

CHAPTER I

INTRODUCTION

This chapter provides an overview of the research, including the background of the issue, the research question, the research objectives, the benefits of the research, and the scope of the study. The discussion in this chapter aims to provide an initial understanding of the urgency of the research, the scope of the study, and the direction of the research, thereby serving as a foundation for understanding the subsequent chapters.

1.1 Research Background

The availability of solar energy in Indonesia demonstrates great potential as a renewable energy source that can support national energy transition targets. As a tropical country, Indonesia receives relatively high solar irradiance throughout the year, presenting a significant opportunity to develop solar power plants (SPPs) as a low-carbon energy alternative. However, the power output of SPPs is highly dependent on solar radiation levels, which are dynamic and change on very short time scales. Variations in radiation are influenced by the sun's position, atmospheric thickness, and atmospheric optical conditions, all of which affect the amount of radiant energy reaching the Earth's surface. Therefore, an accurate solar radiation prediction model is needed to support operational efficiency, stable power output, and optimal planning of solar power plant-based energy systems in Indonesia [1].

The use of solar energy has significant social, economic, and environmental impacts [2]. Solar energy plays a crucial role in reducing dependence on fossil fuels and curbing carbon emissions, as explained in [3]. In addition to supporting the national energy transition agenda, the implementation of solar power plant technology also opens up opportunities for economic growth through the development of the photovoltaic industry and the expansion of green jobs. Furthermore, accurate radiation forecasts are essential for ensuring the stability of the power system, as solar energy is a fluctuating resource [4]. Precise forecasts help system operators maintain load–supply balance, improve operational efficiency, and minimize the risk of supply mismatches [5].

Various approaches have been developed to predict solar radiation, ranging from statistical methods to artificial intelligence-based models [6]. Several studies have shown that Convolutional Neural Networks (CNNs) are effective at extracting local and nonlinear feature patterns from solar radiation and meteorological data [7], while Gated Recurrent Units (GRUs) have proven capable of modeling temporal dependencies in time-series data with a simpler and

more efficient structure compared to other recurrent architectures [8]. Based on these characteristics, this study developed a hybrid CNN–GRU model as an approach to predict solar radiation on a per-minute basis in the city of Medan, utilizing CNN for feature extraction and GRU for modeling temporal relationships.

The city of Medan was chosen as the research site because its geographic and climatological characteristics are representative of the tropical region of western Indonesia. Medan is located at coordinates approximately 3.6° N and 98.7° E, with high levels of solar radiation throughout the year [9]. Based on solar radiation measurements by Ambarita [10], radiation levels in Medan can vary significantly within minutes, even under clear skies. In addition, the dataset used in this study contains seven main measurement features, all of which were recorded directly using field instruments in the city of Medan: temperature, humidity, solar radiation, wind speed, gust speed, measurement time (date and time), and observation sequence index. These seven features fully reflect the microclimatic characteristics of Medan, which are influenced by local factors such as atmospheric conditions, coastal wind patterns, tropical humidity levels, and surface thermal dynamics. Because the interrelationships among these features are highly specific to Medan’s geographical conditions, the prediction model developed cannot be directly applied to other cities without conducting new measurements and retraining the model [11]. Thus, these unique data characteristics make Medan an ideal location for developing and testing short-term prediction models based on deep learning that are capable of capturing both temporal and spatial dynamics simultaneously. Furthermore, Medan is also one of the priority regions in the national solar energy development map [12].

Ambarita’s study [10] was used as the primary reference because it provides a dataset of radiation per minute that is relevant to Indonesia’s tropical climate. Previously developed radiation prediction methods include Multiple Linear Regression (MLR), Autoregressive Integrated Moving Average (ARIMA), Support Vector Machine (SVM), and Random Forest (RF). These classical methods are effective for simple patterns but are less capable of handling nonlinear relationships and rapid fluctuations in high-resolution data [13]. Meanwhile, machine learning has improved prediction performance but remains limited in capturing long-term patterns and complex temporal dynamics [14]. CNN-GRU has been shown to deliver high accuracy over a three-day forecast horizon in multivariate solar energy studies, as demonstrated by comparisons with other models including LSTM, CNN, and GRU [15]. A single GRU model also exhibits stable performance and high accuracy in short-term photovoltaic power forecasting, reinforcing the potential for using lighter-weight recursive units compared to LSTM in renewable energy applications [16]. By adapting this approach to historical irradiance

data and local meteorological variables in Medan, the CNN-GRU model can generate radiation forecasts that are more accurate and responsive to atmospheric dynamics, supporting optimal operational planning and solar energy integration.

Implementing a CNN-GRU model requires hyperparameter tuning to ensure the model achieves optimal performance [17]. Parameters such as the number of filters, kernel size, number of GRU units, learning rate, batch size, and dropout rate have a direct impact on the model's generalization ability [18]. Selecting an inappropriate hyperparameter configuration can cause the model to underfit or overfit, resulting in suboptimal predictive performance on previously unseen data. Through a systematic hyperparameter tuning process, the model can balance architectural complexity and learning capacity, thereby producing more stable and reliable predictive performance on per-minute solar radiation data [19][20].

In addition to focusing on the development of predictive models, this study also developed spatial-temporal visualizations of the prediction results using the Folium and TimestampedGeoJson libraries [21]. These web-based visualizations were designed to display the dynamics of solar radiation interactively, making them easy to understand for both non-technical users and decision-makers in the energy sector [22]. Interactive visualizations have proven helpful in interpreting prediction results in the context of operational and planning aspects of solar power plant systems, particularly in understanding the spatial and temporal variations of solar resources [23][24]. This approach allows users to dynamically monitor minute-by-minute changes in radiation through a digital map of Medan City, with color gradients representing solar radiation intensity [25].

Therefore, this study not only develops a solar radiation prediction model using a hybrid CNN-GRU architecture but also integrates the prediction results with a web-based visualization system to produce information that is more intuitive, practical, and easy to interpret by a wide range of users. This integration of the prediction model and visualization allows solar radiation predictions to be presented in a spatio-temporal format, enabling the dynamics of radiation changes to be observed directly based on the location and time of observation. This approach is expected to support more efficient, adaptive, and data-driven planning and operation of solar power plants, particularly in tropical regions such as the city of Medan, which is characterized by dynamic and variable solar radiation patterns.

1.2 Problem Formulation

Based on the research background outlined above, the research question that serves as the focus of this study is as follows:

1. How is the hybrid CNN-GRU algorithm applied to predict solar radiation per minute in the city of Medan through hyperparameter tuning?
2. How accurate are the predictions of solar radiation per minute using the hybrid CNN-GRU model?
3. How can the predictions of solar radiation per minute be visualized spatially and temporally on an interactive map of the city of Medan using a website?

1.3 Research Objectives

Based on the research question that has been established, the objectives of this study are as follows:

1. To implement a hybrid CNN–GRU algorithm through hyperparameter tuning to build a model for predicting solar radiation per minute in the city of Medan.
2. To evaluate the accuracy and performance of the hybrid CNN–GRU model in predicting solar radiation per minute.
3. To develop a spatial-temporal visualization of the predicted solar radiation per minute on a web-based interactive map.

1.4 Significance of the Study

The results of this study are expected to provide both academic and practical benefits, which are outlined as follows:

1. To contribute to the advancement of research in the field of deep learning-based solar energy prediction and visualization, particularly at a per-minute time resolution—an area that has yet to be extensively studied in Indonesia.
2. To serve as a scientific reference for the application of the CNN–GRU model, which not only generates numerical predictions but is also capable of presenting interactive spatiotemporal visualizations
3. To provide a prediction model that can assist in the planning, operation, and management of solar power plant systems to make them more optimal, efficient, and adaptive to short-term changes in solar radiation.
4. To support the development of renewable energy in Indonesia, particularly in the city of Medan, as a step toward national energy independence and carbon emission reduction.

5. To enhance knowledge and skills in the fields of data processing, deep learning implementation, and the application of spatiotemporal visualization technology to support decision-making in the renewable energy sector.

1.5 Scope of the Study

To ensure that the discussion in this study remains focused and does not deviate from the research objectives, the scope of the study is defined as follows:

1. This study uses per-minute solar radiation data obtained from measurements in the city of Medan, based on the Ambarita research dataset.
2. The prediction model used is a hybrid CNN-GRU.
3. Model Performance evaluation uses only statistical metrics, such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and the coefficient of determination (R^2).
4. Visualization of the prediction results is conducted solely in the form of interactive spatiotemporal maps using the Folium and TimestampedGeoJson libraries on the website.