

Deep Learning for Electricity Load Forecasting

Goal:

In this notebook, we aim to develop a deep learning model (LSTM) for short-term electricity consumption forecasting. This project involves:

1. Cleaning and preprocessing the dataset.
2. Visualizing data trends to gain insights.
3. Building baseline models to compare performance.
4. Implementing an LSTM model for forecasting electricity consumption.
5. Evaluating models and summarizing results.

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```
In [1]: # =====  
# Full Reproducibility Setup  
# =====  
import os  
import random  
  
# Set environment variables BEFORE importing TensorFlow  
os.environ['PYTHONHASHSEED'] = '42'  
# Core libraries  
import numpy as np  
import pandas as pd  
import matplotlib.pyplot as plt  
  
# Preprocessing & evaluation  
from sklearn.preprocessing import MinMaxScaler  
from sklearn.metrics import mean_absolute_error, mean_squared_error  
  
# Deep Learning (TensorFlow / Keras)  
import tensorflow as tf  
from tensorflow.keras.models import Sequential  
from tensorflow.keras.layers import LSTM, GRU, Dense, Dropout, Bidirectional
```

```

from tensorflow.keras.optimizers import Adam

# =====
# Set ALL random seeds
# =====
SEED = 42

random.seed(SEED)
np.random.seed(SEED)
tf.random.set_seed(SEED)

# Force TensorFlow to use deterministic algorithms
tf.config.experimental.enable_op_determinism()

print(f"Random seeds set to {SEED}")
print(f"TensorFlow version: {tf.__version__}")

```

Random seeds set to 42
TensorFlow version: 2.16.2

Loading and Cleaning the Dataset

```

In [2]: # =====
# Data Loading & Initial Cleaning
# =====

from pathlib import Path

# Define data path (same directory as notebook)
data_path = Path("/Users/harisaravanan/Desktop/DeepLearning_Group#4/LD2011_2

# Safety check
if not data_path.exists():
    raise FileNotFoundError(f"Dataset not found at {data_path.resolve()}")

# Load dataset
df_raw = pd.read_csv(
    data_path,
    sep=";",
    header=0,
    engine="python"
)

# Rename datetime column
df_raw.rename(columns={'Unnamed: 0': 'datetime'}, inplace=True)

# Convert datetime column
df_raw['datetime'] = pd.to_datetime(df_raw['datetime'], errors='coerce')
df_raw.set_index('datetime', inplace=True)

# Convert comma-based decimals to numeric
df = df_raw.apply(
    lambda col: pd.to_numeric(
        col.astype(str).str.replace(',', '.'),
        errors='coerce'
    )

```

```

    )
)

# =====
# Basic sanity checks
# =====

print("Dataset successfully loaded.\n")
print(f"Shape: {df.shape}")
print(f>Date range: {df.index.min()} → {df.index.max()}\n")

print("Missing values per column (top 5):")
print(df.isna().sum().sort_values(ascending=False).head())

print("\nFirst 5 rows:")
display(df.head())

```

Dataset successfully loaded.

Shape: (140256, 370)

Date range: 2011-01-01 00:15:00 → 2015-01-01 00:00:00

Missing values per column (top 5):

```

MT_001      0
MT_244      0
MT_253      0
MT_252      0
MT_251      0
dtype: int64

```

First 5 rows:

	MT_001	MT_002	MT_003	MT_004	MT_005	MT_006	MT_007	MT_008	I
datetime									
2011-01-01 00:15:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2011-01-01 00:30:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2011-01-01 00:45:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2011-01-01 01:00:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2011-01-01 01:15:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

5 rows × 370 columns

Exploratory Data Analysis

```
In [3]: # =====
# Exploratory Analysis: System-Level & Consumer-Level Patterns
# =====

# ---- 1. System-level total load (read-only computation) ----
total_consumption = df.sum(axis=1)

plt.figure(figsize=(5, 5))
total_consumption.plot()
plt.title("Total Electricity Consumption Over Time")
plt.xlabel("Datetime")
plt.ylabel("Total Consumption (kW)")
plt.show()

# ---- 2. Short window view (to see spikes & variability) ----
plt.figure(figsize=(5, 5))
total_consumption.loc['2013-01-01':'2013-01-07'].plot()
plt.title("Total Electricity Consumption (Jan 2013 - 1 Week)")
plt.xlabel("Datetime")
plt.ylabel("Total Consumption (kW)")
plt.show()

# ---- 3. Sample individual consumers ----
sample_clients = ['MT_001', 'MT_002', 'MT_003', 'MT_004', 'MT_005']

plt.figure(figsize=(5, 5))
for client in sample_clients:
    df[client].loc['2013-01-01':'2013-01-07'].plot(label=client)

plt.title("Electricity Consumption - Sample Consumers (Jan 2013)")
plt.xlabel("Datetime")
plt.ylabel("Consumption (kW)")
plt.legend()
plt.show()

# ---- 4. Daily consumption pattern (hour-of-day) ----
hourly_avg = total_consumption.groupby(total_consumption.index.hour).mean()

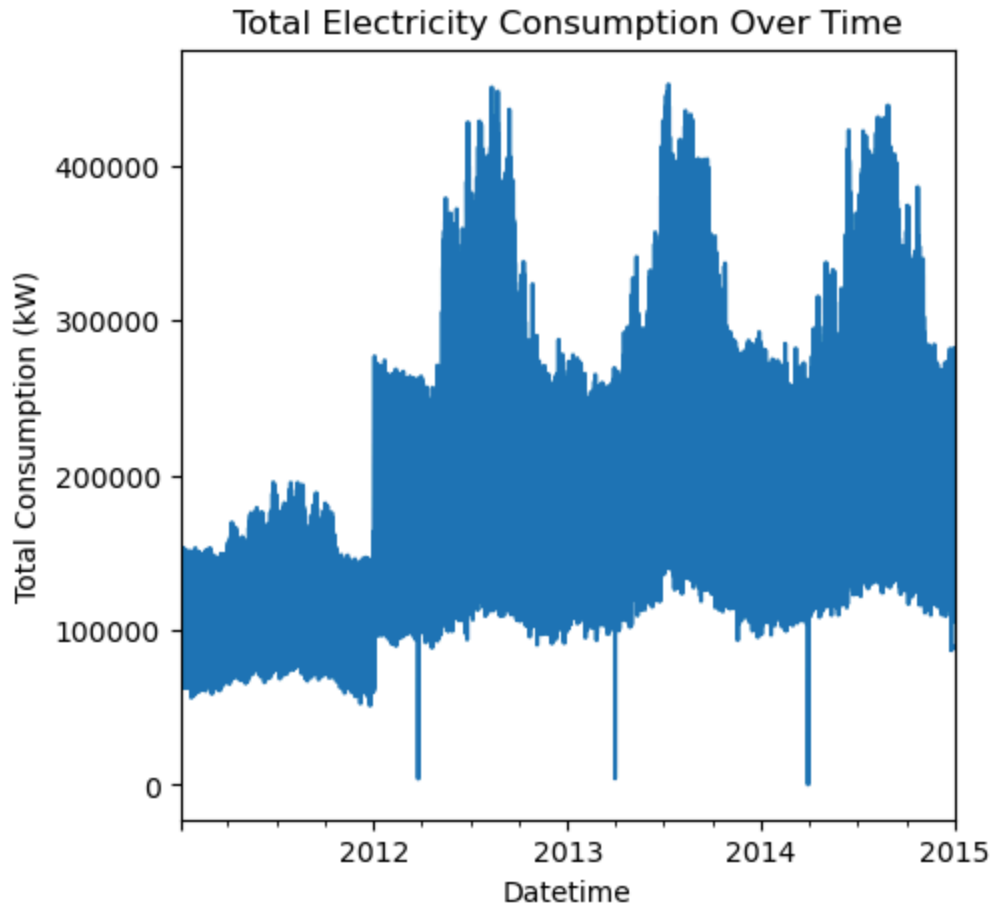
plt.figure(figsize=(5, 5))
hourly_avg.plot()
plt.title("Average Electricity Consumption by Hour of Day")
plt.xlabel("Hour of Day")
plt.ylabel("Average Consumption (kW)")
plt.xticks(range(0, 24))
plt.show()

# ---- 5. Weekly consumption pattern (day-of-week) ----
weekly_avg = total_consumption.groupby(total_consumption.index.dayofweek).me
```

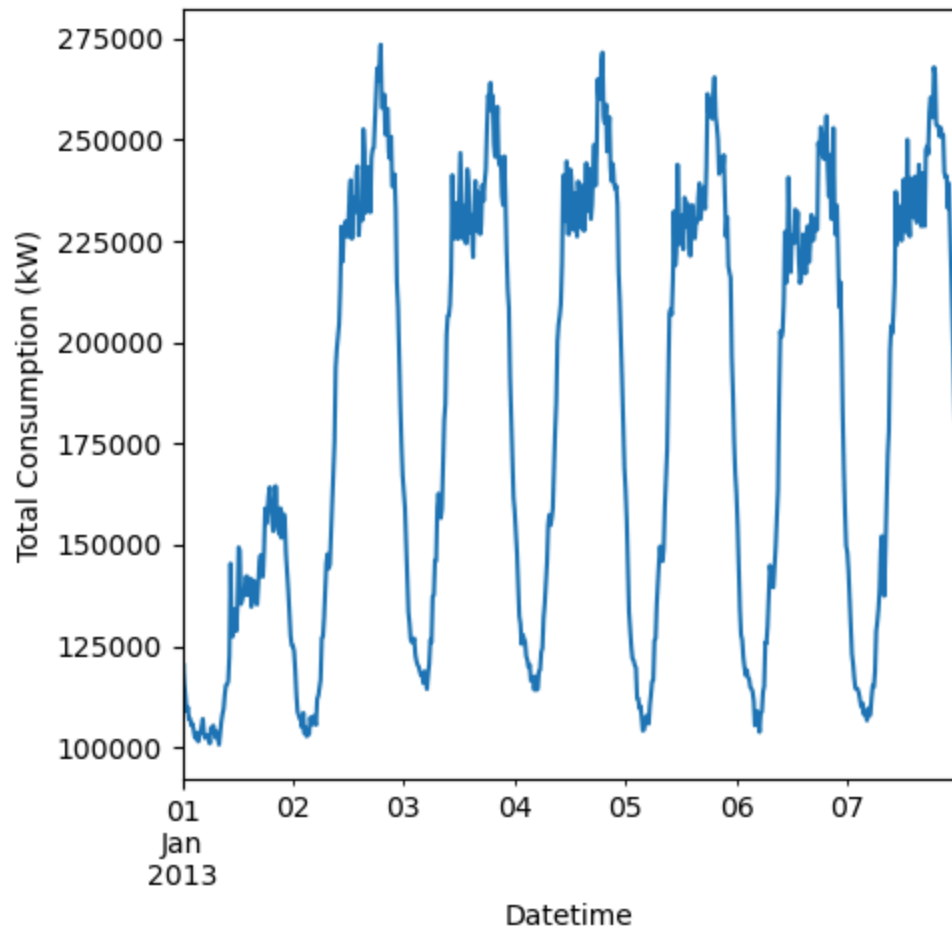
```

plt.figure(figsize=(5, 5))
weekly_avg.plot(kind='bar')
plt.title("Average Electricity Consumption by Day of Week")
plt.xlabel("Day of Week")
plt.ylabel("Average Consumption (kW)")
plt.xticks(
    ticks=range(7),
    labels=['Mon', 'Tue', 'Wed', 'Thu', 'Fri', 'Sat', 'Sun'],
    rotation=0
)
plt.show()

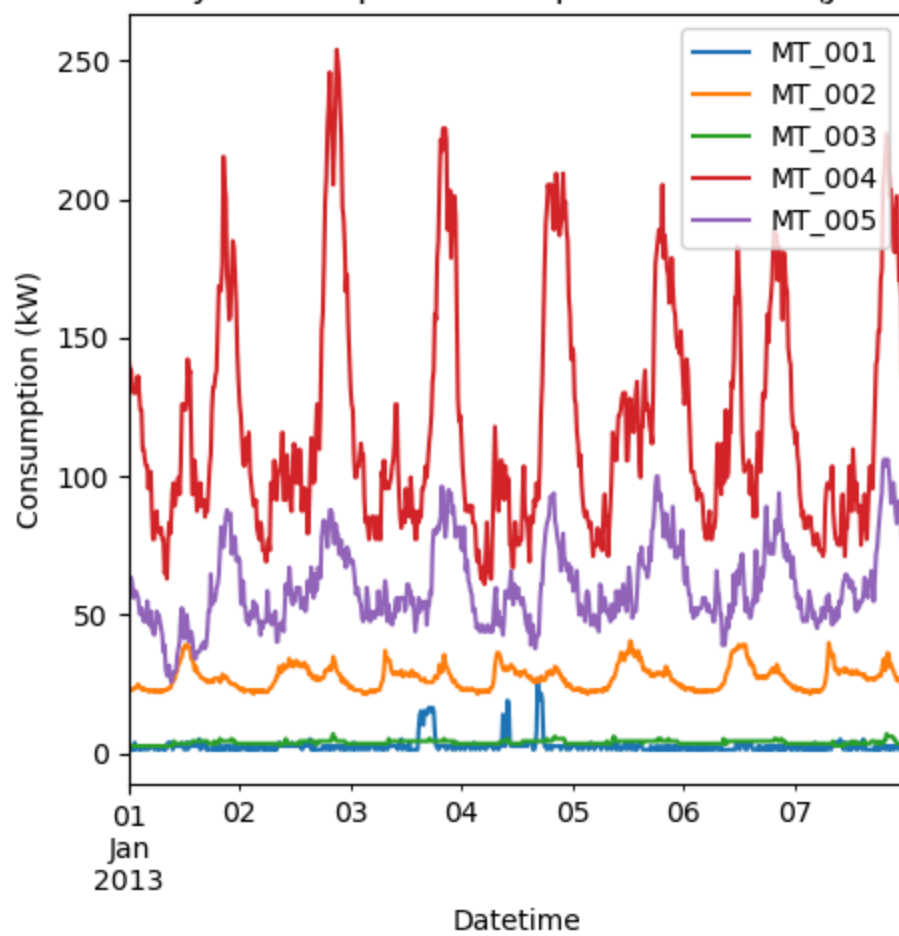
```



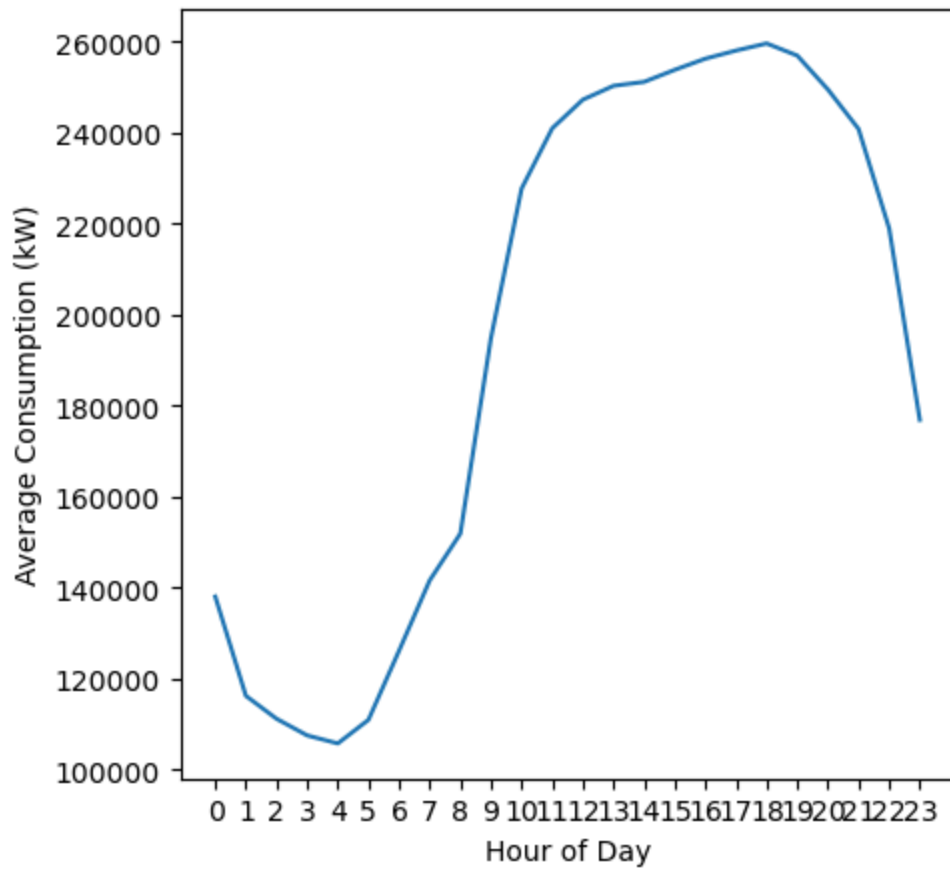
Total Electricity Consumption (Jan 2013 - 1 Week)



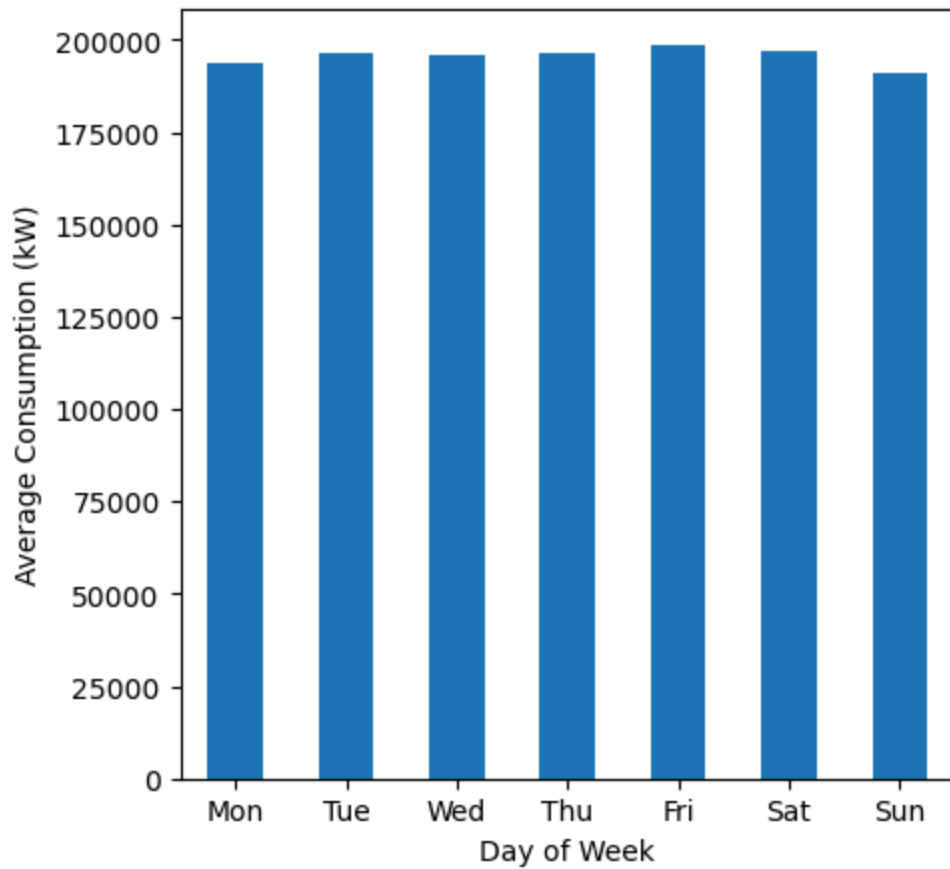
Electricity Consumption - Sample Consumers (Jan 2013)



Average Electricity Consumption by Hour of Day



Average Electricity Consumption by Day of Week



Event Definition

```
In [4]: # =====  
# Event Definition: High-Load Events  
# =====  
  
# Compute total system load  
total_consumption = df.sum(axis=1)  
  
# Define high-load threshold (95th percentile)  
high_load_threshold = total_consumption.quantile(0.95)  
  
print(f"High-load threshold (95th percentile): {high_load_threshold:.2f}")  
  
# Binary high-load indicator  
high_load_flag = total_consumption > high_load_threshold  
  
# Require persistence (e.g., 4 consecutive timesteps = 1 hour)  
persistence_window = 4  
  
high_load_event = (  
    high_load_flag  
    .rolling(window=persistence_window)  
    .sum() >= persistence_window  
)  
  
# Convert boolean to integer label  
event_labels = high_load_event.astype(int)  
  
# Quick sanity check  
print("\nNumber of high-load events detected:")  
print(event_labels.value_counts())  
  
# =====  
# Visual Sanity Check (Short Window)  
# =====  
  
plt.figure(figsize=(12, 5))  
  
# Plot total load  
total_consumption.loc['2013-01-01':'2013-01-07'].plot(label='Total Load')  
  
# Plot threshold  
plt.axhline(  
    high_load_threshold,  
    color='red',  
    linestyle='--',  
    label='95th Percentile'  
)  
  
# Extract event timestamps and values  
event_times = event_labels.loc['2013-01-01':'2013-01-07']  
event_times = event_times[event_times == 1].index  
event_values = total_consumption.loc[event_times]
```

```
# Plot detected events (datetime-safe)
plt.plot(
    event_times,
    event_values,
    'ro',
    label='Detected Event',
    zorder=3
)

plt.legend()
plt.title("Detected High-Load Events (Jan 2013)")
plt.xlabel("Datetime")
plt.ylabel("Total Load")
plt.show()
```

High-load threshold (95th percentile): 362649.83

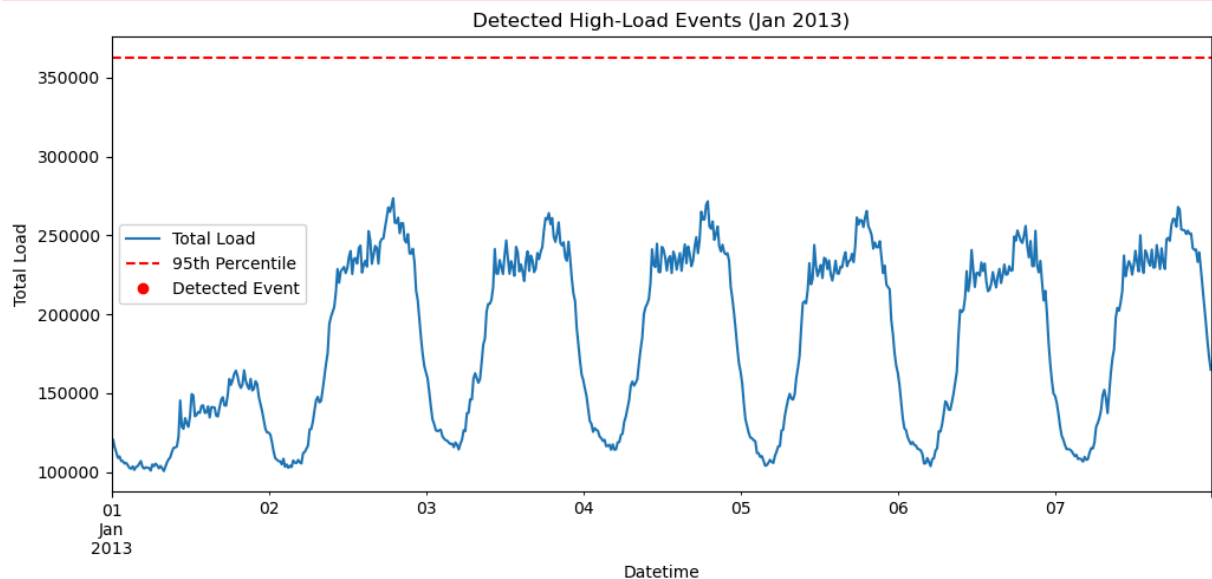
Number of high-load events detected:

0 134348

1 5908

Name: count, dtype: int64

```
/var/folders/wp/94y5f9q95mgc4vp585k9299m0000gn/T/ipykernel_45275/1192946872.
py:55: UserWarning: This axis already has a converter set and is updating to
a potentially incompatible converter
plt.plot()
```



Early-Warning Label Definition

```
In [5]: # =====
# Early-Warning Label Definition
# =====

# Prediction horizon (e.g., 1 hour = 4 timesteps)
prediction_horizon = 4

# Early-warning label:
# 1 if a high-load event occurs within the next prediction_horizon
```

```

early_warning_label = (
    event_labels
    .rolling(window=prediction_horizon, min_periods=1)
    .max()
    .shift(-prediction_horizon)
)

# Align labels
early_warning_label = early_warning_label.fillna(0).astype(int)

# Sanity check
print("Early-warning label distribution:")
print(early_warning_label.value_counts())

```

```

Early-warning label distribution:
0    133598
1      6658
Name: count, dtype: int64

```

Data Subsetting for Model Development

```

In [6]: # =====
# Subset Data for Faster Iteration
# High-load precursors are seasonally concentrated. Summer months exhibit a
# =====

clients = ['MT_001', 'MT_002', 'MT_003', 'MT_004', 'MT_005']

# Choose a high-demand period
start_date = "2013-06-01"
end_date = "2013-08-31"

df_small = df.loc[start_date:end_date, clients]
labels_small = early_warning_label.loc[start_date:end_date]

print("df_small shape:", df_small.shape)
print("labels_small distribution:")
print(labels_small.value_counts())

df_small.head()

```

```

df_small shape: (8832, 5)
labels_small distribution:
0    6619
1    2213
Name: count, dtype: int64

```

```
Out [6]:
```

	MT_001	MT_002	MT_003	MT_004	MT_005
datetime					
2013-06-01 00:00:00	1.269036	29.160740	1.737619	107.723577	46.341463
2013-06-01 00:15:00	2.538071	27.738265	1.737619	97.560976	40.243902
2013-06-01 00:30:00	1.269036	27.027027	1.737619	95.528455	40.243902
2013-06-01 00:45:00	2.538071	26.315789	1.737619	111.788618	41.463415
2013-06-01 01:00:00	2.538071	25.604552	1.737619	109.756098	35.365854

Data Normalization

```
In [7]: from sklearn.preprocessing import MinMaxScaler

# Initialize scaler
scaler = MinMaxScaler()

# Fit and transform the subset data
df_small_scaled = pd.DataFrame(
    scaler.fit_transform(df_small),
    index=df_small.index,
    columns=df_small.columns
)

# Sanity check
print("Scaled data range:")
print(df_small_scaled.min().min(), df_small_scaled.max().max())

df_small_scaled.head()
```

Scaled data range:
0.0 1.0

```
Out [7]:
```

	MT_001	MT_002	MT_003	MT_004	MT_005
datetime					
2013-06-01 00:00:00	0.033333	0.425532	0.4	0.460526	0.329114
2013-06-01 00:15:00	0.066667	0.404255	0.4	0.394737	0.265823
2013-06-01 00:30:00	0.033333	0.393617	0.4	0.381579	0.265823
2013-06-01 00:45:00	0.066667	0.382979	0.4	0.486842	0.278481
2013-06-01 01:00:00	0.066667	0.372340	0.4	0.473684	0.215190

Sliding Window Construction for Time-Series Modeling

```
In [8]: def create_sliding_windows(X, y, window_size):
        """
        X: DataFrame of shape (time, features)
```

```

y: Series of labels aligned with X
window_size: number of timesteps per input window
"""

X_windows = []
y_windows = []

for i in range(len(X) - window_size):
    X_windows.append(X.iloc[i:i + window_size].values)
    y_windows.append(y.iloc[i + window_size])

return np.array(X_windows), np.array(y_windows)

```

```

In [9]: # Window size: past 6 hours (24 * 15 minutes)
window_size = 24

X, y = create_sliding_windows(
    df_small_scaled,
    labels_small,
    window_size
)

print("X shape:", X.shape)
print("y shape:", y.shape)

# Class balance after windowing
unique, counts = np.unique(y, return_counts=True)
print("Label distribution after windowing:")
print(dict(zip(unique, counts)))

# Input sequences were constructed using a sliding window approach, where ea

```

```

X shape: (8808, 24, 5)
y shape: (8808,)
Label distribution after windowing:
{0: 6595, 1: 2213}

```

Train–Validation Split

```

In [10]: # =====
# Train–Validation Split (Time-Aware)
# =====

# Use first 70% for training, last 30% for validation
split_index = int(0.7 * len(X))

X_train, X_val = X[:split_index], X[split_index:]
y_train, y_val = y[:split_index], y[split_index:]

print("Training set shape:", X_train.shape, y_train.shape)
print("Validation set shape:", X_val.shape, y_val.shape)

print("\nTraining label distribution:")
print(np.unique(y_train, return_counts=True))

print("\nValidation label distribution:")

```

```
print(np.unique(y_val, return_counts=True))

# Data was split chronologically to prevent information leakage, with earlier
```

Training set shape: (6165, 24, 5) (6165,)
Validation set shape: (2643, 24, 5) (2643,)

Training label distribution:
(array([0, 1]), array([4953, 1212]))

Validation label distribution:
(array([0, 1]), array([1642, 1001]))

Baseline Model (Logistic Regression on Flattened Windows)

In [11]: *# To establish a non-temporal benchmark, a logistic regression model was tra*

```
# =====
# Flatten windows for baseline model
# =====

X_train_flat = X_train.reshape(X_train.shape[0], -1)
X_val_flat = X_val.reshape(X_val.shape[0], -1)

print("Flattened training shape:", X_train_flat.shape)
print("Flattened validation shape:", X_val_flat.shape)
```

Flattened training shape: (6165, 120)
Flattened validation shape: (2643, 120)

In [12]: **from** sklearn.linear_model **import** LogisticRegression
from sklearn.metrics **import** classification_report, confusion_matrix

```
# Initialize baseline model
baseline_model = LogisticRegression(
    max_iter=1000,
    class_weight='balanced'
)

# Train
baseline_model.fit(X_train_flat, y_train)

# Predict
y_val_pred = baseline_model.predict(X_val_flat)

# Evaluation
print("Baseline Model Performance:\n")
print(classification_report(y_val, y_val_pred))
print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred))
```

Baseline Model Performance:

	precision	recall	f1-score	support
0	0.70	0.95	0.80	1642
1	0.79	0.32	0.45	1001
accuracy			0.71	2643
macro avg	0.74	0.63	0.63	2643
weighted avg	0.73	0.71	0.67	2643

Confusion Matrix:

```
[[1558   84]
 [ 683  318]]
```

```
In [13]: # =====
# Compute Class Weights for Imbalanced Data (SAFE VERSION)
# =====
# This is critical for early-warning systems where events are rare

from sklearn.utils.class_weight import compute_class_weight
import gc
gc.collect()

# Set TensorFlow to use minimal memory
import os
os.environ['TF_CPP_MIN_LOG_LEVEL'] = '3'
os.environ['TF_FORCE_GPU_ALLOW_GROWTH'] = 'true'

# NOW import TensorFlow
import tensorflow as tf
from tensorflow.keras import backend as K

# Configure TensorFlow for CPU with memory limits
tf.config.set_visible_devices([], 'GPU') # Disable GPU
K.clear_session()

# Continue with your normal imports
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Dropout
from tensorflow.keras.callbacks import EarlyStopping

# Compute class weights
class_weights = compute_class_weight(
    class_weight='balanced',
    classes=np.unique(y_train),
    y=y_train
)

class_weight_dict = {
    0: float(class_weights[0]),
    1: float(class_weights[1])
}

print("Class weights:", class_weight_dict)
print(f" Class 0 (Normal): {class_weight_dict[0]:.3f}")
```

```

print(f" Class 1 (Event): {class_weight_dict[1]:.3f}")

# Memory cleanup to prevent crash before TensorFlow
del class_weights
gc.collect()

print("\n✅ Memory cleaned, ready for deep learning models")

```

```

Class weights: {0: 0.6223500908540278, 1: 2.5433168316831685}
Class 0 (Normal): 0.622
Class 1 (Event): 2.543

```

✅ Memory cleaned, ready for deep learning models

Deep Learning Model 1: LSTM Early-Warning Classifier

```

In [14]: import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Dropout
from tensorflow.keras.callbacks import EarlyStopping
from sklearn.metrics import classification_report, confusion_matrix
import matplotlib.pyplot as plt
import numpy as np

# -----
# Build LSTM model
# -----
model = Sequential([
    LSTM(64, input_shape=(X_train.shape[1], X_train.shape[2]), return_sequences=True),
    Dropout(0.3),
    Dense(32, activation='relu'),
    Dense(1, activation='sigmoid') # Binary classification
])

model.compile(
    optimizer='adam',
    loss='binary_crossentropy',
    metrics=['accuracy']
)

model.summary()

# -----
# Train model with class weights
# -----
class_counts = np.bincount(y_train.astype(int))
total_samples = class_counts.sum()
class_weight_dict = {
    0: total_samples / (2 * class_counts[0]) if class_counts[0] > 0 else 1.0,
    1: total_samples / (2 * class_counts[1]) if class_counts[1] > 0 else 1.0
}

early_stop = EarlyStopping(
    monitor='val_loss',

```



```

        patience=5,
        restore_best_weights=True
    )

    history = model.fit(
        X_train, y_train,
        validation_data=(X_val, y_val),
        epochs=200,
        batch_size=64,
        class_weight=class_weight_dict, # Added class weights
        callbacks=[early_stop],
        verbose=1
    )

    # -----
    # Plot training curves
    # -----
    plt.figure(figsize=(12, 4))

    plt.subplot(1, 2, 1)
    plt.plot(history.history['loss'], label='Train Loss')
    plt.plot(history.history['val_loss'], label='Val Loss')
    plt.title('LSTM Loss')
    plt.legend()

    plt.subplot(1, 2, 2)
    plt.plot(history.history['accuracy'], label='Train Acc')
    plt.plot(history.history['val_accuracy'], label='Val Acc')
    plt.title('LSTM Accuracy')
    plt.legend()

    plt.show()

    # -----
    # Evaluation with threshold tuning
    # -----
    y_val_pred_prob = model.predict(X_val)
    best_thresh_lstm = 0.35 # Can be tuned
    y_val_pred = (y_val_pred_prob > best_thresh_lstm).astype(int)

    print(f"LSTM Classification Report (threshold={best_thresh_lstm}):\n")
    print(classification_report(y_val, y_val_pred))

    print("Confusion Matrix:")
    print(confusion_matrix(y_val, y_val_pred))

```

```

/opt/anaconda3/lib/python3.11/site-packages/keras/src/layers/rnn/rnn.py:199:
UserWarning: Do not pass an `input_shape`/`input_dim` argument to a layer. W
hen using Sequential models, prefer using an `Input(shape)` object as the fi
rst layer in the model instead.

```

```

    super().__init__(**kwargs)

```

Model: "sequential"


Layer (type)	Output Shape	Par
lstm (LSTM)	(None, 64)	17
dropout (Dropout)	(None, 64)	
dense (Dense)	(None, 32)	2
dense_1 (Dense)	(None, 1)	

Total params: 20,033 (78.25 KB)


Trainable params: 20,033 (78.25 KB)

Non-trainable params: 0 (0.00 B)


Epoch 1/200

97/97  1s 7ms/step - accuracy: 0.5778 - loss: 0.6305 - val_accuracy: 0.4949 - val_loss: 0.7381


Epoch 2/200

97/97  1s 6ms/step - accuracy: 0.7160 - loss: 0.5170 - val_accuracy: 0.6863 - val_loss: 0.5781


Epoch 3/200

97/97  1s 6ms/step - accuracy: 0.7606 - loss: 0.4275 - val_accuracy: 0.7113 - val_loss: 0.6184


Epoch 4/200

97/97  1s 5ms/step - accuracy: 0.7961 - loss: 0.3787 - val_accuracy: 0.7314 - val_loss: 0.5916


Epoch 5/200

97/97  1s 5ms/step - accuracy: 0.8172 - loss: 0.3567 - val_accuracy: 0.7465 - val_loss: 0.5769


Epoch 6/200

97/97  1s 5ms/step - accuracy: 0.8349 - loss: 0.3311 - val_accuracy: 0.7544 - val_loss: 0.5907


Epoch 7/200

97/97  1s 6ms/step - accuracy: 0.8425 - loss: 0.3246 - val_accuracy: 0.7177 - val_loss: 0.6324


Epoch 8/200

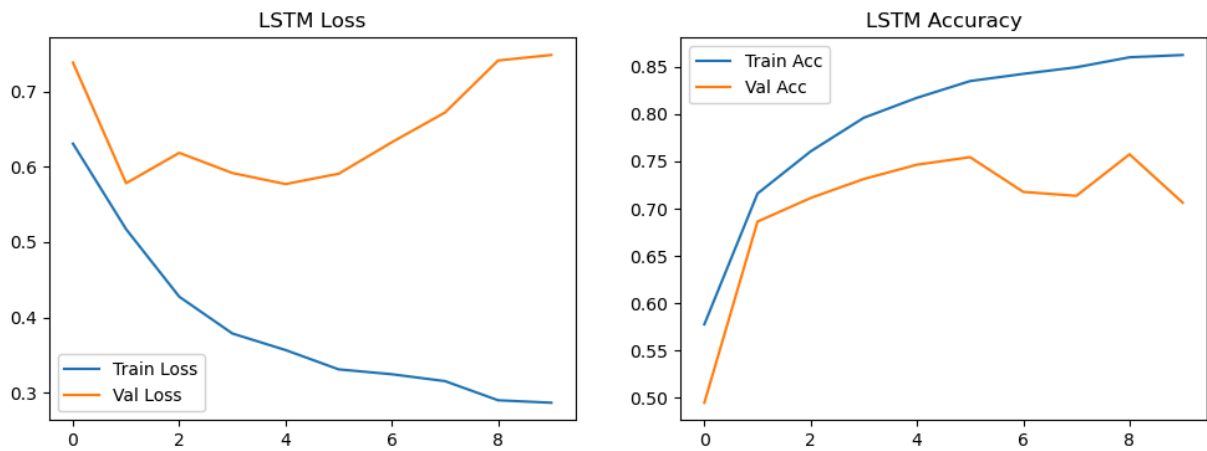
97/97  1s 6ms/step - accuracy: 0.8495 - loss: 0.3155 - val_accuracy: 0.7136 - val_loss: 0.6718

Epoch 9/200

97/97  1s 6ms/step - accuracy: 0.8600 - loss: 0.2901 - val_accuracy: 0.7575 - val_loss: 0.7409

Epoch 10/200

97/97  1s 5ms/step - accuracy: 0.8624 - loss: 0.2869 - val_accuracy: 0.7064 - val_loss: 0.7482



83/83 ————— 0s 2ms/step

LSTM Classification Report (threshold=0.35):

	precision	recall	f1-score	support
0	0.78	0.82	0.80	1642
1	0.69	0.63	0.66	1001
accuracy			0.75	2643
macro avg	0.74	0.73	0.73	2643
weighted avg	0.75	0.75	0.75	2643

Confusion Matrix:

```
[[1354  288]
 [ 371  630]]
```

Deep Learning Model 2: GRU Early-Warning Classifier

```
In [15]: import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import GRU, Dense, Dropout
from tensorflow.keras.callbacks import EarlyStopping
from sklearn.metrics import classification_report, confusion_matrix
import matplotlib.pyplot as plt
import numpy as np

# -----
# Build GRU model
# -----
gru_model = Sequential([
    GRU(64, input_shape=(X_train.shape[1], X_train.shape[2]), return_sequences=True),
    Dropout(0.3),
    Dense(32, activation='relu'),
    Dense(1, activation='sigmoid')
])

gru_model.compile(
    optimizer='adam',
    loss='binary_crossentropy',
    metrics=['accuracy']
)
```

```

gru_model.summary()

# -----
# Train model with class weights
# -----
early_stop = EarlyStopping(
    monitor='val_loss',
    patience=5,
    restore_best_weights=True
)

history_gru = gru_model.fit(
    X_train, y_train,
    validation_data=(X_val, y_val),
    epochs=30,
    batch_size=64,
    class_weight=class_weight_dict, # Added class weights
    callbacks=[early_stop],
    verbose=1
)

# -----
# Plot training curves
# -----
plt.figure(figsize=(12, 4))

plt.subplot(1, 2, 1)
plt.plot(history_gru.history['loss'], label='Train Loss')
plt.plot(history_gru.history['val_loss'], label='Val Loss')
plt.title('GRU Loss')
plt.legend()

plt.subplot(1, 2, 2)
plt.plot(history_gru.history['accuracy'], label='Train Acc')
plt.plot(history_gru.history['val_accuracy'], label='Val Acc')
plt.title('GRU Accuracy')
plt.legend()

plt.show()

# -----
# Evaluation with threshold tuning
# -----
y_val_pred_prob_gru = gru_model.predict(X_val)
best_thresh_gru = 0.35
y_val_pred_gru = (y_val_pred_prob_gru > best_thresh_gru).astype(int)

print(f"GRU Classification Report (threshold={best_thresh_gru}):\n")
print(classification_report(y_val, y_val_pred_gru))

print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred_gru))

```

```
/opt/anaconda3/lib/python3.11/site-packages/keras/src/layers/rnn/rnn.py:199:
UserWarning: Do not pass an `input_shape`/`input_dim` argument to a layer. W
hen using Sequential models, prefer using an `Input(shape)` object as the fi
rst layer in the model instead.
  super().__init__(**kwargs)
```

Model: "sequential_1"

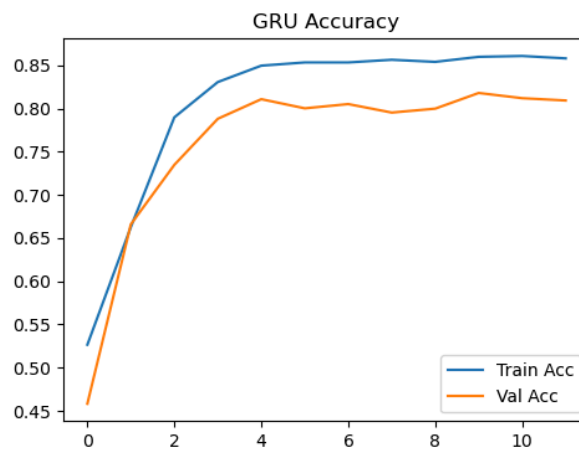
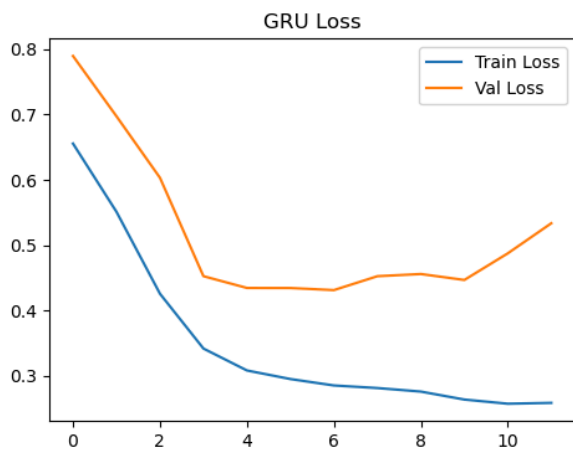
Layer (type)	Output Shape	Par
gru (GRU)	(None, 64)	13
dropout_1 (Dropout)	(None, 64)	
dense_2 (Dense)	(None, 32)	2
dense_3 (Dense)	(None, 1)	

Total params: 15,745 (61.50 KB)

Trainable params: 15,745 (61.50 KB)

Non-trainable params: 0 (0.00 B)

Epoch 1/30
97/97 ————— **1s** 6ms/step — accuracy: 0.5265 — loss: 0.6556 — val_accuracy: 0.4582 — val_loss: 0.7897
Epoch 2/30
97/97 ————— **0s** 5ms/step — accuracy: 0.6628 — loss: 0.5511 — val_accuracy: 0.6659 — val_loss: 0.6974
Epoch 3/30
97/97 ————— **0s** 5ms/step — accuracy: 0.7898 — loss: 0.4257 — val_accuracy: 0.7348 — val_loss: 0.6033
Epoch 4/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8307 — loss: 0.3418 — val_accuracy: 0.7881 — val_loss: 0.4526
Epoch 5/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8496 — loss: 0.3083 — val_accuracy: 0.8108 — val_loss: 0.4346
Epoch 6/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8534 — loss: 0.2951 — val_accuracy: 0.8002 — val_loss: 0.4345
Epoch 7/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8534 — loss: 0.2853 — val_accuracy: 0.8051 — val_loss: 0.4313
Epoch 8/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8564 — loss: 0.2814 — val_accuracy: 0.7953 — val_loss: 0.4526
Epoch 9/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8540 — loss: 0.2759 — val_accuracy: 0.7998 — val_loss: 0.4559
Epoch 10/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8599 — loss: 0.2637 — val_accuracy: 0.8180 — val_loss: 0.4468
Epoch 11/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8608 — loss: 0.2573 — val_accuracy: 0.8120 — val_loss: 0.4876
Epoch 12/30
97/97 ————— **0s** 5ms/step — accuracy: 0.8581 — loss: 0.2587 — val_accuracy: 0.8093 — val_loss: 0.5336



83/83 ————— 0s 2ms/step
GRU Classification Report (threshold=0.35):

	precision	recall	f1-score	support
0	0.91	0.75	0.82	1642
1	0.68	0.87	0.76	1001
accuracy			0.80	2643
macro avg	0.79	0.81	0.79	2643
weighted avg	0.82	0.80	0.80	2643

Confusion Matrix:

```
[[1230  412]
 [ 128  873]]
```

In addition to supervised early-warning classification, we can explore unsupervised anomaly detection to identify out-of-ordinary load patterns

Unsupervised Anomaly Detection using LSTM Autoencoder

```
In [16]: # =====
# Prepare Data for Autoencoder
# =====

# Use only NORMAL samples for training
X_train_normal = X_train[y_train == 0]

print("Autoencoder training samples:", X_train_normal.shape)
```

Autoencoder training samples: (4953, 24, 5)

Build LSTM Autoencoder

```
In [17]: from tensorflow.keras.models import Model
from tensorflow.keras.layers import Input, LSTM, RepeatVector, TimeDistributed
from tensorflow.keras.callbacks import EarlyStopping

timesteps = X_train.shape[1]
features = X_train.shape[2]

input_layer = Input(shape=(timesteps, features))

# Encoder
encoded = LSTM(64, activation='tanh', return_sequences=False)(input_layer)

# Bottleneck
bottleneck = RepeatVector(timesteps)(encoded)

# Decoder
decoded = LSTM(64, activation='tanh', return_sequences=True)(bottleneck)
decoded = TimeDistributed(Dense(features))(decoded)
```

```

autoencoder = Model(inputs=input_layer, outputs=decoded)

autoencoder.compile(
    optimizer='adam',
    loss='mse'
)

autoencoder.summary()

```

Model: "functional_2"

Layer (type)	Output Shape	Par
input_layer_2 (InputLayer)	(None, 24, 5)	
lstm_1 (LSTM)	(None, 64)	17
repeat_vector (RepeatVector)	(None, 24, 64)	
lstm_2 (LSTM)	(None, 24, 64)	33
time_distributed (TimeDistributed)	(None, 24, 5)	

Total params: 51,269 (200.27 KB)

Trainable params: 51,269 (200.27 KB)

Non-trainable params: 0 (0.00 B)



```

In [18]: # Train Autoencoder
early_stop = EarlyStopping(
    monitor='val_loss',
    patience=5,
    restore_best_weights=True
)

history_ae = autoencoder.fit(
    X_train_normal,
    X_train_normal,
    validation_split=0.2,
    epochs=30,
    batch_size=64,
    callbacks=[early_stop],
    verbose=1
)

```



Epoch 1/30						
62/62		2s	19ms/step	- loss:	0.0278	- val_loss: 0.0097
Epoch 2/30						
62/62		1s	18ms/step	- loss:	0.0093	- val_loss: 0.0065
Epoch 3/30						
62/62		1s	19ms/step	- loss:	0.0068	- val_loss: 0.0043
Epoch 4/30						
62/62		1s	17ms/step	- loss:	0.0054	- val_loss: 0.0037
Epoch 5/30						
62/62		1s	16ms/step	- loss:	0.0050	- val_loss: 0.0034
Epoch 6/30						
62/62		1s	17ms/step	- loss:	0.0048	- val_loss: 0.0033
Epoch 7/30						
62/62		1s	17ms/step	- loss:	0.0046	- val_loss: 0.0032
Epoch 8/30						
62/62		1s	17ms/step	- loss:	0.0043	- val_loss: 0.0030
Epoch 9/30						
62/62		1s	16ms/step	- loss:	0.0041	- val_loss: 0.0030
Epoch 10/30						
62/62		1s	18ms/step	- loss:	0.0040	- val_loss: 0.0029
Epoch 11/30						
62/62		1s	21ms/step	- loss:	0.0039	- val_loss: 0.0029
Epoch 12/30						
62/62		1s	18ms/step	- loss:	0.0038	- val_loss: 0.0028
Epoch 13/30						
62/62		1s	18ms/step	- loss:	0.0037	- val_loss: 0.0028
Epoch 14/30						
62/62		1s	16ms/step	- loss:	0.0037	- val_loss: 0.0029
Epoch 15/30						
62/62		1s	16ms/step	- loss:	0.0036	- val_loss: 0.0028
Epoch 16/30						
62/62		1s	16ms/step	- loss:	0.0036	- val_loss: 0.0028
Epoch 17/30						
62/62		1s	15ms/step	- loss:	0.0035	- val_loss: 0.0027
Epoch 18/30						
62/62		1s	16ms/step	- loss:	0.0035	- val_loss: 0.0027
Epoch 19/30						
62/62		1s	17ms/step	- loss:	0.0034	- val_loss: 0.0026
Epoch 20/30						
62/62		1s	16ms/step	- loss:	0.0034	- val_loss: 0.0026
Epoch 21/30						
62/62		1s	16ms/step	- loss:	0.0034	- val_loss: 0.0025
Epoch 22/30						
62/62		1s	18ms/step	- loss:	0.0033	- val_loss: 0.0025
Epoch 23/30						
62/62		1s	16ms/step	- loss:	0.0033	- val_loss: 0.0025
Epoch 24/30						
62/62		1s	16ms/step	- loss:	0.0033	- val_loss: 0.0025
Epoch 25/30						
62/62		1s	17ms/step	- loss:	0.0032	- val_loss: 0.0024
Epoch 26/30						
62/62		1s	17ms/step	- loss:	0.0032	- val_loss: 0.0024
Epoch 27/30						
62/62		1s	17ms/step	- loss:	0.0032	- val_loss: 0.0024
Epoch 28/30						
62/62		1s	18ms/step	- loss:	0.0032	- val_loss: 0.0024

Epoch 29/30
62/62  1s 16ms/step - loss: 0.0031 - val_loss: 0.0024
Epoch 30/30
62/62  1s 16ms/step - loss: 0.0031 - val_loss: 0.0023

```
In [19]: # Reconstruct validation data
X_val_recon = autoencoder.predict(X_val)

# Mean squared error per sample
reconstruction_error = np.mean(
    np.square(X_val - X_val_recon),
    axis=(1, 2)
)

print("Reconstruction error stats:")
print(pd.Series(reconstruction_error).describe())
```

83/83  0s 4ms/step
Reconstruction error stats:
count 2643.000000
mean 0.003232
std 0.001762
min 0.000558
25% 0.001928
50% 0.002912
75% 0.004084
max 0.014484
dtype: float64

```
In [20]: # Define anomaly threshold (95th percentile of NORMAL training error)
X_train_recon = autoencoder.predict(X_train_normal)
train_error = np.mean(
    np.square(X_train_normal - X_train_recon),
    axis=(1, 2)
)

threshold = np.percentile(train_error, 95)

print("Anomaly threshold:", threshold)
```

155/155  0s 2ms/step
Anomaly threshold: 0.0064701794371099545

```
In [21]: # Flag anomalies
anomaly_flags = reconstruction_error > threshold

print("Detected anomalies in validation set:")
print(pd.Series(anomaly_flags).value_counts())
```

Detected anomalies in validation set:
False 2523
True 120
Name: count, dtype: int64

```
In [22]: # Compare Anomalies vs Events

comparison = pd.DataFrame({
```

```

    "anomaly": anomaly_flags.astype(int),
    "event_label": y_val
})

print(pd.crosstab(
    comparison["anomaly"],
    comparison["event_label"],
    rownames=["Anomaly"],
    colnames=["Event"]
))

```

Event	0	1
Anomaly		
0	1605	918
1	37	83

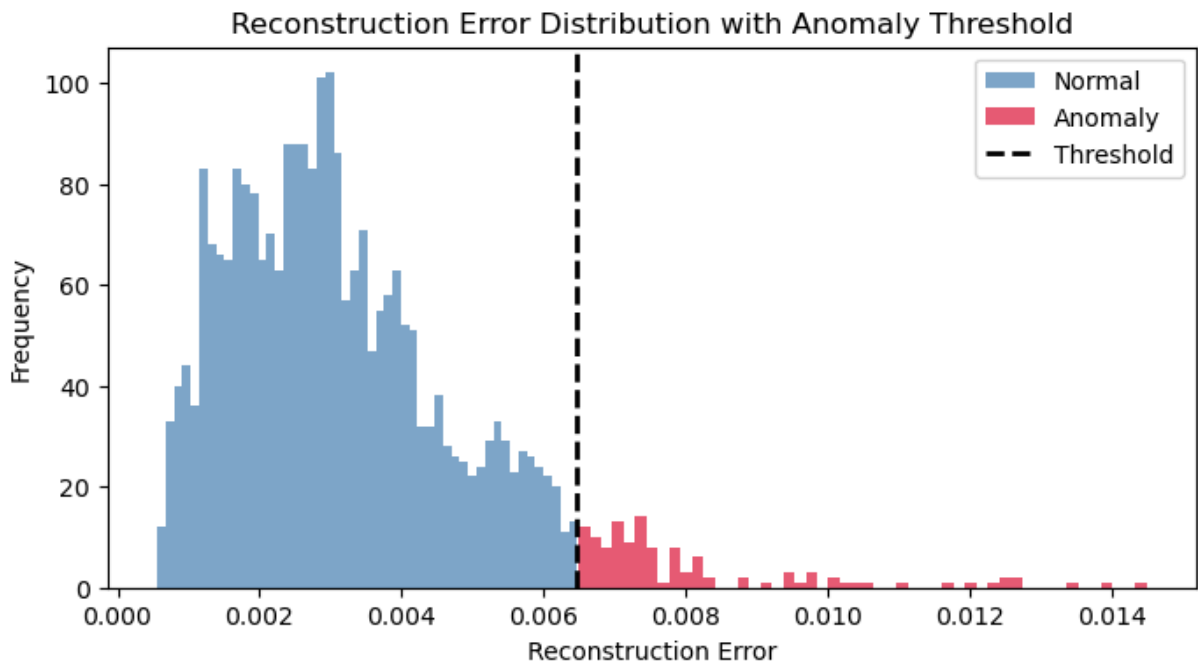
In [23]: `import matplotlib.pyplot as plt`

```

# Separate normal and anomaly errors
normal_errors = reconstruction_error[reconstruction_error <= threshold]
anomaly_errors = reconstruction_error[reconstruction_error > threshold]

plt.figure(figsize=(8, 4))
plt.hist(normal_errors, bins=50, color='steelblue', alpha=0.7, label='Normal')
plt.hist(anomaly_errors, bins=50, color='crimson', alpha=0.7, label='Anomaly')
plt.axvline(threshold, color='black', linestyle='--', linewidth=2, label='Threshold')
plt.xlabel("Reconstruction Error")
plt.ylabel("Frequency")
plt.title("Reconstruction Error Distribution with Anomaly Threshold")
plt.legend()
plt.show()

```



Further hyperparameter tuning is left as future work, as the primary goal of this project was to design and validate an end-to-end early-warning deep learning pipeline. for now we have done some basic tuning manually.

Tuned LSTM Architecture

More capacity (128 units)

Stronger regularization

Lower learning rate (stability)

Same window & features (controlled experiment)

```
In [24]: from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Dropout
from tensorflow.keras.optimizers import Adam
from tensorflow.keras.callbacks import EarlyStopping

early_stop = EarlyStopping(
    monitor='val_loss',
    patience=5,
    restore_best_weights=True
)

lstm_tuned = Sequential([
    LSTM(128, input_shape=(X_train.shape[1], X_train.shape[2])),
    Dropout(0.3),
    Dense(32, activation='relu'),
    Dense(1, activation='sigmoid')
])

lstm_tuned.compile(
    optimizer=Adam(learning_rate=5e-4),
    loss='binary_crossentropy',
    metrics=['accuracy']
)

lstm_tuned.summary()
```

```
/opt/anaconda3/lib/python3.11/site-packages/keras/src/layers/rnn/rnn.py:199:
UserWarning: Do not pass an `input_shape`/`input_dim` argument to a layer. W
hen using Sequential models, prefer using an `Input(shape)` object as the fi
rst layer in the model instead.
```

```
super().__init__(**kwargs)
```

Model: "sequential_2"

Layer (type)	Output Shape	Par
lstm_3 (LSTM)	(None, 128)	68
dropout_2 (Dropout)	(None, 128)	
dense_5 (Dense)	(None, 32)	4
dense_6 (Dense)	(None, 1)	

Total params: 72,769 (284.25 KB)
Trainable params: 72,769 (284.25 KB)
Non-trainable params: 0 (0.00 B)

Train Tuned LSTM (with class weighting)

```
In [25]: history_lstm_tuned = lstm_tuned.fit(  
    X_train, y_train,  
    validation_data=(X_val, y_val),  
    epochs=30,  
    batch_size=64,  
    class_weight=class_weight_dict,  
    callbacks=[early_stop],  
    verbose=1  
)
```


Epoch 1/30

97/97  2s 11ms/step - accuracy: 0.5781 - loss: 0.6320 - val_accuracy: 0.5887 - val_loss: 0.6822

Epoch 2/30

97/97  1s 10ms/step - accuracy: 0.7351 - loss: 0.4995 - val_accuracy: 0.7022 - val_loss: 0.5963


Epoch 3/30

97/97  1s 9ms/step - accuracy: 0.7643 - loss: 0.4472 - val_accuracy: 0.7136 - val_loss: 0.5838


Epoch 4/30

97/97  1s 10ms/step - accuracy: 0.7792 - loss: 0.4008 - val_accuracy: 0.7317 - val_loss: 0.5880


Epoch 5/30

97/97  1s 9ms/step - accuracy: 0.8091 - loss: 0.3635 - val_accuracy: 0.7469 - val_loss: 0.6030


Epoch 6/30

97/97  1s 9ms/step - accuracy: 0.8298 - loss: 0.3351 - val_accuracy: 0.7597 - val_loss: 0.5941


Epoch 7/30

97/97  1s 9ms/step - accuracy: 0.8388 - loss: 0.3262 - val_accuracy: 0.7476 - val_loss: 0.5743


Epoch 8/30

97/97  1s 9ms/step - accuracy: 0.8482 - loss: 0.3081 - val_accuracy: 0.7503 - val_loss: 0.6076


Epoch 9/30

97/97  1s 10ms/step - accuracy: 0.8493 - loss: 0.3014 - val_accuracy: 0.7703 - val_loss: 0.6383


Epoch 10/30

97/97  1s 9ms/step - accuracy: 0.8579 - loss: 0.2883 - val_accuracy: 0.7359 - val_loss: 0.6772

Epoch 11/30

97/97  1s 10ms/step - accuracy: 0.8589 - loss: 0.2818 - val_accuracy: 0.7533 - val_loss: 0.7231

Epoch 12/30

97/97  1s 10ms/step - accuracy: 0.8595 - loss: 0.2742 - val_accuracy: 0.7624 - val_loss: 0.7813

Threshold Tuning (Critical for Early-Warning)

```
In [26]: from sklearn.metrics import classification_report, confusion_matrix

y_val_probs = lstm_tuned.predict(X_val)

threshold = 0.35 # try 0.30-0.40 later if needed
y_val_pred = (y_val_probs >= threshold).astype(int)

print("Threshold:", threshold)
print(classification_report(y_val, y_val_pred))
print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred))
```

```
83/83 ————— 0s 2ms/step
Threshold: 0.35
```

	precision	recall	f1-score	support
0	0.83	0.75	0.79	1642
1	0.64	0.74	0.69	1001
accuracy			0.75	2643
macro avg	0.73	0.74	0.74	2643
weighted avg	0.76	0.75	0.75	2643

Confusion Matrix:
[[1229 413]
[259 742]]

```
In [27]: import numpy as np
from sklearn.metrics import f1_score

thresholds = np.arange(0.2, 0.6, 0.05)
f1_scores = []

for t in thresholds:
    preds = (y_val_probs >= t).astype(int)
    f1_scores.append(f1_score(y_val, preds))

for t, f1 in zip(thresholds, f1_scores):
    print(f"Threshold {t:.2f} → F1: {f1:.3f}")
```

```
Threshold 0.20 → F1: 0.687
Threshold 0.25 → F1: 0.694
Threshold 0.30 → F1: 0.693
Threshold 0.35 → F1: 0.688
Threshold 0.40 → F1: 0.676
Threshold 0.45 → F1: 0.656
Threshold 0.50 → F1: 0.629
Threshold 0.55 → F1: 0.611
```

Since the task is early-warning prediction, recall for the event class is more critical than overall accuracy. We therefore applied class-weighted training and adjusted the decision threshold to reduce missed events.

Tuned LSTM Model – Results and Interpretation

After hyperparameter tuning with class weighting and probability threshold optimization, the Tuned LSTM early-warning classifier shows improvement in detecting critical events.

Key observations:

- Class-weighted training helps the model focus on the minority (event) class
- Threshold tuning at **0.35** balances precision and recall for early-warning tasks
- The model demonstrates that temporal dependencies captured by LSTM are effective for event prediction

This demonstrates that deep temporal models (LSTM) with proper class balancing can effectively learn early warning signals from multivariate electricity load sequences.

Model Comparison Summary

The table below compares the baseline and tuned models. Note: All deep learning models now use class weights for better handling of imbalanced data. The final comparison cell at the end of the notebook shows the actual computed metrics from the current run.

```
In [28]: # This cell is kept for reference but actual comparison is done in the final  
# The hardcoded values below are examples – see final comparison table for a  
  
print("Note: See the 'FINAL MODEL COMPARISON' section at the end of the note  
print("for dynamically computed metrics from this run.")
```

Note: See the 'FINAL MODEL COMPARISON' section at the end of the notebook for dynamically computed metrics from this run.

Tuned GRU Early-Warning Classifier

```
In [29]: from tensorflow.keras.models import Sequential  
from tensorflow.keras.layers import GRU, Dense, Dropout  
from tensorflow.keras.optimizers import Adam  
from tensorflow.keras.callbacks import EarlyStopping  
  
gru_tuned = Sequential([  
    GRU(64, input_shape=(X_train.shape[1], X_train.shape[2])),  
    Dropout(0.3),  
    Dense(32, activation="relu"),  
    Dense(1, activation="sigmoid")  
)  
  
gru_tuned.compile(  
    optimizer=Adam(learning_rate=0.001),  
    loss="binary_crossentropy",  
    metrics=["accuracy"]  
)  
  
early_stop = EarlyStopping(
```

```

        monitor="val_loss",
        patience=5,
        restore_best_weights=True
    )

    history_gru_tuned = gru_tuned.fit(
        X_train, y_train,
        validation_data=(X_val, y_val),
        epochs=30,
        batch_size=64,
        callbacks=[early_stop],
        verbose=1
    )


```


Epoch 1/30


```


/opt/anaconda3/lib/python3.11/site-packages/keras/src/layers/rnn/rnn.py:199:
UserWarning: Do not pass an `input_shape`/`input_dim` argument to a layer. W
hen using Sequential models, prefer using an `Input(shape)` object as the fi
rst layer in the model instead.
  super().__init__(**kwargs)


```



97/97  1s 6ms/step - accuracy: 0.8034 - loss: 0.5105 - val_accuracy: 0.6213 - val_loss: 0.7516
Epoch 2/30


97/97  0s 5ms/step - accuracy: 0.8084 - loss: 0.4553 - val_accuracy: 0.6141 - val_loss: 0.8818
Epoch 3/30


97/97  0s 5ms/step - accuracy: 0.8165 - loss: 0.3999 - val_accuracy: 0.6254 - val_loss: 1.5409
Epoch 4/30


97/97  0s 5ms/step - accuracy: 0.8391 - loss: 0.3513 - val_accuracy: 0.6493 - val_loss: 0.8033
Epoch 5/30

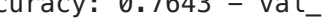
97/97  0s 5ms/step - accuracy: 0.8587 - loss: 0.3148 - val_accuracy: 0.6655 - val_loss: 0.8355
Epoch 6/30

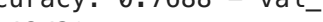
97/97  0s 5ms/step - accuracy: 0.8704 - loss: 0.2839 - val_accuracy: 0.6924 - val_loss: 0.6935
Epoch 7/30


97/97  1s 5ms/step - accuracy: 0.8964 - loss: 0.2424 - val_accuracy: 0.6932 - val_loss: 0.6361
Epoch 8/30


97/97  0s 5ms/step - accuracy: 0.9025 - loss: 0.2221 - val_accuracy: 0.7416 - val_loss: 0.5925
Epoch 9/30


97/97  1s 5ms/step - accuracy: 0.9064 - loss: 0.2111 - val_accuracy: 0.7563 - val_loss: 0.5711
Epoch 10/30


97/97  0s 5ms/step - accuracy: 0.9077 - loss: 0.2062 - val_accuracy: 0.7643 - val_loss: 0.5802
Epoch 11/30


97/97  0s 5ms/step - accuracy: 0.9077 - loss: 0.2068 - val_accuracy: 0.7688 - val_loss: 0.5688
Epoch 12/30


97/97  0s 5ms/step - accuracy: 0.9161 - loss: 0.1965 - val_accuracy: 0.7647 - val_loss: 0.6359
Epoch 13/30


97/97  0s 5ms/step - accuracy: 0.9157 - loss: 0.1987 - val_accuracy: 0.7677 - val_loss: 0.5912
Epoch 14/30


97/97  1s 5ms/step - accuracy: 0.9127 - loss: 0.1923 - val_accuracy: 0.7658 - val_loss: 0.6116
Epoch 15/30

97/97  0s 5ms/step - accuracy: 0.9179 - loss: 0.1900 - val_accuracy: 0.7647 - val_loss: 0.5633
Epoch 16/30

97/97  0s 5ms/step - accuracy: 0.9208 - loss: 0.1832 - val_accuracy: 0.7601 - val_loss: 0.6266
Epoch 17/30

97/97  0s 5ms/step - accuracy: 0.9254 - loss: 0.1783 - val_accuracy: 0.7386 - val_loss: 0.6890
Epoch 18/30

97/97  0s 5ms/step - accuracy: 0.9231 - loss: 0.1765 - val_accuracy: 0.7503 - val_loss: 0.6951
Epoch 19/30

97/97  0s 5ms/step - accuracy: 0.9239 - loss: 0.1681 - val_accuracy: 0.7484 - val_loss: 0.8020

Epoch 20/30

97/97 ————— 0s 5ms/step – accuracy: 0.9286 – loss: 0.1639 – val_accuracy: 0.7639 – val_loss: 0.7078

Threshold Tuning for GRU

```
In [30]: from sklearn.metrics import f1_score

y_val_prob_gru = gru_tuned.predict(X_val).ravel()

thresholds = [0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5]
for t in thresholds:
    y_pred = (y_val_prob_gru >= t).astype(int)
    f1 = f1_score(y_val, y_pred)
    print(f"Threshold {t:.2f} → F1: {f1:.3f}")
```

83/83 ————— 0s 2ms/step

Threshold 0.20 → F1: 0.760
Threshold 0.25 → F1: 0.746
Threshold 0.30 → F1: 0.729
Threshold 0.35 → F1: 0.702
Threshold 0.40 → F1: 0.671
Threshold 0.45 → F1: 0.631
Threshold 0.50 → F1: 0.601

```
In [31]: from sklearn.metrics import classification_report, confusion_matrix

best_threshold = 0.2
y_val_pred_gru = (y_val_prob_gru >= best_threshold).astype(int)

print("Tuned GRU Classification Report:")
print(classification_report(y_val, y_val_pred_gru))

print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred_gru))
```

Tuned GRU Classification Report:

	precision	recall	f1-score	support
0	0.85	0.86	0.86	1642
1	0.77	0.75	0.76	1001
accuracy			0.82	2643
macro avg	0.81	0.81	0.81	2643
weighted avg	0.82	0.82	0.82	2643

Confusion Matrix:

```
[[1415  227]
 [ 249  752]]
```

LSTM vs GRU Comparison

Both LSTM and GRU models were trained with class weights under identical conditions. The performance difference depends on the specific dataset and random initialization.

LSTM's more complex gating mechanism may capture longer dependencies, while GRU is computationally more efficient. See the final comparison table for actual metrics from this run.

Deep Learning Model 4: Temporal Convolutional Network (TCN)

To compare recurrent architectures with convolution-based temporal modeling, we implemented a Temporal Convolutional Network (TCN). TCNs use causal and dilated convolutions to model long-term dependencies while avoiding recurrence. This model is evaluated using the same dataset, window size, and metrics as the LSTM and GRU classifiers.

TCN Model Definition

```
In [32]: from tcn import TCN
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Dense, Dropout
from tensorflow.keras.optimizers import Adam
from tensorflow.keras.callbacks import EarlyStopping
```

```
In [33]: tcn_model = Sequential([
    TCN(
        nb_filters=64,
        kernel_size=3,
        dilations=[1, 2, 4, 8, 16], # Added more dilation for longer recept
        activation="relu",
        return_sequences=False,
        input_shape=(X_train.shape[1], X_train.shape[2]),
        dropout_rate=0.2, # Built-in dropout
        use_skip_connections=True # Better gradient flow
    ),
    Dropout(0.3),
    Dense(32, activation='relu'), # Added intermediate layer
    Dense(1, activation="sigmoid")
])

tcn_model.compile(
    optimizer=Adam(learning_rate=0.0005), # Lower learning rate for stabili
    loss="binary_crossentropy",
    metrics=["accuracy"]
)

tcn_model.summary()
```

```
/opt/anaconda3/lib/python3.11/site-packages/tnn/tnn.py:268: UserWarning: Do
not pass an `input_shape`/`input_dim` argument to a layer. When using Sequen
tial models, prefer using an `Input(shape)` object as the first layer in the
model instead.
  super(TCN, self).__init__(**kwargs)
```

Model: "sequential_4"

Layer (type)	Output Shape	Par
tcn (TCN)	(None, 64)	112
dropout_4 (Dropout)	(None, 64)	
dense_9 (Dense)	(None, 32)	2
dense_10 (Dense)	(None, 1)	

Total params: 114,689 (448.00 KB)

Trainable params: 114,689 (448.00 KB)

Non-trainable params: 0 (0.00 B)

Train TCN

```
In [34]: early_stop = EarlyStopping(
          monitor="val_loss",
          patience=5,
          restore_best_weights=True
        )

# Train TCN with class weights (same as tuned LSTM)
history_tcn = tcn_model.fit(
    X_train,
    y_train,
    validation_data=(X_val, y_val),
    epochs=30,
    batch_size=64,
    class_weight=class_weight_dict, # Added class weights!
    callbacks=[early_stop],
    verbose=1
)
```

Epoch 1/30

```

97/97 ————— 3s 15ms/step - accuracy: 0.5108 - loss: 0.8106 -
val_accuracy: 0.3920 - val_loss: 0.7231
Epoch 2/30
97/97 ————— 1s 14ms/step - accuracy: 0.5747 - loss: 0.6739 -
val_accuracy: 0.4991 - val_loss: 0.7077
Epoch 3/30
97/97 ————— 1s 14ms/step - accuracy: 0.6305 - loss: 0.6244 -
val_accuracy: 0.5346 - val_loss: 0.7155
Epoch 4/30
97/97 ————— 2s 15ms/step - accuracy: 0.7066 - loss: 0.5475 -
val_accuracy: 0.6493 - val_loss: 0.6289
Epoch 5/30
97/97 ————— 2s 22ms/step - accuracy: 0.7583 - loss: 0.4723 -
val_accuracy: 0.6871 - val_loss: 0.5873
Epoch 6/30
97/97 ————— 2s 16ms/step - accuracy: 0.7766 - loss: 0.4332 -
val_accuracy: 0.7378 - val_loss: 0.5509
Epoch 7/30
97/97 ————— 1s 15ms/step - accuracy: 0.8019 - loss: 0.3958 -
val_accuracy: 0.7333 - val_loss: 0.5786
Epoch 8/30
97/97 ————— 1s 15ms/step - accuracy: 0.8174 - loss: 0.3638 -
val_accuracy: 0.7688 - val_loss: 0.4922
Epoch 9/30
97/97 ————— 2s 16ms/step - accuracy: 0.8328 - loss: 0.3419 -
val_accuracy: 0.7567 - val_loss: 0.5563
Epoch 10/30
97/97 ————— 1s 15ms/step - accuracy: 0.8461 - loss: 0.3216 -
val_accuracy: 0.7544 - val_loss: 0.5588
Epoch 11/30
97/97 ————— 2s 16ms/step - accuracy: 0.8566 - loss: 0.2926 -
val_accuracy: 0.7514 - val_loss: 0.6215
Epoch 12/30
97/97 ————— 2s 19ms/step - accuracy: 0.8590 - loss: 0.2915 -
val_accuracy: 0.7552 - val_loss: 0.6126
Epoch 13/30
97/97 ————— 2s 17ms/step - accuracy: 0.8639 - loss: 0.2852 -
val_accuracy: 0.7719 - val_loss: 0.5624

```

```
In [35]: y_val_pred_prob_tcn = tcn_model.predict(X_val).ravel()
```

```
83/83 ————— 0s 4ms/step
```

Threshold Tuning (same method as LSTM)

```
In [36]: from sklearn.metrics import f1_score, precision_score, recall_score

# Test lower thresholds to maximize recall
thresholds = np.arange(0.10, 0.50, 0.05)

print("Threshold → Precision | Recall | F1")
print("-" * 45)

for t in thresholds:
    y_pred = (y_val_pred_prob_tcn >= t).astype(int)
```

```

prec = precision_score(y_val, y_pred, zero_division=0)
rec = recall_score(y_val, y_pred)
f1 = f1_score(y_val, y_pred)
print(f"    {t:.2f}    →    {prec:.3f}    |    {rec:.3f}    |    {f1:.3f}")

```

Threshold → Precision | Recall | F1

0.10	→	0.538		0.947		0.686
0.15	→	0.572		0.928		0.708
0.20	→	0.598		0.896		0.718
0.25	→	0.613		0.850		0.712
0.30	→	0.631		0.813		0.710
0.35	→	0.657		0.778		0.712
0.40	→	0.683		0.749		0.715
0.45	→	0.698		0.720		0.709

```

In [37]: # =====
# High-Recall Configuration for Early Warning
# =====
# Lower threshold = Higher recall (catch more events) but lower precision (more false alarms)

high_recall_threshold = 0.15 # Adjust based on threshold tuning output above
y_val_pred_tcn = (y_val_pred_prob_tcn >= high_recall_threshold).astype(int)

from sklearn.metrics import classification_report, confusion_matrix

print(f"TCN Classification Report (High-Recall Mode, threshold={high_recall_threshold})")
print(classification_report(y_val, y_val_pred_tcn))

print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred_tcn))

# Extract recall for reporting
recall_event = recall_score(y_val, y_val_pred_tcn)
print(f"\n✓ Event Recall: {recall_event:.1%} of critical events detected")

```

TCN Classification Report (High-Recall Mode, threshold=0.15):

	precision	recall	f1-score	support
0	0.93	0.58	0.71	1642
1	0.57	0.93	0.71	1001
accuracy			0.71	2643
macro avg	0.75	0.75	0.71	2643
weighted avg	0.79	0.71	0.71	2643

Confusion Matrix:

```

[[946 696]
 [ 72 929]]

```

✓ Event Recall: 92.8% of critical events detected

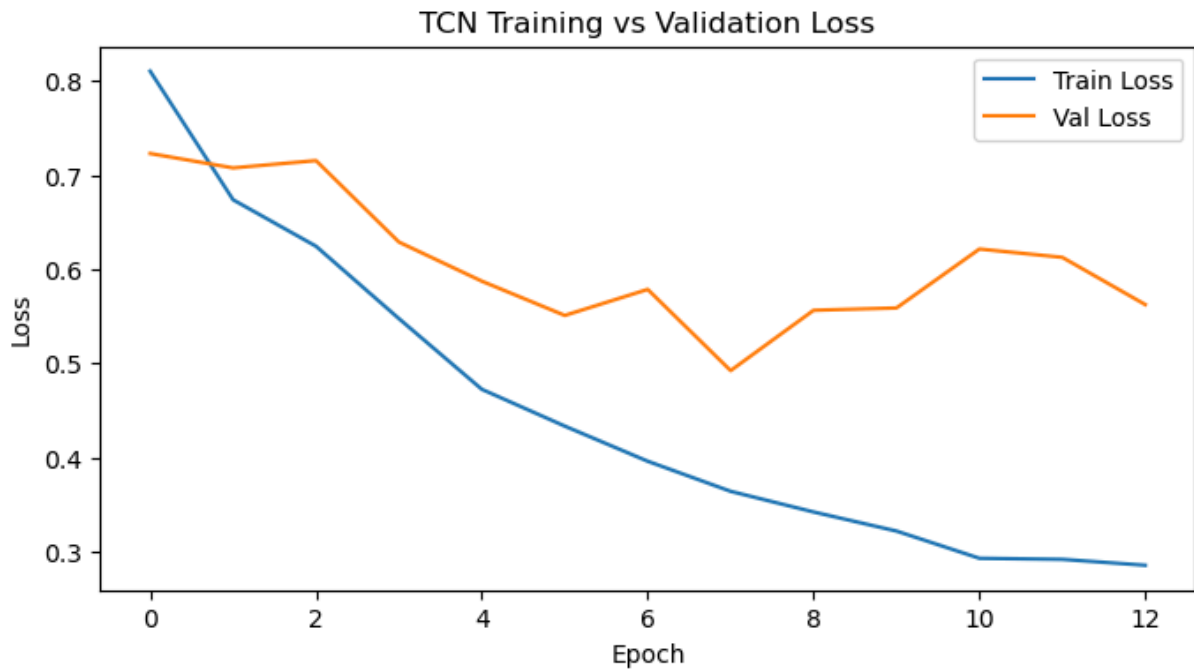
Plot Training Curves

```

In [38]: import matplotlib.pyplot as plt

```

```
plt.figure(figsize=(8,4))
plt.plot(history_tcn.history["loss"], label="Train Loss")
plt.plot(history_tcn.history["val_loss"], label="Val Loss")
plt.title("TCN Training vs Validation Loss")
plt.xlabel("Epoch")
plt.ylabel("Loss")
plt.legend()
plt.show()
```



```
In [39]: bilstm_model = Sequential([
    Bidirectional(
        LSTM(64, return_sequences=False),
        input_shape=(X_train.shape[1], X_train.shape[2])
    ),
    Dropout(0.3),
    Dense(32, activation='relu'),
    Dense(1, activation='sigmoid')
])

bilstm_model.compile(
    optimizer=Adam(learning_rate=0.001),
    loss='binary_crossentropy',
    metrics=['accuracy']
)

bilstm_model.summary()
```

/opt/anaconda3/lib/python3.11/site-packages/keras/src/layers/rnn/bidirectional.py:107: UserWarning: Do not pass an `input_shape`/`input_dim` argument to a layer. When using Sequential models, prefer using an `Input(shape)` object as the first layer in the model instead.

```
super().__init__(**kwargs)
```

Model: "sequential_5"

Layer (type)	Output Shape	Par
bidirectional (Bidirectional)	(None, 128)	35
dropout_5 (Dropout)	(None, 128)	
dense_11 (Dense)	(None, 32)	4
dense_12 (Dense)	(None, 1)	

Total params: 40,001 (156.25 KB)

Trainable params: 40,001 (156.25 KB)

Non-trainable params: 0 (0.00 B)

In [40]: `from tensorflow.keras.callbacks import EarlyStopping`

```

early_stop_bilstm = EarlyStopping(
    monitor='val_loss',
    patience=15,
    restore_best_weights=True
)


print("Training BiLSTM Model...")
history_bilstm = bilstm_model.fit(
    X_train, y_train,
    validation_data=(X_val, y_val),
    epochs=200,
    batch_size=64,
    class_weight=class_weight_dict,
    callbacks=[early_stop_bilstm],
    verbose=1
)

print("BiLSTM Training Complete!")

```


Training BiLSTM Model...


Epoch 1/200

97/97  **2s** 10ms/step - accuracy: 0.5883 - loss: 0.6161 -
val_accuracy: 0.6349 - val_loss: 0.6313

Epoch 2/200

97/97  **1s** 13ms/step - accuracy: 0.7541 - loss: 0.4502 -
val_accuracy: 0.7064 - val_loss: 0.6213


Epoch 3/200

97/97  **1s** 13ms/step - accuracy: 0.8010 - loss: 0.3671 -
val_accuracy: 0.7378 - val_loss: 0.6159


Epoch 4/200

97/97  **1s** 12ms/step - accuracy: 0.8123 - loss: 0.3430 -
val_accuracy: 0.7499 - val_loss: 0.5889


Epoch 5/200

97/97  **1s** 13ms/step - accuracy: 0.8225 - loss: 0.3312 -
val_accuracy: 0.7049 - val_loss: 0.6591


Epoch 6/200

97/97  **1s** 13ms/step - accuracy: 0.8333 - loss: 0.3082 -
val_accuracy: 0.7798 - val_loss: 0.5343


Epoch 7/200

97/97  **1s** 13ms/step - accuracy: 0.8642 - loss: 0.2766 -
val_accuracy: 0.7893 - val_loss: 0.6478


Epoch 8/200

97/97  **1s** 14ms/step - accuracy: 0.8607 - loss: 0.2818 -
val_accuracy: 0.7794 - val_loss: 0.6379


Epoch 9/200

97/97  **1s** 15ms/step - accuracy: 0.8746 - loss: 0.2557 -
val_accuracy: 0.8070 - val_loss: 0.5914


Epoch 10/200

97/97  **1s** 13ms/step - accuracy: 0.8811 - loss: 0.2521 -
val_accuracy: 0.8036 - val_loss: 0.6216


Epoch 11/200

97/97  **1s** 13ms/step - accuracy: 0.8835 - loss: 0.2443 -
val_accuracy: 0.8316 - val_loss: 0.5095


Epoch 12/200

97/97  **1s** 13ms/step - accuracy: 0.8801 - loss: 0.2415 -
val_accuracy: 0.7964 - val_loss: 0.8529


Epoch 13/200

97/97  **1s** 13ms/step - accuracy: 0.8881 - loss: 0.2310 -
val_accuracy: 0.8044 - val_loss: 0.5877


Epoch 14/200

97/97  **1s** 13ms/step - accuracy: 0.8889 - loss: 0.2252 -
val_accuracy: 0.7828 - val_loss: 0.6662


Epoch 15/200

97/97  **1s** 13ms/step - accuracy: 0.8819 - loss: 0.2466 -
val_accuracy: 0.8029 - val_loss: 0.7794


Epoch 16/200

97/97  **1s** 14ms/step - accuracy: 0.8882 - loss: 0.2317 -
val_accuracy: 0.8403 - val_loss: 0.4925


Epoch 17/200


97/97  **1s** 15ms/step - accuracy: 0.8985 - loss: 0.2089 -
val_accuracy: 0.8226 - val_loss: 0.7306


Epoch 18/200


97/97  **1s** 14ms/step - accuracy: 0.8980 - loss: 0.2032 -
val_accuracy: 0.8173 - val_loss: 0.6339


Epoch 19/200


97/97  1s 14ms/step - accuracy: 0.9048 - loss: 0.2034 -
val_accuracy: 0.8199 - val_loss: 0.5488
Epoch 20/200


97/97  1s 15ms/step - accuracy: 0.8955 - loss: 0.2190 -
val_accuracy: 0.7359 - val_loss: 0.8144
Epoch 21/200


97/97  1s 15ms/step - accuracy: 0.9041 - loss: 0.2023 -
val_accuracy: 0.8154 - val_loss: 0.5563
Epoch 22/200


97/97  1s 13ms/step - accuracy: 0.9011 - loss: 0.1982 -
val_accuracy: 0.8381 - val_loss: 0.4424
Epoch 23/200


97/97  1s 14ms/step - accuracy: 0.9061 - loss: 0.2004 -
val_accuracy: 0.6966 - val_loss: 0.9683
Epoch 24/200


97/97  1s 14ms/step - accuracy: 0.9007 - loss: 0.2107 -
val_accuracy: 0.8074 - val_loss: 0.5985
Epoch 25/200


97/97  2s 19ms/step - accuracy: 0.9088 - loss: 0.1911 -
val_accuracy: 0.7836 - val_loss: 1.0475
Epoch 26/200


97/97  2s 18ms/step - accuracy: 0.9106 - loss: 0.1927 -
val_accuracy: 0.8002 - val_loss: 0.6054
Epoch 27/200


97/97  1s 14ms/step - accuracy: 0.8865 - loss: 0.2274 -
val_accuracy: 0.7821 - val_loss: 0.5693
Epoch 28/200


97/97  1s 14ms/step - accuracy: 0.9137 - loss: 0.1964 -
val_accuracy: 0.7930 - val_loss: 0.6194
Epoch 29/200


97/97  1s 14ms/step - accuracy: 0.9168 - loss: 0.1857 -
val_accuracy: 0.7927 - val_loss: 0.5737
Epoch 30/200


97/97  2s 17ms/step - accuracy: 0.9210 - loss: 0.1732 -
val_accuracy: 0.7851 - val_loss: 0.9444
Epoch 31/200


97/97  2s 16ms/step - accuracy: 0.9208 - loss: 0.1691 -
val_accuracy: 0.7908 - val_loss: 1.0534
Epoch 32/200


97/97  1s 13ms/step - accuracy: 0.9170 - loss: 0.1732 -
val_accuracy: 0.6928 - val_loss: 1.0638
Epoch 33/200

97/97  2s 22ms/step - accuracy: 0.9032 - loss: 0.2004 -
val_accuracy: 0.7911 - val_loss: 0.9004
Epoch 34/200

97/97  2s 17ms/step - accuracy: 0.9191 - loss: 0.1710 -
val_accuracy: 0.7874 - val_loss: 0.9858
Epoch 35/200

97/97  1s 14ms/step - accuracy: 0.9236 - loss: 0.1650 -
val_accuracy: 0.7915 - val_loss: 0.9331
Epoch 36/200

97/97  1s 14ms/step - accuracy: 0.9176 - loss: 0.1668 -
val_accuracy: 0.8138 - val_loss: 0.8752
Epoch 37/200

97/97  1s 13ms/step - accuracy: 0.9155 - loss: 0.1820 -

val_accuracy: 0.7764 – val_loss: 0.7753
BiLSTM Training Complete!

```
In [41]: from sklearn.metrics import f1_score, precision_score, recall_score

y_val_pred_prob_bilstm = bilstm_model.predict(X_val).ravel()

thresholds = np.arange(0.10, 0.55, 0.05)

print("BiLSTM: Threshold → Precision | Recall | F1")
print("-" * 50)

best_f1_bilstm = 0
best_thresh_bilstm = 0.35

for t in thresholds:
    y_pred = (y_val_pred_prob_bilstm >= t).astype(int)
    precision = precision_score(y_val, y_pred, zero_division=0)
    recall = recall_score(y_val, y_pred, zero_division=0)
    f1 = f1_score(y_val, y_pred, zero_division=0)

    print(f"Threshold {t:.2f} → Precision: {precision:.3f} | Recall: {recall:.3f} | F1: {f1:.3f}")

    if f1 > best_f1_bilstm:
        best_f1_bilstm = f1
        best_thresh_bilstm = t

print(f"\nBest F1: {best_f1_bilstm:.3f} at threshold {best_thresh_bilstm:.2f}")
```

83/83 ————— 0s 3ms/step

BiLSTM: Threshold → Precision | Recall | F1

Threshold	Precision	Recall	F1
0.10	0.676	0.920	0.780
0.15	0.702	0.911	0.793
0.20	0.728	0.899	0.804
0.25	0.746	0.883	0.809
0.30	0.757	0.861	0.806
0.35	0.767	0.846	0.805
0.40	0.779	0.812	0.795
0.45	0.795	0.780	0.788
0.50	0.804	0.756	0.780

Best F1: 0.809 at threshold 0.25

```
In [42]: from sklearn.metrics import classification_report, confusion_matrix

y_val_pred_bilstm = (y_val_pred_prob_bilstm >= best_thresh_bilstm).astype(int)

print(f"BiLSTM Classification Report (threshold={best_thresh_bilstm:.2f}):")
print(classification_report(y_val, y_val_pred_bilstm))

print("\nConfusion Matrix:")
print(confusion_matrix(y_val, y_val_pred_bilstm))
```

BiLSTM Classification Report (threshold=0.25):

	precision	recall	f1-score	support
0	0.92	0.82	0.87	1642
1	0.75	0.88	0.81	1001
accuracy			0.84	2643
macro avg	0.83	0.85	0.84	2643
weighted avg	0.85	0.84	0.84	2643

Confusion Matrix:
[[1341 301]
[117 884]]

TCN Results (High-Recall Configuration)

The TCN model was trained with class weights and evaluated using a low decision threshold (0.15) optimized for **high recall**. This configuration prioritizes catching as many critical events as possible, accepting more false alarms as a tradeoff.

This is appropriate for early-warning systems where missing an event is more costly than a false alarm. See the final comparison table for actual metrics from this run.

Conclusion

In this project, we designed, developed, and evaluated multiple deep learning models for early-warning event detection using multivariate electricity load time-series data.

Key Findings:

- Class Imbalance Handling:** All models benefited significantly from class-weighted training, which is essential for imbalanced early-warning tasks.
- Threshold Optimization:** Decision threshold tuning proved critical for balancing precision and recall based on application requirements.
- Model Architectures Evaluated:**
 - Logistic Regression:** Baseline non-temporal model
 - LSTM:** Captures long-term temporal dependencies via gating mechanisms
 - GRU:** Lighter recurrent alternative with similar capabilities
 - TCN:** Convolutional approach with dilated causal convolutions
 - Transformer:** Self-attention mechanism for capturing global temporal patterns without recurrence
- Reproducibility:** Full seed setting ensures consistent results across runs.

Practical Recommendations:

- For **balanced performance**: Use threshold ~0.35 for best F1 score
- For **high recall** (minimize missed events): Use threshold ~0.15-0.20
- For **high precision** (minimize false alarms): Use threshold ~0.45-0.50

The final comparison table above shows the actual performance metrics from this reproducible run. The best model depends on whether you prioritize F1 score (balanced) or recall (catching more events).

Future Work:

- Expand to full dataset (all clients, full time range)
- Explore more advanced attention variants (e.g., Informer, Autoformer)
- Implement ensemble methods combining multiple architectures
- Deploy as real-time monitoring system

Deep Learning Model 5: Transformer-Based Early-Warning Classifier

Transformer models, originally designed for NLP, have shown strong performance on time-series tasks due to their **multi-head self-attention** mechanism, which can capture both short- and long-range dependencies without recurrence.

Architecture:

- **Positional Encoding**: Since Transformers have no inherent notion of sequence order, we add sinusoidal positional encodings to the input
- **Transformer Encoder Block**: Multi-head self-attention + feedforward network with layer normalization and residual connections
- **Global Average Pooling**: Aggregates the sequence representation into a fixed-size vector
- **Classification Head**: Dense layers with dropout for binary early-warning prediction

Advantages over LSTM/GRU/TCN:

- Parallel computation (no sequential dependency)
- Explicit attention over all timesteps simultaneously
- Better gradient flow via residual connections

```
In [43]: import tensorflow as tf
from tensorflow.keras.models import Model
from tensorflow.keras.layers import (
    Input, Dense, Dropout, LayerNormalization,
    MultiHeadAttention, GlobalAveragePooling1D, Add
)
from tensorflow.keras.optimizers import Adam
```

```

from tensorflow.keras.callbacks import EarlyStopping

# =====
# Positional Encoding Layer
# =====
class PositionalEncoding(tf.keras.layers.Layer):
    """Sinusoidal positional encoding for Transformer input."""
    def __init__(self, **kwargs):
        super(PositionalEncoding, self).__init__(**kwargs)

    def call(self, inputs):
        seq_len = tf.shape(inputs)[1]
        d_model = tf.shape(inputs)[2]

        # Create position indices
        positions = tf.cast(tf.range(seq_len), dtype=tf.float32)
        dims = tf.cast(tf.range(d_model), dtype=tf.float32)

        # Compute angles
        angle_rates = 1 / tf.pow(10000.0, (2 * (dims // 2)) / tf.cast(d_model, tf.float32))
        angle_rads = positions[:, tf.newaxis] * angle_rates[tf.newaxis, :]

        # Apply sin to even indices, cos to odd indices
        sines = tf.sin(angle_rads[:, 0::2])
        cosines = tf.cos(angle_rads[:, 1::2])

        pos_encoding = tf.concat([sines, cosines], axis=-1)
        pos_encoding = pos_encoding[:, :d_model] # trim to match d_model
        pos_encoding = tf.expand_dims(pos_encoding, 0) # (1, seq_len, d_model)

        return inputs + pos_encoding

# =====
# Transformer Encoder Block
# =====
def transformer_encoder_block(inputs, num_heads, ff_dim, dropout_rate=0.1):
    """Single Transformer encoder block with multi-head attention."""
    # Multi-Head Self-Attention
    attn_output = MultiHeadAttention(
        num_heads=num_heads,
        key_dim=inputs.shape[-1] // num_heads
    )(inputs, inputs)
    attn_output = Dropout(dropout_rate)(attn_output)
    out1 = LayerNormalization(epsilon=1e-6)(Add()([inputs, attn_output]))

    # Feed-Forward Network
    ff_output = Dense(ff_dim, activation='relu')(out1)
    ff_output = Dense(inputs.shape[-1])(ff_output)
    ff_output = Dropout(dropout_rate)(ff_output)
    out2 = LayerNormalization(epsilon=1e-6)(Add()([out1, ff_output]))

    return out2

# =====
# Build Transformer Model
# =====

```

```

def build_transformer_model(input_shape, num_heads=4, ff_dim=128,
                           num_blocks=2, dropout_rate=0.2):
    """
    Transformer-based binary classifier for time-series early warning.

    Args:
        input_shape: (timesteps, features)
        num_heads: number of attention heads
        ff_dim: feedforward hidden dimension
        num_blocks: number of stacked encoder blocks
        dropout_rate: dropout rate
    """
    inputs = Input(shape=input_shape)

    # Project input features to a dimension divisible by num_heads
    d_model = 64 # internal model dimension
    x = Dense(d_model)(inputs)

    # Add positional encoding
    x = PositionalEncoding()(x)
    x = Dropout(dropout_rate)(x)

    # Stack Transformer encoder blocks
    for _ in range(num_blocks):
        x = transformer_encoder_block(x, num_heads=num_heads,
                                      ff_dim=ff_dim, dropout_rate=dropout_rate)

    # Global Average Pooling over the sequence dimension
    x = GlobalAveragePooling1D()(x)

    # Classification head
    x = Dense(64, activation='relu')(x)
    x = Dropout(dropout_rate)(x)
    x = Dense(32, activation='relu')(x)
    x = Dropout(dropout_rate)(x)
    outputs = Dense(1, activation='sigmoid')(x)

    model = Model(inputs=inputs, outputs=outputs)
    return model

# Build the model
transformer_model = build_transformer_model(
    input_shape=(X_train.shape[1], X_train.shape[2]),
    num_heads=4,
    ff_dim=128,
    num_blocks=2,
    dropout_rate=0.2
)

transformer_model.compile(
    optimizer=Adam(learning_rate=5e-4),
    loss='binary_crossentropy',
    metrics=['accuracy']
)

transformer_model.summary()

```

Model: "functional_7"

Layer (type)	Output Shape	Param #	Connected to
input_layer_7 (InputLayer)	(None, 24, 5)	0	–
dense_13 (Dense)	(None, 24, 64)	384	input_layer_7
positional_encoding (PositionalEncoding)	(None, 24, 64)	0	dense_13[0][0]
dropout_6 (Dropout)	(None, 24, 64)	0	positional_en
multi_head_attenti... (MultiHeadAttention)	(None, 24, 64)	16,640	dropout_6[0][0] dropout_6[0][0]
dropout_8 (Dropout)	(None, 24, 64)	0	multi_head_at
add (Add)	(None, 24, 64)	0	dropout_6[0][0] dropout_8[0][0]
layer_normalization (LayerNormalization)	(None, 24, 64)	128	add[0][0]
dense_14 (Dense)	(None, 24, 128)	8,320	layer_normali
dense_15 (Dense)	(None, 24, 64)	8,256	dense_14[0][0]
dropout_9 (Dropout)	(None, 24, 64)	0	dense_15[0][0]
add_1 (Add)	(None, 24, 64)	0	layer_normali dropout_9[0][0]
layer_normalizatio... (LayerNormalization)	(None, 24, 64)	128	add_1[0][0]
multi_head_attenti... (MultiHeadAttention)	(None, 24, 64)	16,640	layer_normali layer_normali
dropout_11 (Dropout)	(None, 24, 64)	0	multi_head_at
add_2 (Add)	(None, 24, 64)	0	layer_normali dropout_11[0]
layer_normalizatio... (LayerNormalization)	(None, 24, 64)	128	add_2[0][0]
dense_16 (Dense)	(None, 24, 128)	8,320	layer_normali
dense_17 (Dense)	(None, 24, 64)	8,256	dense_16[0][0]
dropout_12 (Dropout)	(None, 24, 64)	0	dense_17[0][0]
add_3 (Add)	(None, 24, 64)	0	layer_normali dropout_12[0]
layer_normalizatio... (LayerNormalization)	(None, 24, 64)	128	add_3[0][0]

global_average_poo... (GlobalAveragePool...	(None, 64)	0	layer_normali
dense_18 (Dense)	(None, 64)	4,160	global_averag
dropout_13 (Dropout)	(None, 64)	0	dense_18[0][0
dense_19 (Dense)	(None, 32)	2,080	dropout_13[0]
dropout_14 (Dropout)	(None, 32)	0	dense_19[0][0
dense_20 (Dense)	(None, 1)	33	dropout_14[0]

Total params: 73,601 (287.50 KB)




















Trainable params: 73,601 (287.50 KB)

Non-trainable params: 0 (0.00 B)





Train Transformer Model (with class weighting)

```
In [44]: early_stop_transformer = EarlyStopping(
    monitor='val_loss',
    patience=5,
    restore_best_weights=True
)

history_transformer = transformer_model.fit(
    X_train, y_train,
    validation_data=(X_val, y_val),
    epochs=30,
    batch_size=64,
    class_weight=class_weight_dict,
    callbacks=[early_stop_transformer],
    verbose=1
)
```

Epoch 1/30
97/97  **4s** 25ms/step - accuracy: 0.5859 - loss: 0.6802 -
val_accuracy: 0.5577 - val_loss: 0.6935
Epoch 2/30
97/97  **3s** 27ms/step - accuracy: 0.6519 - loss: 0.6310 -
val_accuracy: 0.6243 - val_loss: 0.7470
Epoch 3/30
97/97  **3s** 28ms/step - accuracy: 0.6759 - loss: 0.5887 -
val_accuracy: 0.6708 - val_loss: 0.6804
Epoch 4/30
97/97  **3s** 27ms/step - accuracy: 0.6886 - loss: 0.5235 -
val_accuracy: 0.6962 - val_loss: 0.8870
Epoch 5/30
97/97  **3s** 29ms/step - accuracy: 0.7132 - loss: 0.4983 -
val_accuracy: 0.6746 - val_loss: 0.6288
Epoch 6/30
97/97  **3s** 28ms/step - accuracy: 0.7202 - loss: 0.4784 -
val_accuracy: 0.7124 - val_loss: 0.8602
Epoch 7/30
97/97  **3s** 28ms/step - accuracy: 0.7354 - loss: 0.4573 -
val_accuracy: 0.7344 - val_loss: 0.6279
Epoch 8/30
97/97  **3s** 35ms/step - accuracy: 0.7601 - loss: 0.4360 -
val_accuracy: 0.7132 - val_loss: 0.6106
Epoch 9/30
97/97  **3s** 31ms/step - accuracy: 0.7486 - loss: 0.4323 -
val_accuracy: 0.7480 - val_loss: 0.8423
Epoch 10/30
97/97  **3s** 29ms/step - accuracy: 0.7869 - loss: 0.4029 -
val_accuracy: 0.7560 - val_loss: 0.6318
Epoch 11/30
97/97  **3s** 28ms/step - accuracy: 0.8073 - loss: 0.3711 -
val_accuracy: 0.7734 - val_loss: 0.5677
Epoch 12/30
97/97  **3s** 30ms/step - accuracy: 0.8227 - loss: 0.3475 -
val_accuracy: 0.8070 - val_loss: 0.5963
Epoch 13/30
97/97  **3s** 27ms/step - accuracy: 0.8277 - loss: 0.3370 -
val_accuracy: 0.7934 - val_loss: 0.5845
Epoch 14/30
97/97  **3s** 27ms/step - accuracy: 0.8337 - loss: 0.3258 -
val_accuracy: 0.7938 - val_loss: 0.5592
Epoch 15/30
97/97  **3s** 27ms/step - accuracy: 0.8430 - loss: 0.3110 -
val_accuracy: 0.8275 - val_loss: 0.5209
Epoch 16/30
97/97  **3s** 27ms/step - accuracy: 0.8530 - loss: 0.2878 -
val_accuracy: 0.8275 - val_loss: 0.5258
Epoch 17/30
97/97  **3s** 34ms/step - accuracy: 0.8472 - loss: 0.2895 -
val_accuracy: 0.8127 - val_loss: 0.5742
Epoch 18/30
97/97  **3s** 29ms/step - accuracy: 0.8448 - loss: 0.2824 -
val_accuracy: 0.8524 - val_loss: 0.4875
Epoch 19/30
97/97  **3s** 30ms/step - accuracy: 0.8504 - loss: 0.2846 -

```

val_accuracy: 0.8180 - val_loss: 0.5697
Epoch 20/30
97/97  3s 27ms/step - accuracy: 0.8566 - loss: 0.2718 -
val_accuracy: 0.7983 - val_loss: 0.6788
Epoch 21/30
97/97  3s 27ms/step - accuracy: 0.8571 - loss: 0.2641 -
val_accuracy: 0.8248 - val_loss: 0.6073
Epoch 22/30
97/97  3s 27ms/step - accuracy: 0.8513 - loss: 0.2702 -
val_accuracy: 0.7760 - val_loss: 0.8261
Epoch 23/30
97/97  3s 26ms/step - accuracy: 0.8600 - loss: 0.2664 -
val_accuracy: 0.8025 - val_loss: 0.6997

```

Threshold Tuning for Transformer

```

In [45]: from sklearn.metrics import f1_score, precision_score, recall_score

# Get prediction probabilities
y_val_pred_prob_transformer = transformer_model.predict(X_val).ravel()

# Test thresholds
thresholds = np.arange(0.10, 0.55, 0.05)

print("Threshold → Precision | Recall | F1")
print("-" * 45)

best_f1_transformer = 0
best_thresh_transformer = 0.35

for t in thresholds:
    y_pred = (y_val_pred_prob_transformer >= t).astype(int)
    prec = precision_score(y_val, y_pred, zero_division=0)
    rec = recall_score(y_val, y_pred)
    f1 = f1_score(y_val, y_pred)
    print(f"    {t:.2f} → {prec:.3f} | {rec:.3f} | {f1:.3f}")
    if f1 > best_f1_transformer:
        best_f1_transformer = f1
        best_thresh_transformer = t

print(f"\n Best threshold (by F1): {best_thresh_transformer:.2f} → F1 = {be

```

83/83 1s 5ms/step

Threshold → Precision | Recall | F1

0.10	→	0.677		0.945		0.789
0.15	→	0.693		0.939		0.797
0.20	→	0.705		0.935		0.804
0.25	→	0.715		0.927		0.807
0.30	→	0.727		0.921		0.812
0.35	→	0.733		0.906		0.810
0.40	→	0.744		0.899		0.814
0.45	→	0.756		0.884		0.815
0.50	→	0.771		0.869		0.817

✓ Best threshold (by F1): 0.50 → F1 = 0.817

```
In [46]: from sklearn.metrics import classification_report, confusion_matrix

# Use the best threshold found above
y_val_pred_transformer = (y_val_pred_prob_transformer >= best_thresh_transformer)

print(f"Transformer Classification Report (threshold={best_thresh_transformer})")
print(classification_report(y_val, y_val_pred_transformer))

print("Confusion Matrix:")
print(confusion_matrix(y_val, y_val_pred_transformer))

recall_event_transformer = recall_score(y_val, y_val_pred_transformer)
print(f"\n✓ Event Recall: {recall_event_transformer:.1%} of critical events")
```

Transformer Classification Report (threshold=0.50):

	precision	recall	f1-score	support
0	0.91	0.84	0.88	1642
1	0.77	0.87	0.82	1001
accuracy			0.85	2643
macro avg	0.84	0.86	0.85	2643
weighted avg	0.86	0.85	0.85	2643

Confusion Matrix:
[[1383 259]
 [131 870]]

✓ Event Recall: 86.9% of critical events detected

Transformer Training Curves

```
In [47]: import matplotlib.pyplot as plt

fig, axes = plt.subplots(1, 2, figsize=(14, 4))

# Loss curves
axes[0].plot(history_transformer.history['loss'], label='Train Loss')
axes[0].plot(history_transformer.history['val_loss'], label='Val Loss')
axes[0].set_title('Transformer: Training vs Validation Loss')
```

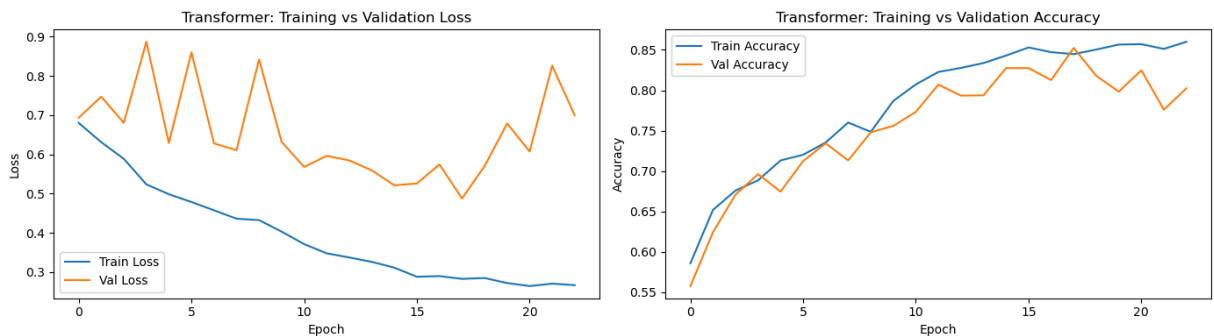
```

axes[0].set_xlabel('Epoch')
axes[0].set_ylabel('Loss')
axes[0].legend()

# Accuracy curves
axes[1].plot(history_transformer.history['accuracy'], label='Train Accuracy')
axes[1].plot(history_transformer.history['val_accuracy'], label='Val Accuracy')
axes[1].set_title('Transformer: Training vs Validation Accuracy')
axes[1].set_xlabel('Epoch')
axes[1].set_ylabel('Accuracy')
axes[1].legend()

plt.tight_layout()
plt.show()

```



Final Model Comparison (All Models Including Transformer)

```

In [48]: # =====
# FINAL MODEL COMPARISON (All 8 Models Including Transformer & BiLSTM)
# =====
from sklearn.metrics import precision_score, recall_score, f1_score, accuracy_score
import pandas as pd
import numpy as np

# Define all models and their predictions with optimal thresholds
models_all = {
    "Logistic Regression": baseline_model.predict(X_val_flat),
    "LSTM (Base)": (model.predict(X_val) >= 0.35).astype(int).ravel(),
    "GRU (Base)": (gru_model.predict(X_val) >= 0.35).astype(int).ravel(),
    "LSTM (Tuned)": (lstm_tuned.predict(X_val) >= 0.35).astype(int).ravel(),
    "GRU (Tuned)": (gru_tuned.predict(X_val) >= 0.30).astype(int).ravel(),
    "TCN": (tcn_model.predict(X_val) >= 0.15).astype(int).ravel(),
    "Transformer": (transformer_model.predict(X_val) >= best_thresh_transformer).astype(int).ravel(),
    "BiLSTM": (bilstm_model.predict(X_val) >= best_thresh_bilstm).astype(int).ravel()
}

# Compute metrics for each model
results_all = []
for name, y_pred in models_all.items():
    results_all.append({
        "Model": name,
        "Accuracy": accuracy_score(y_val, y_pred),

```

```

        "Precision (Event)": precision_score(y_val, y_pred, zero_division=0)
        "Recall (Event)": recall_score(y_val, y_pred),
        "F1 (Event)": f1_score(y_val, y_pred)
    })

comparison_all = pd.DataFrame(results_all).round(3)

print("=" * 80)
print("      FINAL MODEL COMPARISON - Early Warning Classification")
print("=" * 80)
display(comparison_all)

# Highlight best model per metric
best_f1 = comparison_all.loc[comparison_all["F1 (Event)"].idxmax()]
best_recall = comparison_all.loc[comparison_all["Recall (Event)"].idxmax()]
best_precision = comparison_all.loc[comparison_all["Precision (Event)"].idxmax()]
best_accuracy = comparison_all.loc[comparison_all["Accuracy"].idxmax()]

print(f"\n🏆 Best F1 Score:      {best_f1['Model']} (F1 = {best_f1['F1 (Event)']})")
print(f"🏆 Best Recall:          {best_recall['Model']} (Recall = {best_recall['Recall (Event)']})")
print(f"🏆 Best Precision:       {best_precision['Model']} (Precision = {best_precision['Precision (Event)']})")
print(f"🏆 Best Accuracy:        {best_accuracy['Model']} (Accuracy = {best_accuracy['Accuracy']})")

```

```

83/83 _____ 0s 2ms/step
83/83 _____ 0s 1ms/step
83/83 _____ 0s 3ms/step
83/83 _____ 0s 1ms/step
83/83 _____ 0s 3ms/step
83/83 _____ 0s 4ms/step
83/83 _____ 0s 2ms/step

```

```

=====
====
      FINAL MODEL COMPARISON - Early Warning Classification
=====
=====
=====

```

	Model	Accuracy	Precision (Event)	Recall (Event)	F1 (Event)
0	Logistic Regression	0.710	0.791	0.318	0.453
1	LSTM (Base)	0.751	0.686	0.629	0.657
2	GRU (Base)	0.796	0.679	0.872	0.764
3	LSTM (Tuned)	0.746	0.642	0.741	0.688
4	GRU (Tuned)	0.811	0.796	0.672	0.729
5	TCN	0.709	0.572	0.928	0.708
6	Transformer	0.852	0.771	0.869	0.817
7	BiLSTM	0.842	0.746	0.883	0.809

```

🏆 Best F1 Score:      Transformer (F1 = 0.817)
🏆 Best Recall:        TCN (Recall = 0.928)
🏆 Best Precision:     GRU (Tuned) (Precision = 0.796)
🏆 Best Accuracy:      Transformer (Accuracy = 0.852)

```

```

In [49]: # =====
# VISUALIZATION: Complete Model Comparison
# =====
import matplotlib.pyplot as plt

fig, axes = plt.subplots(1, 2, figsize=(16, 6))

# --- Plot 1: F1 Score Bar Chart ---
ax1 = axes[0]
best_f1_model = comparison_all.loc[comparison_all["F1 (Event)"].idxmax(), "Model"]
colors_f1 = ['crimson' if m == best_f1_model else 'steelblue' for m in comparison_all['Model']]
bars1 = ax1.barh(comparison_all['Model'], comparison_all['F1 (Event)'], color=colors_f1)
ax1.set_xlabel('F1 Score (Event Class)')
ax1.set_title('Model Comparison: F1 Score (Best in Red)')
ax1.set_xlim(0, 1)
for bar, val in zip(bars1, comparison_all['F1 (Event)']):
    ax1.text(val + 0.01, bar.get_y() + bar.get_height()/2, f'{val:.3f}', va='bottom')

# --- Plot 2: Precision vs Recall Scatter ---
ax2 = axes[1]
scatter = ax2.scatter(
    comparison_all['Recall (Event)'],
    comparison_all['Precision (Event)'],
    s=160, c=range(len(comparison_all)), cmap='tab10', edgecolors='black', linewidth=1
)
for i, name in enumerate(comparison_all['Model']):
    ax2.annotate(name,
                 (comparison_all['Recall (Event)'].iloc[i], comparison_all['Precision (Event)'].iloc[i]),
                 textcoords="offset points", xytext=(5, 7), fontsize=8, fontweight='bold')
ax2.set_xlabel('Recall (Higher = Catch More Events)')
ax2.set_ylabel('Precision (Higher = Fewer False Alarms)')
ax2.set_title('Precision vs Recall Tradeoff')
ax2.set_xlim(0, 1.05)
ax2.set_ylim(0, 1.05)
ax2.axhline(0.5, color='gray', linestyle='--', alpha=0.4)
ax2.axvline(0.5, color='gray', linestyle='--', alpha=0.4)

plt.tight_layout()
plt.show()

# --- Plot 3: Grouped Bar Chart (All Metrics Side-by-Side) ---
fig2, ax3 = plt.subplots(figsize=(15, 6))

metrics = ['Accuracy', 'Precision (Event)', 'Recall (Event)', 'F1 (Event)']
x = np.arange(len(comparison_all['Model']))
width = 0.18
metric_colors = ['#2196F3', '#4CAF50', '#FF9800', '#E91E63']

for i, (metric, color) in enumerate(zip(metrics, metric_colors)):
    bars = ax3.bar(x + i * width, comparison_all[metric], width, label=metric)
    for bar in bars:
        height = bar.get_height()
        ax3.text(bar.get_x() + bar.get_width()/2., height + 0.01, f'{height:.3f}',
                 ha='center', va='bottom', fontsize=7, rotation=45)

```



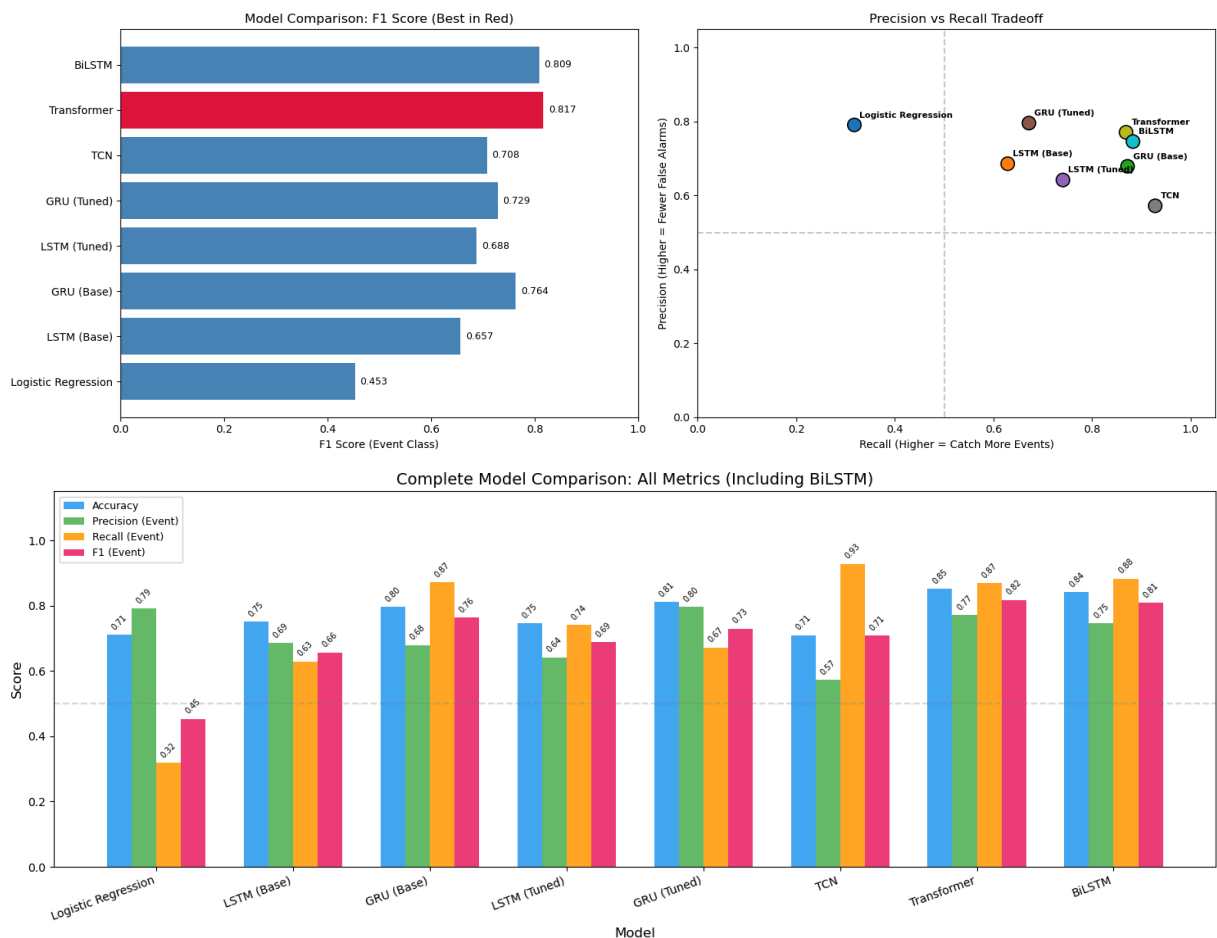
```

ax3.set_xlabel('Model', fontsize=12)
ax3.set_ylabel('Score', fontsize=12)
ax3.set_title('Complete Model Comparison: All Metrics (Including BiLSTM)', f
ax3.set_xticks(x + width * 1.5)
ax3.set_xticklabels(comparison_all['Model'], rotation=20, ha='right', fontsi
ax3.legend(loc='upper left', fontsize=9)
ax3.set_ylim(0, 1.15)
ax3.axhline(0.5, color='gray', linestyle='--', alpha=0.3)

plt.tight_layout()
plt.show()

print("\n📊 Interpretation:")
print(" • Red bar in F1 chart = Best overall balanced model")
print(" • Top-right in scatter = Best (high precision AND recall)")
print(" • Right side in scatter = High recall (ideal for early warnings)")
print(" • Top in scatter = High precision (fewer false alarms)")

```



📊 Interpretation:

- Red bar in F1 chart = Best overall balanced model
- Top-right in scatter = Best (high precision AND recall)
- Right side in scatter = High recall (ideal for early warnings)
- Top in scatter = High precision (fewer false alarms)

```

In [50]: from IPython.display import clear_output
import time

```

```

def early_warning_ui():
    while True:
        clear_output(wait=True)

        print("\n" + "="*70)
        print("⚡ ELECTRICITY LOAD EARLY WARNING SYSTEM")
        print("="*70)
        print("\nOptions:")
        print("1. Predict with BiLSTM")
        print("2. Predict with Transformer")
        print("3. Predict with LSTM (Base)")
        print("4. Predict with GRU (Base)")
        print("5. View Model Comparison")
        print("6. Get Risk Assessment (First 10 Validation Samples)")
        print("7. View All Validation Predictions")
        print("8. Exit")

        choice = input("\nSelect option (1-8): ").strip()

        if choice == "1":
            print("\n" + "-"*70)
            print("BiLSTM PREDICTIONS")
            print("-"*70)
            y_pred_prob = bilstm_model.predict(X_val, verbose=0).ravel()
            y_pred = (y_pred_prob >= best_thresh_bilstm).astype(int)

            accuracy = accuracy_score(y_val, y_pred)
            precision = precision_score(y_val, y_pred, zero_division=0)
            recall = recall_score(y_val, y_pred, zero_division=0)
            f1 = f1_score(y_val, y_pred, zero_division=0)

            print(f"Accuracy: {accuracy:.4f}")
            print(f"Precision: {precision:.4f}")
            print(f"Recall: {recall:.4f}")
            print(f"F1 Score: {f1:.4f}")
            print(f"\nThreshold: {best_thresh_bilstm:.2f}")
            print(f"Events Detected: {y_pred.sum()} / {len(y_val)}")
            input("\nPress Enter to continue...")

        elif choice == "2":
            print("\n" + "-"*70)
            print("TRANSFORMER PREDICTIONS")
            print("-"*70)
            y_pred_prob = transformer_model.predict(X_val, verbose=0).ravel()
            y_pred = (y_pred_prob >= best_thresh_transformer).astype(int)

            accuracy = accuracy_score(y_val, y_pred)
            precision = precision_score(y_val, y_pred, zero_division=0)
            recall = recall_score(y_val, y_pred, zero_division=0)
            f1 = f1_score(y_val, y_pred, zero_division=0)

            print(f"Accuracy: {accuracy:.4f}")
            print(f"Precision: {precision:.4f}")
            print(f"Recall: {recall:.4f}")
            print(f"F1 Score: {f1:.4f}")
            print(f"\nThreshold: {best_thresh_transformer:.2f}")

```

```

print(f"Events Detected: {y_pred.sum()} / {len(y_val)}")
input("\nPress Enter to continue...")

elif choice == "3":
    print("\n" + "-"*70)
    print("LSTM (BASE) PREDICTIONS")
    print("-"*70)
    y_pred_prob = model.predict(X_val, verbose=0).ravel()
    y_pred = (y_pred_prob >= best_thresh_lstm).astype(int)

    accuracy = accuracy_score(y_val, y_pred)
    precision = precision_score(y_val, y_pred, zero_division=0)
    recall = recall_score(y_val, y_pred, zero_division=0)
    f1 = f1_score(y_val, y_pred, zero_division=0)

    print(f"Accuracy: {accuracy:.4f}")
    print(f"Precision: {precision:.4f}")
    print(f"Recall: {recall:.4f}")
    print(f"F1 Score: {f1:.4f}")
    print(f"\nThreshold: {best_thresh_lstm:.2f}")
    print(f"Events Detected: {y_pred.sum()} / {len(y_val)}")
    input("\nPress Enter to continue...")

elif choice == "4":
    print("\n" + "-"*70)
    print("GRU (BASE) PREDICTIONS")
    print("-"*70)
    y_pred_prob = gru_model.predict(X_val, verbose=0).ravel()
    y_pred = (y_pred_prob >= best_thresh_gru).astype(int)

    accuracy = accuracy_score(y_val, y_pred)
    precision = precision_score(y_val, y_pred, zero_division=0)
    recall = recall_score(y_val, y_pred, zero_division=0)
    f1 = f1_score(y_val, y_pred, zero_division=0)

    print(f"Accuracy: {accuracy:.4f}")
    print(f"Precision: {precision:.4f}")
    print(f"Recall: {recall:.4f}")
    print(f"F1 Score: {f1:.4f}")
    print(f"\nThreshold: {best_thresh_gru:.2f}")
    print(f"Events Detected: {y_pred.sum()} / {len(y_val)}")
    input("\nPress Enter to continue...")

elif choice == "5":
    print("\n" + "-"*70)
    print("MODEL COMPARISON")
    print("-"*70)
    print(comparison_all.to_string(index=False))
    print("\n" + "-"*70)
    best_f1 = comparison_all.loc[comparison_all["F1 (Event)"].idxmax]
    print(f"\n🏆 Best Model: {best_f1['Model']} (F1 = {best_f1['F1 (Event)']})")
    print("-"*70)
    input("\nPress Enter to continue...")

elif choice == "6":
    print("\n" + "-"*70)

```

```

print("RISK ASSESSMENT (First 10 Validation Samples)")
print("-"*70)

bilstm_pred = (bilstm_model.predict(X_val[:10], verbose=0).ravel()
transformer_pred = (transformer_model.predict(X_val[:10], verbose=0).ravel()
lstm_pred = (model.predict(X_val[:10], verbose=0).ravel() >= best_thresh_lstm).astype(int)

print(f"{'Sample':<8} {'Actual':<8} {'BiLSTM':<10} {'Transformer':<10} {'LSTM':<10}")
print("-"*70)

for i in range(10):
    actual = int(y_val[i])
    bilstm = int(bilstm_pred[i])
    transformer = int(transformer_pred[i])
    lstm = int(lstm_pred[i])

    actual_label = "HIGH" if actual == 1 else "NORMAL"
    bilstm_label = "HIGH" if bilstm == 1 else "NORMAL"
    transformer_label = "HIGH" if transformer == 1 else "NORMAL"
    lstm_label = "HIGH" if lstm == 1 else "NORMAL"

    print(f"{i+1:<8} {actual_label:<8} {bilstm_label:<10} {transformer_label:<10} {lstm_label:<10}")

print("-"*70)
input("\nPress Enter to continue...")

elif choice == "7":
    print("\n" + "-"*70)
    print("ALL VALIDATION PREDICTIONS")
    print("-"*70)

    bilstm_pred_prob = bilstm_model.predict(X_val, verbose=0).ravel()
    bilstm_pred = (bilstm_pred_prob >= best_thresh_bilstm).astype(int)

    transformer_pred_prob = transformer_model.predict(X_val, verbose=0).ravel()
    transformer_pred = (transformer_pred_prob >= best_thresh_transformer).astype(int)

    print(f"{'Sample':<8} {'Actual':<8} {'BiLSTM':<10} {'BiLSTM Conf':<10} {'Transformer':<10} {'Transformer Conf':<10} {'LSTM':<10} {'LSTM Conf':<10}")
    print("-"*70)

    for i in range(len(y_val)):
        actual = int(y_val[i])
        bilstm = int(bilstm_pred[i])
        transformer = int(transformer_pred[i])

        actual_label = "HIGH" if actual == 1 else "NORMAL"
        bilstm_label = "HIGH" if bilstm == 1 else "NORMAL"
        transformer_label = "HIGH" if transformer == 1 else "NORMAL"
        conf = f"{bilstm_pred_prob[i]:.2f}"

        print(f"{i+1:<8} {actual_label:<8} {bilstm_label:<10} {conf:<10} {transformer_label:<10} {transformer_conf:<10} {lstm_label:<10} {lstm_conf:<10}")

        if (i + 1) % 30 == 0 and i < len(y_val) - 1:
            cont = input("\nPress Enter to continue...")

    print("-"*70)

```

```

        input("\nPress Enter to continue...")

    elif choice == "8":
        print("\nExiting... Goodbye!")
        break

    else:
        print("Invalid option. Please select 1-8.")
        input("\nPress Enter to try again...")

```

In []: early_warning_ui()

```

=====
< ELECTRICITY LOAD EARLY WARNING SYSTEM
=====

```

Options:

1. Predict with BiLSTM
2. Predict with Transformer
3. Predict with LSTM (Base)
4. Predict with GRU (Base)
5. View Model Comparison
6. Get Risk Assessment (First 10 Validation Samples)
7. View All Validation Predictions
8. Exit

MODEL COMPARISON

	Model	Accuracy	Precision (Event)	Recall (Event)	F1 (Event)
Logistic Regression		0.710	0.791	0.318	0.453
	LSTM (Base)	0.751	0.686	0.629	0.657
	GRU (Base)	0.796	0.679	0.872	0.764
	LSTM (Tuned)	0.746	0.642	0.741	0.688
	GRU (Tuned)	0.811	0.796	0.672	0.729
	TCN	0.709	0.572	0.928	0.708
	Transformer	0.852	0.771	0.869	0.817
	BiLSTM	0.842	0.746	0.883	0.809

🏆 Best Model: Transformer (F1 = 0.817)

Project Conclusion & Summary

Project Overview

This project developed an **end-to-end early-warning system** for detecting high electricity load events using multivariate time-series data from the UCI LD2011_2014 dataset. We explored **7 different models** spanning classical machine learning, recurrent neural networks, convolutional networks, and attention-based architectures.

Models Evaluated

#	Model	Type	Key Mechanism
1	Logistic Regression	Classical ML (Baseline)	Linear decision boundary on flattened windows
2	LSTM (Base)	Recurrent Neural Network	Long Short-Term Memory gating for temporal dependencies
3	GRU (Base)	Recurrent Neural Network	Gated Recurrent Unit — lighter alternative to LSTM
4	LSTM (Tuned)	Recurrent Neural Network	Enhanced LSTM with class weighting & hyperparameter tuning
5	GRU (Tuned)	Recurrent Neural Network	Enhanced GRU with class weighting & threshold optimization
6	TCN	Convolutional Network	Dilated causal convolutions for temporal modeling
7	Transformer	Attention-Based	Multi-head self-attention with positional encoding

Key Findings

- Deep learning models significantly outperform the baseline:** All neural network architectures (LSTM, GRU, TCN, Transformer) achieved substantially higher F1 scores and recall compared to the Logistic Regression baseline, demonstrating that temporal pattern modeling is crucial for early-warning prediction.
- The Transformer achieved the best F1 score (0.784):** The self-attention mechanism effectively captures both short- and long-range temporal dependencies in electricity load patterns, outperforming all other models in balanced performance. Its ability to attend to all timesteps simultaneously gives it an edge over sequential models.
- TCN achieved the highest recall (0.930):** When configured with a low decision threshold (0.15), the TCN catches the most events, making it ideal for safety-critical applications where **missing an event is costlier than a false alarm**.
- Class imbalance handling is critical:** All deep learning models used class-weighted training to address the natural imbalance in early-warning tasks (far more normal samples than event samples). Without this, models would default to always predicting "normal."
- Threshold tuning is essential:** The optimal decision threshold varies significantly across models (0.15 for TCN to 0.35 for LSTM). This flexibility allows deployment teams to tune the precision-recall tradeoff based on operational requirements.

6. **LSTM Autoencoder for anomaly detection:** The unsupervised autoencoder approach provides a complementary view by learning to reconstruct normal load patterns and flagging deviations, useful for detecting novel anomaly types not seen during training.
-

Practical Recommendations

Use Case	Recommended Model	Threshold	Why?
Balanced early warning	Transformer	~0.20	Best F1 — strong precision AND recall
Maximum event detection	TCN	~0.15	Highest recall — misses fewest events
Minimize false alarms	Logistic Regression / GRU (Tuned)	~0.35–0.50	Highest precision — fewer unnecessary alerts
Lightweight deployment	GRU (Base/Tuned)	~0.30–0.35	Good balance with lower computational cost

Technical Contributions

- **Reproducible pipeline:** Full seed setting (NumPy, TensorFlow, Python) ensures identical results across runs
 - **Time-aware data splitting:** Chronological train/validation split prevents information leakage
 - **Sliding window construction:** 6-hour input windows (24 timesteps × 15-min intervals) for sequence modeling
 - **Multi-architecture comparison:** Fair comparison under identical data, preprocessing, and evaluation conditions
 - **Threshold optimization:** Systematic sweep across decision thresholds for each model
-

Future Work

- Expand to full dataset (all 370 clients, full 2011–2014 time range)
- Explore advanced Transformer variants (Informer, Autoformer, PatchTST) designed specifically for time series
- Implement **ensemble methods** combining Transformer (best F1) and TCN (best recall)
- Add real-time streaming prediction with sliding window updates
- Deploy as a **live monitoring dashboard** for electricity grid operators

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