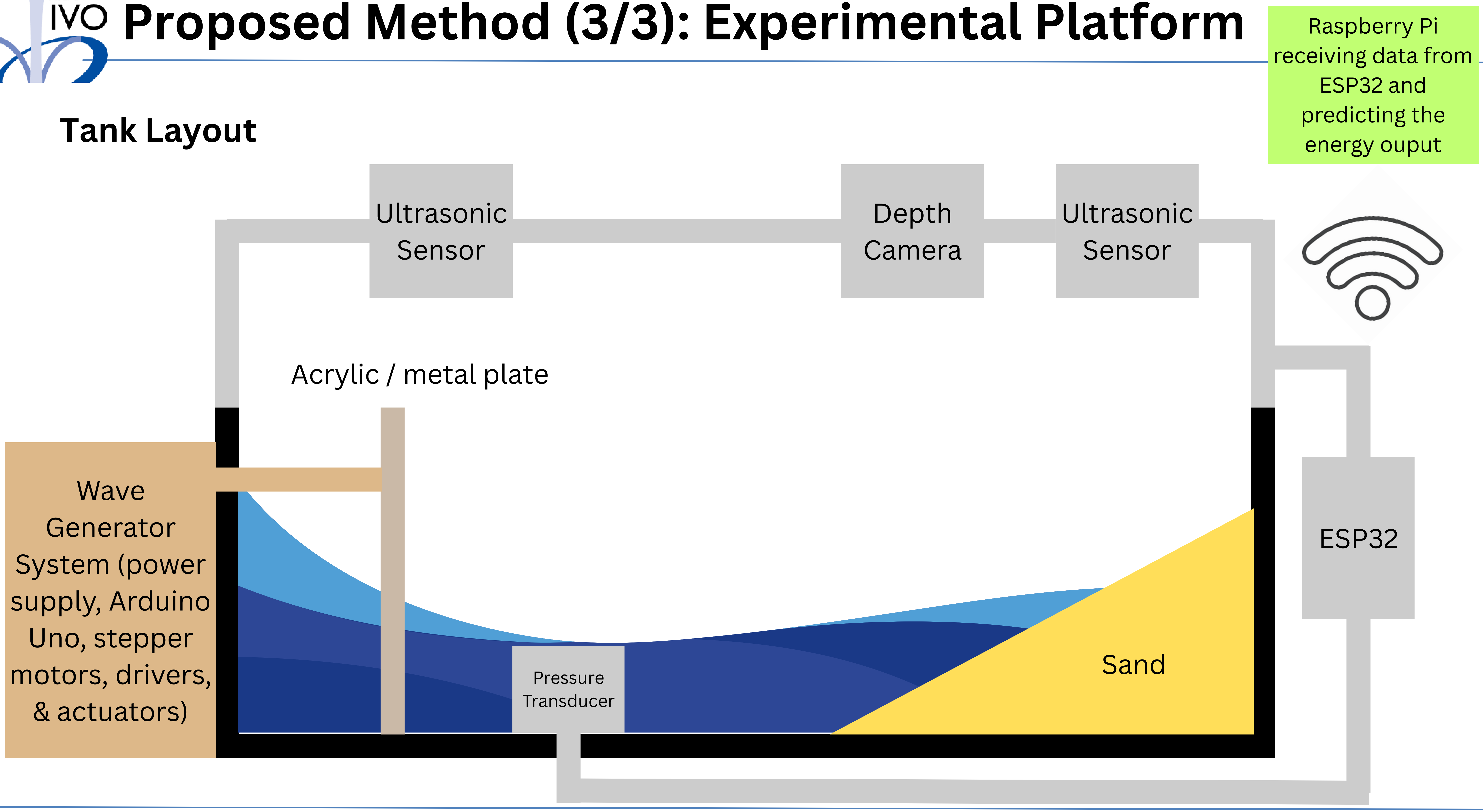


Figure 4: 3D Model of Wave Flume, and simulation with FOS of 1.5

Proposed Method (3/3): Experimental Platform

Tank Layout



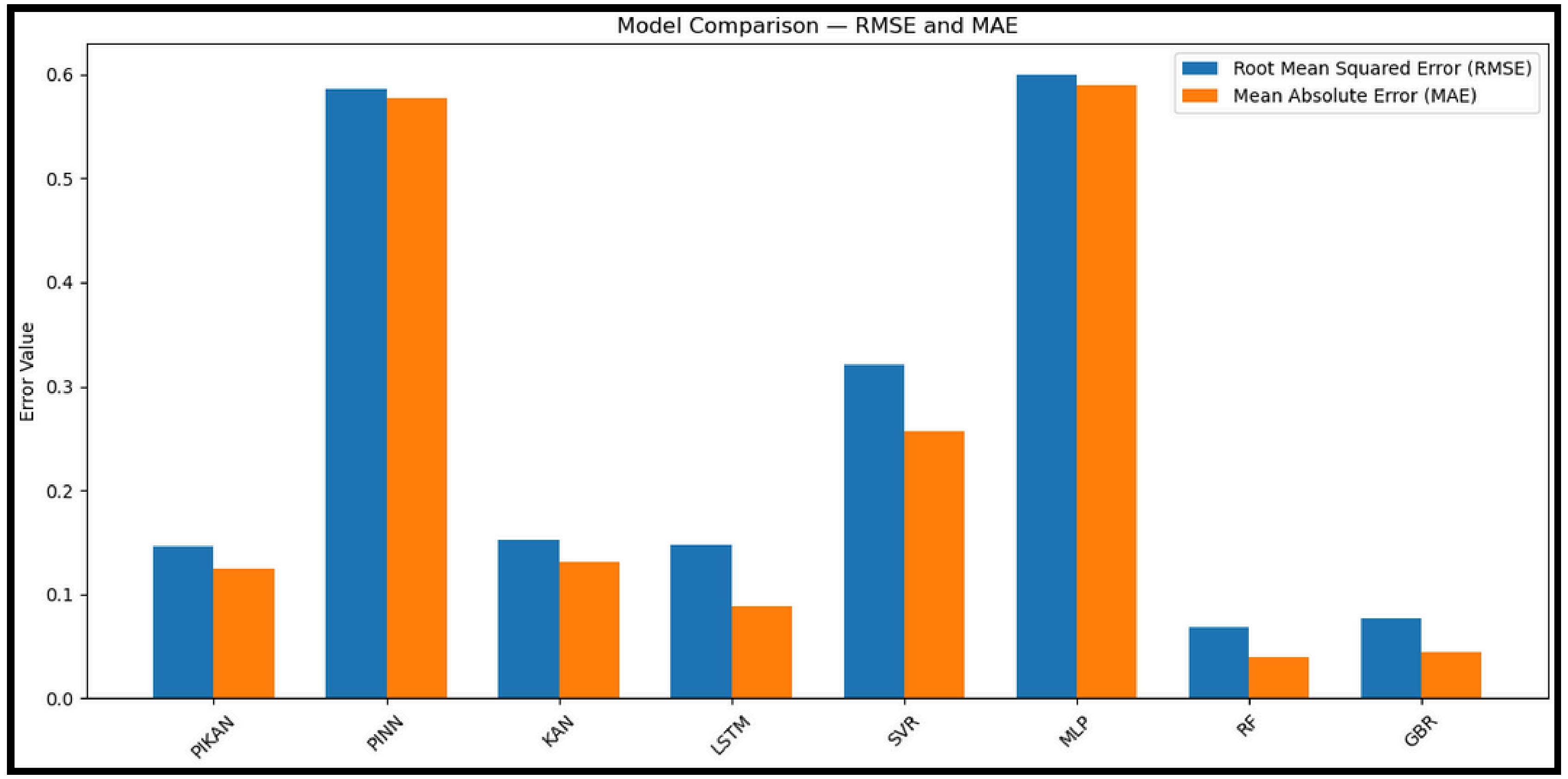
Impact (Scientific & Technological)

Scientific Impact

- Demonstrates integration of AI, IoT, and physics-based computing.
- Produces interpretable, robust forecasts for fluid systems.
- Advances embedded edge-AI design for smart coastal sensors.

Technological Impact

- Scalable ICT system for wave forecasting, aquaculture, and port safety.
- PIKAN model = blueprint for future 4IR hybrid AI architectures.
- Smart forecasting system supports the ASEAN Renewable Energy Roadmap's goal of managing high shares of renewables by 2045.



Model	RMSE	MAE	MAPE (%)	Physics Loss	Latency (ms)	Size (MB)
PIKAN	0.146	0.125	16.20	0.919	3.1	0.72
PINN	0.586	0.577	85.08	0.886	8.2	3.60
KAN	0.153	0.131	16.73	0.000	3.3	0.80
LSTM	0.146	0.089	11.30	0.000	6.8	3.00
SVR	0.321	0.256	42.59	0.000	-	-
MLP	0.600	0.590	84.30	0.000	5.1	2.00
RF	0.068	0.040	4.62	0.000	-	-
GBR	0.077	0.045	5.03	0.000	-	-

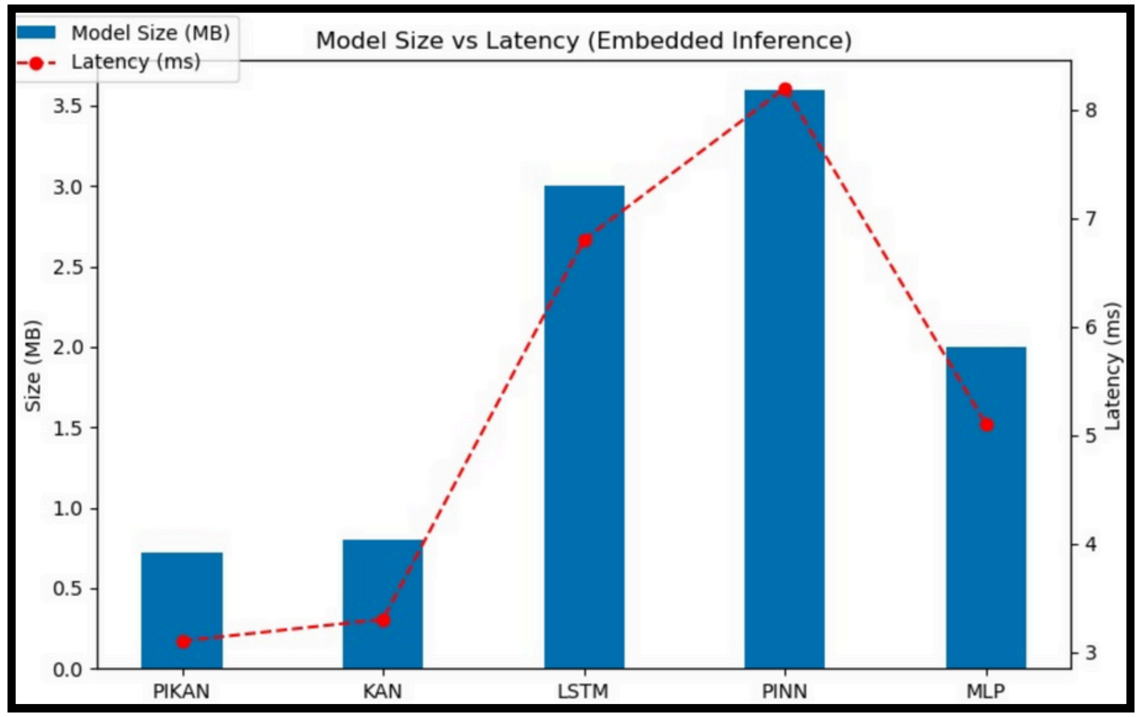


Figure 5: PIKAN vs LSTM vs MLP Learning Performance Graphs

Impact (Societal & Collaborative)

- **Supports Wawasan Brunei 2035 and ASEAN Community Vision 2045:** Knowledge-based, sustainable regional innovation

- **UN SDGs 7 & 13 + ACCSAP 2025-2030:** Clean energy, climate resilience, and a net-zero, climate-resilient ASEAN community.

- **Regional Value:** ASEAN platform for data-driven marine R&D.

- **Digital Service Potential:** Positions the platform as a scalable regional digital service under DEFA’s digital economy agenda.

- **Collaboration:** Potential cross-lab manufacturing of IoT-AI modules.

Figure 6.1: Framework for Turning Vision into Action of ASEAN 2045

Figure 6.2: SDG Alignment Infographic – Energy & Climate Action

Outcomes

Scientific

- Validated PIKAN achieves RMSE = 0.146, MAE = 0.125, Physics-Loss = 0.9189.
- Sub-second embedded forecasting verified on Raspberry Pi.

Societal

- Open-source dataset & lab-scale design available for replication.

Collaborative

- Expands ICT R&D partnerships in marine forecasting across ASEAN.
- A replicable case study for ASEAN implementation of the Renewable Energy Roadmap and the ACCSAP climate action plan.

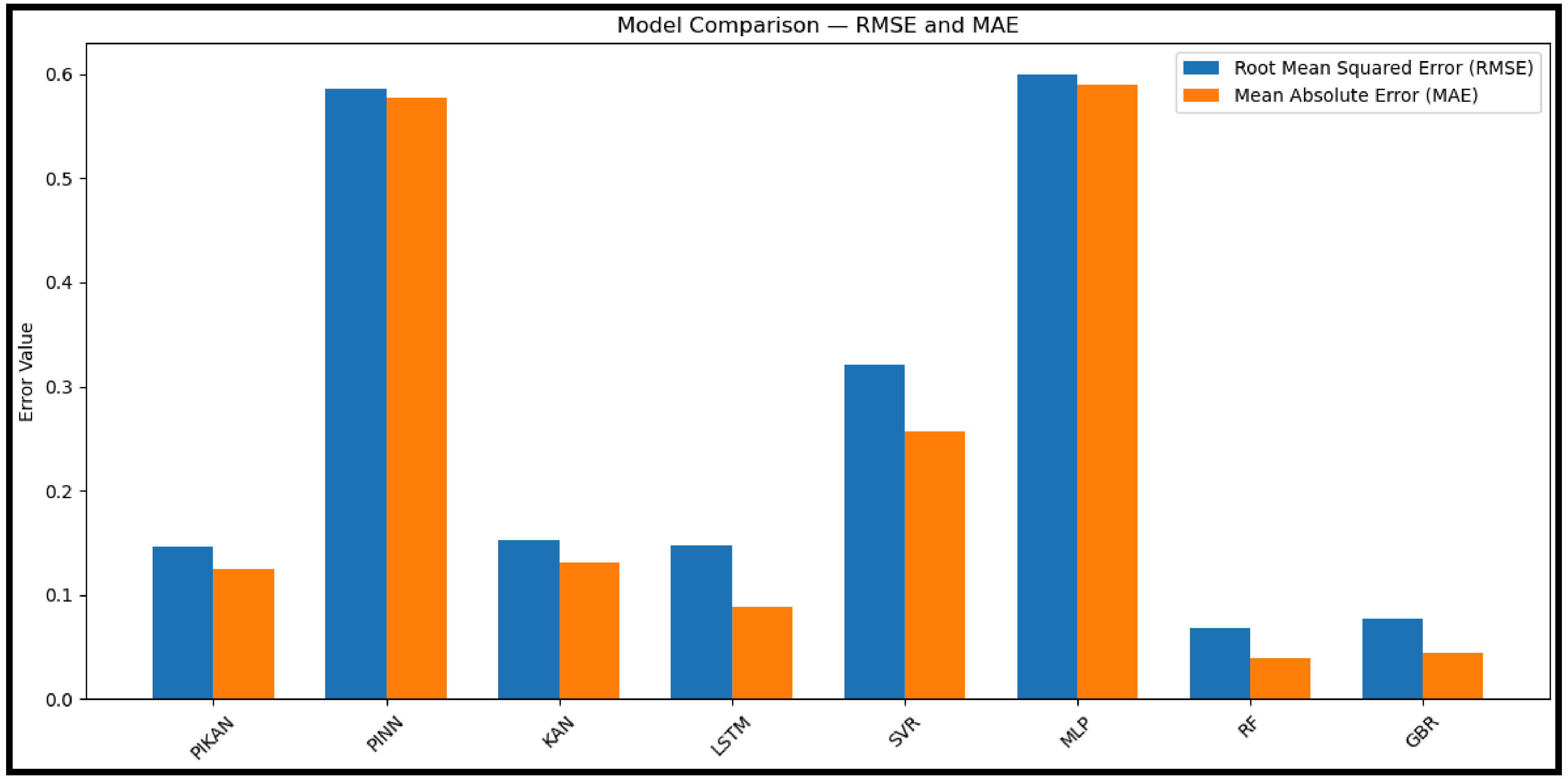


Figure 7: Benchmark Comparison Bar Chart for RMSE and MAE Across Models from before

Timeline & Progress

Phase	Duration	Activities
Phase 1	Aug 2025 - Oct 2025	Design, simulation, literature review
Phase 2	Nov 2025 - February 2027	Fabrication & sensor integration
Phase 3	March 2027 - March 2028	Model training, deployment, evaluation

Status: Phase 1 complete, fabrication ongoing.

Conclusion & Future Work

Summary

- **Target:** Develop low-cost, real-time ICT system for wave forecasting.
- **Method:** IoT data pipeline + Physics-Informed AI (PIKAN).
- **Impact:** Integrates AI + IoT + Big Data under ICT for Advanced Technologies and Applications.

This project is a pilot that aligns with DEFA, the Renewable Energy Roadmap and the ACCSAP, by linking digital innovation, renewable-energy forecasting and regional climate resilience.

Future Work

- Extend model to field-deployed buoys for long-term forecasting.
- Incorporate adaptive learning for dynamic marine conditions.
- Scale as an ASEAN digital-energy platform that plugs into DEFA, the Renewable Energy Roadmap and ACCSAP initiatives.

THANK YOU

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