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A Knowledge-Based Energy Management Model that Supports Smart Metering Networks for Korean Residential Energy Grids

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Abstract The various energy management technologies that are required in order to deliver effective energy demand responses have resulted from the integrated use of digital technologies with energy grids. Therefore, the core technologies for smart metering infrastructure are regarded as a key issue in the design of future energy grids. The proposed knowledge-based model that supports advanced metering networks is capable of estimating energy consumption according to the characteristics of residential buildings. The energy consumption data is analyzed according to the residential building's properties, which can significantly affect the energy consumption pattern. Therefore, appropriately designed models for energy consumption patterns with respect to identifying each energy consumption feature's potential impact can be applied to create smart metering networks for future energy grid environments. This study introduces a knowledge-based model that considers both the energy and building management profiles. Then, case studies for the estimation of the energy consumption are presented. The proposed model could be effectively utilized in managing the energy demand response process with respect to market prices and residential energy shortages, and it provides a good reference for designing energy demand response strategies in Korean residential energy grid environments.

Keywords Knowledge-based model · Energy-efficient management · Smart grid network · Energy grid environment · Smart metering network

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1 Introduction

Enhancing energy efficiency has become a crucial issue in many countries as a result of the emerging requirements for energy conservation and carbon emission reduction. Building energy consumption accounts for forty percent of the total world energy use. Therefore, much attention has been focused on energy reduction in the building sector. Korean apartment complexes have the highest percentage of total building energy consumption in Korea, and approximately half of the Korean population lives in apartment complexes [1, 2]. Korean apartment complexes have various characteristics such as shapes, types, and uses. Therefore, their energy consumption patterns should be investigated in response to the various building types and characteristics.

Over the past decade, smart energy grids have garnered significant attention with respect to the world's energy shortages. A smart grid contains advanced distributed capabilities such as self-healing, high reliability, energy management, and real-time pricing [3, 4]. A smart grid also integrates new technologies, which can include advanced metering infrastructures, automation, communication, and distributed energy generation.

The key component of smart energy grids for generating cost effective electricity and providing stable energy supply and demand is the energy management system (EMS). The EMS supports real-time knowledge and regulates distribution and transmission grids to support stable energy supply and demand, through which utility companies can remotely automate various grid functionalities.

Until recently, research on energy grids that considers both electrical and thermal energy has been developed with a common goal of optimizing energy management in terms of generation and demand in order to ensure balanced energy supply and demand.

A smart grid changes analog meters to digital meters, which enables data collection in real time. Smart metering devices are part of the Advanced Metering Infrastructure (AMI) that includes the deployment of a number of technologies and enables two-way communication, which supports customers and utilities with data on electricity prices and electricity consumption.

This study presents a knowledge-based model that considers energy consumption patterns with respect to identifying each feature's potential impact on energy consumption based on smart metering networks, which provide a communication path that contains useful information extending from energy generation plants to energy end-use. This paper is organized as follows. Section 2 introduces the background literature related to energy management technology in residential energy grids. Section 3 describes the proposed system through presenting an overview as well as specific information. Exemplary case studies for the energy consumption estimation model are presented in Sect. 4. Finally, the conclusion and future work are discussed in Sect. 5.

2 Energy Management Strategies and Smart Metering Technologies for Residential Energy Grids

The term "smart grid" refers to a variety of applications that automate the electrical distribution and monitoring for increased energy efficiency [5]. Traditional power energy grid infrastructures are centralized and require electricity to be transmitted to the customers or end-use. In contrast, distributed energy resource (DER) systems tend to be decentralized and have more flexible technologies that can be engaged to effectively reduce the overall load profile in a service area. In a decentralized power energy grid environment, the demand response (DR) has an increasingly important function in the electric power distribution under uncertain and constantly changing variables. Before designing a DR model for Korean energy grids, the primary energy generation and consumption environment in Korea must be examined in order to identify the current Korean energy grid infrastructure including the unique Korean residential environments with interesting energy saving potentials. In addition, the current policies of the energy supply and demand model must be considered.

2.1 Current Residential Energy Management Strategy in Korea

In Korea, Korea Electric Power Corporation (KEPCO) is responsible for the generation, transmission, and distribution of electricity, as well as the development and deployment of electrical power projects including nuclear, wind, and coal power [6]. The electricity contracts for each apartment complex have a direct influence on the energy consumption and utility cost.

Most Korean residential houses use natural gas energy for heating and cooking. Korea Gas Corporation (KOGAS) dominates South Korea's gas sector, and it is the largest single liquid natural gas (LNG) importer in the world [7]. KOGAS supplies gas to energy distribution companies located in different areas, and each company then delivers gas to consumers. The most commonly used heating systems in Korean apartment complexes are categorized into central heating, individual heating, district heating, and combined heat and power (CHP). Each type of heating system has a different supply and demand mechanism.

In the Korean residential energy grid, thermal energy is regarded as a significant energy source. Therefore, energy management processes to improve energy efficiency and optimize energy flow in buildings (i.e. the generation, transformation, distribution, and consumption of electricity) require thermal energy, compressed air, or water in order to attain successful energy management.

2.2 Energy Consumption Patterns of Korean Apartment buildings

According to the growing importance of energy supply and demand strategies related to green house gas (GHG) reduction, a number of studies of apartment complexes, which account for a large portion of the total energy use in Korea, have been conducted. There have been many investigations of electricity or thermal energy consumption through evaluating the monthly and annual energy consumption profiles with regard to morphological factors (e.g. tower type, flat type), significant characteristics of apartment complexes (e.g. elapsed years, number of buildings, number of stories, number of households, maintenance area, household size, etc.), heating types (central heating, individual heating, etc.), and usage types (hotels, schools, hospitals, and apartment complexes) [1, 2, 8–13].

Most studies related to energy consumption with respect to Korean apartment complexes usually derive consumption patterns or phenomena analyses rather than develop energy consumption estimation models. However, such studies cannot fully provide appropriate solutions to develop an effective energy management strategy. Therefore, it is essential to estimate the required primary energy and other resource consumption amounts, particularly for Korean apartment buildings.

2.3 Current Energy Grid Test Beds and Energy Management Technologies

Many different power and energy grid systems have been constructed and various concepts of intelligent energy grids have been utilized in electric grid renovation, especially distribution automation [4, 14, 15]. The IntelliGrid demonstration project of Electric Power Research Institute (EPRI) has accelerated the development of standards and technologies for utility use in planning, specifying, and procuring IT-based systems, such as advanced metering, distribution automation, and demand response [5].

In particular, in Korea, both the Jeju Smart Grid Test Bed and Korea Micro Energy Grid (K-MEG) project led by the government have invested approximately 500 million dollars [16]. These projects have focused on R&D and overseas export model development related to renewable energy resources and distributed energy generation in order to promote energy savings, economic growth, and CO_2 reduction in the residential and commercial sectors. They have generally investigated energy management models in relation to frameworks of economic demand response systems. The power energy grid has been considered within the context of optimal control of electricity generation, transmission, distribution, storage, and end-use, among many others. Results from the newly developed energy grid, demand response, and smart metering devices have received significant attention with regards to the key component technologies of intelligent energy management solutions, which include energy efficiency, building energy management, and distributed renewable resources.

From a consumer's perspective, smart metering provides numerous potential benefits. In contrast, from a supplier's perspective, they can take advantage of smart meters in order to realize real-time pricing regarding energy loads, which provides users with feedback about their energy savings and it may encourage them to reduce their energy use in peak load periods, according to the information sent from the demand side. Therefore, effective demand response modeling should consider the relationship between the smart metering network and entire energy grids.

3 Proposed Energy Management Model

The energy supply and demand systems in Korean residential sectors have very diverse characteristics with respect to energy sources, housing types, energy policies, and heating system types. In particular, the energy policies for energy demand responses are very diverse and depend on the characteristics of the apartment, contract type, and region. Therefore, it is necessary to design energy efficient solutions that consider energy savings in addition to supply and demand in order to manage the diverse environments. This study proposes a knowledge-based energy management model that is applicable to Korean apartment buildings. This study also introduces the current energy infrastructure and issues, and a knowledge-based model is subsequently presented for both energy and housing management profiles.

3.1 Current Residential Energy Grid Infrastructure in Korea

The existing analog electricity and gas metering devices measure the amount of energy consumption by the end-users. The billing cycles and energy usage are based on periodic readings of the electricity and gas meters [6]. However, a smart metering network system differs from the traditional metering system in that smart meters allow two-way communication between the metering device and the main grid system, which is similar in many respects to the way that the advanced metering infrastructure (AMI) differs from traditional metering systems. Sometimes, smart metering networks are regarded as part of the AMI [17].

Figures 1 and 2 presents a general smart metering architecture for a typical Korean residential environment. The energy and water resource consumption data are collected and transmitted to the integrated management server that is located in the total operation center for monitoring and controlling energy consumption. The smart metering infrastructure manages the metering electricity and other energy sources; it also provides useful information that enables energy grids to be more intelligent from the customer's perspective. A smart meter allows real-time billing, accounts for energy consumption in 15-min intervals, and delivers useful information including energy price notifications, power quality monitoring, and two-way feedback to customers via a user interface.

3.2 Proposed Knowledge-Based Energy Management Model

Understanding the features of buildings and residential housing is indispensable when creating energy management models for Korean energy grids because the energy consumption patterns tend to be influenced by the building's characteristics and the unique residential environment [1]. Therefore, this study considers both housing and energy management properties in order to build an integrated management model, as seen in Fig. 3. The features of buildings having potential impact on energy consumption are derived from previous researches [1, 2, 8–12], guidelines and Korean apartment

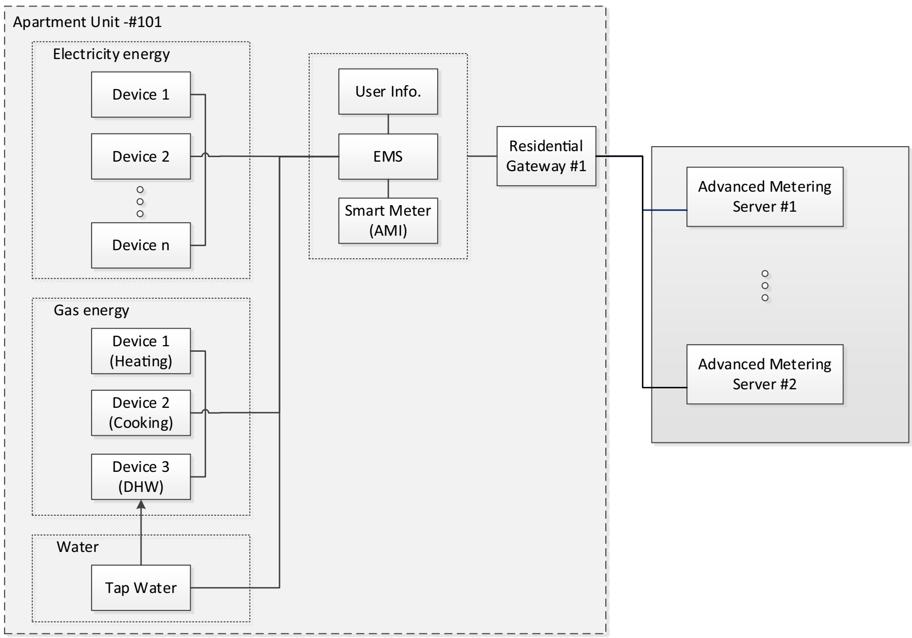

Fig. 1 Architecture of smart metering infrastructure for a typical Korean residential environment

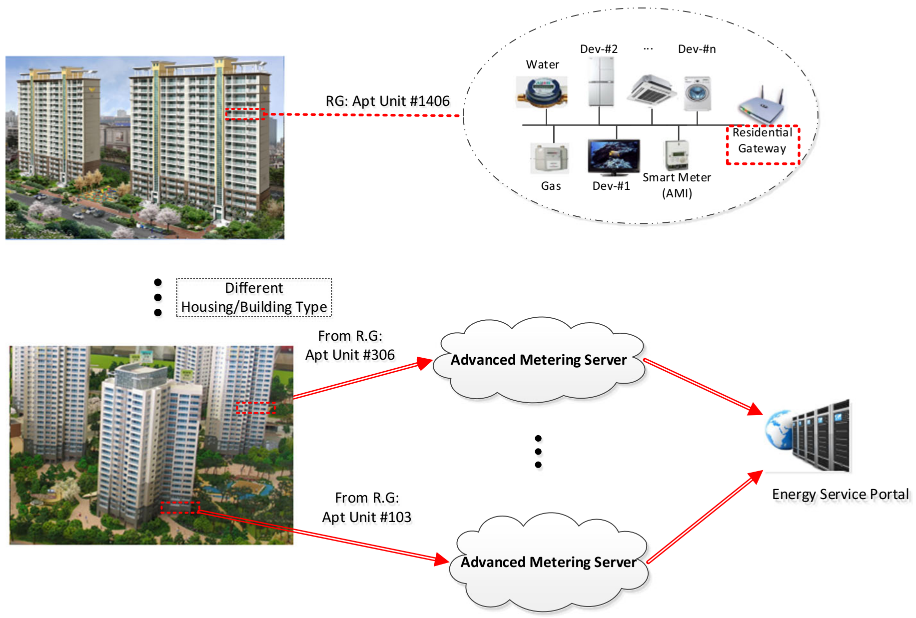

Fig. 2 Architecture of a smart metering network for Korean energy grids

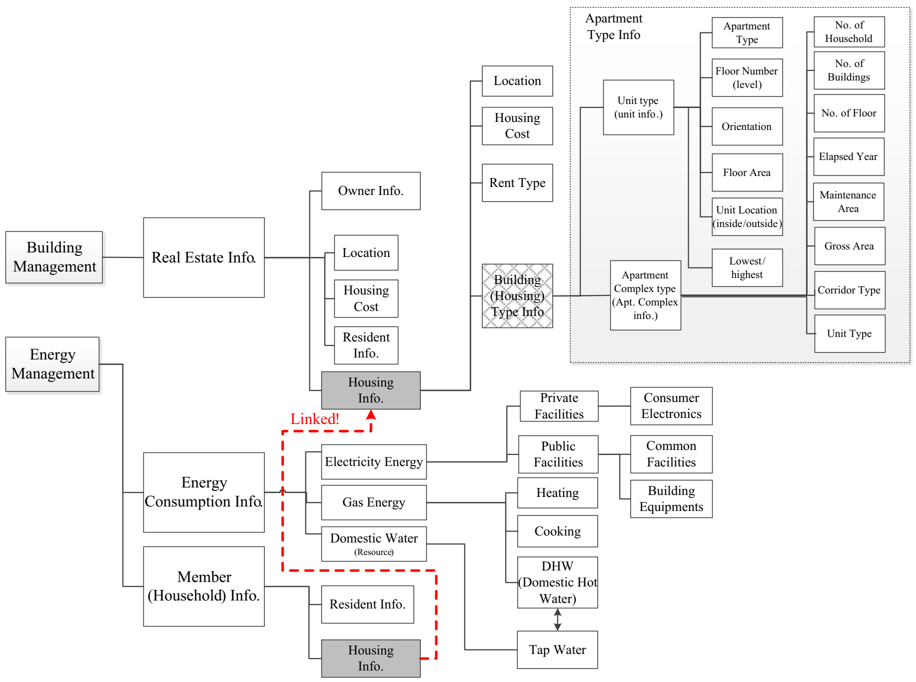

Fig. 3 Proposed energy management model for Korean apartment complexes

management systems including Onnara Real Estate Information Portal [18], Korea Land Information System [19], and Apartment Management Information System (AMIS) [20].

The building (housing) management properties include real estate information such as location, housing cost, owner information, resident information, and building information. In contrast, the energy management properties contain energy consumption information and resident's (end-user's) information. In Korea, the energy use information generally encompasses the electricity, gas, and water resource consumption, as well as household information.

The proposed model has several features:

- *Energy consumption patterns with respect to the residential building or apartment complex type* Energy consumption for each household has varying results according to the difference in building shape, type, use, and specific information such as the number of floors and gross area of the apartment units. It is essential to investigate energy consumption data with respect to various residential building types affecting the energy consumption pattern. This approach is an effective solution to accelerate energy conservation studies since Korean apartment complexes are diverse.
- *Different types of contracts and policies* Energy consumption patterns may vary according to the different types of contracts and policies for the supply of electricity and gas in Korean apartment complexes. Therefore, this model provides customers and service providers with useful energy services through the smart metering system.
- *Useful information and feedback based on end-use energy consumption patterns* Advanced metering infrastructure allows real-time billing, accounts for energy consumption in intervals of 1 h or less, and provides useful information based on the end-use energy consumption patterns including customer feedback.

4 Case Studies

For the case studies, empirical data analyses were performed and an energy estimate model was developed in order to provide a comparison and contrast analysis of energy consumption patterns for various architectural components, which resulted in empirical energy consumption data for those features. Several housing units were selected and the relevant information collected using floor plans, expert advice, and cooperation with apartment management offices.

The housing units with the smallest margins of error when compared with similar apartment groups were selected for investigation. Through comparing the empirical energy loads with the estimated analyses using a multi-layer perceptron neural network (MLP-NN), it was possible to verify the accuracy of the estimations using the proposed model's grouping and classification [21, 22], and to test the functioning of the knowledge-based energy management model.

First, considering the floor plan and the building characteristics, twelve buildings from same Korean apartment complexes were examined as case studies in order to evaluate the energy consumption estimation based on the proposed model. Second, the required parameters of the monthly heating energy consumption datasets from the selected residential complexes for 2012 were collected from city gas energy supply companies [23], management offices of the apartment complexes, and Korea Land and Housing Corporation. The construction and architectural features of the multi-family housing were acquired

Table 1 Characteristics of the apartment complex (Period: Jan. 2012–Dec. 2012)

Subject	Selected apartment complex in Gyeonggi province
Total no. of households	870
Total no. of buildings	12
Floor areas	80 m^2, 100 m^2, 114 m^2
Orientation	South, southwest, southeast
Floor level	Bottom, middle, top
Unit location	Inside, outside

from the administration office for each apartment, AMIS [20], and real estate information [18], as well as conducting expert interviews. For the use of climate data, we obtained the monthly weather history data for 2012 from the Korea Meteorological Administration [24].

Based on the consumption dataset, significant differences in the 95 % confidence interval for the calculated mean data were analyzed. Table 1 presents the information of the selected apartment complex.

A MLP-NN estimating method was used to build the energy and resource usage model for commercial and residential buildings [1, 2, 25, 26]. The MLP-NN can accurately analyze complex nonlinear and linear patterns through its learning system that involves carefully identified factors.

A dataset classified using the building characteristics was utilized in the estimation analysis. First, estimation analyses were conducted in accordance with the three groups, which were units of households, buildings, and complexes. Through comparing the empirical energy consumption data with the estimated results from the MLP-NN model, the prediction accuracy of the classification method in the proposed model could be identified. In this case study, SPSS version 20 and Matlab were used to estimate the energy consumption and to compare the performances of these estimation methods.

4.1 Energy Consumption Estimation of the Apartment Buildings

In this case study, the electricity energy and gas energy consumption were used separately as dependent variables. Based on the precedent studies [1] and related references, the input vectors were selected based on three different influential factors: the building, climate, and geometric information. The private floor area of the target apartment buildings ranged from 80 to 114 m^2, and the orientation of each building was to the southwest, south, and southeast.

In this experiment, the output data included two different categories related to energy and gas use in the individual household unit.

Firstly, a total 870 samples of each household's electricity and gas energy consumption are classified into 14 dataset by the features, such as 'orientation', 'unit location (inside or outside)', 'floor level (top, middle, bottom floor)', and 'floor area size', which are the main components of the knowledge-based model. Chosen dataset is calculated on the basis of average monthly energy consumption data.

The final input and output data of the proposed MLP-NN estimation model consisted of the following:

A total 168 samples were used and the training data corresponded to 70 % of the available observations (117 of 168) and the test data was 30 % of the available observations (51 of 168). This study used a three-layer back propagation neural network with a single hidden layer. The number of hidden units was calculated using both the theoretical and experimental methods. The model parameters were set to an input layer of 21 neurons, an output layer of 2 neurons, and a hidden layer of 18 neurons. As the activation function, the hyper-tangent function $\tanh(x) = (e^x - e^{-x})/(e^x + e^{-x})$ was used for the neurons in the hidden layer.

The input data consisted of 21 × 168 datasets that defined 21 attributes for 168 different cases including '1–12 coded months of the year', 'dry bulb temperature', 'relative humidity, 'heating degree days', 'cooling degree days', 'orientation', average floor area', 'unit location (inside/outside)', and 'floor level'. The output data was a 2 × 168 matrix for electricity and gas energy consumption as estimated from the inputs (Fig. 4).

In order to evaluate the goodness of fit of a model, two distinct error-related statistical indicators are used; the Coefficient of variation of the root mean square error (CVRMSE) and the mean absolute percentage error (MAPE) as follows in Eqs. 1 and 2 respectively:

$$\text{CVRMSE}\ (\%) = \frac{\sqrt{\frac{\left(\sum_{i=1}^{n} (EnergyUse_{estimated,i} - EnergyUse_{measured,i})^2\right)}{n}}}{\overline{EnergyUse_{measured,i}}} \times 100 \tag{1}$$

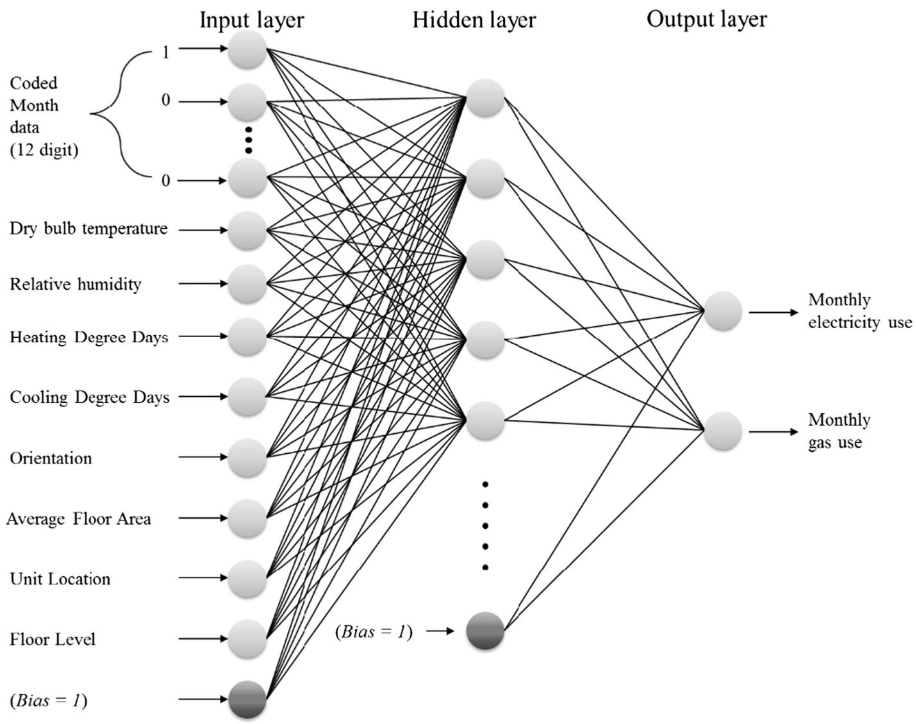

Fig. 4 Topology of the multilayer perceptron (MLP) neural network (NN)

Table 2 Test case groups for energy consumption estimation

Case no.	Average floor area (m^2)	Orientation	Unit location	Floor level	Corridor type	Unit type
1	100	Southwest	Outside	Bottom	Stair	Flat
2	100	Southeast	Outside	Middle	Stair	Flat
3	100	Southeast	Outside	Top	Stair	Flat
4	100	Southwest	Outside	Bottom	Stair	Flat
5	100	Southeast	Outside	Middle	Stair	Flat
6	80	Southeast	Outside	Top	Stair	Flat
7	80	Southeast	Outside	Bottom	Stair	Flat
8	80	Southeast	Outside	Middle	Stair	Flat
9	80	Southeast	Inside	Middle	Stair	Flat
10	80	Southeast	Outside	Top	Stair	Flat
11	80	Southeast	Inside	Top	Stair	Flat
12	114	Southwest	Inside	Bottom	Stair	Flat
13	114	Southwest	Inside	Middle	Stair	Flat
14	114	Southwest	Inside	Top	Stair	Flat

$$\text{MAPE }(\%) = \frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{EnergyUse_{estimated,i} - EnergyUse_{measured,i}}{EnergyUse_{measured,i}}\right|\right) \times 100 \tag{2}$$

where, n is the number of data (month), $EnergyUse_{estimated,i}$ is the estimated output for input i-month and $EnergyUse_{measured,i}$ is the empirical measurement for i-month, and $\overline{EnergyUse_{measurement,i}}$ represents the average.

According to the guideline of ASRAE [27], the tolerance of the estimation results should be within 25 %. The statistical error indicators of the proposed model in Table 2 are within acceptable tolerances of the empirical measured data.

As illustrated in Table 3 and Fig. 5, the estimated values of the electricity and gas energy use models were very close and are in good agreement with the actually measured values. The accuracy of the estimation demonstrates that the prediction of monthly gas energy consumption (the multiple R was 0.89) was more accurate than that of the monthly electricity energy consumption (the multiple R was 0.76).

In most cases, the proposed model precisely estimated the energy consumption using the MLP-NN for each examined apartment buildings, and it was used to compute the total annual energy capacity in the context of multi-family residential housing in Korea.

Through these case studies, potential uses were presented regarding the proposed energy consumption prediction model. The results indicate that the estimated outcomes for the energy consumption were appropriately fitted to the empirical data. It was also found that the dataset classified using the knowledge-based model could be utilized in the estimation process.

The estimation model could be effectively utilized to manage energy demand response processes with respect to market prices and residential energy shortages. It could also provide a good reference for designing energy demand response strategies in Korean residential buildings.

Table 3 Error statistical indicators of the estimation models

Case no.	Model error indicators	Electricity use	Gas use
1	CVRMSE (%)	6.80	35.28
	MAPE (%)	6.01	25.41
2	CVRMSE (%)	4.63	9.51
	MAPE (%)	3.8	24.27
3	CVRMSE (%)	7.92	26.31
	MAPE (%)	6.58	23.94
4	CVRMSE (%)	5.11	28.09
	MAPE (%)	3.75	20.06
5	CVRMSE (%)	7.03	17.54
	MAPE (%)	6.68	20.63
6	CVRMSE (%)	7.15	7.27
	MAPE (%)	5.58	6.25
7	CVRMSE (%)	7.02	28.48
	MAPE (%)	4.81	17.50
8	CVRMSE (%)	7.13	20.06
	MAPE (%)	6.30	27.58
9	CVRMSE (%)	5.16	20.09
	MAPE (%)	4.69	25.81
10	CVRMSE (%)	11.82	12.57
	MAPE (%)	11.21	33.40
11	CVRMSE (%)	6.75	10.24
	MAPE (%)	6.01	21.78
12	CVRMSE (%)	18.98	33.26
	MAPE (%)	19.98	24.77
13	CVRMSE (%)	4.57	46.39
	MAPE (%)	3.13	32.33
14	CVRMSE (%)	3.70	31.76
	MAPE (%)	3.01	24.90

5 Conclusion

The energy grid represents the entire network that carries electricity and thermal energy from the energy plants to the consumers. Smart metering networks also have numerous benefits in the current energy grid environment in terms of effectively managing grid networks from the generation side to end-use. Moreover, a smart metering network, which can be regarded as a key technology in future energy grids that have the principal functional characteristics of distributed energy resources, could also have a crucial function in supporting effective energy management for smart energy grids under the uncertain and ever-changing environment regarding energy supply and demand.

The proposed knowledge-based energy management model that supports intelligent metering can estimate energy consumption in response to the characteristics of apartment buildings. Therefore, an appropriately designed knowledge-based model that considers energy consumption patterns with respect to identifying each feature’s potential impact on

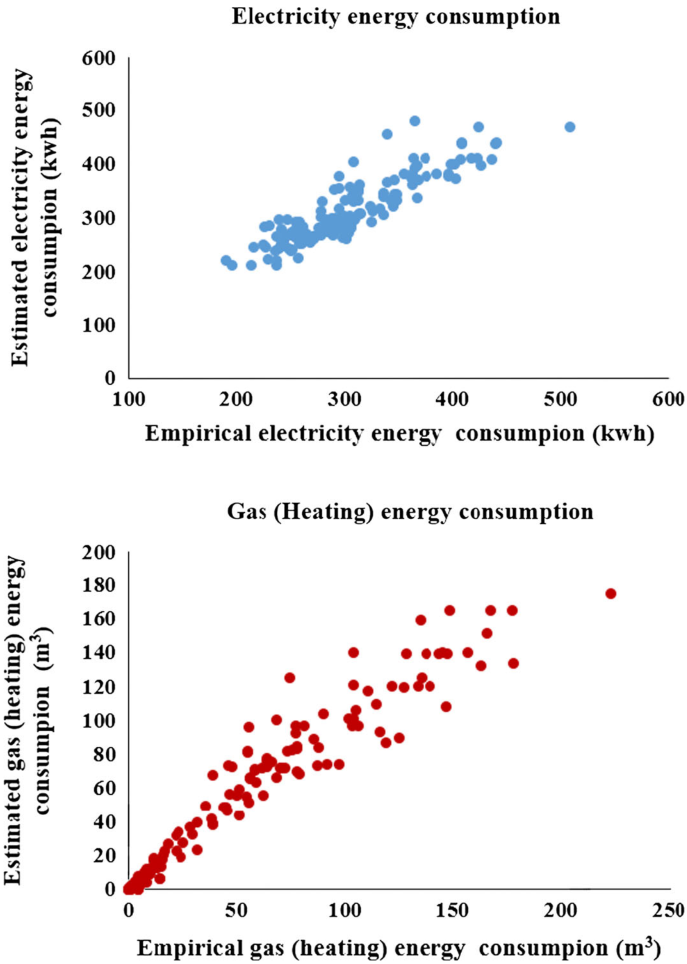

Fig. 5 Comparison between measured and estimated monthly electricity and gas (heating) energy use in apartment buildings

energy consumption could be applied to advanced demand response systems, which could effectively reduce the overall load profile in a service area.

In addition, through the case studies, the effective utilization of the proposed energy management model in smart metering network was demonstrated. The model could also be beneficial in providing useful feedback to customers in real time via smart metering networks, and it could be a useful reference for governments and facility management in apartment complexes, which have a joint goal of maximizing domestic energy use efficiency.

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