Reporting Rate Impact on Deep Residential Energy Measurement Prediction

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***Abstract*—Forecasting and anomaly detection for energy time series is emerging as an important application area for computational intelligence and learning algorithms. The training of robust data-driven models relies on large measurement datasets sampled at ever increasing rates and demand large computational and storage resources for off-line power quality analysis and on-line control in energy management schemes. We analyze the impact of the reporting rate of energy measurements on deep learning based forecasting models in a residential scenario. The work is also motivated by the development of embedded energy gateways for online inference and anomaly detection that avoids the dependence on costly, high-latency, cloud systems for data storage and algorithm evaluation. This in turn requires increased local computation and memory requirements to generate predictions within the control sampling period. We report quantitative forecasting metrics (MSE, MAE, MAPE) to establish an empirical trade-off between reporting rate and model accuracy. Additional results consider the rate-variable feature extraction using a time series data mining algorithm for multi-scale analytics.**

***Index Terms*—energy forecasting, embedded inference, model robustness, cyber-physical systems, smart buildings**

I. Introduction

Using dense deployments of Internet of Things (IoT) devices, multi-variate electrical measurements are being reliability collected at ever increasing reporting rates, not only in grid measurement, large commercial consumers but also at the residential consumer level. Making use of this dense data requires complex intelligent algorithms for prediction and anomaly detection. Many methods are described in the literature using mostly deep neural networks (FCNN) and sequence models (RNN, LSTM, CNN-LSTM) alongside conventional machine learning methods as regression methods, trees, SVMs, etc. that allow fine grained control over the input data through expert guided feature engineering. For training such systems, large amounts of quality input data are required to capture fine grained nonlinearities over various operating conditions. In some conditions e.g. deploying models on resource constrained embedded hardware, there is a need to downsample the measurement/sensor signal to achieve a bounded training or inference time with limited decrease in accuracy.

We investigate the dependence of the energy prediction model accuracy on the sampling rate of the input signal. This allows to adapt and fine tune the algorithm for detecting and anticipating both fast transient phenomena e.g. switching behaviour or faults, and more persistent changes in the signal behaviour e.g. through appliance usage and daily activities. This approach applies to both uni-variate measurement time series e.g. the power drawn at the electrical meter of an apartment or house, and to multi-variate measurements that can include multiple electrical parameters as well as fine grained submetering traces for individual appliances or other significant consumers. These types of insights become helpful also when setting up an IT system for data acquisition, storage and processing, of the electrical measurements in conjunction with the latency and off-line/on-line of the results analysis. As the performance and complexity of modern measurement device has increased the resulting collected information can be classified using most the typical characteristics of big data in terms of volume, velocity, variety, and value, minus the veracity which we assume not valid in a technical measurement context. This requires specialized computing infrastructure and efficient primitives for information extraction [1] leading to improved labelling of relevant phenomena.

Main tasks that are carried out to derive the relevant contributions of the paper are as follows:

- Training and accuracy evaluation of deep learning (DL) energy forecasting models for high reporting rate data;
- Illustrate an empirical dependence between input reporting rate and model accuracy (MSE, MAE, MAPE) along with comments regarding the generalisation of such approach to different scenarios.

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The rest of the paper is structured as follows. Section II discusses related work mainly aimed at identifying suitable time periods for training data-driven time series forecasting models. We present out methodology, the algorithms and benchmarking dataset in Section III. Section IV introduces the results achieved for the target application, including replicable implementation details, along with an exemplification of energy time series feature extraction using the Matrix Profile algorithm at various time scales. Section V discusses the foreseen context of leveraging the results to automatically adjust the reporting rate based on application required performance in multi-scale analytics for energy systems.

II. Related Work

Modelling and forecasting time series sampled at different frequencies in a general econometric context is discussed in [2]. The authors present their findings in the key that by lowering the sampling rate of the respective time series the core dynamic components remain observable while fine grained and seasonal elements become unobservable through aggregation. Disaggregation and establishing a correspondence between the lower and higher sampled data can be realised but requires a highly nonlinear model leading to inexact matching and reconstruction. This insight can be used in our technical context as well when discarding dense measurements due to lack of storage or computational limitations. On a energy system relevant macroscopic scale, a similar work is presented in [3] where the authors report the decrease in computational requirements with various downsampling rates for renewable energy generation. A nonlinear decrease in normalized CPU time is reported when switching from 1h timesteps to 3, 6, 12 and finally 24h timesteps on 25 years of simulated wind and PV generation data from the UK. The suitable approach should be flexible to accomodate different input data and constraints regarding the modelling technique. Our goal through this contribution is to perform this approach at the microscopic level for low voltage residential consumers with different factors affecting the load shape, with second-level reported measurements.

A statistical framework to select appropriate sampling rates for time series analysis is introduced by [4]. The study combines historical data sampled at a slow rate with cost information for higher rate data collection and a small subset of more frequently sampled data. The relation between the two can be framed as a missing data problem for the less often sampled dataset where specific methods such as spectrum estimation and others can be applied to achieve a correspondence between the two. For the particular context of power system analysis for load flow calculations, the authors of [5] leverage feature extraction to reconstruct synthetically representative time series as a means for reduction of computational demands of the algorithms with bounded modelling quality degradation. Computational intelligence methods such as generative adversarial networks can be used to learn and extrapolate measurement time series patterns as is the case with the TimeGANs for generating quality datasets [6].

In [7] 1s load power profiles for residential consumers are analysed with the goal of detecting power steps in a sampled load power profile. A noninvasive error monitoring technique is devised through comparison of the tested and reference meters and synchronized statistical processing between the two. Smart energy information systems design with IoT features and reporting rate discussion are performed in [8], Main contribution lays in establishing the requirements of an Energy Information Management System (EIMS) for large scale energy consumption in buildings: hardware and software for data collection, transmission and analysis. Embedded monitoring and control for energy storage systems is presented in [9] using distributed sensor and data acquisition nodes and hardware-in-the-loop type evaluation of the performance.

III. Methodology

We briefly introduce the methods, the reference dataset and associated metrics that we use for this work. Recently many data-driven methods for energy time series forecasting rely on sequence learning models. These algorithms operate on subsequences of the input time series and can be used for both single and multi-step forecasting or for classification tasks. Standard implementation is in the form of recurrent neural networks (RNN) which are neural network architectures with built-in loops that allow the learning process to consider the time dependencies between individual components as oposed to independente training examples for conventional networks. In order to mitigate negative effects that can appear during training over long sequences, such as exploding or vanishing gradients, more complex architectures have been devised such as gated recurrent units (GRU) and long short-term memory (LSTM) networks. A common characteristic of these structures is the use of dedicated ”gates” that control the information flow through the networks and include additional trainable parameters for the gate weights. This allows the network to propagate relevant information through multiple time steps while selectively discarding irrelevant or redundant extracted features. The basic LSTM cell [10] includes an input gate, a layer input gate to update the cell state, a forget gate for discarding information and an output gate. The state of the LSTM cell memory at time step t is updated through the Hadamard product as follows:

$$c_t = f_t \otimes c_{t-1} \oplus i_t \otimes g_t, \tag{1}$$

The output state at time step t is given by the output gate (o) which implements a read function combined with the cell state (c) as in:

$$h_t = o_t \otimes tanh(c_t), \tag{2}$$

where

$$o_t = \sigma(W_o x_t + R_o h_{t-1} + b_o). \tag{3}$$

Based on a single layer LSTM networks several variants are available and implemented through specific software packages. Further layers can be stacked for increased complexity and the ability to extract more fine grained features. Bidirectional networks are able to parse through the input sequences in both directions. An adaptation of the convolutional layers, typical for bidimensional inputs as encountered in image processing, can be applied for time series models by assembling the input sequences into bidimensional formats and applying the convolution operator for feature extraction.

The dataset used in this study stems from a long term data collection of energy measurements from a typical residential appartment from Bucharest, Romania. The dataset is available for testing purposes from the authors. For illustration purposes, a daily plot of active power in Watts from the month of September 2020 is shown in Figure 1.

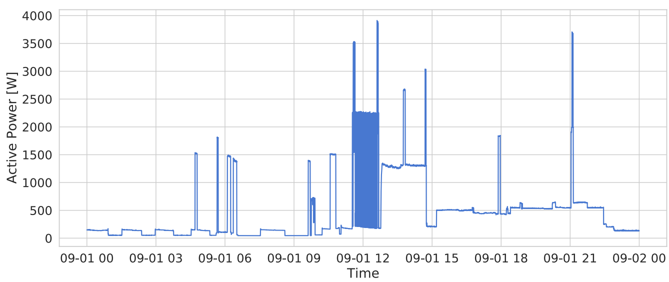

Fig. 1. Sample input data

For evaluation of the energy prediction performance at various reporting rates we use the following metrics: Mean Squared Error (MSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). MSE , MAE balances small and large prediction errors, while MAPE provides a relative metric of accuracy that can be used across different input magnitude scales. These are computed as follows:

$$MSE = \sum_{i=1}^{n} \frac{(y_i - \hat{y}_i)^2}{n}; MAE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n};$$
$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right| 100; \quad (4)$$

where y_i is the actual value of sample i, $\hat{y}_i$ is the predicted value of the sample i, and n the number of samples. In particular for MAPE we use the Python *sci-kit learn* package implementation[1] which as a small error term in the denominator to avoid division by zero and numerical inconsistencies.

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{|y_i - \hat{y}_i|}{max(\epsilon, |y_i|)} \quad (5)$$

where ϵ is an arbitrary small constant, thereby shifting the interval of the relative metric from $[0, 100]$ to $[0, 1/\epsilon]$.

A basic prediction example for the test set associated with one day of residential power measurements sampled at 1s and using a single layer LSTM network is illustrated in Figure 2.

[1] https://scikit-learn.org/stable/modules/model_evaluation.html#mean-absolute-percentage-error

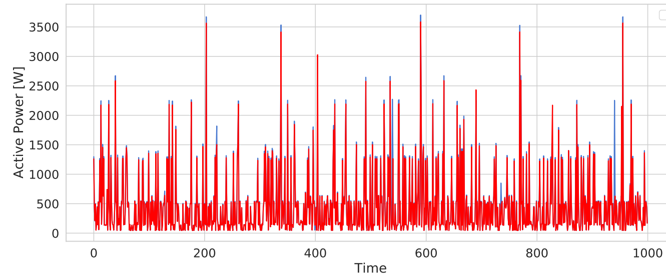

Fig. 2. Prediction results

IV. Results

For the purpose of our study, we have trained and evaluated the following deep learning models: single-layer LSTM network (LSTM-1), two-layer stacked LSTM network (LSTM-2), bidirectional LSTM network (BiLSTM), and a hybrid convolutional and LSTM network (ConvLSTM). The number of units per layer is fixed at 50. For each of the models we report the MSE, MAE and MAPE testing metrics at the baseline (1s) reporting rate as well as 2x/5x/10x decimated reporting rate. The first goal is to derive an empirical relative dependency between the reporting rate and the prediction model accuracy for these variations of state-of-the-art deep learning algorithms. From the available data we establish a 70/30% split between the training and testing sets. The $random\_seed = 42$ parameter is set for the implementation to control for the randomness of the training and test datasets. The training data is reshaped in a suitable manner as input to the algorithms with the parameter $n\_steps = 4$ denoting that each training example uses a sequence of four previous values as input features. Each model is trained for 50 epochs. Implementation is based on [11] using *sci-kit learn v0.24*, *numpy*, *pandas* and *keras* packages on a server-class system with Intel Xeon processor and 16GB RAM under the Linux operating system.

Prediction test set accuracy results are summarised in Table I-III for each of the available metrics. The hardware and software dependant training time in Table IV is relevant for relative comparisons between the trained model types at different reporting rates. In general the convolutional variant of the LSTM prediction model yields the best results albeit at very large training times. The bidirectional LSTM model provides the best trade-off between test set forecasting accuracy and training time in our study.

TABLE I
TEST PREDICTION RESULTS - MSE

	MSE $[kW^2]$			
	LSTM-1	***LSTM-2***	***BiLSTM***	***ConvLSTM***
Baseline	6.53	8.72	6.6	7.25
2x	16.36	15.59	16.46	15.92
5x	37.8	40.62	37	36.2
10x	62.46	61.52	65.48	60.12

TABLE II
TEST SET PREDICTION RESULTS - MAE

	MAE $[W]$			
	LSTM-1	***LSTM-2***	***BiLSTM***	***ConvLSTM***
Baseline	9.9	14	9.5	19
2x	25	24	26	19
5x	39	47	34	45
10x	55	58	92	59

TABLE III
TEST SET PREDICTION RESULTS - MAPE

	MAPE [%]			
	LSTM-1	***LSTM-2***	***BiLSTM***	***ConvLSTM***
Baseline	0.032	0.032	0.027	0.069
2x	0.066	0.05	0.056	0.078
5x	0.13	0.12	0.095	0.1
10x	0.12	0.18	0.17	0.18

Figure 3 shows the comparison between test MSE and training time for the four models at various reporting rate reduction factors. A light nonlinear relation between both the error and decimation rate as well as training time and decimation rate of the time series can be observed. We can therefore reduce the input data reporting rate in accordance to the dynamics of the observed measurement phenomena with bounded decrease in MSE.

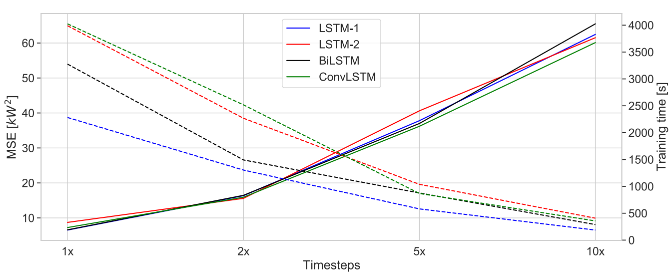

Fig. 3. MSE versus Training time Results

We attempt to further validate and generalized the study results by running one of the models (BiLSTM) on a full month of data as global model. The model is chosen based on the previous results that show the best performance in the trade-off between the decrease in MSE versus the increase in training time for a more complex model, over the various investigated reporting rates of the data. The same parameters are kept, in particular the sequence length for the $n\_steps = 4$ parameter. The global approach is tested on the baseline reporting rate (1s) and the 10x decimated reporting rate (10s). Figure 4 illustrates the validation loss for the baseline model over the training epochs. The global model - 10s achieves $MSE = 10kW^2$ and $MAE = 24W$ while the global model at the baseline reporting rate of 1s achieves $MSE = 0.910kW^2$ and $MAE = 2.49W$. Training time for the decimated model is $t = 8400s$ while for the baseline model we use an early stopping criterion to stop the training once there is no significant decrease in the loss

TABLE IV
TRAINING TIME

	Time $[s]$			
	LSTM-1	***LSTM-2***	***BiLSTM***	***ConvLSTM***
Baseline	2282	3990	3276	4025
2x	1304	2268	1492	2517
5x	581	1038	878	868
10x	187	408	289	357

over multiple training epochs. This allows for multiple testing iterations within the same computing time.

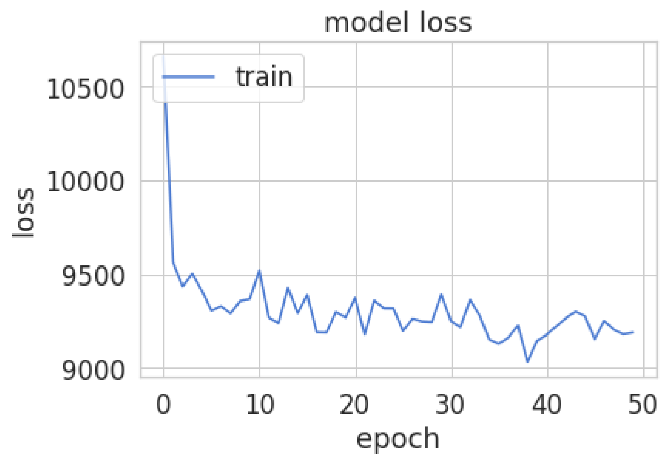

Fig. 4. Training loss for monthly global model (1s)

Individual models for a full month are also trained and tested, composed of 30 daily subsequences corresponding to the month of September 2020 at the baseline and 10x decimated reporting rates. The aggregated results are presented in the form of testing MSE metric histograms over the 30 individual models in Figures 6 and 7. Top 15% of the outliers have been eliminated from the error array. Further segmentation of time of day and day of week models is possible for more specific forecasting performance. Reducing the variability of the MSE can be achieved for the residential energy use case by including contextual variables and time series in the model such as outdoor temperatures.

We also present a Matrix Profile (MP) exemplification at the $1s$ reporting rate for multi-scale feature extraction applied to energy measurements. This is an efficient time series data mining method which allows feature extraction and anomaly detection over large series. The algorithm outputs the minimum sequence by sequence Euclidean distance based on a single parameter, the subsequence size, which is used for finding motifs, recurring patterns in the series, and discords, the most dissimilar patterns. Figure 5 illustrates the computed profile for the baseline rate while identifying the most dissimilar sequence in the original daily data - corresponding to the readings at noon from the daily series (Fig. 1).

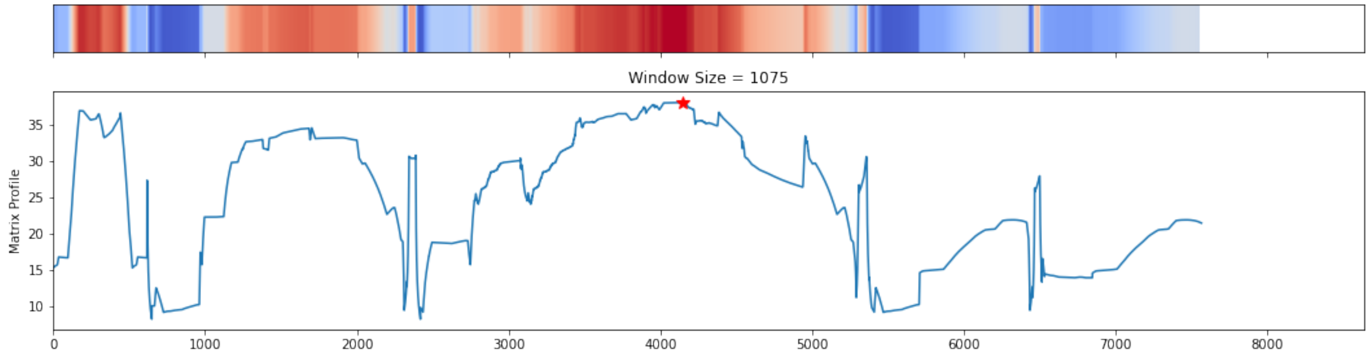

Fig. 5. Matrix profile for anomaly detection (1s)

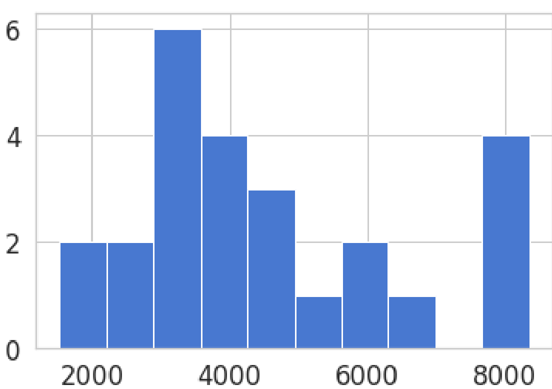

Fig. 6. MSE distribution for daily models (1s)

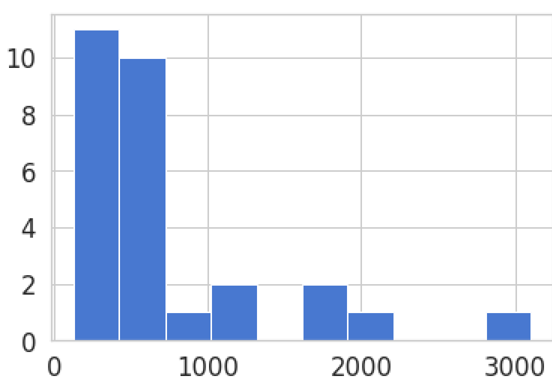

Fig. 7. MSE distribution for daily models (10s)

V. Conclusion

We have investigated the performance of various types of deep learning models on residential energy measurement data at various reporting rates. The goal was to establish an empirical relation useful for choosing the appropriate amount of data required to train a good quality model while considering the limitation of available computing resources. Future work will consider extending the study to publicly available benchmarking datasets such as Pecan Street Dataport [12] and use the derived results to guide a energy time series classification framework for steady-state evaluation on multi-variate data.

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