Development of Performance Prediction Model of Deep Neural Network-Based Solar and Air Source Heat Pump Convergence System

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Abstract

This paper is to develop a performance prediction model of an integrated system that combines a solar heat pump and an air heat pump based on the DNN (Deep Neural Network) model. In this paper, we describe the overall procedure for building a DNN model to predict the performance of an integrated system, including the data collection method, data set construction, and DNN model structure. To validate the reliability of the performance prediction model based on the DNN model, the mean square error of the coefficient of variation CV(RMSE) proposed by the American Society of Heating, Refrigeration and Air Conditioning Engineers Guideline 14 was used. The RMSE between the prediction result of the CV DNN model and the output variable was calculated as 5%. Therefore, the reliability of the performance prediction model based on the DNN model was verified, and the performance prediction accuracy was similar to the energy simulation model.

Keywords
deep neural network, Integrated system, solar source heat pump, Air source heat pump, DNN

1. Introduction
New and renewable energy technologies that can produce energy are being introduced to realize zero-energy buildings, but single technologies centered on solar power, solar heat, and geothermal heat pumps are mostly applied. . New and renewable energy single technology has limitations in realizing zero energy buildings due to problems such as temporal and quantitative inconsistency of energy supply and demand, securing sufficient installation space, and initial cost. (Bae, 2022; Lee, 2016)

Therefore, it is essential to develop a new and renewable energy convergence system that can handle all the energy demands (hot, cold, electric power) of a building in one system to overcome the technical limitations of a single renewable energy technology and implement it efficiently. A new and renewable energy fusion system that combines a solar-thermal module and a geothermal or air source heat pump to supply heat and electricity to a building at the same time has been proposed.

Abu et al. (2020) tried to overcome the high power consumption and power shortage of buildings in Jordan using the solar-geothermal source heat pump fusion system and reviewed the feasibility of the fusion system through energy simulation. As a result, the COP (coefficient of performance) of the fusion system could be improved by 35% compared to the single system of the geothermal heat pump due to the combined use of solar and underground heat sources. Ruoping et al. (2021) evaluated the applicability of the solar heat-geothermal source fusion system for the purpose of realizing a zero energy building in rural detached houses using energy simulation. It was confirmed that the zero energy building can be achieved as the power output of the solar heat module is higher than the power consumption of the system. Li and Huang (2022) proposed a double heat source heat pump combined with a solar heat module to solve the instability of the existing air heat source heat pump and improve energy efficiency. This system was able to produce heat and electricity at the same time by effectively utilizing a solar power source and an air heat source. In addition, compared to the existing air heat source heat pump, the double heat source heat pump was able to maintain stable performance even in poor environments. Ai et al. (2022) proposed a system in which an air heat source heat pump and a photovoltaic module are combined. The system performance was compared depending on whether photovoltaic modules were coupled or not using energy simulations to verify the validity of this system. The system in which the photovoltaic module is combined has improved exergy efficiency by about 10% compared to the single heat pump system. Bae et al. (2022) proposed a fusion system in which a photovoltaic module and a geothermal source heat pump were combined, built a real-scale experimental plant, and evaluated the performance of the system by considering actual environmental conditions. The average cooling and heating COP of the fusion system was calculated as 6.9 and 8.3, respectively, and it was confirmed that a zero-energy building could be realized by the solar heat module in the summer.

The table below shows a prior study of integrated systems using PVT, GSHP, and ASHP. (Table 1)

Table 1. Previous study for integrated system using PVT, GSHP and ASHP

Analytical method	System configuration	Description	Author
Energy simulation	PVT + GSHP	Performance & life cycle cost analysis of single source system and integrated system	Abu-Rumman et al.
Energy simulation	PVT + GSHP	Applicability analysis for ZEB implementation using integrated system	Ruoping et al.
Mathematical model	PVT + ASHP	Comparative analysis between ASHP & PVT-ASHP	Li and Huang
Energy simulation	PVT + ASHP	Energy and exergy analysis between ASHP & PVT-ASHP	Ai et al.
Real-scale experiment	PVT + GSHP	Evaluation of integrated system through real-scale experiment	Bae and Nam

These research methods require expensive off-the-shelf programs to build simulation or mathematical models, and require expertise and experience in model validation and analysis processes. In particular, it is difficult to estimate and verify the performance of the system in a real-scale empirical experiment because a large budget and dedicated manpower are required for plant construction.

The performance prediction method using artificial intelligence technology does not require the construction of a mathematical model or an empirical experimental plant, unlike the approaches of existing research, which can dramatically reduce the budget and analysis time. Due to these advantages, artificial intelligence technology is being used in various fields such as performance prediction, control algorithm, system design, and fault diagnosis. However, most research is limited to single renewable energy technologies such as light, solar and geothermal heat pumps. Renewable nuclear fusion systems that combine two or more heat sources are difficult to interpret because complex influencing factors are interconnected, so there are few studies on performance prediction methods based on artificial intelligence technology.(Zhang et al. 2018; Li et al. 2021; Noye et al. 2022)

Therefore, in this study, a DNN (Deep Neural Network)-based solar-air heat source heat pump fusion system performance prediction model was developed for the purpose of predicting the performance of a renewable nuclear fusion system using artificial intelligence technology. The developed performance prediction model can be provided as a simple analysis tool for performance evaluation to relevant workers in the initial design stage of the convergence system, and will be utilized as basic data for the development of an optimal control algorithm in the future.

2. Body

In the process of developing the performance prediction model of the deep neural network-based convergence system performed in this study, the author's previous simulation model study was used for training and validation of the deep neural network performance prediction model. As for the analysis method of the simulation model, the performance prediction model verified through the empirical experiment of the preceding study was referred to, and the data obtained through the simulation model was filtered through correlation analysis and configured as a CSV format data set. (Bae et al. 2022; Nam et al. 2022)

The data sets are separated into three types: training, validation and testing, the data sets are randomly blended through a random number algorithm and fed to a deep neural network model through data normalization. The deep neural network model then predicts the performance of the converging system based on the refined data set. The accuracy of the artificial neural network performance prediction model is verified by analyzing the error rate between the predicted value of the test data and the actual value.

In this study, data required for the development of a deep neural network performance prediction model was collected using the simulation model of the solar-air heat source heat pump fusion system constructed in the previous study. (Bae et al. 2022; Figure 1)

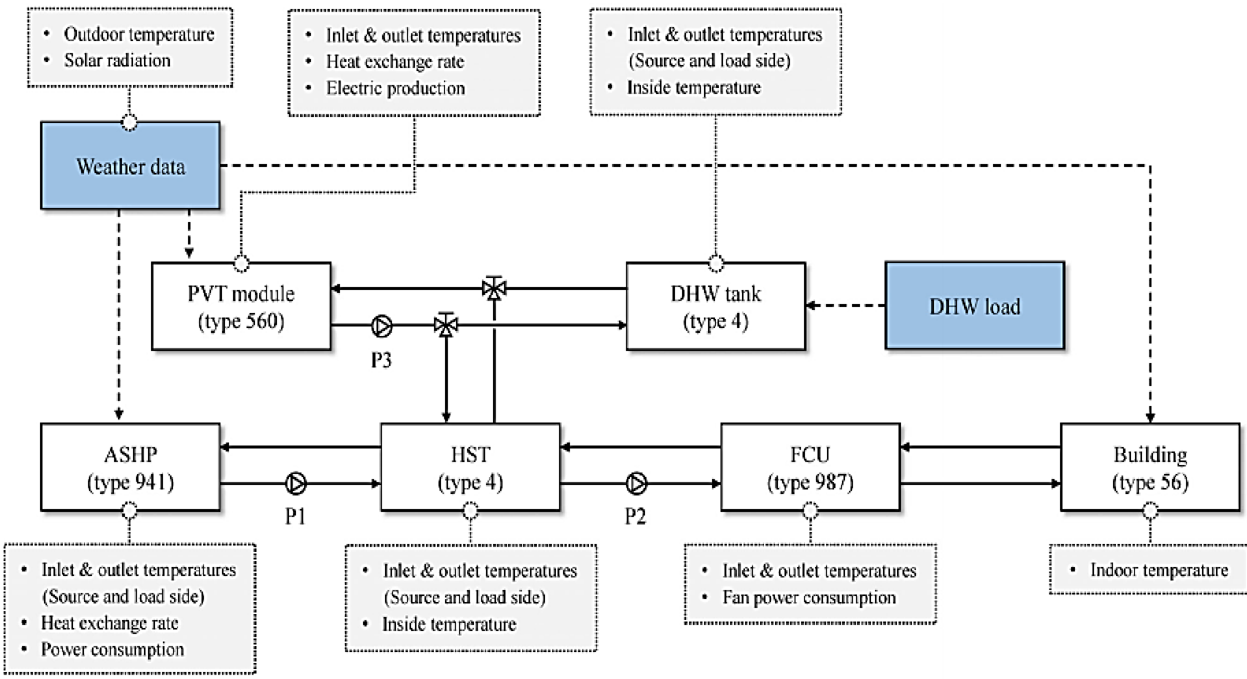

Figure 1. Schematic diagram of an integrated system combining PVT and ASHP.

The size of one solar module is 1.012×1.972 m^2, and a total of 10 modules with 16% power efficiency were installed. The air heat source heat pump is an air-based type, and equipment with heating and cooling capacities of 11.36 kW and 7.55 kW, respectively, was selected in consideration of the air conditioning area (110 m^2) of the building.

Based on the design capacity of the system, the circulation pump was selected as a specification capable of handling a circulation flow rate of 50 L/min, and was installed in the solar module, heat pump, and load-side buffer tank. The fan coil unit used equipment with heating and cooling capacities of 11.63 kW and 7.38 kW, respectively, considering the rated capacity of the air heat source heat pump and the air conditioning area of the building.

In order to accurately predict the performance of a solar-air heat source heat pump convergence system using a deep neural network model, data affecting the output variables were first collected through a simulation model based on the performance coefficient calculation formula of the system.

$$A = B \times C(D-E)$$

A : Heat output of air heat pump [W], B : Circulating flow rate [L/min], C: specific heat of fluid [kJ/kg K], D: Outlet temperature of air heat pump [℃], E : Intake temperature of air heat pump [℃]

Big data collected through the simulation model was divided into input variables and output variables. Input variables consist of solar module, air heat source heat pump, load-side buffer tank and hot water supply tank in/out temperature, heat output, power output, power consumption, outdoor temperature, indoor temperature, and total solar radiation.

The deep neural network model predicts that the output variable is set as the coefficient of performance of the solar-air heat source heat pump fusion system.

The Pearson correlation coefficient was used to shorten the analysis time of the deep neural network model and to quantitatively analyze the relationship between input and output variables. The relationship between the input variable and the output variable was quantified through the Pearson correlation coefficient.

The Pearson correlation coefficient is calculated in the form of a real number from -1 to 1, and the closer the correlation coefficient is to -1 or 1, the higher the correlation between the input variable and the output variable.

The coefficient of determination indicates a value from 0 to 1. The heat source side and load side inlet/outlet temperature of the load side buffer tank, the internal temperature of the buffer tank, and the outlet temperature of the fan coil, respectively, values calculated to be less than 0.2 or 0.04 were excluded from the input variables of the deep neural network model. Therefore, in the deep neural network model, 17 input variables having a significant relationship with the output variables were used.

Input variables selected through analysis of Pearson correlation coefficients and coefficients of determination are divided into training, validation, and test datasets to prevent overfitting, and 60%, 10%, and 30% ratio variables of the total input are applied. In the process of data set segmentation, if the data is biased into one category, all data sets are incomplete, making accurate training and prediction difficult. Therefore, when dividing the input variables into datasets for training, validation, and testing, the data were randomly shuffled using a random number algorithm to avoid biasing into one category.

On the other hand, numerical differences in data occur according to the unique units of input variables obtained from the simulation model. In particular, data such as calorific value, power generation, and power consumption are numerically larger than temperature data. In the artificial neural network learning process, low weight is given to small data because it is not related to output variables. Therefore, for accurate prediction of the deep neural network model, the numerical size of all data was converted to a value between 0 and 1 through data normalization.

The solar-air heat source heat pump fusion system has a large amount of data compared to the existing single heat source system, and it is difficult to predict the performance because the input variables are complicatedly connected. Therefore, in this study, we used a deep neural network model that can learn nonlinear relationships between input variables without being constrained by the characteristics of the variables. On the other hand, since the prediction performance improves as the amount of data increases, it was judged that the deep neural network is suitable for predicting the performance of the solar-air heat source heat pump fusion system that can extract a large amount of data.

The performance prediction model of the deep neural network-based solar-air heat source heat pump convergence system used in this study is presented. A performance prediction model using a deep neural network consists of one input layer, two hidden layers, and one output layer.

The input layer is composed of 21 nodes (n, Nodes) using input variables that have undergone a refinement process such as correlation. The number of nodes in the hidden layer was set to 43 (2n+1) based on the optimal number of nodes in the hidden layer derived from previous studies. The number of hidden layers was determined to be 2 through a case study. When the number of hidden layers is 3 or more, the analysis time increases depending on the number of hidden layers, but it does not significantly affect the prediction performance of the deep neural network. The output layer is the final predicted value derived by the artificial neural network model and was set as the coefficient of performance of the solar-air heat source heat pump fusion system. (Lim et al. 2005)

The reliability verification of the deep neural network-based performance prediction model developed in this study is the mean square error coefficient of variation (CV(RMSE), Coefficient of variation root suggested by ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) Guideline 14). mean square error). ASHRAE Guideline 14 suggests reliability when the CV (RMSE) is 30% or less based on time data, and the closer it is to 0%, the higher the reliability. (ASHRAE, 2014)

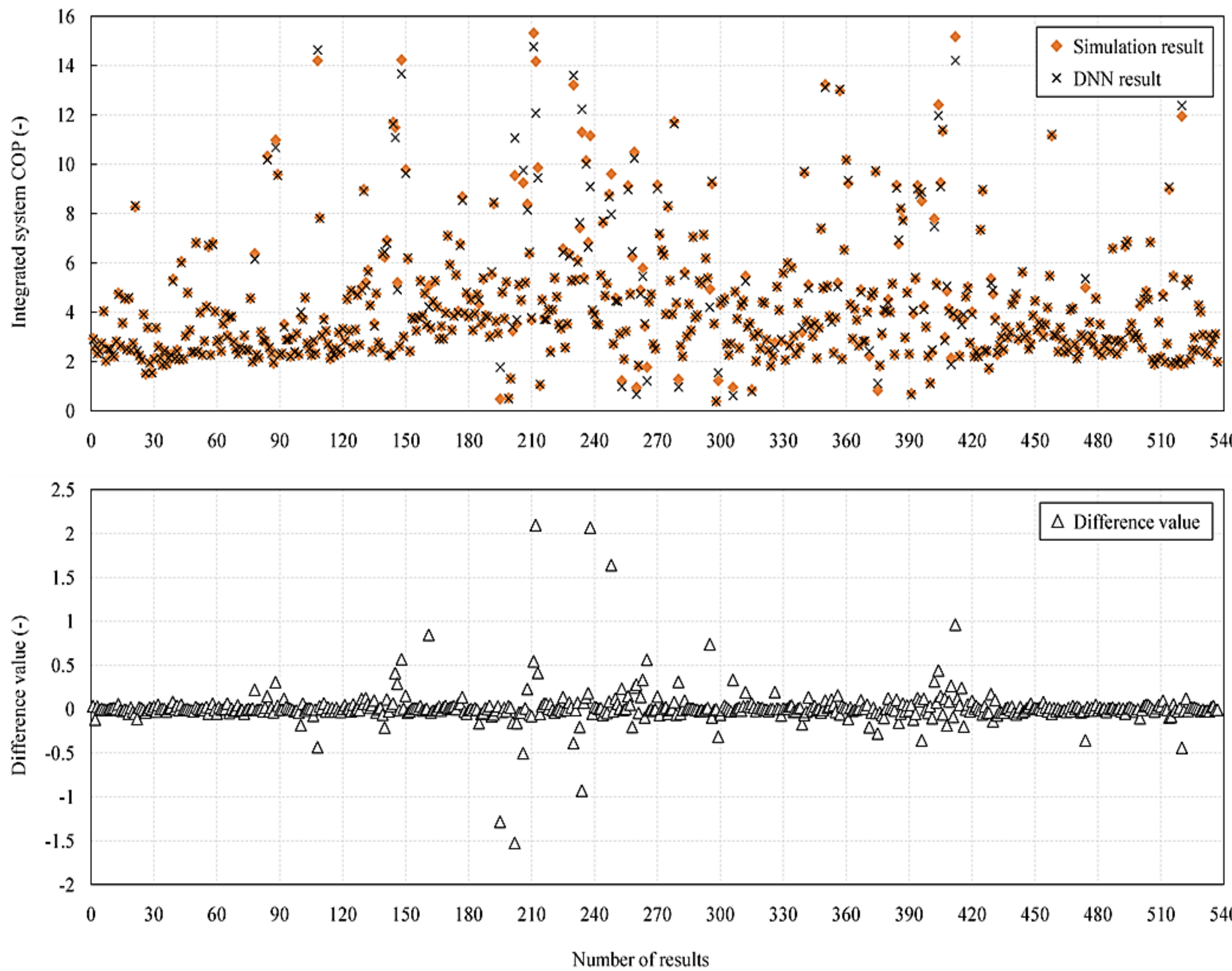

Figure 2. Comparative analysis between simulation result and DNN result.

Figure 2. shows the prediction result values of the deep neural network-based performance prediction model and the output variables input through the simulation model. The CV (RMSE) between the predicted result value and the output variable was calculated as 5%. The deep neural network-based performance prediction model developed in this study satisfies the criteria proposed in ASHRAE Guideline 14.

3. Conclusion

In this study, the performance prediction model of the deep neural network-based solar-air heat source heat pump convergence system was developed, and the reliability of the developed performance prediction model was verified through the CV (RMSE) error analysis method proposed in ASHRAE Guideline 14.

The input variables of the solar-air heat source heat pump convergence system were collected using energy simulation, and the data were refined through the Pearson correlation coefficient and the coefficient of determination. The refined 21 input variables were divided into learning, validation, and evaluation, and a data set was constructed through a random number algorithm and data normalization.

A deep neural network model capable of learning non-linear combinations and relationships between input variables was constructed. The structure of the deep neural network model consists of an input layer, a hidden layer, and an output layer, and the number of nodes in the input layer is set to 21, and the number of nodes in the hidden layer is set to 43. The number of hidden layers was determined to be two through a case study.

The CV (RMSE) between the predicted result value of the deep neural network model and the output variable was calculated to be 5%. Therefore, it is judged that the performance prediction model of the deep neural network-based solar-air heat source heat pump convergence system developed in this study has reliability.

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