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Sustainable Air-Conditioning Systems Enabled by Artificial Intelligence: Research Status, Enterprise Patent Analysis, and Future Prospects

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Abstract: Artificial intelligence (AI) technologies have developed rapidly since 2000. Numerous academic papers have been published regarding energy efficiency improvements for air-conditioning systems. This study reviewed 12 review papers and selected 85 specific cases of applications of AI for HVAC energy usage reduction. In addition to academic studies, 31,221 patents related to HVAC energy-saving equipment filed by 11 companies were investigated. In order to analyze the large amount of data, this study developed a resource description framework (RDF) as an analysis tool. This tool was used with a natural language processing (NLP) program to compare the contents of academic papers and patents. With the automated analysis program, this study aimed to link academic research and corporate research and development, mainly the enterprise patent applications, to analyze the reasons why AI can effectively save energy. This represents a complete analysis of the current status of academic and industrial development. Six methods were identified to save energy effectively, including model-based predictive control (MPC), thermal comfort control, model-free predictive control, control optimization, multi-agent control (MAC), and knowledge-based system/rule set (KBS/RS)-based control. The energy savings of these methods were quantified to be 8.8–25.5%. These methods are widely covered by the examined corporate patent applications. After using NLP to retrieve patent keywords, the landscapes of enterprise patents were constructed and the future research directions were identified. It is concluded that 10 topics, including novel neural network designs, smartphone-assisted machine learning, and transfer learning, can be used to increase the energy-saving effects of AI and enable sustainable air-conditioning systems.

Keywords: artificial intelligence (AI); sustainable air-conditioning system; energy saving; model-based predictive control (MPC); patent; commercialization

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1. Introduction

In a project supported by the Ministry of Science and Technology at Taiwan, the keywords 'artificial intelligence' (AI) and 'heating, ventilation, and air-conditioning' (HVAC) were searched for in the ScienceDirect database and IEEE Explore in August 2021. A total of 664 academic papers were identified. The main purpose of this study was to explore sustainable air-conditioning systems enabled by AI. This study first analyzed review papers to identify the technology gap.

A total of 14 review papers published between 2000 and 2020 were analyzed. The abstract information of these papers is presented as follows: smart buildings and HVAC equipment related papers, reviewed by Wong et al. [1]; a review of advanced control systems, especially multi-agent control systems (MACSs) for energy and comfort management in buildings, presented by Dounic and Caraiscos [2]; a review of AI applications for refrigeration, air-conditioning, and heat pump systems, presented by Mohanraj et al. [3]; a review of computing models developed for predicting building energy consumption by

Zhao and Magoulès [4]; a review of the applications of artificial neural networks (ANNs), the support vector machine (SVM), and the hybrid method with genetic algorithms (GAs) or particle swarm optimization (PSO) for forecasting building energy consumption by Ahmad et al. [5]; a review of HVAC control methods, presented by Belic et al. [6]; a review of AI-based load demand forecasting for smart grids and buildings, presented by Raza and Khosravi [7]; a review of demand-side management with ANNs by Macedo et al. [8]; a review of AI methods including decision tree (DT) algorithms, hidden Markov models, machine learning (ML), multilayer perceptron (MLP), and SVM&R for smart control of HVAC equipment by Mulia et al. [9]; a review of AI-based methods for predicting building energy usage, reported by Wang and Srinivasan [10]; a review of state-of-the-art electric load forecasting technologies, reported by Mamun et al. [11]; a review of building occupancy detection systems and smart control, reported by Sun et al. [12]; a review of model-based predictive control (MPC) in institutional buildings by Cotrufo et al. [13]; and a review of AI-based methodologies used to enhance thermal comfort in indoor spaces, reported by Ngarambe et al. [14].

The following conclusions can be drawn on the basis of the aforementioned review papers:

- Three review papers report that MPC is an effective energy-saving method.
- One review paper indicated that MAC is an effective energy-saving method for multi-zone air-conditioning.
- Other review papers mainly discuss the prediction accuracy. Their primary conclusion is that combinations of several AI technologies can improve prediction accuracy.

On the basis of the aforementioned conclusions, this study identified the following research gaps.

- In addition to MPC and MAC, can other AI technologies be effectively applied to sustainable air-conditioning system?
- Lack of a comprehensive and quantitative analysis of HVAC energy savings by AI. In addition, not only energy-saving effects, but also the improvement in thermal comfort, should be included.
- Since 2020, numerous commercial HVAC products claim to use AI to improve their products. Do any differences exist between commercial developments and academic research? Not only are review papers not discussed, but research papers are rarely seen.

In order to fill these research gaps, a research framework was established in this study. Figure 1 illustrates the steps of this research framework.

Referring to Figure 1, the results of step 1—review paper survey—are illustrated in Section 1. Sections 2 and 3 illustrate the details of the academic study case collection and patent survey, respectively. An automatic program—a resource description framework (RDF)—was developed for data analysis of a large number of patents.

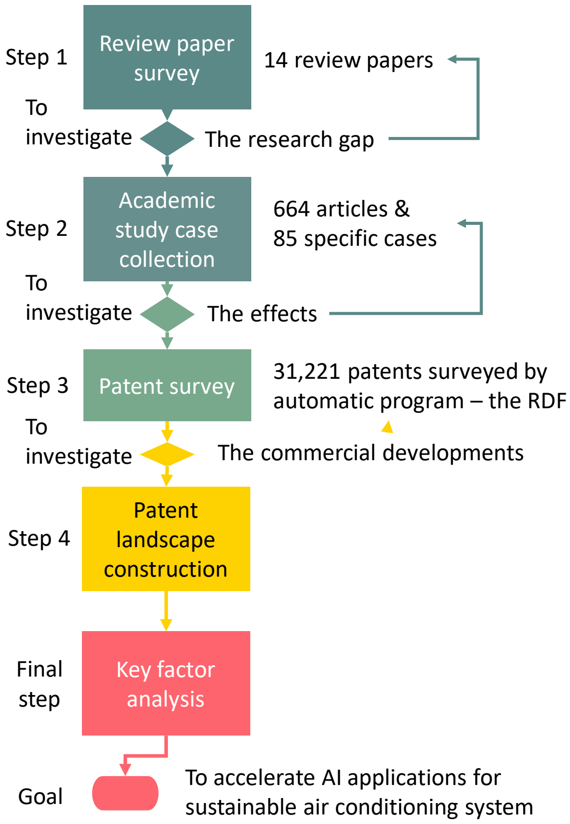


Figure 1. The research framework of this study. 14 review papers [1–14]. 664 article & 85 specific cases [15–99].

This study's novelty is the first usage of an RDF to analyze patent data. In contrast to academic paper surveys, it is difficult to find review reports, especially for this specific topic, i.e., AI for HVAC energy saving. By comparison, the number of surveyed patents is much larger than that of surveyed papers. In this study, 31,221 surveyed patents were identified, compared to 664 surveyed papers, i.e., almost fifty times as many. The RDF can be used to construct a metadata model for data analysis and obtain useful information from both academic research and enterprise patents. Section 4 present the details.

Section 5 presents the results and discussions. In this section, Section 5.1 illustrates energy-saving effects using AI and Section 5.2 illustrates cost saving and thermal comfort improvement. Both of these are the results of step 2. The patent landscape is discussed in Section 5, and is derived from step 3. The metadata model is the base to draw the landscape. From Sections 5.3.1–5.3.11, the landscape of over thirty-thousand patents from 10 companies is constructed, thus completing step 4.

Finally, the RDF was used to establish interchangeability between the different contents of academic papers and patent claims. Through the information interchange, the differences between research papers and patents can be identified to obtain the key factors, and the final step can be completed. It is expected that the five steps of this research will fulfil the technology gaps identified in this study. Furthermore, the manner in which AI research should be changed in the future, and the areas that should be focused on to accelerate the commercialization of these technologies, are discussed in Section 6.

2. Academic Study Cases

This study required structured information to develop the RDF. Thus, while performing step 2, we manually re-examined 664 articles from a database and selected 85 study cases. These cases met the following four conditions:

1. Specific description of the type of HVAC equipment used;

2. Specification of the type of building in which the equipment was used;
3. Use of AI technology;
4. Quantitative presentation of energy-saving effects and other benefits.

2.1. Case List

All the study cases are listed in Table 1.

Table 1. Study cases obtained from the reviewed academic papers.

HVAC System Description	Experimental Method	Location/Experimental Conditions	Used AI Technology and Key Results	Ref
Air handling unit (AHU) for a lecture theatre with a floor area of 315 m² and a maximum seating capacity of 200 people	Simulation by HevaStar	United Kingdom/21-day test; outdoor temperatures were 3–20 °C	• Knowledge-based system (KBS) in central control to regulate the optimal start and stop • Occupancy status could be predicted with an accuracy of approximately 3% • Energy savings of 20% (heating and lighting power)	[15]
Air-conditioning system for ACT test cells consisting of seven cells, each of which has a volume of 30 or 60 m³	Simulation with a GENESYS test cell simulation model	Spain/Full control of the temperature range (−15 to 45 °C), RH (10–90%), and maximum heating or cooling power (48 W)	• Fuzzy logic controller with a rule selection process • Stability improvement of 34.48% for thermal comfort control • Energy savings of 9.5% compared with on–off control	[16]
Split-type air conditioner for the heating and cooling of one building zone with a floor area of 144 m² and up to 45 occupants	Simulation with a SIBIL model	Greece/In winter, outdoor temperatures were 16–18 °C, and indoor temperatures had to be 22–24 °C	• A fuzzy Proportional (P) controller was used for maintaining indoor thermal comfort and saving energy • Compared with on–off control, energy consumption could be reduced by 20.1%	[17]
Heating system for a single room with a length of 3 m, a width of 6 m, and a height of 2.5 m	Simulation with a MATLAB model	Bulgaria/Outdoor temperature was 8–10 °C, and the indoor temperature was regulated to 20 °C	• Neuro-fuzzy control was used to regulate hot water flow in the heating system • Indoor temperature oscillation could be reduced from 3.5 °C for PID control to 0.5 °C for neuro-fuzzy control • No energy savings were observed	[18]
FC for a small commercial building with eight test rooms	Simulation with an inverse building model	United States/Energy-efficient set-up control for the 5-h on-peak period from 13:00 to 18:00	• MPC for changing the zone temperature set point • MLP model trained with a few weeks of hourly data • 30% reduction in peak cooling load	[19]
Heat pump system for two small buildings, namely Building A, which had an area of 15 m² with insulated walls, and Building B, which had an area of 14 m² and walls without insulation	Simulation with a SIBIL model	United States/A simulation period of 4 years but without detailed information	• Fuzzy proportional differential (PD) control could reduce energy consumption but resulted in poor thermal comfort • Reinforcement learning (RL) can improve thermal comfort but results in an increased energy consumption	[20]

			• Thermal comfort was evaluated using the percentage per disagree (PPD) • On–off PPD ≈ 13.4% Fuzzy PPD ≈ 16.5% RL PPD ≈ 1 2.1% • Annual energy consumption On–off ≈ 4.77 MWh Fuzzy PD ≈ 3.28 MWh RL ≈ 4.85 MWh	
Chiller for a 7000 m^3 chilled water tank for thermal storage to provide building cooling on the campus of the University of California Merced, USA	Simulation with a simplified model	Unites States/One-day operation with the cooling load varying from 300 to 2000 kW	• MPC controller for optimally storing thermal energy in the tank by using predictive knowledge of building loads and weather conditions • Compared with manual operation, daily electricity consumption could be reduced by 24.5% with AI	[21]
AHU VAV system for a 1200 m^2 air-conditioned area	A dynamic simulation of a typical AHU VAV system	China/One-day test; the designed air flow rate was 7.2 kg/s; the designed supply air temperature was 13 °C; and the designed supply chilled water flow rate and temperature were 7.0 kg/s and 7 °C, respectively	• An off-line based robust MPC could track the set point with an error of 0.13 °C • Fast response was achieved with MPC than with conventional proportional integral (PI) control, and the temperature error in conventional PI control was higher than that in MPC at approximately 0.16 °C	[22]
An HVAC system composed of two heat exchangers: an air-to-air heat exchanger and a water-to-air heat exchanger	Real experiment in an industrial HVAC system	Germany/8000-sec operation under indoor temperatures of 20–22.5 °C; the outdoor temperatures were 8.5–10 °C	• MPC with a cost function of electrical and thermal energy consumption by the HVAC system • Chilled water flow rate could be reduced, and the energy consumption of the tertiary pump could be reduced by 82%	[23]
Chiller plant with two chillers for the Dai Jia Wan Plaza in Baoji	Real experiment in a shopping center	China/the maximum cold load of the building was 2812 kW	• Genetic algorithm (GA) was used to optimize the number of running chillers, the running parameters, and the distribution of the real-time loads of running chillers • 7.4% Energy saving	[24]
A 1.5-ton split-type air conditioner in a laboratory with dimensions of 5.97 m × 3.96 m × 3.42 m (80.05 m^3) and an average occupancy of three people per hour	Real experiment in a laboratory	India/One-day test from 10:00 to 17:00	• Fuzzy logic control system used for maintaining a comfortable temperature and relative humidity (RH) in an indoor environment • In the winter season, thermostat (on–off) control consumed 2.9% higher energy than did fuzzy control; in the summer, thermostat control consumed 21.4% more energy than fuzzy control	[25]

Smart air conditioner in a bedroom with an indoor space of 13.24–20.68 m^2	Real experiment in a building	Taiwan/One night and a whole day with 1–3 occupants	• Intension causing control by using MACS • Total compressor output of a smart air conditioner was 48.4% less than that of an air conditioner using on–off control	[26]
AHU VAV system for three-zone temperature control in the Bancroft library located on the campus of UC Berkeley	Simulation with a simplified model	United States/One-day test; cooling loads ranged from −1.2 to 6 kW. The room temperature was maintained between 19.5 and 21 °C	• Using MPC to increase the fan power and decrease the chilled water consumption while maintaining the same thermal comfort • Compared with PID control, energy consumption could be reduced by 10.2% when using MPC	[27]
A water feed air heating system in a 150-m^2 lecture room	Simulation with a simplified model	United States/1.5-h test with heating loads of 5 kW	• MPC for reducing energy and maintaining the same thermal comfort • Compared with on–off control, energy consumption could be reduced by 8.21% when using MPC	[28]
Ceiling radiant heating system at Czech Technical University; the building comprises four 5-floor blocks, three 8-floor blocks and four-level intermediary parts	Real experiment in a university building	Czech Republic/Two-month winter season test; indoor temperatures were maintained at 17.5–21.5 °C	• MPC with weather forecast • Comparing with the original start–stop control, energy consumption could be reduced by 17–24% when using MPC control	[29,30]
Climaveneta HPAT/LN 0704 chiller, which is rated at 100 kW in an office building	Simulation using EnergyPlus and MATLAB	New Belgrade/One-day test from 07:00 to 17:00; the average external temperature on the observed days was 17–20 °C	• Chiller model identification with ANN • Optimization with GA • Energy savings of 9–13%	[31]
AHU variable air volume (VAV) system for a 7000-ft^2 (650.32 m^3) three-story university building; the test floor was divided into 33 rooms	Simulation with OpenGL; the environment was based on the open-source project OpenSteer	United States/ 24 h test during spring; the supply air temperature was set as 55 °F (12.78 °C)	• MACS for the distributed control of 14 VAV boxes • Compared with the original PID control, thermal comfort satisfaction levels were improved by 5% with the MACS • Energy savings of 12–17% were achieved with the MACS	[32]
AHU constant air volume (CAV) system and chiller plant at Terminal One of Adelaide Airport	Simulation with a simplified model	Australia/One-day test in January (the hottest month); the indoor temperatures were maintained at 22–24 °C	• Chiller model identification with an MLP model • Mean square error was 0.129–0.23 °C • An optimal start and stop time could reduce energy consumption by approximately 5%	[33]
AHU with VAV and VWF capabilities in a single thermal zone	Simulation with a simplified model	Iran/1.5-h test of the transient control response; the thermal zone RH varied from 50% to 55%, and the	• Wavelet neural network (WNN) with an infinite impulse response filter for the fast and accurate identification of a system model	[34]

		temperature remained constant at 21.1 °C	• Compared with PID control, the adaptive self-tuning PD control enabled by the WNN could reduce energy consumption by 5.88–11.85%	
Vapor-compression-cycle air conditioner in a single thermal zone of a small (511 m^2) single-story office building in Chicago, Illinois, USA	Simulation with EnergyPlus and MATLAB	United States/On a typical July day, the building housed 28 people at a standard occupant density of 5.38/100 m^2 per zone; the building was occupied between 08:00 and 18:00; and the zone temperatures were maintained at a constant set point of 24 °C	• MPC could achieve better tracking control than did conventional approaches, such as PI control • The integral of the squared error for step changes in the temperature set point decreased by 70% • Energy savings of 16%	[35]
Chiller plant with thermal storage at UC Merced	Real experiment in a university, with the relevant simulations conducted in [21]	United States/Five-day test from 1 to 5 June 2009; chiller plant energy consumption was 3.58×10^6 to 8.63×10^6 kJ, and the COP changed from 4.7 to 5.6	• MPC for chiller plant operation was proposed to store the thermal energy in the tank optimally by using predictive knowledge of building loads and weather conditions • Compared with PID control, coefficient of performance (COP) has an improvement of 11.9%	[36]
AHU with a recovery section with bypass control, a heating coil, and a cooling coil for the air-conditioning of a two-zone building	Simulation with TRNSYS	Belgium/Test period of more than one year; the AHU supplied air at a flow rate of 36 m^3/person, it operated from 07:00 to 19:00, the heating power was 26 W/m^2, and the cooling power was 31 W/m^2	• MPC was used to reduce the energy cost while guaranteeing thermal comfort • MPC was conducted with a second-order model by using information about past operative temperature prediction errors without using solar or internal heat gain predictions • Compared with PID control, energy savings of 15% were achieved with MPC	[37]
AHU VAV system to serve the second floor of the library at UC Berkely	Simulation with a set of nonlinear regression models	United States/One-month test between 1 December 2011 and 31 January 2012; zone temperatures were maintained at 18–28 °C before 06:00; the zones were then loaded with occupants until 20:00; and the control input had an upper bound of 8 kW	• Stochastic MPC is subject to joint chance constraints • Compared with two-stage algorithms, MPC could reduce energy consumption while maintaining thermal comfort • Compared with other algorithms, Energy savings of 13.7% were achieved by MPC	[38]

Air conditioner for a computer laboratory with an area of 58.8 m^2	Real experiment in a laboratory	United States/An experiment was performed from 12:00 to 17:30; the room was in use and not in use at different times	• MPC was used to learn and compensate for the heating caused by occupancy because occupancy varied throughout the day • Energy savings of 30% compared with two-position (on–off) control	[39]
AHU system for the CSIRO ICT centre	Simulation with a simulator that uses empirical data to simulate different HVAC control strategies in realistic scenarios	Australia/Over a 3-week period, an AHU was controlled with a PIR sensor on the basis of occupant feedback from their smart phones	• Model-free and sensor-free control based on occupant feedback • Compared with conventional thermostat control, energy savings of 60% could be achieved for a relatively small increase of 0.3 °C in the average occupants' discomfort	[40]
Air conditioner at a single-story commercial building located in Chicago, Illinois, USA	Simulation with EnergyPlus and MATLAB	United States/A test was conducted for more than one day; the original set point was 24 °C; and by using MPC, five-period division was suggested for changing the set point from 18 °C to 23 °C	• MPC for regulating the set point in advance • Compared with PI control, 8% energy savings were achieved at the set point of 24 °C • Cost savings of up to 28.52% by load shifting to off-peak hours	[41]
Under-floor air distribution system in a multizone open office	Simulation with Energy Plus and MATLAB	United States/Simulation was conducted for 1 week each in winter and summer	• MPC for causing the predicted mean vote (PMV) approaching to the upper set limit • Energy savings of 28.9% in winter and 2.7% in summer were achieved. • Energy savings of 18.9% in average were achieved while maintaining the occupant PMV	[42]
AHU system for a two-zone office building	Simulation with a resistor–capacitor network	Italy/A simulation was conducted for 3 days in winter; the building was occupied during the day and vacant at night	• MPC for learning and controlling buildings for optimal occupants' comfort and minimal energy usage; the building's existing HVAC sensors and hardware were used • 7.5% Energy savings	[43]
Campus cooling system with thermal energy storage	Simulation with a semi-empirical model	United States/One-day test with the total cooling demand ranging from 39,600 to 65,300 kW;	• Decision tree (DT) for dynamic optimal chiller control • Energy savings of 9.4% compared with the original chiller control • Cost savings of 17.4% by load shifting to off-peak period	[44]
Chiller plant with thermal energy storage for a three-story office building	Simulation with TRNSYS	United States/One-day operation with the existing centrifugal main chiller that has a nominal capacity of 1200 kW, a new centrifugal	• Multiple MPC systems for ensuring near-optimal load shifting • Energy savings of 9–15% compared with original control • Cost savings of 13–20%	[45]

		chiller that has a nominal capacity of 600 kW, and a thermal energy storage system with a nominal capacity of 6000 kWh		
Chilled beam system for a single air-conditioning zone	Simulation with a simplified model	Singapore/The transient time in the simulation was 3000 s to maintain the zone temperature at 24 °C	• Fuzzy controller for accurate temperature control with quick response • Temperature oscillations were less than 0.5 °C	[46]
Two AHU VAV systems for a three-story building with 60 permanent occupants and approximately 2000 temporary residents each semester	Real experiment in a building	United States/One-day test with all modes controlling the targeted zones between 06:30 and 21:00	• KBS with a control algorithm and thermal preference profiler • Feedback from temperature sensors and occupants • A reduction in daily average air flow rates of 26–39%	[47]
Air cooling chiller with ice-cold thermal energy storage	Simulation with a MATLAB model	Italy/One-day test from 06:00 to 18:00 with a chilled water temperature of 7 °C and an ice temperature of −5 °C	• MPC development by using a predictor based on a plant model to process information, a cost function, and the PSO algorithm • Energy cost savings of 6% by load shifting	[48]
AHU VAV system for a commercial building	Real experiments in two buildings	Australia/Over 2 winter months, an average energy reduction of 19% and 32% was achieved in the two buildings over 51 and 10 days of operation, respectively	• MPC for training a model from historical data; a given temperature set point profile and weather forecasts were used to predict building zone conditions and thermal comfort • Energy savings of 19–32% compared with the original set point	[49]
Heating/cooling system for a test building in a solar house located in Pittsburgh, Pennsylvania, USA	Simulation with a two-capacitor and three-resistor model	United States/The experiment was conducted most of time during the cooling and heating seasons	• Real-time MPC based on occupancy behavior pattern detection and local weather forecasting • Measured energy reduction of 30.1% during the heating season and 17.8% during the cooling season compared with the conventional scheduled temperature set points	[50]
Air conditioner for a one-zone building	Simulation with an information service evaluation model	Slovak Republic/ During a 24-day period, the reference temperature setting was 20 °C, and the cooling or heating loads ranged from 2000 to −1000 W	• RL for deriving the dependence of real-valued control inputs • A simple feedback law attained almost the same performance as the complex MPC controller • Energy savings of 3% compared with the original strategy	[51]
Heat pump for a one-story detached house with a 100-m^2 footprint	Simulation with a state space model	France/Simulation was conducted for one week each in the mid-	• MPC for improving thermal comfort • Occupant discomfort, energy consumption, and the number of on–off	[52]

		season and winter; the outdoor temperatures were 5–17 °C during the mid-season and −5 to 5 °C during the winter	cycles of the heat pump were reduced by up to 97%, 18%, and 78%, respectively	
Heating system with surface opening control for a single zone with dimensions of 4.5 m × 4.2 m × 3.05 m (57.65 m^3)	Simulation with a MATLAB model	South Korea/During a 10-day test in winter, the indoor temperature was set as 21.5 °C	● ANN-based algorithm and adaptive-network-based fuzzy inference system (ANFIS) for operating the surface openings of the building and the heating system ● ANFIS provided the best solution for optimized control ● Energy savings of 11.2% were achieved	[53]
An HVAC system with a centralized architecture serving multiple AHUs in two large buildings located at the Navy Recruit Training Centre	Simulation with the optimization modeling developed by Berkeley Library	United States/One-day simulation with similar outdoor air temperature patterns for historical HVAC baseline data as in the conducted MPC tests	● MPC can enable fault-tolerant control of an AHU VAV system ● Energy savings of 35% were achieved compared with operation at the fault conditions	[54]
Radiant slab with an underfloor air distribution system at the David Brower Center, which is a four-story, 4042-m^2 office building located in downtown Berkeley, California, USA	Simulation with EnergyPlus	United States/One-day test in a mild climate with moderate temperatures throughout the year; the cooling design temperatures (dry bulb/wet bulb) were 27.7 and 18.3 °C, and the heating design temperature was 2.9 °C	● MPC for maintaining zone operating temperatures at thermal comfort levels for >95% of the occupied hours for all zones ● Cooling tower energy savings of 55% ● Pumping power savings of 25% ● Energy savings of 15% compared with heuristic control	[55]
Chiller plant with thermal storage at UC Irvine	Simulation with a MATLAB model	United States/One day of operation during summer	● MPC for obtaining an optimal set point ● Energy savings of 9.7% compared with original PID control ● Energy cost savings of 10.84% through load shifting	[56]
Chiller plant for a university building in Salzburg, Austria; the building contains 250 office rooms, and each floor is identical with an effective area of approximately 6500 m^2	Simulation with a simplified model	Australia/Two weeks during September 2014	● Hybrid MPC for coordinating the different input–output manipulated variables ● Control performance could be improved ● Energy savings of 43% compared with optimized PID control ● An increase of at least 50% in the usage of renewable energy sources ● A reduction of approximately 50% in energy costs	[57]

Air conditioner and other office automation equipment in a standard office	Simulation with a three-module model, which comprises an occupant behavior module, electricity consumption module, and indoor temperature control module	China/Work day simulation with the following parameters: body heat of 26.9%, transmission heat of 24.9%, computer heat of 20.8%, solar radiation of 12.5% light heat of 7.9%, and basic load of 3.4%	● MACS for exploring the energy-saving potential of various types of appliances in an office under different pricing mechanisms ● An energy-saving potential of 6.9–12.1% was achieved for air-conditioning	[58]
A building containing independent heaters and coolers with one integrated controller	Simulation with a MATLAB model	United States/Annual energy consumption of an office building and residential buildings	● ANN responding to abnormal indoor environments ● ANN improved thermal comfort levels by approximately 2.5% for an office building and 10.2% for residential buildings ● The ANN reduced annual energy consumption by approximately 17.4% for an office building and approximately 25.7% for residential buildings	[59]
HVAC for a five-zone building	Simulation using an EnergyPlus model with real weather and pricing data	United States/One-month experiment with the desired temperature of 19–24 °C	● RL of an effective strategy for operating the building HVAC system ● RL for regulating on–off control could reduce energy consumption by 4.9%–56.8% ● RL for regulating the five zones could provide energy savings of 22.3–71.2%	[60]
Data-driven control of an AHU system for a university building	Real experiment conducted between 25 February and 3 March	Iran/Educational building simulation	● ANN for learning and proposing an optimized course timetable ● The ANN model accuracy was 94.12–99.78% ● Energy savings were 1.22–18.97% compared with the previous schedule	[61]
HVAC system for a commercial building with a LoRa-enabled sensor network; this sensor network was evaluated in George Moore Building	Real experiment in a commercial building	United States/Five-day test between 10:00 and 18:00; the environment test chamber was occupied with up to three people during the test	● ML for identifying if a room was unoccupied and turning off the HVAC ● The accuracy of occupancy estimation with the recurrent neural network (RNN) model was 78.5% ● Energy savings of 19.8% compared with manual operation	[62]
HVAC system used to cool a multi-zone building with an AHU, FCs, a VAV, and a chiller	Simulation with a simplified model	Singapore/A meeting was scheduled in zone 6 at 11:00 but was cancelled at the last minute	● ANN-based distributed AI for HVAC scheduling control ● Energy savings of 5.6% for the suddenly cancelled meeting	[63]

Predictive chiller for a three-floor university campus building with an area of 2400 m²	Simulation with a MATLAB model	Spain/One-day simulation with two chillers, two heat pumps, a gas boiler, and two AHUs	• MPC for anticipating future cooling demands and scheduling operation • Daily average of chiller COP increased by 19.54% with a standard deviation of 2.68%	[64]
Split-type air-conditioning for a two-room residential building	Simulation with a two-zone residential HVAC model	United States/Ten-day test with outdoor temperatures ranging from −12 to 8 °C and indoor temperatures of 17–19 °C	• Deep neural network (DNN) and RL for changing the set point of the air-conditioning temperature • Comfort violations could be reduced by 98% • Energy savings of 15% compared with the fixed set point control	[65]
Heating and ventilation systems for a laboratory	Real experiment in a testing facility for an integrated smart home	Germany/One-day test in the winter; the weather was sunny but also cold; and two people walked into the room randomly during the test period	• Fuzzy-based supervisory control for the optimization of HVAC systems with respect to different performance requirements • The maximum comfort condition required 13.3 kWh of power per day • Under the maximum economy condition, 3.7 kWh of power was consumed per day	[66]
Chiller plant comprising two AHUs for a building with a total floor area of 1166 m² that is divided into eight zones	Real experiment in four exterior zones orientated north and equipped with a VAV and CAV as well as other zones equipped with a VAV only	Hong Kong/Four-day tests under the following conditions: sunny summer, cloudy summer, sunny spring, and sunny winter	• MPC based on predicting the responses of the overall system environment and energy performance under different control settings • The model was optimized with a GA • For the four test days, the energy savings were 1.1%, 0.2%, 0.9%, and 39.8%	[67]
A VAV HVAC system for a single-zone building	Simulation with dynamic models	Hong Kong/One-day simulation; for cooling, outdoor temperatures were 25–33 °C and the outdoor humidity was 65–85%; and for heating, outdoor temperatures were 4–12 °C and the outdoor humidity was 45–65%	• The back propagation neural network (BPNN) controller could maintain an indoor comfort level within the desired range in the heating and cooling modes • Energy savings of 10.4% were achieved compared with the constant air volume system for on–off control	[68]
A VAV box with a hot water supply to maintain heat in a single-zone building	Simulation with HVACSIM+	Hong Kong/Transient time simulation under a maximum absolute value of 10°C for the temperature difference between the set point and the output point	• GA for the automatic tuning of a PID controller • Control stability could be improved • Overshoot was 0.381 °C, and the settling time was 14.5 sec • For PID control, the overshoot and settling time were 0.922 °C and 358 sec, respectively	[69]

FC system supplied by a reverse-cycle heat pump and a mechanical extractor with variable fan speed for ventilation at test sites	Real experiments at two test sites	France/Two-day experiment during summer	• Fuzzy control optimized by GA • Compared with on–off control, only fuzzy logic control exhibited energy savings of 4.05% • After optimization with the GA, energy savings of 14.47% were achieved	[70]
FC systems for two-zone test chambers with a volume of 0.5 m^3	Real experiment in a test chamber	Turkey/Thirty-minute transient test for investigating the control response	• ANN with wavelet decomposition to predict the fan speed and damper gap rates of an HVAC system • Accurate prediction with an R^2 value of 0.9953 • Fan power savings of 25%	[71]
Vehicle air-conditioning systems	Real experiment in a cabin room	Australia/One-day test with a comfortable cabin room specification temperature of 21–24 °C, an RH of 40–60%, and an air speed of 1–5 m/s	• ANN for PID tuning • Prediction of K_p, K_i, and K_d according to the set temperature and feedback temperature • The energy consumption in the original PID setting was approximately 6.18 MJ • PID parameters tuned with the conventional method resulted in an energy consumption of 5.46 MJ • PID parameters tuned with an ANN resulted in an energy consumption of approximately 5.34 MJ • Energy savings of 13.6%	[72]
Air conditioner in an office room with a size of 3.6 m (height) × 3.6 m (width) × 7.7 m (depth)	Simulation with a PMV model	Thailand/One-day test with data recorded every 10 min between 08:00 to 17:00	• ANN model for calculating the PMV index • Accuracy of 5% for determining PMV values during the day	[73]
Window-type air conditioner in a thermal chamber with dimensions of 2.92 m (width) × 2.39 m (depth) × 2.51 m (height)	Real experiment in a test chamber	United States/Six-day test each in two seasons (27 January–1 February for winter and 3–8 July) for summer in Ann Arbor, Michigan	• ANN for PMV control • In both seasons, the comfort period increased by 2.6% • Compared with PID control, ANN control reduced the heating power by 0.9% and cooling power by 1.4%	[74]
Heating system in offices with floor sizes ranging from 50 to 250 m^2 and ceiling heights ranging from 2.4 to 2.8 m	Real experiments in several buildings	South Korea/Transient start times for light-, medium-, and heavy-load buildings	• ANN model for determining the optimal start time of the heating system in a building • Correct prediction of the start time with a coefficient of determination of approximately 0.97 • Potential energy savings of 12% for buildings with heavy loads • Potential energy savings of 34% for buildings with light loads	[75]
Air conditioner for a meeting room within an area of 2.5 m × 2.5 m	Real experiment in a meeting room	Italy/24 h period of manually processed video feedback	• ANN with a feedforward neural structure for thermal sensing control under occupancy	[76]

			• Energy savings of 25% compared with no occupancy sensing	
HVAC and window control systems for a residential building	Simulation with a thermal model	United States/24 h occupancy under two climates: the hot and humid climate of Miami the and mild to warm climate of Los Angeles	• RL for control HVAC and window systems • HVAC energy consumption was 12–23% when using natural ventilation	[77]
Air conditioner for a test chamber with dimensions of 0.75 m (width) × 1.6m (depth) × 1.5 m (height)	Real experiment in a chamber	Canada/A transient time of 10000 s	• Grey-box model for energy-efficient set point selection • Energy savings of 6.6% when using different high and low set point hysteresis values	[78]
AHU VAV system for an open-plan office with dimensions of 2.8 m (height) × 22.8 m (width) × 14.2 m (depth)	Real experiment in an office building	Denmark/Three-week test with 16 participants The median preferred temperatures of the participants were between 22.5 and 25.4 °C, and 95% of preferred temperatures for a single occupant varied by ±1.2 °C	• Fuzzy logic for calculating the demand-driven set point of an HVAC system • The results revealed that only 29% of the occupants' thermal comfort improved; it decreased for 71% of occupants when implementing the user-driven control strategy • Energy savings of 6% compared with the fixed set point	[79]
Mitsubishi variable refrigerant flow (VRF) systems that contain an outdoor air-cooled inverter compressor unit and are connected to ceiling-concealed ducted indoor units	Real experiment in three areas on different floors of a school building belonging to the Faculty of Sciences and Technology of the University of Algarve	Portugal/48-h test under summer conditions	• MPC for maintaining a desired thermal comfort level while minimizing the electrical energy required • ANN model optimized by a GA • Energy savings of 50% under normal building occupation	[80]
FC system for the CDdI-CIESOL-ARFRISOL research centre, which has an area of 178 m^2	Real experiment in a school building	Spain/Two datasets each were collected in summer and winter; the first dataset was for a nonworking day, and second dataset was for a working day	• ANN for thermal comfort control • The ANN model predictions exhibited a root mean square error (RMSE) of 0.0296 • An RMSE of 0.0528 was obtained in polynomial approximation • The accuracy of estimation of PMV values could be improved by 43.9%	[81]
Chiller plant, AHU system, and electric heaters for a two-story building with an area of 1000 m^2 that is located in Perpignan, France	Simulation with EnergyPlus	France/The simulation periods were from 6 to 12 January 2011 (heating mode) and from 1 June to 30 September 2011 (cooling mode)	• MPC for thermal comfort control • ANN model optimized by a GA • The operation time for the HVAC subsystems was typically significantly reduced for all rooms	[82]

			• The daily operation time could be reduced by up to 5 h to achieve a decrease of approximately 20% in the energy consumption	
FC system for a typical single-story house; the overall area of the house was 248.6 m^2	Simulation with a MATLAB model	Malaysia/One-day simulation with 24-h weather data for Kuala Lumpur city	• Fuzzy indoor thermal comfort control based on PMV/PPD • The minimum winter temperature was 18 °C and the maximum summer temperature was 27 °C • PPD < 10%	[83]
AHU VAV system for a hotel building with nine stories and a total floor area of 4448.42 m^2	Simulation with EnergyPlus and MATLAB models	Canada/The study area is a large hotel located in Toronto, Canada, where at least some employees are always at work at all times; people are always active in this hotel	• A fuzzy controller and an evolutionary optimization framework were used to moderate energy usage without compromising thermal comfort • $-0.7 \le PMV \le 0.7$ • The overall energy consumption decreased by 16.1% for cooling and by 18.1% for heating compared with on–off control	[84]
HVAC system for Building Lab, which is an online open-access portal	Simulation with a resistor–capacitor model	India/Winter and summer tests	• MPC based on superheating • The model was optimized by PSO • A 60% improvement in thermal oscillation compared with PI control was achieved	[85]
HVAC system for a single-zone building equipped with a thermal energy storage system and an on-site energy generation system	Simulation with a nonlinear autoregressive network with exogenous inputs (NARX) model	United States/One-day simulation with a temperature set point profile of 24 °C from 5:00 to 21:00 and 26.7 °C from 21:00 to 05:00	• MPC for demand response control by considering the dynamic demand response signal, on-site energy storage system, and on-site energy generation system • Energy savings of 25% compared with heuristic control • Cost savings of 30.95%	[86]
Air conditioner for an office	Real experiment in a school building	China/The office was regularly occupied by eight graduate students of different genders aged between 22 and 26 years, and the occupancy hours were usually 08:00 to 22:00	• The SVM&R model was used for constructing a personalized thermal comfort model • Over 3 months, 1955 data points were collected from eight occupants to construct the model • The prediction accuracy was up to 91.62% on average • Energy savings of 6% were obtained by using different set points	[87]
Air conditioners for a laboratory and classroom; the area and height of the laboratory are 45.8 m^2 and 3.82 m, respectively, and the area and height of the classroom are 121.2 m^2 and 4.2 m, respectively	Simulation with EnergyPlus	Taiwan/Hot summer from May to October	• RL and agent-based control that maintained thermal comfort and air quality within optimal levels while consuming minimal energy for air-conditioning units and ventilation fans • Training data covering a period of 5 and 10 years were obtained	[88]

			• Compared with the current control system, a 10% lower CO_2 production and 4–5% lower energy consumption were achieved	
Personalized heating system for a user's desk	Real experiment in a test chamber	The Netherlands/All the tests were performed during winter in January and February 2017	• MPC for microclimate control • NARX model with a Pearson correlation coefficient of approximately 0.966 • A 5% higher thermal comfort was achieved with MPC than with user control	[89]
Chiller plant for a hospital comprising two 300-RT chillers, two 250-RT chillers, two 10-hp cooling towers, six 20-hp cooling water pumps, two primary-side 20-hp chilled water pumps, three 30-hp chilled water pumps, 13 secondary-side 5-hp chilled water pumps, two 25-hp chilled water pumps, and 20 AHU VAV systems	Real experiment in a hospital	Taiwan/Two-week test with similar weather conditions throughout its duration The peak occupancy during the pre-test period was 600 The test period had similar peak indoor occupancy	• Model-free trial-and-error control (MFPC) and RL to achieve energy savings for a hospital with variable cooling loads because of changing numbers of visitors • Energy savings of 31.5% compared with the original PID control were achieved	[90]
Chiller plant of an office building consisting of one 300-RT chiller, one 200-RT chiller, three 7.5-hp cooling towers, two 20-hp cooling water pumps, one primary-side 40-hp chilled water pump, one primary-side 30-hp chilled water pump, one secondary-side 30-hp chilled water pump, two secondary-side 20-hp chilled water pumps, and 12 secondary-side FC systems	Real experiment in an office building	Taiwan/Two-week test with similar weather conditions throughout its duration	• MFPC and RL to achieve energy savings for an office building with a stable cooling load • Energy savings of 29.9% compared with the original PID control were achieved	[90]
Chiller plant for a factory comprising three 800-RT chillers, one 500-RT chiller, four 10-hp cooling towers, three 75-hp cooling water pumps, and one 40-hp cooling water pump Primary side: three 50-hp chilled water pumps and one 30-hp chilled water pump Secondary side: four 60-hp chilled water pumps and 20 FC systems	Real experiment in a factory	Taiwan/Two-week test in a 24 h factory	• MFPC and RL to achieve energy savings for a factory with 24 h loading • Energy savings of 34.2% were achieved • In the top level of control, RL was used instead of value functions; policy gradients were employed to perform predictive output control for the entire chiller plant, which magnified the effects of foundational trial-and-error control in reducing the chiller power	[90]

			• The energy-saving effect at actual test sites was more than twice the 15.7% energy savings estimated from simulations	
Chiller plant for a three-story building with an area of 9072 m^2; this building primarily serves as an office space and a semiconductor production line, and 70% of its energy consumption can be attributed to its air-conditioning system	Real experiment in a factory	Taiwan/Three-year test	• MPC for achieving three-level energy conservation for a building • MPC was performed for controlling the energy consumption at the equipment, facility, and entire building levels • Reductions of 47.5%, 37%, and 36.9% were achieved in the energy usage of the equipment, facility, and entire building, respectively	[91]
Air-conditioning and ventilation system for the Seoul Metropolitan Subway	Real experiment performed on the D-subway station line No. 3, Seoul, South Korea	South Korea/A manually operated ventilation system produced flow rates of 266,750 CMH from 01:00 to 18:00, 380,810 CMH from 19:00 to 22:00 (evening rush hour), and 228,490 CMH from 23:00 to 12:00, regardless of the PM_{10} concentrations of the platform and outdoor environment	• Deep learning (DL) model for predicting environmental data for energy-efficient ventilation control • Energy savings of 8.68% compared with the energy consumption under manually operated ventilation	[92]
Chiller plant for a test room with a total area of 255 m^2	Real experiment in a test room	Singapore/One-day test from 09:00 to 21:00	• MPC for an air-conditioning system with a dedicated outdoor air system • Energy savings of 16–20% compared with the energy consumption in on–off ventilation control	[93]
Three air conditioners for a campus classroom with a maximum of 72 occupants; the classroom has an area of 111.435 m^2 and a height of 4.2 m	Real experiment in a classroom	Taiwan/ Thirty test cases with different weather conditions and occupant numbers of 26–60	• Deep Q-learning for optimizing thermal comfort, indoor air quality, and energy usage • Energy savings of 19–43% compared with the energy consumption under the fixed air-conditioning temperature setting of 25 °C	[94]
AHU VAV system for three rooms with areas ranging from 33.0 to 50.6 m^2	Real experiments in office rooms	China/Experiments began at 08:30 and continued until 17:00; the break time accounted for 2 h; and the experiment involved 31 participants	• Fuzzy control for changing the set point according to real-time thermal perceptions • Energy savings of 10.73% compared with the energy consumption in PMV feedback control • Energy savings of 20.07% compared with the energy consumption for the fixed temperature set point	[95]

FC system for a single room	Real experiment with an FC system	United Kingdom/24 h test with a cooling and heating power of 0.8 kW	• ANN-assisted control for energy savings • Accuracy of 99.7% was achieved after training with 3 years of building data • Energy savings of 5–11.4% compared those achieved with PID control	[96]
Heater in a house with an area of 296.5 m^2 and a height of 4 m	Simulation with a MATLAB model	United States/The average outdoor temperature was set to be constant at 10 °C, and the indoor temperature was maintained within 18.33–23.89 °C	• RL for improving thermal comfort and minimizing energy costs in smart buildings • The AI was trained with hourly temperature data from March 2019 • Thermal comfort could be improved by 15–30% • Energy savings of 5–12% were achieved	[97]
Air conditioners for an office building with an area of 230.04 m^2	Simulation with EnergyPlus	Turkey/Thermal comfort zone according to ASHRAE-55	• Fuzzy logic controller for organizing the air-conditioning and lighting systems • Energy savings of 16% compared with the energy consumption for the fixed set point of the HVAC system	[98]
Split-type air conditioner with a 2.2-kW cooling capacity and a dehumidifying capability of 1.4 L/h for a 10–18-m^2 space	Real experiment by a certified laboratory for energy efficiency measurement	Taiwan/The air conditioner performance test according to ISO 5151	• The static energy efficiency index, was unchanged when using fuzzy logic with PID control; however, MPC increased the energy efficiency rating by 9.12% • The dynamic energy efficiency index, namely the cooling season power factor, increased by 3.46% and 7.37% when using fuzzy logic with PID control and MPC, respectively	[99]

2.2. Study Case Analytics

The studies listed in Table 1 were performed in 27 countries, and the distribution of these cases by country is illustrated in Figure 2.

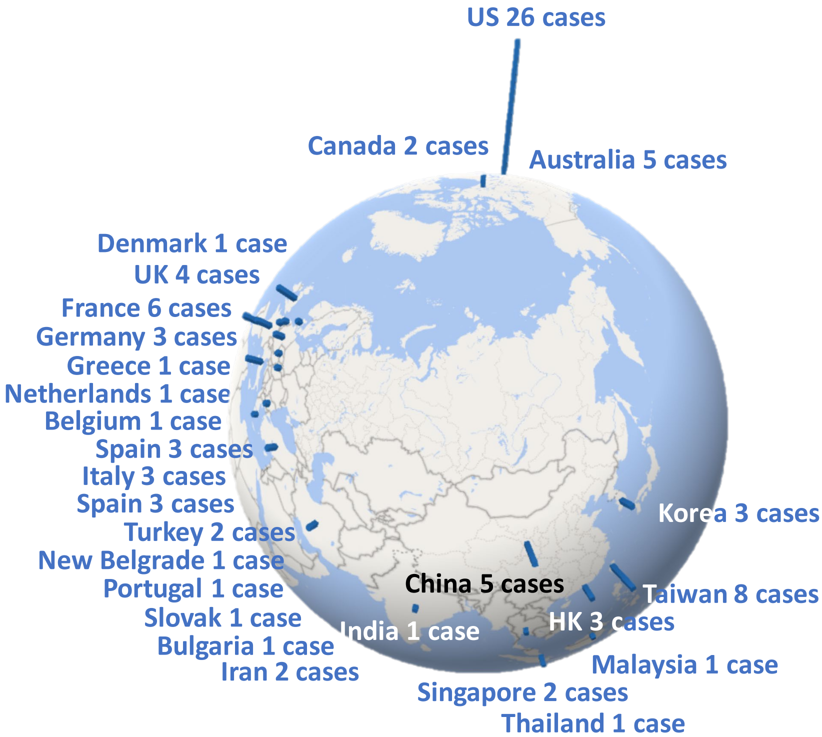


Figure 2. Global distribution of the 85 study cases.

As presented in Figure 2, the AI research cases were distributed worldwide. As summarized in Table 1, all cases clearly state the type of HVAC equipment targeted by the study, the type of building in which the equipment was installed, and which AI technology was applied. Among the aforementioned case studies, 70% focused on energy-saving improvements for chillers; 22% focused on air conditioners; 4% focused on other devices, such as ceiling radiant heating/cooling systems; and 4% focused on HVAC equipment with thermal storage systems. In 40% of the cases, energy savings were verified by experiments, and in 60% of the cases, energy savings were verified by simulation results. The targeted cases were classified according to the floor area of the buildings. Small buildings having a size less than 500 m^2 were investigated in 50% of the research cases, medium-sized buildings with an area of 500–5000 m^2 were investigated in 17% of the cases, and large buildings with an area larger than 5000 m^2 were investigated in 24% of the cases. These statistics are illustrated in Figure 3.

The ratio of the reviewed studies that verified energy-saving effects through numerical simulations or real experiments is 6:4. Such evenly distributed sampling helped clarify the key factors affecting energy savings by AI-based HVAC equipment.

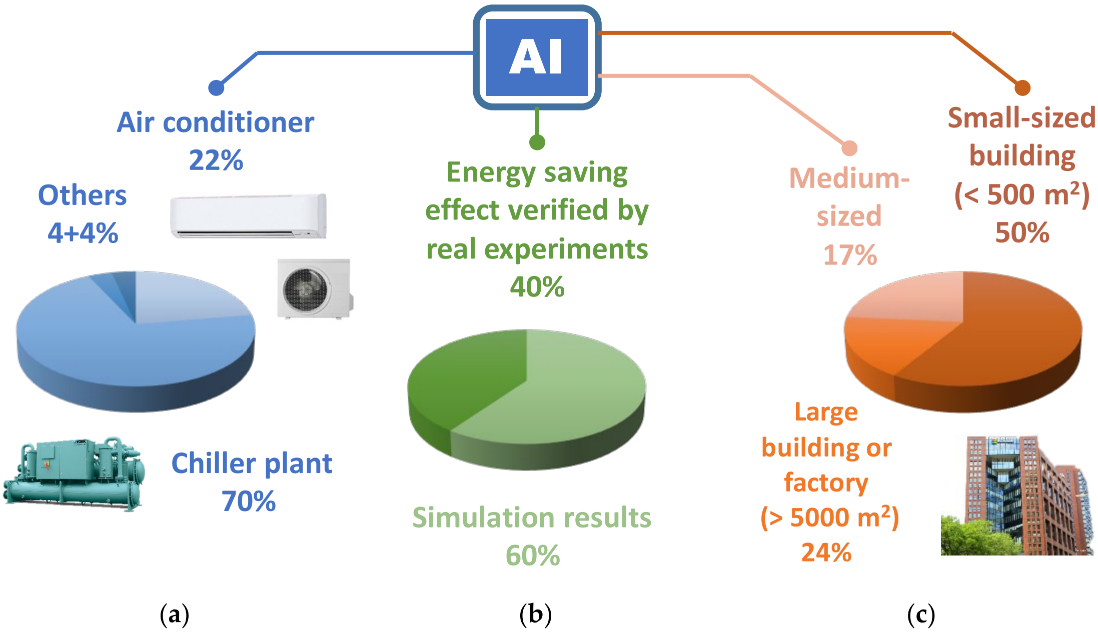


Figure 3. AI for sustainable air-conditioning systems: (**a**) HVAC equipment type, (**b**) method for verifying the energy-saving effect, and (**c**) HVAC equipment for different building sizes.

3. Enterprise Patent Analysis

This study not only investigated the academic cases, but also analyzed the commercialization of AI. In 2020, many HVAC-related companies publicly declared that AI can effectively improve their products, and information relevant to such declarations is summarized in the following section.

3.1. AI-Based HVAC Product

Daikin presented an AI application (an app) to turn on and turn off air conditioners, select the target indoor temperature, and adjust fan speeds and fan mode. It claimed that, by using Daikin AI, the perfect indoor climate can be achieved in every room for every season and time of day. Additional information is available at https://homey.app/en-ca/app/nl.climate.daikin/Daikin-AI/ (accessed on 8 August 2021).

Gree Electric won the world's first AI air-conditioning energy-saving certification from Intertek, which is a British quality assurance company. Intertek conducted a comprehensive evaluation of the energy-saving function of the Gree AI air conditioner according to the NZS 3823.1.1:2012 Australian standard. Energy savings of up to 55% could be achieved. Additional information is available at https://chinahqb.com/news/5420.html (accessed on 8 August 2021).

Google announced that it developed DeepMind, which is an AI platform, to reduce data center cooling bills by 40%. Google began using ML to operate data centers in 2014. Before 2016, DeepMind researchers began working with Google's data center team to considerably improve the utility of data center systems. Using a system of NNs trained for different operating scenarios and parameters within data centers, they created an efficient and adaptive framework to understand data center dynamics and optimize energy efficiency. Additional information regarding the process for creating this network is available in a web report (https://deepmind.com/blog/article/deepmind-ai-reduces-google-data-centre-cooling-bill-40, accessed on 10 August 2021).

IBM announced that they could lower the electricity consumption and costs associated with cooling buildings by an average of 30%. Its website reported a new approach for operating a building's cooling system using ML techniques and Internet of Things (IoT) data. By predicting HVAC energy efficiency and precooling, this approach paves the way for reducing overall building energy consumption, the carbon footprint, and operating electricity costs. Detailed information can be found at https://www.ibm.com/blogs/research/2018/07/reduce-energy-cooling/ (accessed on 10 August 2021).

Johnson Controls announced an AI application for constructing environments through ML. Its application enables systems to learn and improve automatically through exposure to additional data without explicit programming. Johnson Controls demonstrated this application in a smart building in Ireland. Using AI, ML, data analytics, and cloud technologies, electric costs could be reduced by 50%. Additional details are available at https://www.johnsoncontrols.com/insights/2019/bts/applying-artificial-intelligence-to-built-environments-through-machine-learning (accessed on 12 August 2021).

LG Electronics reported a new AI-based air conditioner with 30% increased energy efficiency compared with existing air conditioners. Public information is available at https://www.koreatimes.co.kr/www/tech/2018/01/694_242681.html (accessed on 12 August 2021).

Midea presented an AI- and IoT-based air conditioner with power consumption of 1.5 hp. This Wi-Fi-connected, wall-mounted air conditioner achieved energy savings and could be programmed or controlled with a smartphone to manage the temperature and optimize energy usage. Detailed information on this air conditioner can be found at https://www.midea.com/sg/product/Air-Conditionesrs/AE-PRO-Premium-Multi-Split-(5-Ticks)/Midea-AI-Premium-Multi-Split-Series-Indoor-Unit1 (accessed on 12 August 2021).

Panasonic presented an AI-based air conditioner with the 'ECO' mode. This mode is used to learn about the room environment of occupants and maximize energy savings in each room by automatically adjusting to the optimal ECO level according to the heat load conditions and air-conditioning capacity. Additional information on this air conditioner can be found at https://aircon.panasonic.com/consumer/energy_efficiency.html (accessed on 12 August 2021).

Samsung developed AI autocooling technology. This technology automatically optimizes various modes by analyzing room conditions and energy usage patterns. On the basis of a set preferred temperature, it automatically switches to an appropriate mode. Samsung also announced the 'SmartThings' app. A user using this app on a smart phone can simply tell the AI what they want. The app then suggests the best settings for the air conditioner. Details on the aforementioned technology and the relevant air conditioner can be found at https://www.samsung.com/africa_en/air-conditioners/wall-mount/ar12tshcbwk-fa/ (accessed on 12 August 2021).

Siemens announced the delivery of an AI-based cooling solution for Tier IV data centers. A Tier IV data center is constructed to be completely fault-tolerant with redundancy for every component. These data centers have expected uptimes of 99.995%; thus, they have an annual downtime of 26.3 min. The cooling system for these data centers must not only be energy efficient but must also must be operated in a fault-tolerant mode. A study described in Table 1 focused on fault-tolerant operation. The aforementioned study reported that MPC can enable the fault-tolerant control of AHU VAV systems and can achieve 35% energy savings compared with the energy consumption in conventional fault-tolerant operation. The AI technology developed by Siemens was used in the first Tier IV-certified data center in Paris. Data center energy consumption can be reduced by up to 30% with this AI technology. The operation of the aforementioned data center was scheduled to begin in spring 2021. Additional information can be found at https://www.missioncriticalmagazine.com/articles/93416-siemens-delivers-ai-based-cooling-solution-for-tier-iv-data-center.

The authors of this article cooperated with Hitachi Taiwan (now merged with Johnson Controls). The research team applied an AI-based control to a split-type air conditioner with a cooling capacity of 2.2 kW and a dehumidifying capability of 1.4 L/h. The results revealed that fuzzy logic with PID control could not reduce energy consumption;

however, MPC increased the energy efficiency rating by 9.12%. The dynamic energy efficiency index, namely the cooling season power factor (CSPF), was also used for evaluation. Fuzzy logic with PID control increased the CSPF by 3.46%, and MPC increased the CSPF by 7.37% [85]. More than 10 companies have claimed to use AI for sustainable air-conditioning system design. However, these companies have not revealed the technical information necessary for investigation. Therefore, patents were surveyed in this study to collect sufficient technical information.

3.2. Key Patent Description

Relevant patent applications by the aforementioned companies were investigated. In total, the aforementioned companies, except Hitachi, have applied for more than 100 AI-related patents. Therefore, we did not analyze Hitachi's patents in the present study.

The collected patents were analyzed using an RDF that was developed in this study. Because the number of patents owned by one company may exceed 1000, the analysis was performed in an automated manner. The RDF-based patent survey method is described in the next section. The following sections describe the results of the patent survey and list the key patents held by each company. The patents are described in the alphabetical order of the applying companies.

3.2.1. Patents of Carrier

A total of 157 patents of Carrier were identified from the Derwent Innovation database using the following criteria: CTB = (artificial adj intelligence or machine adj learning or deep adj learning or genetic adj algorithm or expert adj system or knowledge adj base or regression adj tree or support adj vector adj machine or feature adj learning or neural adj network or evolutionary adj algorithm or Reinforce adj learning). Notably, the patent search was not limited to HVAC because this study aimed to obtain a better understanding regarding the extent of a company's AI research and development. Thus, some of the listed patents may not be related to HVAC.

Key patents identified through automated analysis and manual inspection are listed in Table 2.

Table 2. Key patents of Carrier identified in this study.

Patent Name/Translated Name	Abstract of the Patent Content	Ref
Temperature control strategy utilizing neural network processing of occupancy and activity level sensing	The present invention is related to temperature control and contains the following parts: ● A thermostat device that enables an individual to select a set point temperature for a zone ● A sensor for detecting and indicating occupancy status within the zone and the level of activity ● An ANN for receiving the sensor signal and classifying the sensed activity and occupation levels ● A controller that receives ANN output and automatically responds to a difference between the current temperature in the zone and the selected set point temperature	[100]
Predicting the impact of flexible energy demand on thermal comfort	The present invention is related to a computer-implemented method for optimizing the power usage of a building. This method includes the following steps:	[101]

	● Generating a profile for each user in a set of users of the building by using ML ● Retrieving data about the building ● Storing the user profiles and data in a knowledge base ● Calculating power requirements of the set of users according to the user profiles and data	
Mining and deploying profiles in smart buildings	The present invention is related to a computer-implemented method for mining information to configure a file for an intelligent building. This method includes the following steps: ● Monitoring user interactions ● Operating a portion of a smart building by considering user interactions ● Collecting user interactions ● Creating a configuration file for a user	[102]
Building management system having knowledge base	The present invention is related to a building management system (BMS). The BMS interface is configured to receive building system data. A knowledge base is configured to receive BMS data and provide a model of the building. The model includes semantic descriptions of the building and a user interface to access the knowledge base.	[103]
Anonymous chat method and system incorporating machine learning capabilities	The present invention is related to a method for facilitating anonymity. This method can enable automated communication with ML systems. The system can return a response to a query by analyzing its knowledge base.	[104]

3.2.2. Patents of Daikin

Using the aforementioned search criteria, 87 patents of Daikin were identified in the Derwent Innovation database. The key patents of Daikin are listed in Table 3.

Table 3. Key patents of Daikin identified in this study.

Patent Name/Translated Name	Abstract of the Patent Content	Ref
Operation control device for air conditioner	The invention aims to control the operation of each actuator by inputting an operation state, outputting an environmental state, and learning an air conditioner model based on an ANN to determine a specified operation state to meet the target value based on the air conditioner model.	[105]
Data transmission and apparatus, data processing apparatus and a neural network which utilize phase shifted, modulated, convolutional pseudo noise	The present invention is related to the data transmission on an ANN. The innovative content includes a step that modulates maximal-sequence codes which are phase-shifted by different quantities on the basis of considerable transmission data. Then, the modulated maximal-sequence codes are convoluted to obtain transmission data. In the next step, the transmission data are received, and a cross-correlation is obtained with a maximal-sequence code that has been phase-	[106]

	shifted to the same extent as the maximal-sequence code corresponding to the transmission data.	
Air-conditioning system	The information for controlling several air-conditioning apparatuses that air-condition a space is acquired through the Internet. On the basis of the acquired information, the control part that controls each air conditioner separately is provided.	[107]
Machine learning apparatus has learning unit that learns operating conditions of precooling operation or pre-warming operation	The present invention is related to an ML apparatus that determines the driving or running condition for the precooling or preheating operation of an air-conditioning machine. The acquisition part acquires the set temperature, room-temperature data at a certain time, and the external temperature data as a state variable. The ML apparatus contains a learning part that learns the driving or running condition for the precooling or pre-warming operations.	[108]
Heat source system, target operation capacity estimation method and target operation capacity estimation program	The present invention is related to an RL part that learns the relationship between the inputs of the driving and running conditions of a cooling tower. The assessment data acquisition part acquires the energy consumption of the cooling tower to evaluate the control result of the cooling tower and the cooling water pump. The reward calculation part calculates a reward according to the energy consumption.	[109]
Information processing method, information processing device, and program	This information processing method uses datasets acquired from several apparatuses. The acquired information indicates the condition in which each apparatus is driven or operated at a specific time. On the basis of a dataset that includes the information of the power consumption when the apparatus is driven or operated, the process that infers or deduces the power consumption is used as a reference to determine the operation setting according to the conditions. The method can recommend the energy-saving operation settings of an air conditioner to a user.	[110]
Machine learning device, air-conditioning system, and machine learning method	An air-conditioning system with a heat conveyance apparatus provides a thermal medium to the apparatus on the heat-use side from the apparatus on the heat-supply side. The air conditioner includes an ML apparatus that learns the temperature of a heat conveyance apparatus that provides a thermal medium and the flow volume.	[111]
Air-conditioning system, machine learning device, and machine learning method	The present invention is related to an air-conditioning system and optimizes the operating capacity of an outdoor air-conditioning device. The developed air-conditioning system contains a state variable acquisition unit for acquiring state variables, including the condition of the outdoor air, the condition of the inside air, the operating condition of the outdoor air-conditioning unit, the operating condition of the indoor air-conditioning	[112]

	unit, and the temperature and humidity set for the space. The ML unit performs learning by associating the state variable and operating capacity. This unit contains a reward calculation unit for calculating a reward correlated with the total energy consumption. The learning unit uses the reward to achieve energy savings.	
Air-conditioning control system, air-conditioning machine, and machine learning device	The purpose of the present invention is to provide numerous users with an air-conditioning environment by not only controlling an indoor space to maintain uniform temperature but also controlling each area to achieve an optimal temperature for increasing energy savings.	[113]
Machine learning device	The present invention is related to a distributed AI system between one Bluetooth low energy (BLE) module and another BLE module that includes an acquisition unit and a learning unit. The acquisition unit acquires the air conditioner arrangement information and beam arrangement information for obtaining a state variable. The aforementioned information indicates the relationships of one BLE module with other BLE modules. The learning unit learns by associating a state variable with a radio-wave propagation state between two BLE modules.	[114]
Remaining value calculation system for air conditioner and assistance system for air conditioner	The developed remaining value calculation system includes a calculation unit that calculates an initial predicted remaining value or actual-use predicted remaining value based on the actual usage with respect to the remaining value after usage for a set period.	[115]

3.2.3. Patents of Google

Using the aforementioned search criteria, 5370 patents of Google and its parent company, namely Alphabet, were identified in the Derwent Innovation database. Notably, the patent search was not limited to HVAC because this study attempted to obtain a superior understanding of the extent of a company's AI research and development. In particular, Google does not focus on HVAC but is a key player in the global development of AI technology. Therefore, some of the listed patents of Google may not be related to HVAC.

Key patents of Google identified using automated analysis and manual inspection are listed in Table 4.

Table 4. Key patents of Google identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
System and method for zone heating and cooling	The present invention is related to a system for zoned temperature control. The method uses several thermostats to measure temperatures in multiple zones. A central system could be configured to obtain the optimal set point according to the available air flow, the temperature of the air, and zone priority relative to other zones.	[116]

Multi-frame prediction for hybrid neural network/hidden Markov models	The present invention is related to transforming an audio input signal by using an NN and hidden Markov models. This hybrid method can enable accurate speech prediction.	[117]
Temperature controller with model-based time to target calculation and display	A thermostat for controlling the air temperature in a building is described. The time associated with causing the controlled air temperature to reach a target temperature is estimated and displayed to the user. User input indicating the target temperature can be received, and temperature estimation and display can be achieved in real time.	[118]
Privacy-aware personalized content for the smart home	The thermostat includes one or more sensors configured to collect occupant activity data and a network interface configured to communicate with occupants. The signature-based thermostat model uses a current value of one model input and a current measure of occupant activity to provide control signals to the HVAC system and replace the original set point.	[119]
Methods and systems for identification and correction of controlled system data	Computational methods and systems that collect operational data from an intelligent controller to identify information or correct information about a device and a system controlled by the intelligent controller are disclosed.	[120]
Privacy-aware personalized content for the smart home	A computing system may operate within a local area network. This computing system may include a network interface configured to receive a set of rules from a remote content server.	[121]
Smart home environment networking systems and methods	Various systems and methods related to smart home networking are presented. A low-power smart home device that is exclusively battery-powered is described. The low-power smart home device transmits data through a low-power communication protocol to a hub smart home device. The hub smart home device transmits the received data to a cloud-based server system by using a high-power communication protocol.	[122]

3.2.4. Gree Electric Patents

Using the search criteria, 819 patents of Gree Electric were identified in the Derwent Innovation database. The key patents of Gree Electric were identified in Table 5.

Table 5. Key patents of Gree Electric identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
Air conditioner control method and control system	An air conditioner control method is described. This method obtains characteristic user parameters through a pre-set database lookup based on the user characteristic parameter interval, the average thermal sensation index, and the pre-set database of user	[123]

	characteristic parameters corresponding to the average thermal sensation index interval. This method controls the air conditioner operation according to the knowledge database.	
Air conditioner control method and control system	The air outlet for this air conditioner control method uses environmental image information from the target area. The control method can modify the wind direction and speed to achieve temperature control of the environment.	[124]
Air conditioner operation mode adjusting method and device and air conditioner	The present method is related to the adjustments of the running mode of an air conditioner. This method can obtain current position information for occupants or heat sources. According to a preconfigured first condition and information such as images, the method adjusts the air supply of the air conditioner to achieve temperature control of the environment.	[125]
Creating a method for an air conditioner control model based on neural network, control method and air conditioner	A method of creating an air conditioner control model based on ANNs is proposed. This method comprises the following steps: ● Obtaining the user movement range information ● Obtaining the user body temperature information and the environmental temperature information ● Changing the set point according to the movable range information for repeatedly acquiring body temperature information and environmental temperature information for obtaining an air conditioner control model.	[126]
Air conditioner control method and device, storage medium and air conditioner	The developed air conditioner control method comprises the following steps: ● Acquiring the external environment and user state parameters ● Providing an input to an ANN ● Training an ANN model to obtain the human body comfort level value and control the air conditioner according to this value.	[127]
Air conditioner control method and device and air conditioner	The developed method for controlling an air conditioner comprises the following steps: ● Obtaining object information for at least one object in the pre-set area ● Pre-setting the model object by using the information of at least one object for processing ● Obtaining the operation data of the air conditioner device corresponding to the object ● Obtaining the predetermined model by using a trained ANN with multiple datasets. Each dataset comprises object information and operation data	[128]

	● Control the air conditioner device according to at least one object, the operation data, and the environment parameters of the area.	
Control method and control device for intelligent device	The proposed control method for intelligent devices involves the following steps: ● Obtaining environmental data and acquire control parameters according to the environmental data ● Linking intelligent devices with each other ● Linkage of intelligent devices according to the control parameters.	[129]
Information processing method and device, storage medium and electronic device	The developed information processing method involves obtaining environmental information for the point where the air conditioner is located.	[130]
Method and device for controlling an air purifier	The developed method for controlling an air purifier comprises the following steps: ● Obtaining the indoor and outdoor air quality, air exchange capacity, and air exchange rate ● Inputting sensor data into an ANN-based air quality prediction model. The indoor air quality is predicted to determine the time at which the air purifier should be turned off.	[131]
Air conditioner intelligent control method, computer-readable storage medium and air conditioner	The developed method is an intelligent control method for detecting the relative parameters of an air conditioner, including the running time and running parameters, to achieve real-time temperature control precisely. The precision is determined using the following steps: ● Detecting the air cycling time according to a relative parameter ● Matching the operation parameter with the corresponding set air conditioner target ● Determining the operating capacity value and target of the energy efficiency parameter ● Calculating an actual operation time.	[132]
Home appliance energy-saving model construction method based on genetic algorithm, control method and home appliance	A method for constructing a household appliance energy-saving model based on the GA was developed. This method has the following steps: ● Obtaining the current operating state of the household appliance by changing the operating condition setting for the running state ● Obtaining the operation parameter of the appliance under the set running state according to the operating condition ● Using the preset running state under the operating parameter for the home appliance to construct a household energy-saving model	[133]

	• Using the GA for the appliance operating parameter under the set operation state by performing optimization processing to obtain the running optimization parameter for the appliance • Inputting the household energy-saving model into the operating condition of the home appliance to set a running optimization parameter with the home appliance running state as the output.	
Method and device for determining frosting state of air conditioner	An air conditioner frosting state determination method was developed. This method involves obtaining an air conditioner's initial characteristic operating information with a probabilistic NN model trained in advance to determine the frost state of the air conditioner at a subsequent time.	[134]
Air conditioner running state control method and device, processor, and air conditioner equipment	An air conditioner control method with the following steps is proposed: • Obtaining a first parameter in the predetermined three-dimensional space of the parameter set and a second parameter set (the first parameter set describes the pre-set features of the static object in the three-dimensional space, and the second parameter set describes the feature of the dynamic object in the three-dimensional space) • Using an ANN model to analyze the first and second parameter sets • Determining the operating state of the air conditioner.	[135]
Control method and equipment	An energy-saving control model was constructed through deep Q-learning. The energy-saving control model is used to predict the current running state. The device executes the *Q* value corresponding to the next action and outputs the action corresponding to the maximum *Q* value.	[136]
Control method and system for intelligent equipment in multiple regions	A control method was developed for a multi-region smart device that uses a bus connecting intelligent devices from multiple regions. For each intelligent device in each area, the following steps are executed: • Obtaining the area from the executed action knowledge according to the current environmental parameter information of the smart device for inquiring the target execution action of the intelligent device area • Locating the smart device corresponding to the current environment parameter information • Using the executing action and current environmental parameter information based on the target query to determine instructions for control-	[137]

	ling the execution of an action by the smart device (the control command is sent to the smart device through the bus).	
Air conditioner fault prediction method and device, storage medium and air conditioner	The developed method can conduct fault prediction for air conditioners and involves the following steps: ● Training the fault prediction model of an air conditioner with an ANN ● Obtaining the current operation data of the air conditioner, including the external and internal data ● Inputting the current operation data to the fault prediction model to predict the fault If the air conditioner is predicted to have a fault, the corresponding prompt information is sent to the user of the air conditioner.	[138]
Control method and device of air conditioner	The developed method is an air conditioner control method that optimizes the operation of an air conditioner on the basis of the GA.	[139]
Equipment control method and system and network side equipment	The developed method is a device control method that can obtain information on a preset region in one or more spaces.	[140]
Air conditioner air supply control method based on three-dimensional space, computer readable storage medium and air conditioner	The developed method is an air conditioner control method based on a three-dimensional space. This method tracks human body movements and collects spatial images to calculate the distance between the human body and the air conditioner. According to this distance, the air conditioner's fan mode is adjusted.	[141]
Intelligent air supply method and device of air conditioner and air conditioner	The developed intelligent air conditioner blowing method obtains a user voice signal to aim the air conditioner's air supply region at a target.	[142]
Self-adaptive adjustment method and device of air conditioner running state	The present invention is related to a self-adapting adjustment method for an air conditioner's operating state.	[143]
Air-conditioning control method and device	An air conditioner control method with the following steps is proposed: ● Constructing a reward matrix according to multiple groups of target air conditioner operating parameters, including indoor temperature, outdoor temperature, set temperature, indoor evaporator median temperature, outdoor condenser median temperature, compressor operation frequency, opening of the electronic expansion valve, and rotating speed of the external fan ● Calculating the maximum expected benefit of executing an action in the current state by using the first reward matrix and Q-learning algorithm (the current state is characterized by the current indoor environmental temperature and current outdoor environmental temperature)	[144]

	● Performing the current action by modifying the compressor operating frequency, electronic expansion valve, and external fan rotating speed ● Obtaining the target action parameter under the maximum expected profit ● Controlling the operation of the air conditioner according to the target action parameter.	
Control method and device for air conditioner	A control method and device were developed for an air conditioner. The developed method has the following steps: ● Constructing a first reward matrix according to multiple sets of air conditioner operating parameters ● Calculating the maximum expected benefit of performing an action for the current state by using the first reward matrix and deep Q-learning (the current state is represented by the current indoor ambient temperature and current outdoor ambient temperature, and the current action is represented by the current operating frequency of a compressor, the current opening degree of an electronic expansion valve, and the current rotating speed of an external fan) ● Obtaining target action parameters by identifying the maximum expected reward ● Controlling the operation of the air conditioner according to the target action parameters, which include a target compressor operating frequency, a target electronic expansion valve opening, and a target rotation speed for the external fan The invention overcomes the poor adaptability of air-conditioning control in similar technologies that is caused by the requirement of manually setting the closed-loop automatic control parameters of the air conditioner.	[145]
Air conditioner control method and device, storage medium and processor	An air conditioner control method with the following steps is proposed: ● Obtaining the target information in a predetermined space ● Acquisition of the target information by a microwave radar ● Controlling the air conditioner according to the radar information.	[146]
Air conditioner energy efficiency index determination method and device, computer equipment and storage medium	A method is developed for determining air conditioner energy efficiency levels by obtaining the air conditioner operating data and the energy efficiency correction coefficient of the air conditioner. This method can determine the energy efficiency of the air conditioner according to the energy efficiency ratio of the corrected air conditioner.	[147]

Method and device for controlling air conditioner, air conditioner, storage medium and processor	A control method for an air conditioner with the following steps is proposed: ● Determine whether the absolute value of the difference between the current indoor environment parameter and the target indoor environment parameter of the air conditioner is greater than a set threshold value ● If the absolute value of the difference between the current indoor environment parameter and the target indoor environment parameter is greater than the set threshold value, set the air conditioner to operate in the first control mode ● Through the first adjustment of the current indoor environment parameter, the absolute difference between the current indoor environment parameter and the target indoor environment parameter is reduced ● If the absolute difference between the current indoor environment parameter and the target indoor environment parameter is less than or equal to the set threshold value, set the air conditioner to operate in the second control mode ● Through the second adjustment of the current indoor environment parameter, the absolute difference between the current indoor environment parameter and the target indoor environment parameter is reduced.	[148]
Linkage control method and device for air conditioner and ventilator	A linkage control method for an air conditioner and ventilator is proposed. This method determines the operating mode of the ventilator corresponding to a prediction of outdoor moisture content.	[149]
Method, system, and device for controlling air-conditioning unit and air-conditioning unit	An air-conditioning unit control method with the following steps is proposed: ● Obtaining the adjustable environmental range of the user ● Checking if the comfort of the user is unchanged within the adjustable environment range ● Obtaining real-time energy efficiency values ● Determining the energy efficiency state according to the real-time energy efficiency value ● Adjusting the operating parameter to improve the real-time energy efficiency value according to the energy efficiency state.	[150]
Hotel air conditioner control method and device and hotel air conditioner	A control method for a hotel air conditioner with the following steps is proposed: ● Constructing a hotel air conditioner control model ● Obtaining the actual application scene of the hotel air conditioner	[151]

	● Inputting the actual application scene into the hotel air conditioner control model to obtain the control parameter ● Controlling the hotel air conditioner according to the control parameter.	
Multi-split air conditioner energy consumption metering method and system	The developed multi-connected energy consumption metering method is executed as a service. In this method, an ANN model is used to correct the first energy consumption data and obtain modified energy consumption data.	[152]
Intelligent air conditioner control method and device, computer equipment and storage medium	An intelligent air conditioner control method is developed. This method involves obtaining current environmental information to construct a parameter-adjusting model based on an ANN.	[153]
Gymnasium air conditioner control method and device, controller, and air-conditioning system	A control method for an air conditioner in a gymnasium is proposed. This method comprises the following steps: ● Obtaining the gymnasium environmental data, functional partition data, and human body data ● Determining the optimal operating parameters of the air conditioner according to the gymnasium environmental data, function partition data, and human body data ● Controlling the air conditioner according to its optimal operating parameters.	[154]
Control method and device of kitchen air conditioner, controller, and electric appliance system	A control method for a kitchen air conditioner is proposed. This method involves the following steps: ● Obtaining kitchen environment data and human body data ● Determining the corresponding application scene and the user use condition according to the kitchen environment data and the human body data ● Obtaining the optimal operating parameters of the air conditioner in the application scene and the user use condition by using an ANN ● Controlling the air conditioner according to the optimal operation parameters.	[155]
Method and device for determining energy consumption coefficient, storage medium and electronic device	A method for determining the energy consumption coefficient is proposed. This method involves obtaining the environment and power data of a target air conditioner and inputting these data into a dense NN to predict the energy consumption coefficient of the air conditioner.	[156]
Fresh air control method, computer device and computer readable storage medium	The present invention is related to a fresh air control method. By obtaining indoor pollutant concentration, PID control is performed according to the target new air quality. By using a GA, the PID parameters are optimized.	[157]

3.2.5. Patents of IBM

A total 7959 IBM patents were identified. The key patents of IBM identified through automated analysis and manual inspection are listed in Table 6.

Table 6. Key patents of IBM identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
Energy saving control for data center	A data center includes at least one rack containing electronic devices, a data center air-conditioning system (DCAC), and an environmental parameter monitoring system. According to the environmental parameters and corresponding relationships between sets of setting parameters for the DCAC, a control model is determined by an ANN. The power consumption of the DCAC is also obtained.	[158]
Knowledge-based models for data centers	A method is proposed to construct a model of thermal distributions in a data center. This method involves the following steps: ● Obtaining vertical temperature distribution data for multiple locations throughout the data center ● Plotting the vertical temperature distribution data for each location as an s-curve; the vertical temperature distribution data indicate the physical conditions at each location on the s-curve ● Representing each of the s-curves with a set of parameters that characterize the shape of the s-curve ● Using a knowledge-base model of predefined s-curve types, which includes the s-curve representations, to analyze thermal distributions and associated physical conditions at multiple locations throughout the data center.	[159]
Computer-based extraction of complex building operation rules for products and services	A method for generating an operational rule associated with a building management system (BMS) is developed. This method includes identifying a first pattern associated with a series of operational observations corresponding to a property of the building management system by using a processing device, correlating a first contextual attribute with the first pattern, and deriving the operational rule at least in part based on the first pattern and the first contextual attribute.	[160]
Estimating energy savings from building management system point lists	A software program is developed that uses real historic BMS data and machine logic to estimate an amount of energy that would have been consumed. This program performs the following steps: ● Receiving actual BMS information related to the operation of a first set of appliances located in the first building during the first time interval ● Selecting a first proposed rule set ● Determining a first contra factual energy resource use value based, at least in part, on the first actual BMS information. The first contra factual use value corresponds to a quantity of energy resources.	[161]

Computer-based extraction of complex building operation rules for products and services	A method of generating an operational rule associated with a BMS is proposed. This method includes identifying a first pattern associated with a series of operational observations corresponding to a property of the BMS by using a processing device, correlating a first contextual attribute with the first pattern, and deriving the operational rule, at least in part, according to the first pattern and the first contextual attribute.	[162]
Initialization method used for radial base function neural network nodes for reinforcement learning incremental control system	According to one or more embodiments of the present invention, a computer-implemented method for adjusting a process variable by using a closed-loop system with an initializing a radial basis function (RBF) NN is proposed. By using a maximum error, maximum first-order change in error, maximum second-order change in error, and maximum output increment, the proposed method can adjust and change the process variable incrementally.	[163]

3.2.6. Patents of Johnson Controls

A total of 119 patents of Johnson Controls were identified. The key patents of Johnson Controls identified through automated analysis and manual inspection are listed in Table 7.

Table 7. Key patents of Johnson Controls identified by this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
Smart transducer plug-and-play control system and method	A BMS including a communications bus, field devices, a cloud service including an ML engine, and a controller for an HVAC device is proposed. The controller communicates with the cloud service and is configured to transmit messages. By compiling a list of connected field devices, the plug-and-play control system can select a control logic file for the HVAC device according to its identified characteristics.	[164]
Systems and methods for estimating a return time	Systems and methods for estimating a time to cool down or warm up a building zone from a temperature setback condition are provided.	[165]
Predictive building control system with neural network-based constraint generation	A predictive building control system and predictive controller are proposed. The proposed predictive building control system comprises heating and cooling equipment in a building. The proposed predictive controller comprises one or more optimization controllers configured to perform an optimization to generate set points for the equipment at each time step during an optimization period.	[166]
Building management system with simulation and user action reinforcement machine learning	A method is proposed for controlling energy usage of one or more building devices associated with a building space. This method includes the following steps: ● Simulation by one or more processing circuits one or more operating values of one or more building devices for various environmental conditions by varying one or more operating values	[167]

	• Detection and recording of user behaviours that cause at least one of the environmental conditions of the building space to change • Determination of the penalties by increasing the number of penalties associated with a first set containing one or more operating values responsive to user behavior that causes changes in the values of one or more environmental conditions associated with the first set • Selecting one or more operating values from the set of operating values according to one or more predicted environmental conditions and a penalty probability associated with each of the one or more operating values by using one or more processing circuits. The penalty probability is based on the number of the penalties and the operation of one or more processing circuits. On the basis of the aforementioned steps, one or more building devices can control the physical condition of a building space according to the selected operating values.	
Building management autonomous HVAC control using reinforcement learning with occupant feedback	The BMS comprises a voice assistance device, one or more processors, and one or more computer-readable storage media coupled to the processors. The BMS controls an HVAC system to adjust the temperature of the zone or space according to occupant feedback.	[168]
Building management system with artificial intelligence for unified agent-based control of building subsystems	A BMS with AI-based control of a building is proposed. This BMS contains a processing system with one or more processing circuits and one or more non transitory memory devices. The processing system is configured to implement multiple data collectors, a learning engine, and multiple cognitive agents.	[169]
Automatic threshold selection of machine learning/deep learning model for anomaly detection of connected chiller	A chiller threshold management system is proposed. This system includes one or more memory devices and one or more processors. The memory devices are configured to store instructions to be executed on the processors. The processors are configured to determine whether chiller fault data exist in the chiller data used to generate multiple chiller prediction models.	[170]
Building management system and methods for predicting catastrophic HVAC equipment failure	The developed BMS is configured to monitor and control building equipment. The BMS includes a number of sensors configured to transmit input data associated with the building equipment. The method can predict catastrophic HVAC equipment failure.	[171]
Predictive diagnostics system with fault detector for preventative maintenance of connected equipment	The developed BMS includes connected equipment configured to measure various monitored variables and a predictive diagnostics system configured to receive the monitored variables from the connected equipment. The diagnostics system generates a probability distribution for the monitored variables and determines a boundary for the probability distribution	[172]

	by using a supervised ML technique to separate normal conditions from faulty conditions.	
Adaptive selection of machine learning/deep learning with optimal hyper-parameters for anomaly detection of connected chillers	A model management system for a building is proposed. This model includes one or more memory devices and processors. The processors are further configured to generate a first performance evaluation value for each chiller shutdown prediction model. An evaluation technique is used when chiller fault data are detected, and a second performance evaluation value is generated for each chiller shutdown prediction models.	[173]
HVAC control system with model-driven deep learning	A system that includes operating equipment is developed to control the variable state or condition of a space and determine a set of learned weights for an ANN. By modeling the estimated cost of operating the equipment, HVAC equipment can be controlled in accordance with the control dispatch.	[174]
HVAC control system with cost target optimization	A BMS including HVAC equipment is proposed to obtain a cost function that characterizes the cost of operating the HVAC equipment. This method obtains a dataset related to the building and determines the current state of the building by applying the dataset to ANN. It can determine a temperature set point for each time step in a future time period.	[175]
Analysis system with machine learning-based interpretation	The system consists of one or more sensors in communication with the building equipment. The sensors can detect characteristics of the building equipment. The system further comprises a computing device in communication with the sensors and in the same geographic location as the sensors. The computing device comprises one or more memory devices configured to store instructions that, when executed on one or more processors, cause the one or more processors to receive data from the sensors. These data are collected according to the detected characteristics. The processors also generate the predicted performance of the building equipment with an ML model that includes prior data that is substantially similar to the current data.	[176]
Variable refrigerant flow, room air conditioner, and packaged air conditioner control systems with cost target optimization	The controller is configured to obtain a cost function that characterizes the cost of operating the cooling device over a future time period. It obtains a data set relating to the building, determines the current state of the building by applying the data set to an NN, selects a temperature bound associated with the current state, augments the cost function to include a penalty term that increases the cost if the indoor air temperature violates the temperature bound, and determines a temperature set point for each of time step in a future period. The temperature set points achieve the target value of the cost function over the future time period.	[177]

	The controller is configured to control the cooling device to drive the indoor air temperature towards the temperature set point.	
Building management system with apparent indoor temperature and comfort mapping	The proposed method involves obtaining measurements of a dry bulb temperature, a relative humidity, and an airflow rate for an indoor space. This method also involves calculating an apparent temperature for the indoor space by using measurements and generating a visualization that includes a comfort band and a value for each apparent temperature, the dry bulb temperature, the relative humidity, and the airflow rate in the indoor space.	[178]
Building management system with space graphs	A system is proposed for operating a building and managing building information with spatial graphs. The proposed method causes one or more processors to receive building data from one or more building data sources and generate relationships between entities according to the building data.	[179]
Building system with a time-correlated reliability data stream	The developed BMS includes one or more memory devices. The building device data comprise numerous data samples and can be used to generate a time-correlated data stream. The time-correlated data stream comprises values of multiple samples for a data point. The instructions cause the one or more processors to generate a time-correlated reliability data stream for the data point. The time-correlated reliability data stream consists of numerous reliability values, which indicate the reliability of data points.	[180]
Building management system with dynamic energy prediction model updates	The proposed BMS includes building equipment that can affect the variable state or condition of a building. This BMS includes a controller with a processing circuit. The processing circuit is configured to obtain an energy prediction model to predict energy requirements over time.	[181]
Building system with performance identification through equipment exercising and entity relationships	The developed building system is applicable to a building with one or more memory devices configured to store one or more instructions that, when executed on one or more processors, cause the processors to generate building entity data. The instructions cause the processors to identify one or more relationships between one or more building entities according to a relational model. These relationships indicate the operation of the entities; thus, building performance issues can be detected by analyzing the building entity data and their relationships.	[182]
Central plant control system with sub-plant rank generator	A controller is proposed for a central plant with sub-plants operating to produce resources consumed by a building. The proposed controller contains a processing circuit that includes a processor and memory storage instructions executed by the processor. The	[183]

	memory includes an offline rank generator that receives historical sub-plant allocation data and generates sub-plant ranks based on these data.	
Building an HVAC system with modular cascade model	The proposed controller for HVAC equipment stores a cascaded model that includes a disturbance factor. This model is configured to predict a heat disturbance affecting the building zone as a function of one or more exogenous parameters. The model is also configured to predict the temperature of the building zone as a function of the heat disturbance and the heating or cooling provided to the building zone by HVAC equipment.	[184]
User experience system for improving compliance of temperature, pressure, and humidity	A BMS using user experiences is proposed for HVAC equipment in a building. The system uses training temperature, pressure, and humidity (TPH) data from one or more sensors; identifies a fault according to the TPH sensor data; provides the TPH sensor data and fault to the ML engine, outputs a corrective action to resolve the fault; and generates a work order for a user according to the TPH sensor data, the determined fault, and the corrective action.	[185]
Transfer learning of deep neural network for HVAC heat transfer dynamics	A transfer learning method that involves the following steps is proposed: ● Training a DL model by using the first dataset ● Initializing the parameters of the target model for a second building by using the parameters of the DL model ● Collecting a second dataset of input–output data for a second building ● Training the target model for the second building by using the initialized parameters of the target model and the second dataset ● Controlling building equipment by using the target model	[186]

3.2.7. Patents of LG Electronics

A total 2922 patents of LG Electronics were identified. The key patents of LG Electronics identified after automated analysis and manual inspection are listed in Table 8.

Table 8. Key patents of LG Electronics identified in this study.

Patent title/Translated Title	Abstract of the Patent Content	Ref
Air-conditioning system and control method thereof	An air-conditioning system with a communication module to detect the three-dimensional space is proposed. The communication module receives heat source information from a heat sensing unit. The indoor unit contains vanes and a control unit. The vanes open or close a hole to exhaust air. The control unit controls the opening of vanes based on the heating source information and the opening angle of the selected vane to control air flow.	[187]
Air conditioner and method for controlling the same	The developed air conditioner has a specific function for providing a user with a guide to use it. The user manual is presented on the display of the air conditioner in the form of images and is also audibly output using a speaker.	[188]
Control method of inverter air conditioner at night	An inverter-control air conditioner with the following steps is proposed: ● Initialization and remotely starting the period of frequency conversion of the air conditioner system in the standby state ● Using an ANN to identify the operation mode	[189]
Refrigeration control method of air conditioner	A refrigeration control method for an air conditioner is proposed. This method comprises five stages: ● In the first stage, the frequency of the compressor is determined according to the set temperature ● In the second stage for detecting the initial set temperature, the indoor temperature of the user, the outdoor temperature, and the indoor fan air quantity are detected a certain time interval after a change in the room temperature ● On the basis of the input of the first detection data from previous stage, whether the indoor load is sufficient is determined, and the set temperature change for the load is determined ● According to the current set temperature, a new set temperature is determined ● The new set temperature is output to determine the compressor operating frequency and operating conditions	[190]
Artificial intelligence air conditioner system and method of controlling an air conditioner system	The developed air-conditioning system includes several air-conditioning devices located or installed at various air-conditioning sites in a decentralized manner. A control setting with the plurality of air conditioner devices as control devices may be created irrespective of the installation position and the connection state of each air conditioner.	[191]

Artificial intelligence air purifier and method for controlling the same	The developed novel air purifier has an audio input unit with numerous microphones for receiving audio signals. A control unit can recognize sound and generate a control signal according to the sound recognition result. Therefore, sounds generating air pollution can be recognized, and air-purifying functions can be effectively performed.	[192]
Artificial intelligence air conditioner and control method thereof	An air conditioner with a camera that obtains an image of an indoor space is proposed. By using the image, the location of an occupant in the indoor space can be separated into multiple areas. By distinguishing the living area, the direction of airflow can be controlled towards the residential living areas in an intensive cooling or heating mode.	[193]
A method for an air conditioner	A control method can be used to recognize the temperature and humidity of the section set point and to determine the humidity according to the arbitrary cell unit temperature feedback.	[194]
Method for operating an air conditioner	An operation method for an air conditioner with the following steps is proposed: ● Collection of the indoor climate information through multiple sensors ● Receiving information on the external environment through communication ● Output of the inner climate information and the recommended operation mode according to the external environmental information.	[195]
Air conditioner based on parameter learning using artificial intelligence, cloud server, and method of operating and controlling thereof	The proposed air conditioner includes at least one computer memory connectable to at least one processor and instruction storage. The proposed method involves operations to generate parameters in an operating mode, which was executed only within a pre-set time range to control the air conditioner according to the operating mode information obtained during the pre-set period by modifying the wind direction or air volume by at least one blowing unit or by switching the operation mode of the outdoor unit. The operation mode is obtained from at least one ML network.	[196]
Air conditioner	The developed air conditioner can receive control commands from a cloud server to calculate its next status by using a built-in learning unit. The controller sets the wind direction and the air volume of the blower.	[197]
Method for controlling an air conditioner	The developed air conditioner is configured to control the blower and an outdoor unit according to a prediction calculated from a learning unit or obtained from a cloud server.	[198]
Artificial intelligence device	The developed air conditioner includes one computer memory that is operably connected to at least one processor and instruction storage. When executed, the blowing unit can change the wind direction and air volume, and the operation mode of an outdoor unit can be	[199]

	changed after a certain time. The operating mode information includes at least one result factor obtained from at least one ML engine.	
Air conditioner	The developed method for operating an air conditioner involves the following steps: Obtaining an image with a camera ● Determining the distance between an occupant and the air conditioner and the direction from the occupant and air conditioner ● Classifying air blowing spaces as intensive or non-intensive according to the ML image by using an ML network ● Controlling the air conditioner to operate in an intensive operation mode in the identified intensive air blowing areas according to the aforementioned distance and direction ● Controlling the air conditioner to operate in an operation mode with respect to the intensive and non-intensive air blowing areas ● The time duration for the intensive operation mode is smaller than that for the non-intensive operation mode.	[200]
Method for air conditioning and air conditioner based on thermal comfort	A method is proposed to acquire a thermal image in an air-conditioning space by using an image sensor, acquire the thermal comfort information of a human body by using the thermal image, and control the air-conditioning of the air-conditioning space according to the thermal comfort information.	[201]
Air conditioner based on parameter learning using artificial intelligence, cloud server, and method of operating and controlling thereof	An air conditioner is configured to control at least one operation mode and adjust its set values, including its set temperature, wind volume, and wind direction. The control method can update the learning result by using feedback on the adjusted set value.	[202]
Artificial intelligence-based air conditioner	The present invention is an AI-based air conditioner that includes a communication unit and an image capturing system with member data, which enable it to distinguish between members. The air conditioner can learn members to modify its operation to reach the optimal condition to reduce power consumption and increase convenience for individual members	[203]
Artificial intelligence-based air conditioner	An air conditioner is proposed. This air conditioner comprises a compressor, a casing that includes an intake hole and a discharge hole, a fan motor that is installed in the casing and blows air, a discharge vane in the discharge hole, a vane motor for operating the discharge vane, a sensor that acquires data to identify members, memory to store training results corresponding to the identified members, and a processor. The processor can	[204]

	be used to identify a member present in an indoor space by using the training result.	
Cloud server and air conditioner based on parameter learning using artificial intelligence, and method for driving and controlling air conditioner	The present invention is a technology related to a cloud server and an air conditioner that conducts AI-based parameter learning. This technology can be used to calculate the operating period of an air conditioner and then to calculate the necessary parameters during the operating period in accordance with the set temperature. Thus, the air conditioner can be efficiently operated in a period divided into at least two operating modes for the air conditioner.	[205]
Method for predicting filter of air purifier using machine learning	The proposed method can predict the lifespan of a filter in an ML-based air cleaner. An ML-based filter lifespan prediction method precisely predicts the lifespan of a filter by inputting the concentration data and a history related to use of the air cleaner into a lifespan prediction model. The proposed method can be used to determine the purifying efficiency and exchange time for the filter.	[206]

3.2.8. Patents of Midea Group

A total of 1850 patents filed by the Midea Group were identified. Table 9 lists the key patents of the Midea Group identified through automated analysis and manual inspection.

Table 9. Key patents of the Midea Group identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
Control method of air conditioner, air conditioner and storage medium	A control method for an air conditioner is proposed for sensing humans. This sensing method includes the following steps: ● Obtaining a human body image for the monitored area ● Obtaining the resistance of insulation (ROI) of clothing from the human body image ● Matching clothing ROI by a clothes classifier ● Obtaining the current clothing thermal index of the human body ● Judging the cold and hot sensing levels of the human body ● Adjusting the set point if the current operation mode of the air conditioner does not match with the cold and hot sensing levels.	[207]
Multi-split air-conditioning system and its energy-saving control method, control pa and storage medium	A multi-split air-conditioning system with an energy-saving control method is proposed. This method includes the following steps: ● Detecting the operational state of the indoor unit ● Determining the energy consumption level of the multi-connected air-conditioning system according to the working state of the indoor unit ● Judging whether the energy level is at a predetermined consumption interval. If the energy level is at	[208]

	a predetermined consumption level, the indoor unit is controlled to maintain the current working state; otherwise, this unit is used to perform an energy-saving control step.	
Multi-split air-conditioning system, energy-saving control method and device of multi-split air-conditioning system and storage medium	The proposed energy-saving control method for a multi-split air conditioner system involves the following steps: ● Obtaining the starting operation state ● Calculating the parameters for the indoor unit according to the running information ● Judging whether the difference is greater than the pre-set threshold value. If the difference is greater than the pre-set threshold value, the first indoor unit is controlled such that its difference is greater than the difference corresponding to the pre-set threshold value; otherwise, the state of the indoor unit is maintained in the current working state.	[209]
Running state control method and device, purifier, and storage medium	An operating state control method involving the following steps is proposed: ● Detecting the human body state parameter of the user ● Judging the body state parameter to detect whether it satisfies the predetermined conditions ● Obtaining the relevant judgement ● Conducting purifier control in the sleep mode if the judgement result indicates that the human body state parameter of the detection meets the pre-set condition ● Alerting the user to control the operation of the cleaner for high contaminant concentrations.	[210]
Method and device for estimating power of outdoor air fan of air conditioner and computer readable storage medium	A power estimation method is proposed for an outdoor fan of an air conditioner. This method comprises the following steps: ● Obtaining the operation power from historical operation data ● Modeling the operation power of the fan according to the input variable ● Establishing a power estimation model for air conditioner operation ● Using the power estimation model function to calculate the power and output of the outdoor fan.	[211]
Machine learning-based air conditioner control method and device as well as air conditioner	An air conditioner control method based on ML is proposed. This method involves the following steps: ● Obtaining the air conditioner running parameters and pre-set times set by the user ● Obtaining the user settings for the air conditioner operation parameter and the set time corresponding to the environment parameter ● Recording the times of operation for the air conditioner parameter as output ● Training to obtain the control model.	[212]

Method and system for providing air conditioning	An air-conditioning system with one or more cameras for capturing images of a surrounding environment is proposed. This system can determine a factor set through the analysis of the captured images. By using one or more predefined ML models, the aforementioned system can select a suitable operation profile and air flow setting to save energy.	[213]
Control method for air conditioner and storage medium	A control method is proposed for an air conditioner. This method involves the following steps: ● Obtaining the current working parameters for an air conditioner ● Obtaining a target running parameter according to numerous historical operating parameters ● Controlling the air conditioner to run at the target running parameter.	[214]
Air supply method for air conditioner and computer readable storage medium	The proposed air supply method for an air conditioner involves the following steps: ● Obtaining the temperature and the distance from the air outlet to occupants ● Suggesting a temperature according to this distance ● Controlling the longitudinal and transverse air flows of the air conditioner according to the difference between the set temperature and the suggested temperature to save energy.	[215]

3.2.9. Patents of Samsung

A total of 7149 patents of Samsung were identified. The key patents of Samsung identified through automated analysis and manual inspection are listed in Table 10.

Table 10. Key patents of Samsung identified in this study.

Patent title/Translated Title	Abstract of the Patent Content	Ref
Energy management system and method for energy management using group management control	The present invention is related to an object group unit subjected to multiple managed object group units for energy management. The communication interface and remote integration management server are installed in the building automation unit. The energy management system uses numerical control operation in each building automation unit. The controls can be divided into the unity power target amount and the time cycle. The information is stored in multiple driving machines.	[216]
Method for controlling activation of air-conditioning device and apparatus therefor	The present invention is related to control of the activation of an air-conditioning device. Specifically, the present invention provides a method for predicting the time at which a pre-set indoor temperature will be achieved based on information regarding environmental factors, including a ventilation factor. Thus, the method can control the activation time of the air-conditioning device such that the present	[217]

	temperature can be reached at the target time. In addition, the method can predict the target time at which the user will need the air-conditioning device. The aforementioned method can control the activation of an air-conditioning device in accordance with the optimal partial load factor of the air-conditioning device until the preset temperature is reached. The present disclosure is related to technologies for sensor networks, machine-to-machine (M2M) communication, machine-type communication (MTC), and IoT. The collected data may be used in intelligent services, including smart homes, smart buildings, smart cities, smart cars or connected cars, health care, digital education, retail businesses, and services related to security and safety.	
Air conditioner and method for control thereof	The present invention is related to an AI-based air conditioner with a processor. The processor is configured to predict power consumption or the required time for the indoor temperature to reach a desired temperature. It also can display the power consumption or required time.	[218]
Air conditioner and method for controlling the air conditioner thereof	The present invention is related to a control method for an air conditioner. This method comprises the following steps: ● Obtaining a user's voice to determine the state of a user ● Transmitting the user's voice to an external server ● Receiving a control command from the external server according to the cooling-related desire of the user and the state of the user determined according to the usage history of the air conditioner ● Controlling the air-conditioning apparatus according to the control command.	[219]
Electronic device and method for controlling the electronic device thereof	The present invention is related to an electronic device consisting of a communication interface, a memory device storing historical data, and a processor connected to the communication interface. The processor uses the electronic device to execute optimal control. An example of the aforementioned device is a smartphone for performing optimal control. On the basis of the usage information of the first user, a first control condition and first control operation preferred by the first user are obtained to construct a first device knowledge base. When a context corresponding to the first control condition is detected, according to the basic knowledge base and information from smartphone, the developed device determines whether to perform the first control operation stored in the first device knowledge base.	[220]

Electronic device and control method thereof	The electronic device includes a communicator with circuitry, a processor connected to the communicator and controlling the communicator, and memory electrically connected to the processor. The memory is configured to store instructions to control the processor to transmit control information acquired by applying the target information of the air-conditioning system to a learning network model. The learning network model estimates energy consumption and generates virtual data for retraining.	[221]
Electric apparatus and operation method of the electric apparatus	The present invention is related to a method for operating an electronic apparatus to predict the power consumption of an air conditioner. The prediction uses weather forecast data and correlations between weather conditions and the amount of power consumption.	[222]
Air conditioner and control method thereof	The present invention is related to a method for controlling an air conditioner. This method comprises the following steps: ● Obtaining the user's voice, including the user state ● Sending the user's voice to an external server ● Receiving a control command from an external server, which stores the user state and a user cooling propensity determined according to the usage history of the air conditioner ● Controlling the air conditioner according to the control command.	[223]

3.2.10. Patents of Siemens

A total of 5440 patents of Siemens were identified. The key patents of Siemens identified through automated analysis and manual inspection are listed in Table 11.

Table 11. Key patents of Siemens identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
HVAC distribution system identification	The developed controller is implemented in an HVAC distribution system and enables improved control by implementing a general regression NN to generate a control signal according to the identified characteristics of components used within the HVAC system. The general regression NN uses past characteristics and desired characteristics to generate an output control signal. The general regression NN is implemented in a feedforward process, which is combined with a feedback process to generate an improved control signal for controlling components within the HVAC distribution system.	[224]

Model based fault detection and diagnosis methodology for HVAC subsystems	The developed method can be used for the fault detection and diagnosis of HVAC subsystems. In this method, a thermodynamic pre-processor is used for calculating characteristic quantities (CQs) from measured inputs, and a base-case lookup table is used for determining CQ values for the first fault-free operation period. A set of base-case CQ values is interpolated from the first sets of CQ values stored in the lookup table for a given set of measured inputs. A fault is detected if a difference between actual CQ values and base-case CQ values exceeds a predetermined threshold.	[225]
Application of microsystems for a building system employing a system knowledge base	The present invention is an arrangement for use in a control system within a building. The system for obtaining environmental information consists of several sensor microsystems. By collecting information from these microsystems, the proposed method can construct a knowledge base and employ the knowledge base to adjust the operating parameter values.	[226]
Data center thermal performance optimization using distributed cooling systems	The present invention is a power efficiency optimization method for a data center. This method involves using a processing circuit for generating a control law to operate air-conditioning systems for satisfying the thermal demands of a data center on the basis of information representative of rack profiles. The proposed processing circuit may also generate a profile for local racks and simulate a data center environment to develop and test control strategies for later implementation in the actual data center.	[227]
Building automation system using a predictive model	The developed building automation system performs the following steps: ● Reading from one input device ● Processing the reading by feeding at least one reading to a predictive model ● Detecting deviations between the measured value and the output of the predictive model ● Identifying deviations in the output of the predictive model ● Dispatching an alert for identified or unidentified deviations.	[228]
Variable air volume model for an HVAC system	By using information available from the controller or controllers of air handing units (AHUs), a remote server uses a heuristic model to determine settings for the AHUs. Instead of only using rules for each AHU, a model-based solution is used to determine the settings. The model is used to optimize the operation of the air distribution. The measurements are collected and used to derive analytics. The measurements may include data not otherwise used for the rule-based control of the AHUs. The analytics are used to predict	[229]

	needs, as inputs to the model, to identify problems or identify opportunities.	
Intelligent heat, ventilation, and air-conditioning system	The present invention is an intelligent HVAC system. This system uses an occupant detection unit to determine number of occupants in the space. The HVAC system includes a control unit coupled to an occupant detection unit. A controller is configured to determine the HVAC conditions to be attained inside the space according to the number of occupants by using an ANN. The output of the HVAC equipment is automatically controlled such that the desired comfort conditions are attained.	[230]
Adaptive demand response method using batteries with commercial buildings for grid stability and sustainable growth	The present invention is a system for calculating the total lifecycle costs for a building energy management system (BEMS) and the lifecycle costs for a grid-scale battery system. This system includes a battery lifecycle optimizer configured to provide an optimal battery configuration for the BEMS controller. The controller receives the optimal battery configuration information, information related to the HVAC system of the building, the intrinsic thermodynamic properties of the building, energy tariff schedules, and weather forecast data. A simulation is performed by using a battery model, a system model, and tariff and weather information to produce an hourly building energy management plan to minimize overall energy costs with consideration of system lifecycle costs.	[231]
System, device and method for energy and comfort optimization in a building automation environment	A system, device, and method are developed for energy and comfort optimization in a building automation environment. The designed method involves receiving environmental data associated with the building automation environment. A building model is generated for the building automation environment. The building model is represented by a set of states comprising either energy profiles or comfort profiles. Reward vectors for the set of states with energy profiles and the set of states with comfort profiles are determined.	[232]
Smart room allocation	A method and system are proposed for allocating a room, such as a meeting room. In buildings, information regarding rooms is collected and provided to a room allocation system. This information includes availability of rooms, the capacity of the rooms, and the infrastructure of the rooms. When a planned meeting is provided to the room allocation system, the following information should be collected: time or timeframe, the required capacity, and the required infrastructure. Information on participants attending the planned meeting, including their name, contact information, availability, and comfort information, should	[233]

	be included in the room allocation system. On the basis of the aforementioned information, including the comfort information for the participants, the room allocation system can determine the most suitable room for a group of participants.	
Variable air volume model for an HVAC system	A method is developed for modeling HVAC equipment. A heuristic model of air handling in a HVAC system is constructed by a server according to measurements from outdoor sensors, building space sensors, plant sensors, and air handling sensors. Settings for air handling in the HVAC system are determined by the server from the model. The heuristic model may be optimized by indicating a mismatch of a fan with a space based on differences between a fan flow set point and the fan's designed maximum flow.	[234]
Method and apparatus for controlling an integrated energy system, and computer-readable storage medium	A method and an apparatus are developed for controlling an integrated energy system. The developed system involves the following steps: ● Determining the topological structure of an integrated energy system ● Determining general models of the devices and a connector model corresponding to the connection attributes ● Connecting the general models by using the connector model to form a simulation model of the integrated energy system ● Training the simulation model ● Generating a control command for the integrated energy system on the basis of the trained simulation model.	[235]
Optimization method and apparatus for an integrated energy system and computer-readable storage medium	An optimization method and apparatus are developed for an integrated energy system. The developed method involves the following steps: ● Receiving an optimization task, including an optimization goal ● Establishing a nonlinear equation set on the basis of the optimization goal and the simulation model of an integrated energy system ● Solving the nonlinear equation set on the basis of a linear programming algorithm to obtain an optimization result ● Outputting the optimization results The aforementioned method is expected to meet the requirements of various optimization tasks. This method can facilitate energy production optimization and scheduling and factory peak load shifting to reduce energy consumption.	[236]
Integrated energy system simulation method, apparatus, and computer-readable storage medium	The developed integrated energy system simulation method comprises the following steps: ● Determining a topological structure of an integrated energy system	[237]

	● Determining general models of the devices and connector models ● Connecting general models by using a connector model ● Training the simulation model By using the aforementioned method, various simulation tasks can be executed to acquire a system state at a given time or analyze a state under certain operational assumptions.	

3.2.11. Patents of Panasonic

A total of 912 patents of Panasonic were identified. The key patents of Panasonic identified through automated analysis and manual inspection are listed in Table 12.

Table 12. Key patents of Panasonic identified in this study.

Patent Title/Translated Title	Abstract of the Patent Content	Ref
Thermal comfort device and control content determination method	The designed control method for an apparatus involves performing indoor environmental control for thermal comfort by obtaining indoor environment information and applying decision rules.	[238]
Air-conditioning control method and air-conditioning control device	The developed method involves using a processor to process sensor information and make predictions. Two sensors are used in the developed method. The first and second sensors have different frequencies. If a value is acquired for the second sensor but not for the first sensor, a predicted value is generated for the first sensor from the actual value obtained for the second sensor according to the correlation between the values of the two sensors. The operation of the air-conditioning equipment is determined according to the predicted sensor value.	[239]
Prediction model sharing method and prediction model sharing System	The developed method involves the following steps: ● Obtaining a prediction model by using an ANN ● Obtaining a transformation prediction model ● Obtaining a distribution prediction model by using a secret distribution method ● Using the distribution prediction model to predict the state of the processing input.	[240]

3.3. Enterprise Patent Analytics

The key patents held by 11 HVAC-related companies are presented. The company names are abbreviated in the remaining text as follows:

- Carrier (Ca)
- Daikin (Da)
- Google (Go)
- Gree (Gr)
- IBM (I company)
- Johnson Controls (J)
- LG Electric (L company)
- Midea (M)

- Samsung (Sa)
- Siemens (Si)
- Panasonic (Pa).

A total of 31,221 patents filed by the 11 companies were included in the enterprise patent analysis. The number of patents for each company is depicted in Figure 4.

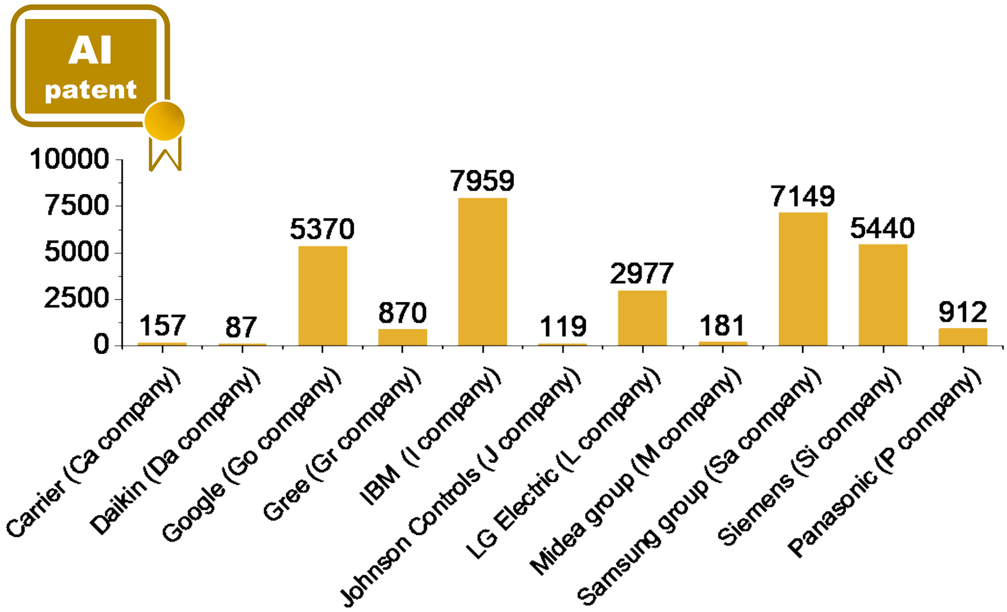


Figure 4. Total of 31,221 patents filed by 11 companies.

This study included all patents filed by the aforementioned companies. However, due to length constraints, all patents could not be included as references. Only the patents deemed critical after analysis are cited, and these patents are listed in Tables 2–12. Statistics for the countries in which the patent applications were submitted are presented in Figure 5.

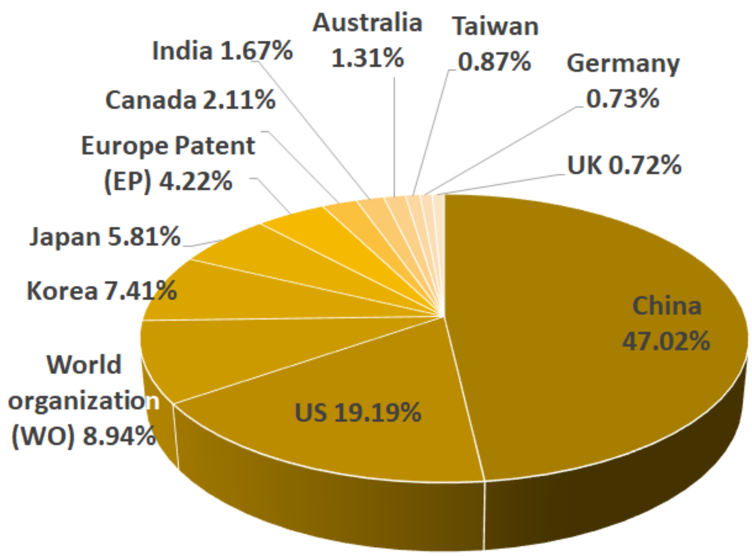


Figure 5. Patent applications by country.

As presented in Figure 5, the country with the most patent applications is China, followed by the United States and World Intellectual Property Organization (WO). Other patent applications are scattered within Europe and Asia, including India. As displayed in Figures 1 and 4, research on, and patents for, AI-based HVAC applications are worldwide phenomena. By comparing global research and corporate patents, the keys for the development of AI technology in terms of academic research and commercialization can be identified.

4. RDF Development

It is not possible to manually analyze over 30,000 patents. A novel RDF for automated analysis was developed in this study. In addition to the developed RDF, a natural language program was developed to obtain keywords from the patent contents.

4.1. RDF-Based Analysis

The study cases listed in Table 1 indicate that academic papers on AI for HVAC energy savings have the following triad data structure:

HVAC Equipment–at–Which Type of Building–Uses–What Kind of AI Technology

This data structure is fundamental to the developed RDF for the structural extraction of knowledge from academic papers. Figure 6 illustrates the fundamentals of the RDF-based analysis.

As presented in Figure 6, the examined academic studies encompass three objects: HVAC equipment, buildings, and AI technology. Each object can be connected by (at, use). The other option is (with) for optional devices such as energy storage systems.

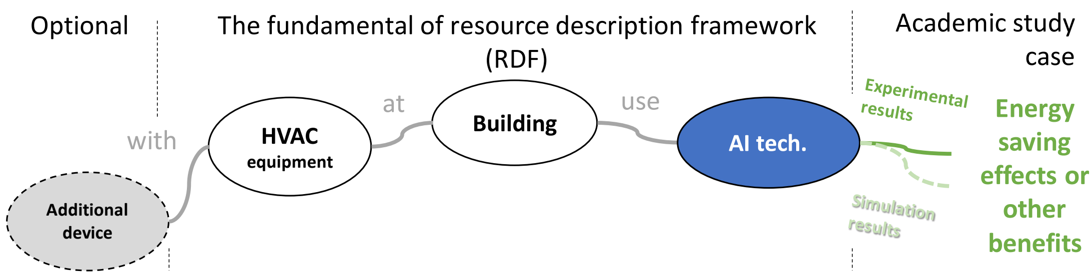


Figure 6. Ternary data structure as the fundamental factor of RDF for knowledge extraction.

RDFs can also be used to describe relationships between objects. By making connections to energy-saving effects or other benefits, including cost savings or thermal comfort improvements, the schema can concisely extract knowledge from academic papers. In this study, the developed RDF was used to analyze patent contents. To achieve data interchangeability and comparative analysis, the data structure displayed in Figure 7 was developed, and a database was established.

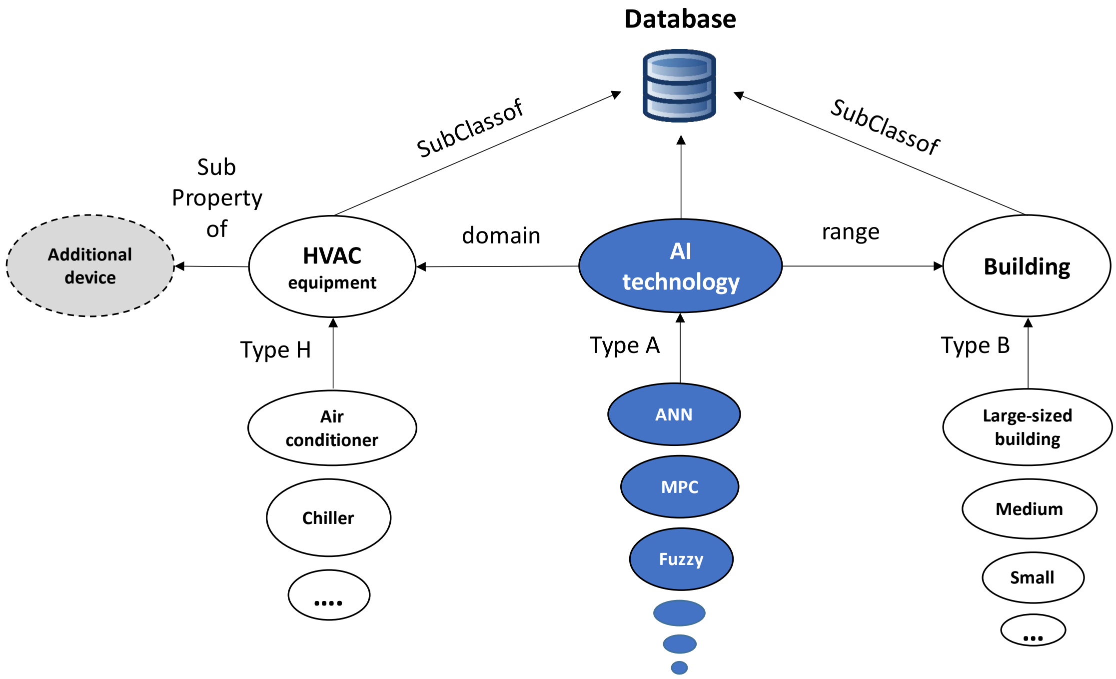


Figure 7. RDF data structure and database construction.

As presented in Figure 7, the RDF provides the following descriptions of types and properties:

- Type: the index of objects, namely H for HVAC equipment, A for AI technologies, and B for building types
- SubClassof: used to specify the parent category of a database
- SubPropertyof: used to specify optional categories of a database
- Domain: used to specify attributes
- Range: used to specify the range of an attribute.

With the ternary data structure displayed in Figure 7, different combinations of data can be analyzed. For example, the (H, B) combination can be used to analyze which type of HVAC equipment is most commonly used in which building. The (H, A) combination can be used to analyze which AI technology is most commonly used with which HVAC equipment. The combination of (H, B, A) with the energy-saving effects and other benefits reported in the 85 study cases can be used to analyze the current status of AI research for HVAC energy savings. Notably, the ternary data structure is interchangeable, which enables further analysis of the patents obtained by the 11 companies, as noted in the previous section.

For patent analysis, the constructed database shown in Figure 7 was used. The automated analysis method is presented in Figure 8.

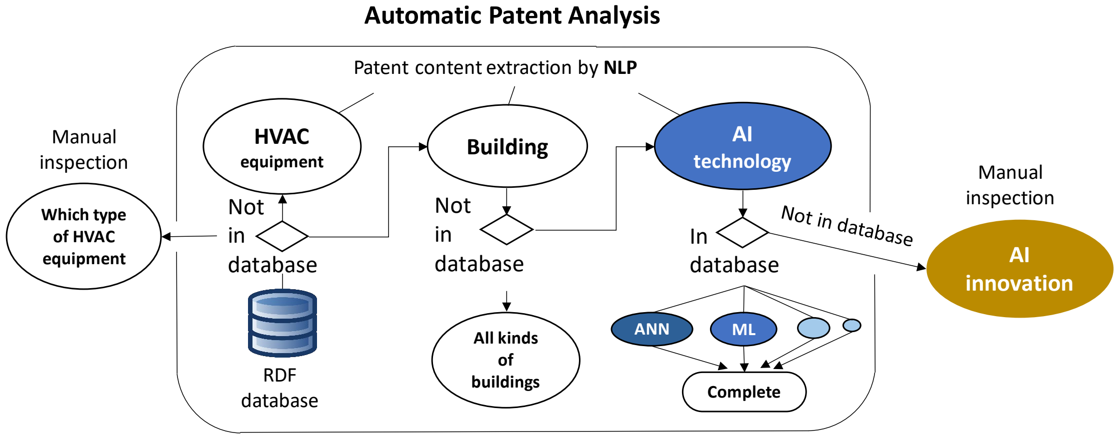


Figure 8. RDF-based automatic patent analysis method.

As displayed in Figure 8, patent content can be abstracted by a natural language processing (NLP) program. NLP can be used to extract keywords from patents. These words were compared with the database constructed by the study cases. If the HVAC equipment mentioned in a patent did not exist within the database, the patent file was examined manually to identify the type of HVAC equipment used. A similar process was used for AI technologies not within the database. The automatic analysis system can identify these files for manual confirmation of other possible AI technology innovations.

Because patent applications typically do not limit the scope of their usage, most patents do not state the type of building they are intended for. The patent automatic analysis system developed by this research automatically classifies AI-related patents into 'all kinds of buildings', as indicated by Figure 8.

4.2. NLP Program

An NLP program was developed to analyze the 31,221 patents collected in this study. This program can automatically extract keywords to identify patents that are highly relevant for AI for sustainable air-conditioning systems. Because not all of the collected patents were written in English, the developed program performed some automatic procedures, including hyphenation, reorganization, and sentence analysis for other languages, such as Chinese. This research used the term-frequency inverse document-frequency algorithm to construct the NLP program. This program outputs the keywords from unigram to pentagram for patent analysis.

5. Results and Discussion

The results described in the following text are based on RDF and NLP analyses. In the first step of the research framework, the academic cases were analyzed to obtain the energy-saving effects and other benefits of AI used in HVAC. Second, the ternary relationship established with the RDF was used to combine the AI technologies reported in academic papers into six effective methods. Third, the RDF was used to analyze the patents for the 11 companies, and the ternary structure diagram obtained from the patent analysis. The current status of AI applications in HVAC energy-saving technologies was analyzed by linking academic papers with corporate patent analysis and making recommendations for future sustainable air-conditioning system development.

5.1. HVAC Energy Savings by Using AI

The results obtained after the analysis of the study cases in Table 1 are presented in Figure 8. The 85 case studies reported energy savings for 14 refrigeration and air-conditioning installations in 17 types of buildings. A total of 15 AI technologies were discussed in the academic papers. In Figure 8, the energy-saving effects obtained through numerical simulation are indicated by the light green coordinate axis, whereas those obtained experimentally are indicated by the dark green coordinate axis.

Triplet data can clearly indicate the connections between different technology applications. For example, ANN technology is widely used in various air-conditioning devices in various buildings. Fuzzy algorithms are typically used for single air conditioners in small buildings or AHUs in central air-conditioning systems to improve performance. The MACS is most commonly used for the coordinated control of multi-zone systems.

By linking the aforementioned AI applications with the reported energy-saving effects, modes of below 30% and below 21.4% were obtained for the simulated and experimental energy savings, respectively. Some extremely high energy savings were observed. For example, two experimental results demonstrated energy savings of 75.22% and 82%. Triplet data revealed that MPC is used in factories and is only activated for a single pump, if necessary; thus, a high energy-saving effect can be achieved. The energy savings of 75.22% were obtained because of the fuzzy use of air conditioning combined with ventilation system control. In the maximum economy mode, ventilation was used as much as possible without turning on the air conditioning; thus, energy conservation was high. Moreover, some cases had HVAC equipment connected to additional devices, such as energy recovery systems or thermal storage systems. These cases are indicated in the grey oval box on the leftmost side of Figure 9.

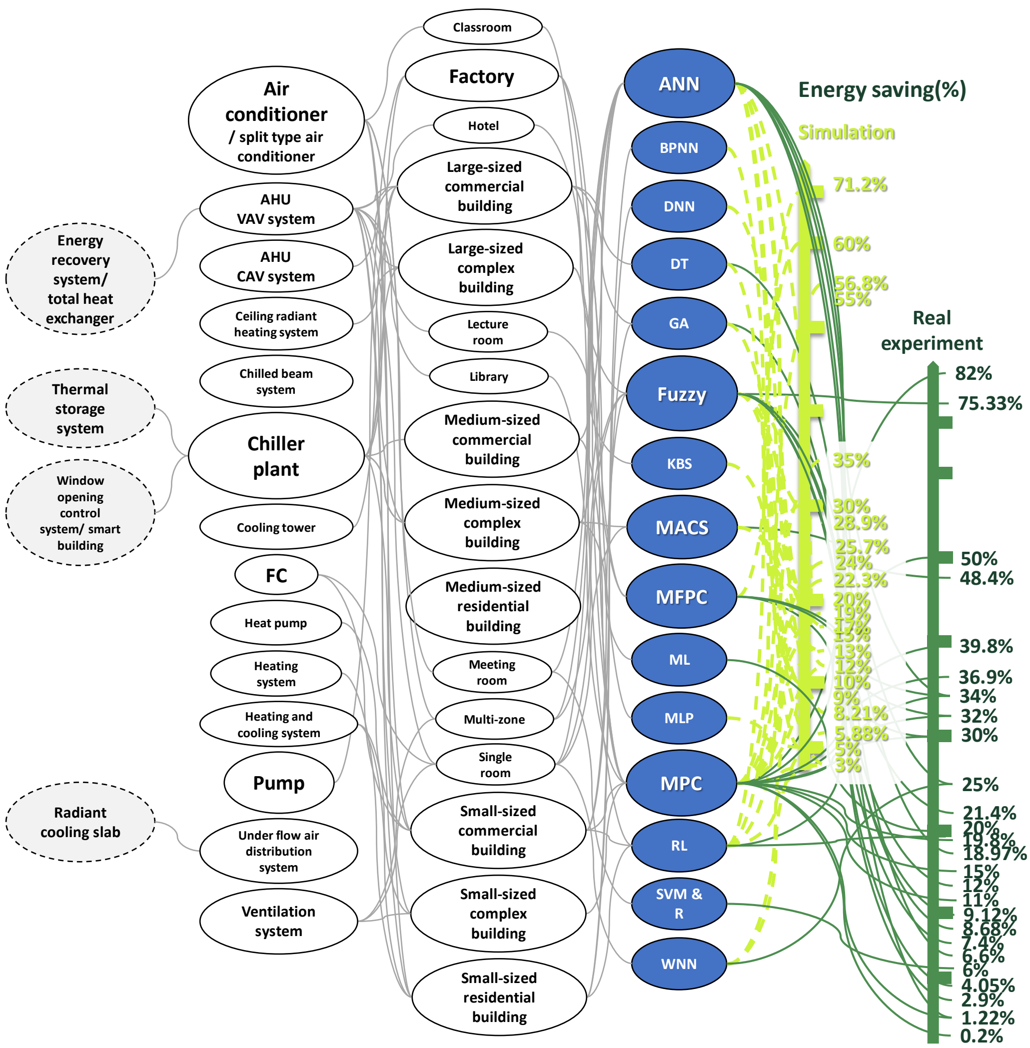


Figure 9. Sustainable air-conditioning systems enabled by AI technologies identified on the basis of the academic study case analysis.

5.2. Cost Savings and Thermal Comfort Improvement

Figure 10 illustrates the effective methods and other benefits of AI technologies, including thermal comfort improvements and energy cost savings. Only two experimental energy cost saving reports were identified; thus, the results were only compiled for simulated energy cost saving research.

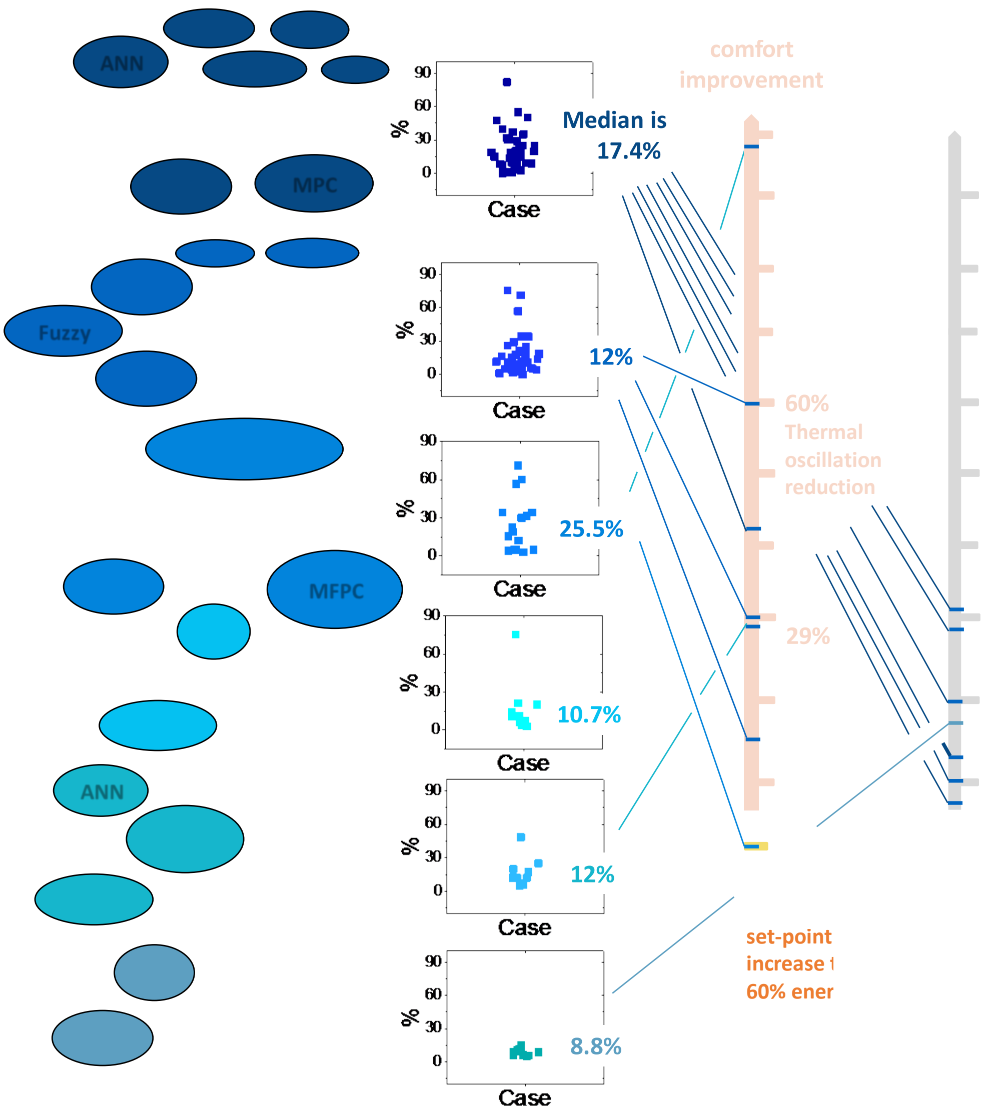


Figure 10. Six methods for applying AI for air-conditioning systems and other benefits.

As displayed in Figures 9 and 10, all AI technologies can be linked by six methods. These six methods are described in the following text:

Method 1. MPC is conducted with different NN and ML structures to learn historical data for constructing a model, which is used to control HVAC equipment to achieve energy savings.

Method 2. Thermal comfort control (Comfort) involves using an ANN and RL to learn human behavior and predict comfort levels to control HVAC equipment and save energy. Some studies have reported using fuzzy inference engines to construct member functions and estimate thermal comfort level, including the PMV.

Method 3. Model-free trial-and-error control (MFPC) does not require historical data. Using deep Q-learning or RL, the method can determine an action according to the status and reward function of the controlled system.

Method 4. Control optimization uses GA or fuzzy algorithms to tune the parameters of the PID controller to improve the control response.
Method 5. The MACS implements distributed AI for multizone air-conditioning control. The distributed AI may use ANN or fuzzy algorithms for decentralized control.
Method 6. The KBS/rule set (RS) uses DT or other classifiers to extract knowledge or rules for energy-saving control.

Method 1 uses predictive control to save energy effectively; this result is consistent with the conclusions of previous review papers. By using ANN, MLP, or SVM&R, energy-saving control methods can learn from historical data to construct a control model. ANN is the core technology of ML. Programs do not need to be written; the neuron structure can learn from data, and the machine can automatically output predicted values to control systems. MPC involves the three steps of constructing a model, outputting the prediction results, and controlling the system; thus, this AI technology was used in the most energy-saving data reports. In the 85 research cases, 33% of the 121 data reports used MPC.

As presented in Figure 9, on the left side of the MPC-related-technology group, 40 cases were identified and the median energy-saving effect was 17.4%. The quantitative results are similar to the conclusions of previous review papers. In addition to data on energy savings, multiple data reports include energy cost savings ranging from 6% to 30.9%.

Method 2 is thermal comfort control. The median energy-saving effect was 12%. Although these energy savings were relatively low, AI effectively improved the comfort of occupants. The data reveal that the occupant comfort data input to an ANN can be controlled by a single output. Research and fuzzy control can reduce temperature shocks by 60%, which improves comfort and saves energy. Evaluation by a quantitative index, PMV, reveals that AI-based thermal comfort control can improve comfort by 15% to 43%.

Because not all buildings or HVAC equipment have historical data available, studies conducted since 2015 used MFPC. MFPC does not require historical data and instead uses RL or deep Q-learning to learn from the control process; it has satisfactory performance. The median energy savings was 25.5%, the highest energy-saving ratio among the six methods. However, fewer data are available for MFPC than for first two methods; thus, more research is necessary to prove that it is effective for energy saving.

By integration with existing HVAC equipment controllers, AI technologies can be used to adjust the controller parameters for effective energy savings. Method 3 combines GA and fuzzy technologies; the median energy savings achieved was 10.7%. Method 4 is distributed AI for multi-zone control. The specific technology for achieving energy conservation was MACS. The median energy reduction was 12%. The final method is the KBS/RS. This method uses DT or a similar classifier to cooperate with human experts to build a knowledge database or control rules to save energy. The median energy reduction was 8.8%.

This research collected AI technology research papers from 2000 to 2020 and identified six methods that can effectively reduce energy consumption. The developed RDF was used to analyze patents. The patent keywords were systematically linked to the six methods to examine whether the current state of academic development is consistent with the current development of enterprise products. From this, the results of the fourth step of this study were generated, as illustrated in the following section.

5.3. Enterprise Patent Landscapes

As described in Section 3.2, this study analyzed 31,221 patents held by 11 companies. The analysis method is described in Section 4.1. The analysis result also produces the triply connected diagram presented in Figure 8; however, the analysis result for academic papers was connected to energy-savings data, whereas the result of the patent analysis was connected to the six methods.

After using NLP to retrieve patent keywords, patents that were not in the database were closely examined. These reviewed patents have content beyond the scope of academic research and were marked as key patents, cited as references, and organized in Sections 3.2.1–3.2.11. The following subsection describes the RDF analysis results and patent landscapes for each company.

5.3.1. Patent Landscape of Carrier

Carrier is a well-known chiller manufacturer and holds 157 AI-related patents. The patents primarily claim heating/cooling or HVAC systems used in multizone air-conditioning or various types of buildings. Among the 157 patents, 48% made this claim. These heating and cooling or HVAC systems for all types of buildings were linked to AI technologies. Of the patents, 15.9% mainly used the KBS for energy-saving control, 12.1% used ANN for energy savings, and 7.6% of patents used MPC. Of the other AI patents, the most common technology was ML, which accounted for 5.0% of Carrier's patents; the remaining AI methods accounted for less than 1%. To avoid overcrowding of the triplet connection diagram, the poorly represented data were discarded. The generated landscape was connected to the aforementioned six AI methods that effectively save energy, as shown in Figure 11.

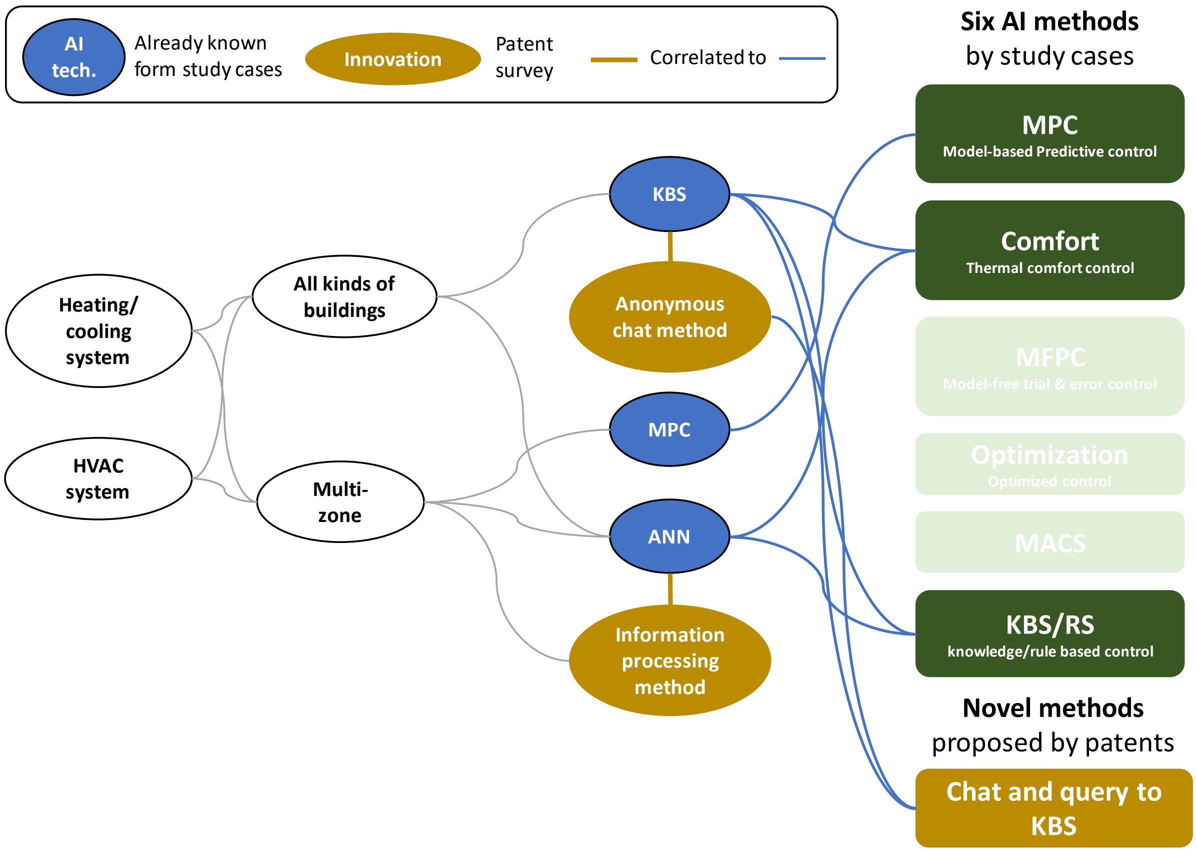


Figure 11. Patent landscape of Carrier.

Carrier's patent claims mostly include methods 1, 2, and 6; however, Carrier also uses the KBS to effectively build a knowledge database and manage large-scale systems for energy usage reduction. Carrier also proposed a novel method: the use of an AI-assisted chat bot to enable general users to query the database, understand the relevant control rules, or assist in establishing of control rules. This method can combine human intelligence and AI to improve energy-saving performance. A review of the literature revealed no similar research result reports; thus, this method was identified as a novel method and is represented by a golden yellow square in the lower-right corner of Figure 11.

5.3.2. Patent Landscape of Daikin

Daikin is a well-known manufacturer of air conditioners in Japan. The company holds 87 AI-related patents. Daikin patents mostly describe the use of air conditioners, chillers, or cooling towers in all types of buildings. These patents also describe multi-zone air conditioning. The main AI technology used was ANNs, which accounted for 45.9% of all Daikin patents, followed by MPC, MAC, and RL, which accounted for 20.7%, 9.2%, and 5.7% of Daikin's patents, respectively. The relevant patents were used to draw a landscape map, as presented in Figure 12.

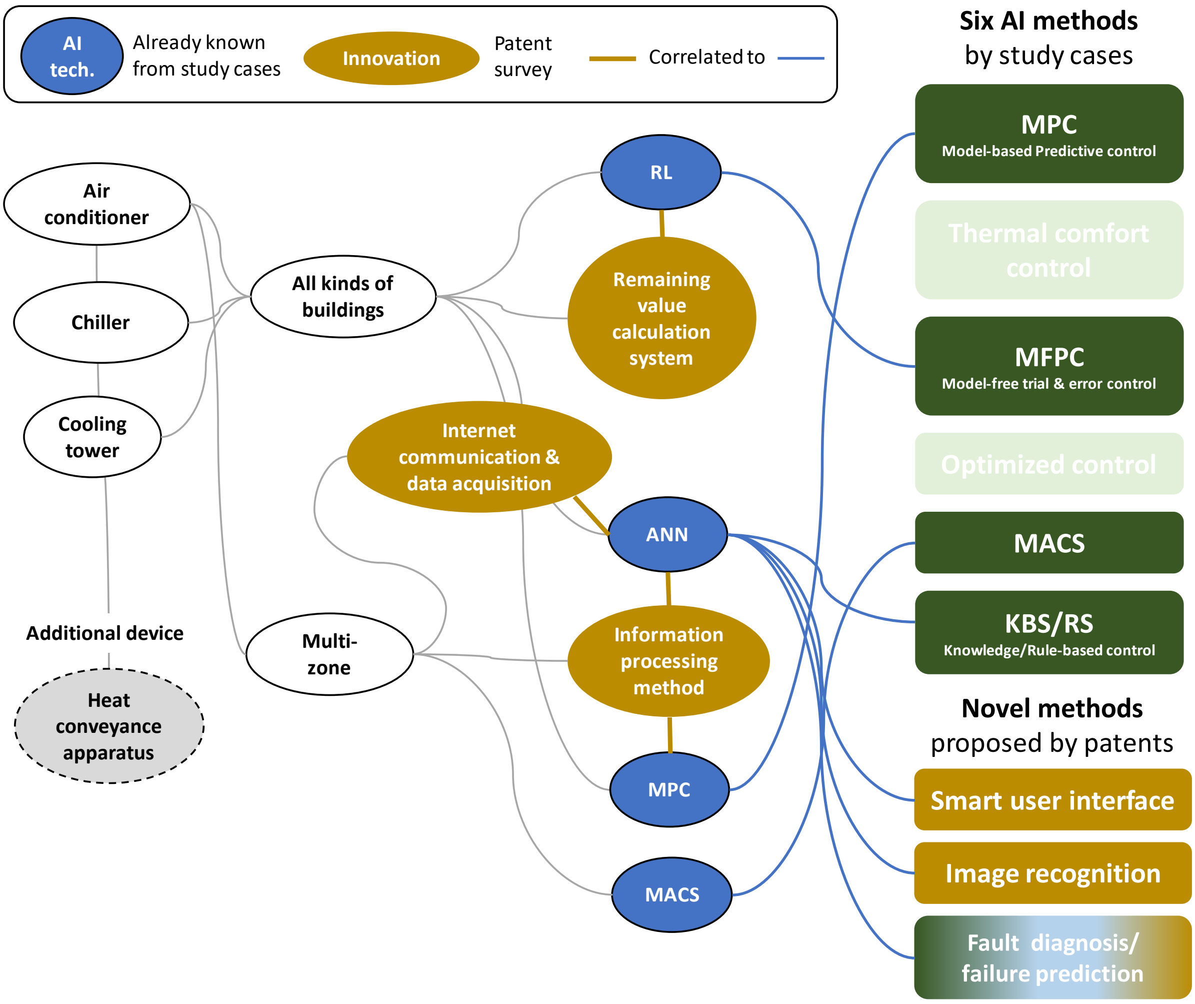


Figure 12. Patent landscape of Daikin.

Daikin's innovations use an ANN as the core to implement smart interfaces, and they have been successfully commercialized. Their AI app was discussed in Section 3.1. Moreover, Daikin has also described an image identification method used to identify the heat source distribution in the air-conditioning area. Some patents also cover fault diagnosis and failure prediction. Only one academic study about fault-tolerant operation was identified; thus, fault-tolerant operation is not yet mainstream in the literature, but is frequently noted in the content of patents. Thus, fault tolerance is classified as an innovative application. The mixture of green and gold indicates that the application is mentioned by both academic research and patents, as in the lower-right corner of Figure 12.

5.3.3. Patent Landscape of Google

Google holds 5370 AI-related patents; of these, only a few are related to HVAC. The HVAC-related patents include smart thermostats for all types of buildings and cooling systems for data centers. The investigation of Google patents was primarily intended to achieve a better understanding of mainstream AI research. The survey results revealed that 32.7% of patents involve ANNs, followed by ML (accounting for 14.8%) and MPC (accounting for 13.9%). The patent landscape of Google is presented in Figure 13.

Google's patent claims are closely related to methods 1, 2, 4, 5, and 6. Google also filed 98 patents related to RL. The main appeal of these patents is continuous control by using DL or RL, which is consistent with this research. Model-free predictive control can also be used to save energy; however, this method accounts for only 1.8% of Google's total patents. Thus, Google does not seem to support method 3.

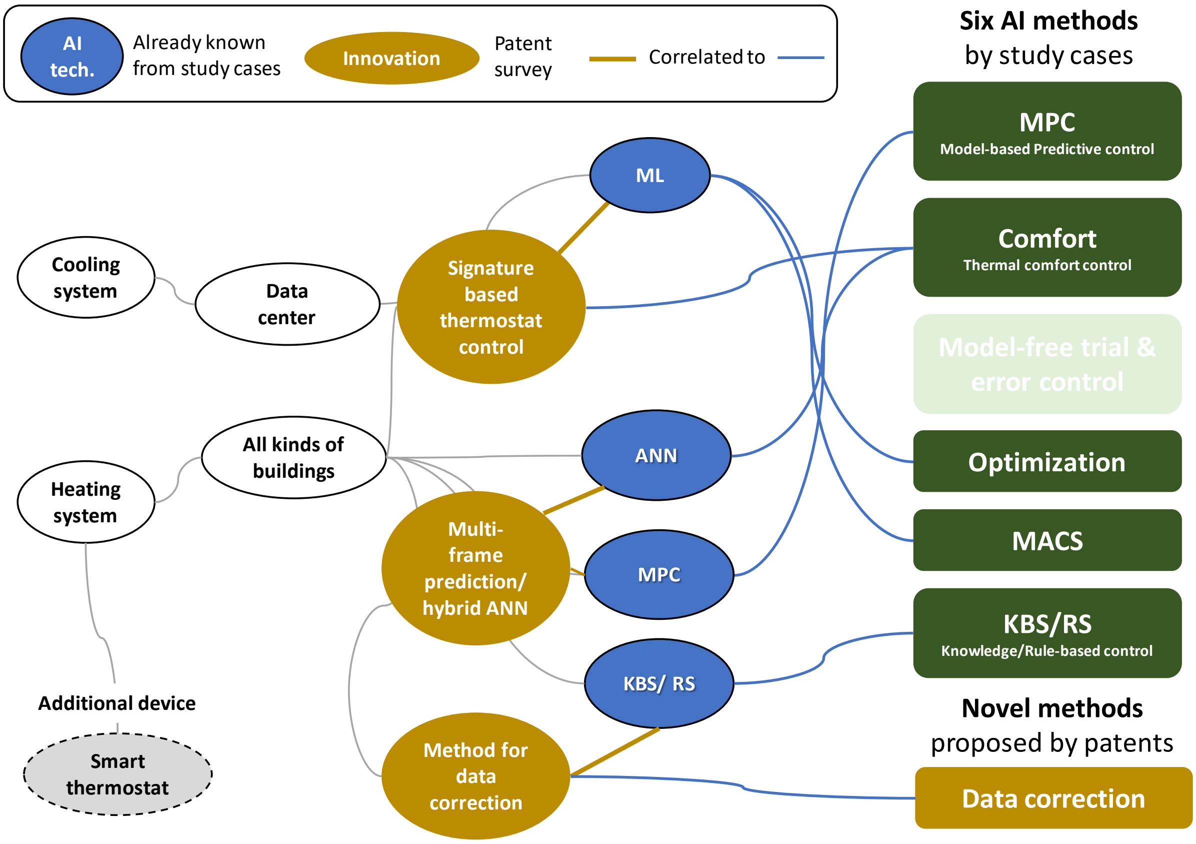


Figure 13. Google's patent landscape.

Innovations proposed by Google are mainly related to the identification and correction of data. All AI methods require data input. The accuracy of this data significantly affects the performance of AI models. Most data used in academic research are guaranteed to be correct. However, in real-world HVAC applications, data may be erroneous. To overcome this problem, Google proposes combining extrinsic information, including weather forecasts, prices, and neighborhood or home information. This method is implemented in the NEST smart thermostat, which can compare a home with neighboring homes. The ability to identify and eliminate incorrect data is the main innovative method proposed by Google, as presented in the lower-right corner of Figure 13.

5.3.4. Patent Landscape of Gree

Gree is a well-known air conditioner manufacturer in China that holds 870 AI-related patents mainly for air conditioners for all kinds of buildings, which account for 51.7% of the patent claims, followed by multizone air-conditioning, which account for 25.2%. Thus, more than 76% of Gree's patents are focused on air conditioners. The main AI technology used is MPC, which accounts for 51.3% of the patents. ANNs account for 24.8% of the patents, and DL or RL for MFPC account for 8.8% of the patents.

Gree's innovations are primarily focused on MPC. In addition to the collection and control of environmental parameters such as temperature and humidity, the company also incorporates air quality prediction models. In addition to temperature adjustments, control methods are also incorporated into the three-dimensional ventilation model. Using image or voice recognition, the location of indoor personnel and air-conditioning needs can be confirmed. Subsequently, the air supply of the air conditioner can be adjusted to use air supply and ventilation for cooling instead of activating the air conditioner, thus saving energy.

For air conditioner fault diagnosis, Gree's patents specifically mention frosting mode detection. Frosting of the air conditioner evaporator reduces the efficiency of the air conditioner; thus, although frosting is not a malfunction, it affects the energy efficiency of the air conditioner in a similar manner to a fault condition. AI technology can also be used to predict and identify the occurrence of frost and automatically reverse the vapor cycle to overcome this problem. Gree's landscape and primary innovations are presented in Figure 14.

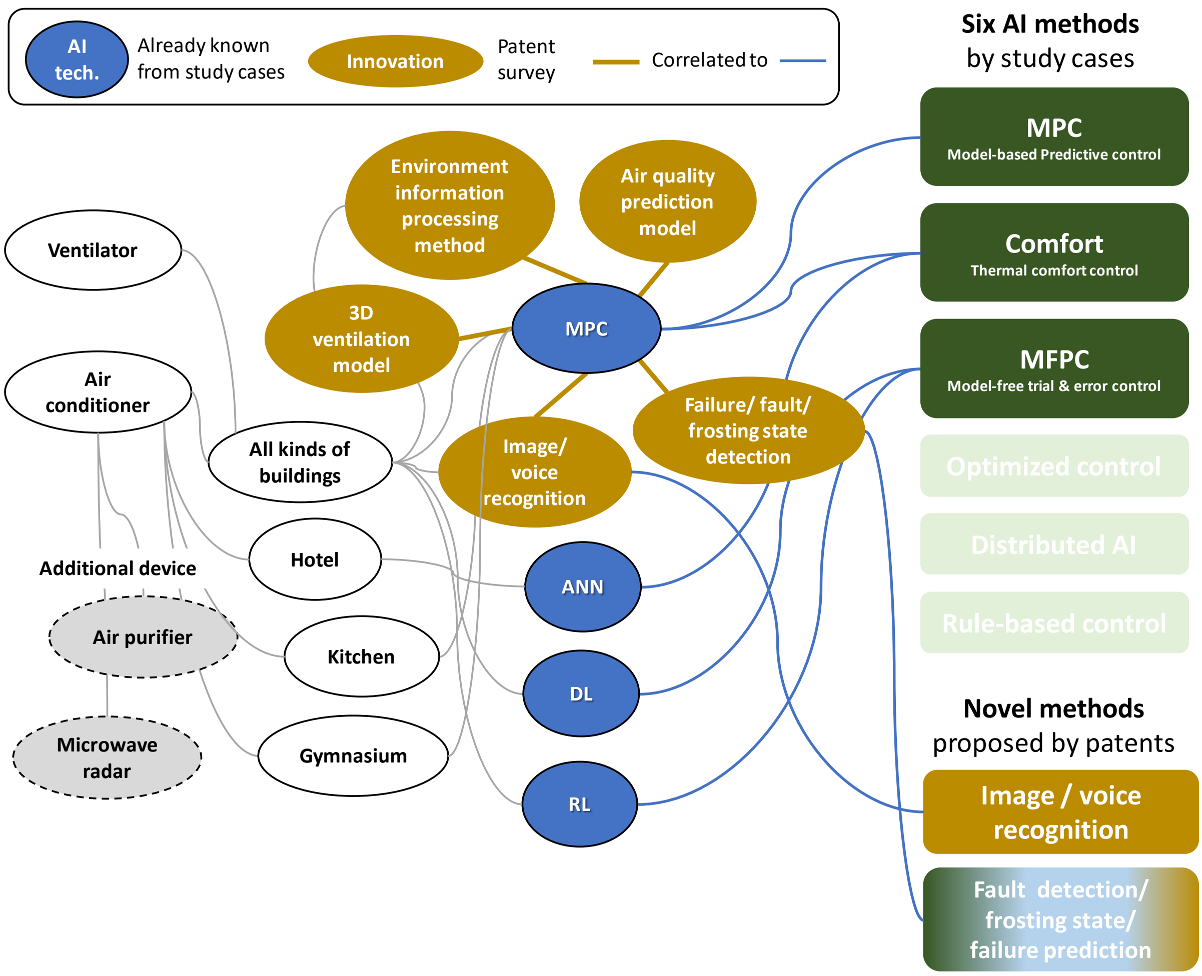


Figure 14. Patent landscape of Gree.

5.3.5. Patent Landscape of IBM

IBM is famous for AI research and has applied AI to cooling systems for data centers. IBM has a total of 7959 related patents; however, only 0.38% of these patents are related to cooling systems in data centers. The eight patents relevant to air-conditioning systems are applicable to all types of buildings. The most common AI method in IBM patents is ML, which accounts for 16.5% of the aforementioned patents, followed by ANNs (accounting for 15.0% of the aforementioned patents), and MPC (accounting for 11% of the aforementioned patents). Notably, in the RDF analysis, 5.3% of IBM patents are related to the KBS, and these patents are primarily related to data center cooling systems. The patents also mention *s*-curves, which are planned curves for energy management, and describe the identification of energy usage patterns and management of multiple energy resources. IBM's proposed related innovations and its patent landscape are illustrated in Figure 15.

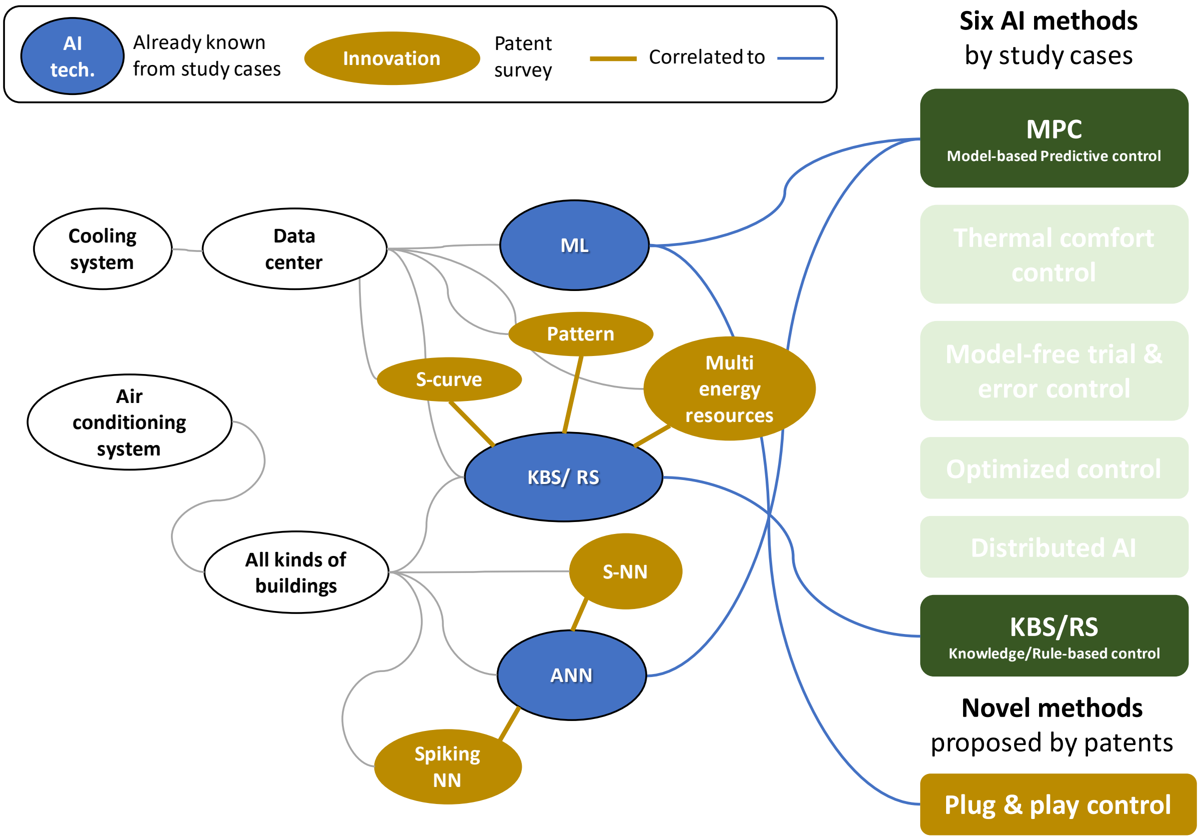


Figure 15. Patent landscape of IBM.

The identified innovations of IBM are spiking NNs and plug-and-play control systems. Spiking NNs are innovative NNs that can simulate the current pulse mode of human neurons, and learning systems based on spiking NNs are more anthropomorphic than are learning systems based on other types of NNs. Plug-and-play control systems are an invention related to self-learning controllers. In combination with ML and pattern recognition engines, the control system can automatically recognize connected sensors, use ML to understand the sensed information pattern, and automatically define its physical sensing quantities. This method is useful for the practical application of AI in HVAC equipment or for building a BMS. It can reduce personnel requirements and errors caused by manual logins.

5.3.6. Patent Landscape of Johnson Controls

Johnson Controls is a well-known manufacturer of chillers and controllers. The company has 119 AI-related patents; 67.2% are related to heating/cooling systems in all types of buildings. The main mentioned AI technology is MPC (accounting for 30.3% of patents), followed by ANNs (16.8%) and ML (10.9%). Moreover, Johnson Controls has applied for numerous patents for fuzzy techniques for controller optimization, DL, and RL to realize MFPC. It has also filed KBS-related patents for equipment scheduling control. The landscape of the Johnson Controls' patents is displayed in Figure 16.

The patents proposed by Johnson Controls are almost completely consistent with the six AI energy-saving methods proposed in this study. The novel methods include reliable data streams, failure prediction, and transfer learning techniques. Failure prediction has also been proposed by other companies. Ensuring data reliability is a newer concept in Johnson Controls' patents. Transfer learning is another notable technology that enables the transfer of an ANN model from one building to another building model for energy-saving control. If each HVAC product must learn each building's features before effective operation, commercial applications of AI will be difficult to achieve. Therefore, transfer learning must be developed to transfer ANN models to other environments.

In addition to Johnson Controls, transfer learning has been promoted by Google, Gree, Samsung, Siemens, and Panasonic. Transfer learning is a crucial innovation for realizing the large-scale applications and commercialization of AI. Several studies related to transfer learning have been conducted. Thus, this method is represented in green and gold in the bottom-right corner of Figure 16.

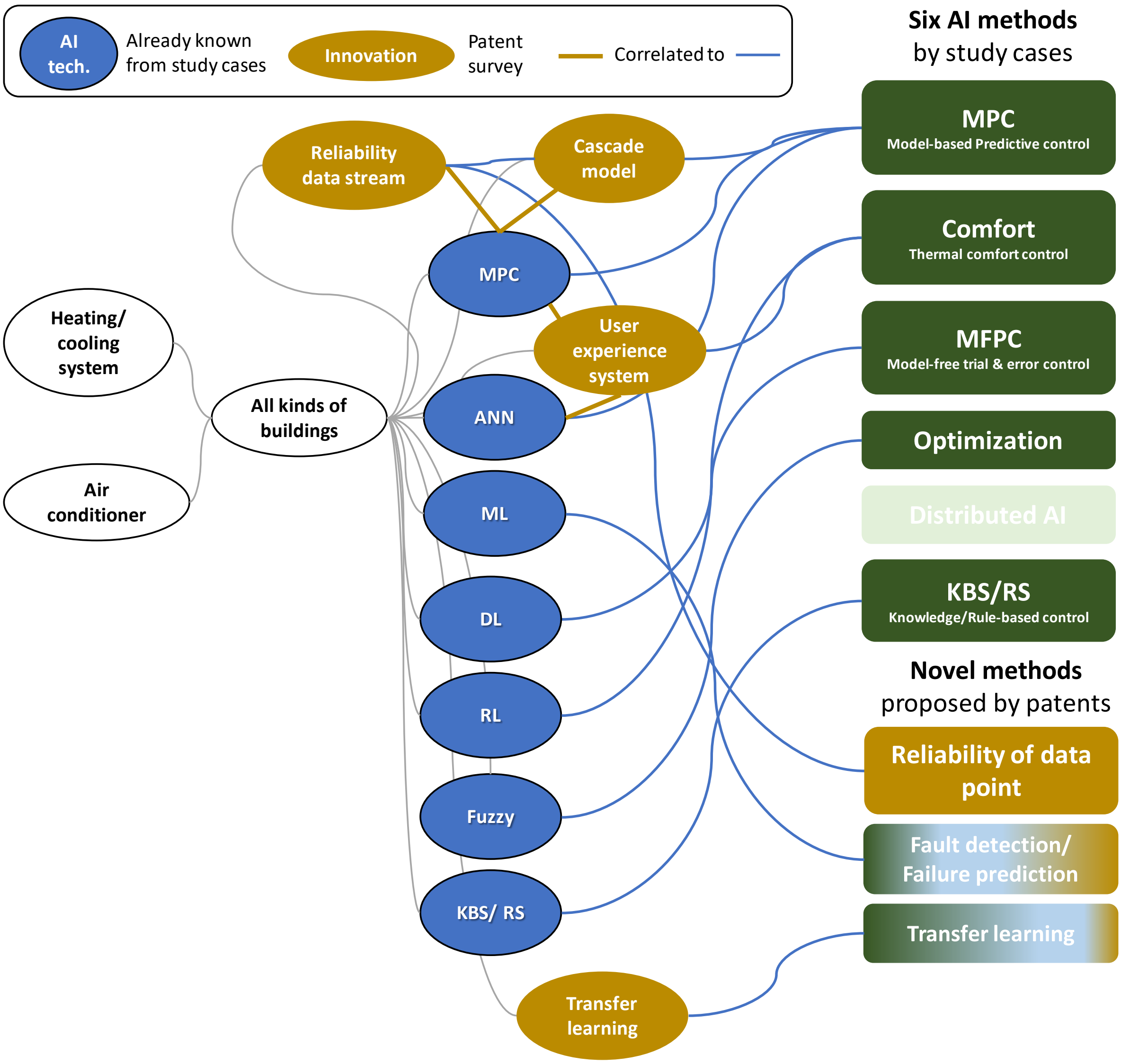


Figure 16. Patent landscape of Johnson Controls.

5.3.7. Patent Landscape of LG

LG is a well-known South Korean air conditioner manufacturer. In addition to air conditioners, LG produces other electronic products. LG holds 2977 AI-related patents. Of these patents, 3% are directly related to air conditioners and heating/cooling systems. The most common AI technology in these patents is ANNs (accounting for 8.1% of the patents), followed by MPC (5.4%) and ML (2.8%). In addition, LG has applied for various AI patents for methods based on DL, RL, the KBS, GA, and fuzzy logic. The patent landscape of LG is depicted in Figure 17.

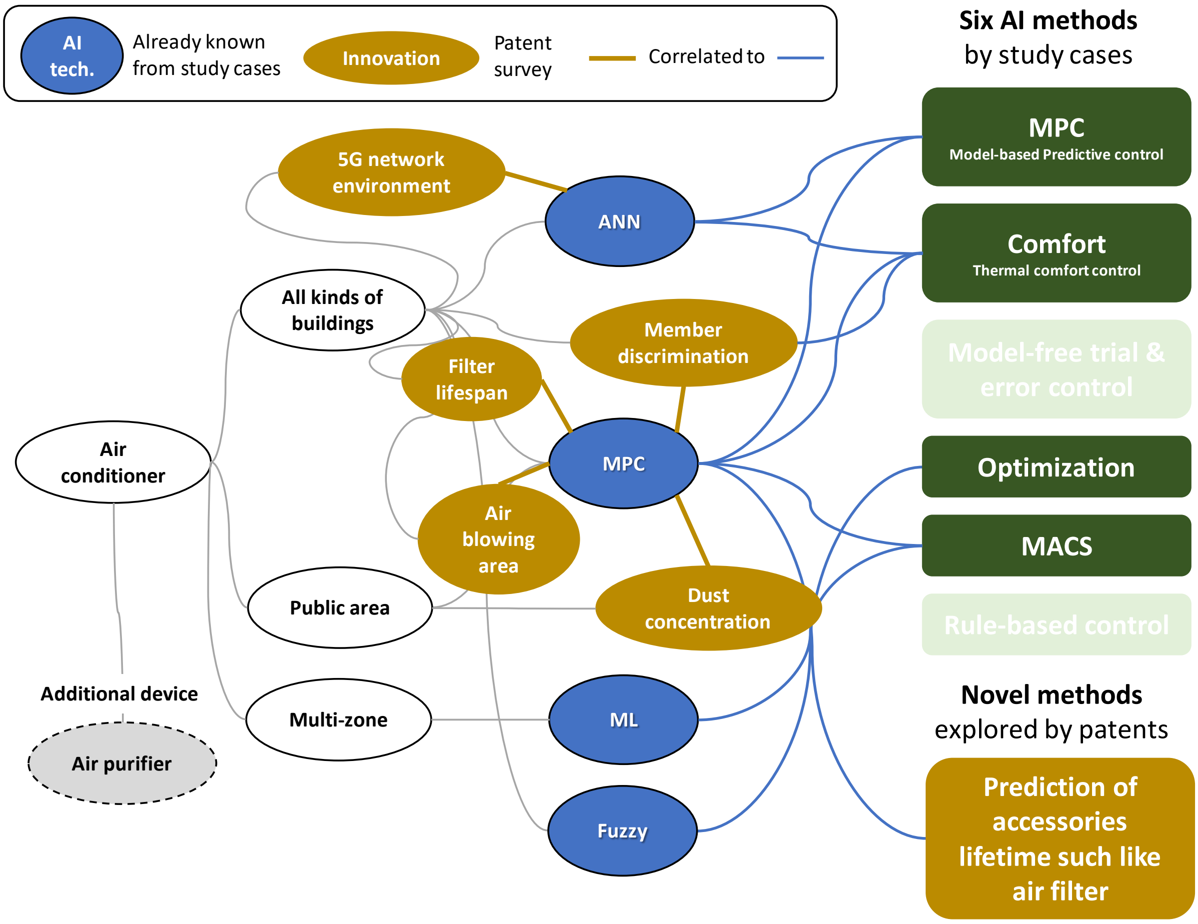


Figure 17. Patent landscape of LG.

Innovations of LG in ANNs are mainly related to 5G networking environment. However, many of these concepts can also be applied to HVAC equipment. The most noteworthy innovation is the application of MPC for lifespan prediction of accessories to maintain normal operation of the peripheral accessories for HVAC equipment. This maintenance also contributes to improved energy efficiency.

5.3.8. Patent Landscape of Midea

Midea is a well-known Chinese air conditioner manufacturer. It holds 181 AI-related patents, 56 (30.8%) of which are related to the use of air conditioners in all types of buildings. The most common AI technology used is ANNs (accounting for 12.7% of the patents), followed by ML (12.2%), and MPC (8.3%). Among the patents, the notable novel method was the use of image sensors to determine the resistance of insulation (ROI) of an occupant's clothing. The patent landscape of Midea is presented in Figure 18.

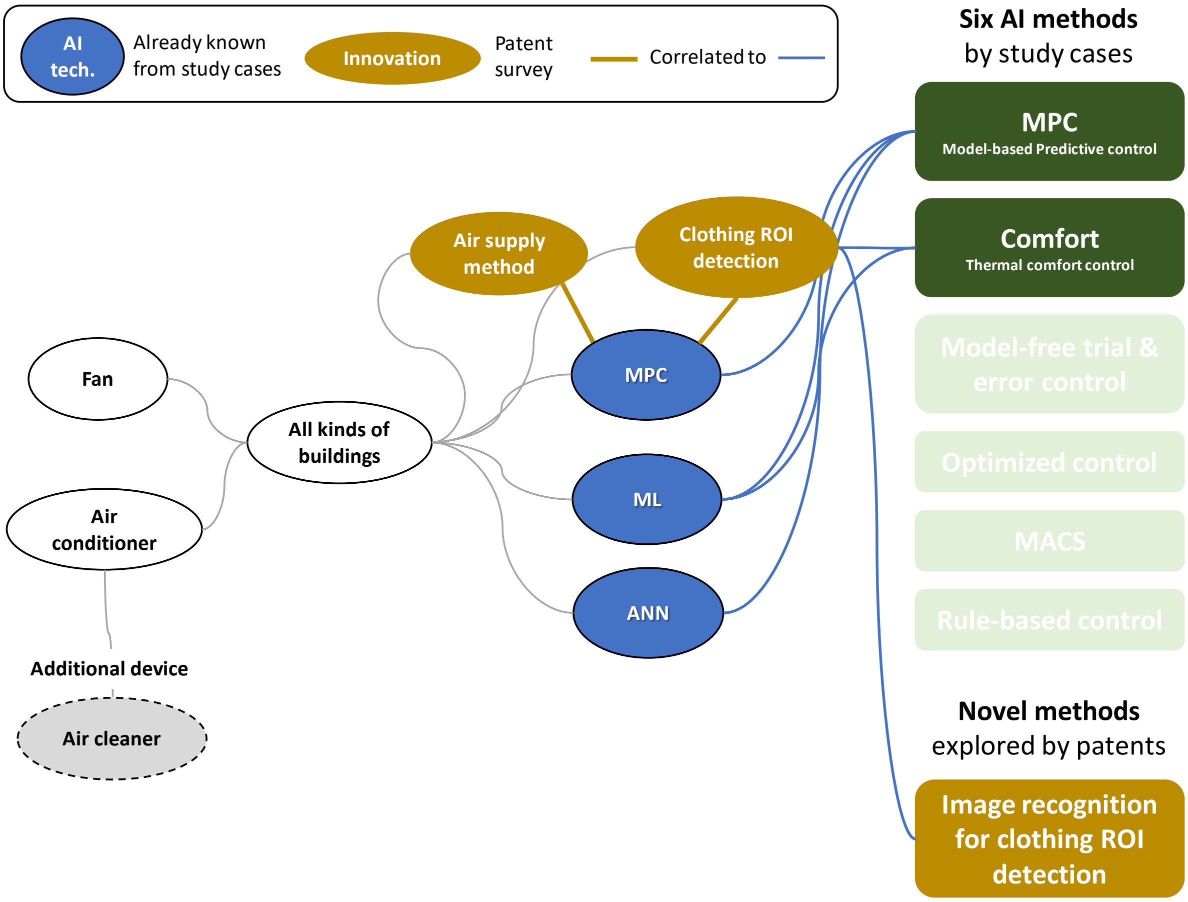


Figure 18. Patent landscape of Midea.

5.3.9. Patent Landscape of Samsung

Samsung is the largest business group in South Korea and sells products including HVAC devices. The group holds 7149 AI-related patents and applies for innovative AI patents. Most of these patents are related to ANNs (accounting for 1754 patents (24.5%)), followed by MPC and ML (6.7%, and 4.9%, respectively). The patent landscape of Samsung is displayed in Figure 19.

The notable innovation in Figure 19 is virtual data generation. This technology is similar to the generative adversarial network (GAN) used by Google. The technology can use existing data to generate substantial virtual data. Although this technology has been called the deep fake technique when combined with DL, its purpose is not to create fake data, but to learn real data and generate a larger amount of virtual data used for ANN training. Historical data are typically not available for HVAC applications; thus, many AI applications are challenging. Virtual data generation with GAN can effectively solve this problem; thus, the GAN is a crucial and innovative technology for AI development.

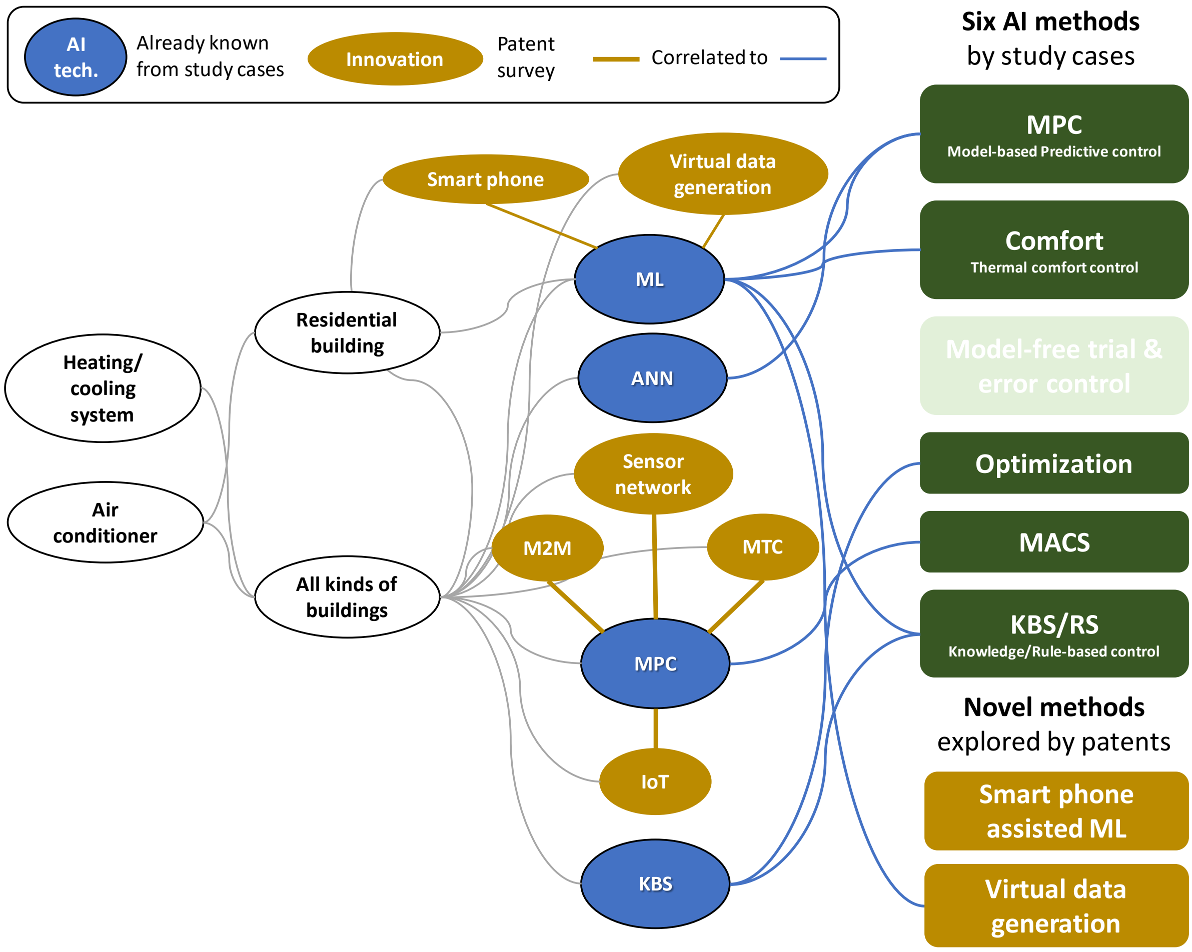


Figure 19. Patent landscape of Samsung.

5.3.10. Patent Landscape of Siemens

Siemens is an internationally renowned controller manufacturer with 5440 AI-related patents. The main AI technology related to the patents of Siemens is ANNs (accounting for 17.8% of the patents of Siemens), followed by MPC, ML, and the KBS (accounting for 9.9%, 9.4%, and 5.3% of the patents of Siemens, respectively). Using triplet data analysis, the patent landscape of Siemens was obtained in Figure 20.

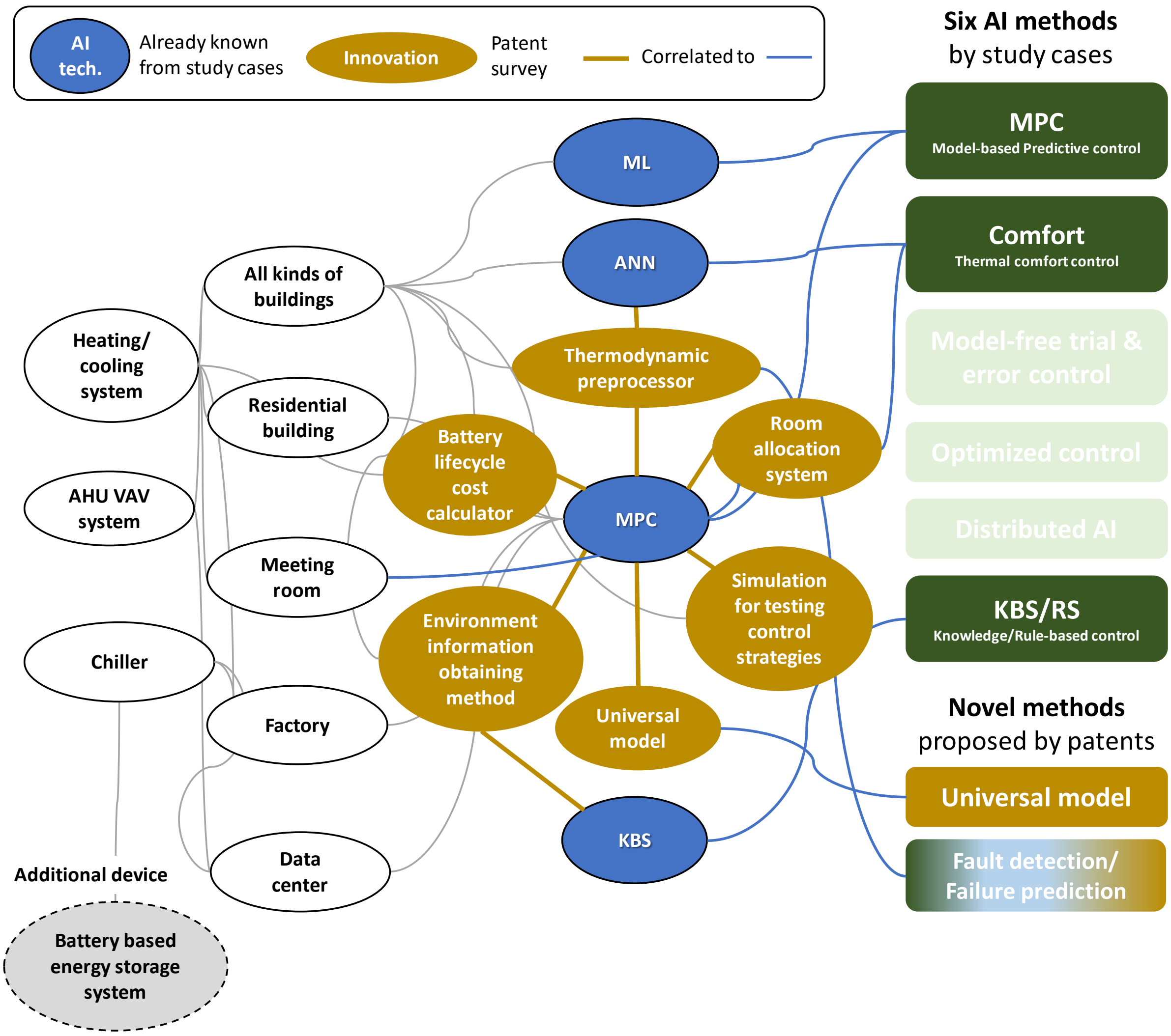


Figure 20. Patent landscape of Siemens.

Siemen's noteworthy innovative method is the universal model. The relevant patent proposes a method of establishing a universal control model for multiple energy systems using a numerical simulation. Siemens also proposed a battery-based energy storage system to store electricity from the grid during off-peak hours using a battery. This energy can then be used to power a chiller during peak hours. The method was effective because AI can predict future weather and electricity prices. Siemen's patented method also mentions battery lifetime and energy storage costs. The patent establishes a universal model for identifying the lowest energy costs.

5.3.11. Patent Landscape of Panasonic

In addition to air conditioners, Panasonic is a well-known manufacturer of electronic products. It holds 912 AI-related patents, with patents related to ANNs accounting for the largest proportion of these patents (accounting for 23.6%), followed by those related to ML (accounting for 12.5%) and MPC (accounting for 7.2%). The main appeal of the methods described in the aforementioned patents is that the air conditioner can be used in all kinds of buildings. The patent landscape of Panasonic is displayed in Figure 21.

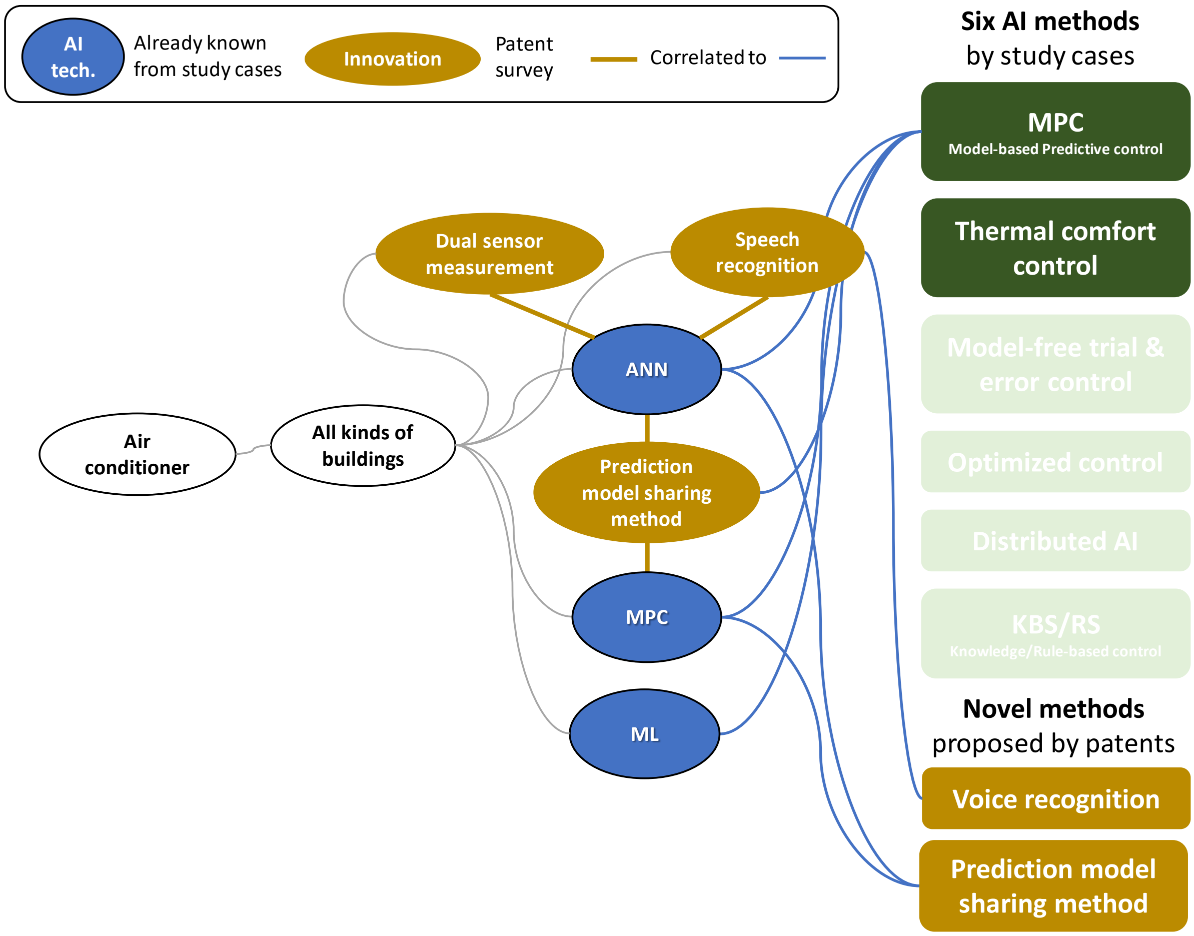


Figure 21. Patent landscape of Panasonic.

Panasonic's innovative proposition is the prediction model sharing method. This method uses a model whose accuracy has been verified, and which uses random number corrections to obtain a distributed prediction model. The model can be used to predict different physical phenomena.

This discussion investigated the patent landscape to illustrate the correlation between the patents owned by 11 companies and the six effective AI energy-saving methods observed in academic research. The next section presents a comparison of the current statuses of academic research and enterprise patents. This comparison was conducted to identify effective methods for rapid AI commercialization.

5.4. Difference between Academic and Commercial Research

We investigated the differences between the current statuses of academic research and enterprise patents. Figure 22 illustrates the difference in the typical thought processes governing relevant academic research and enterprise patents.

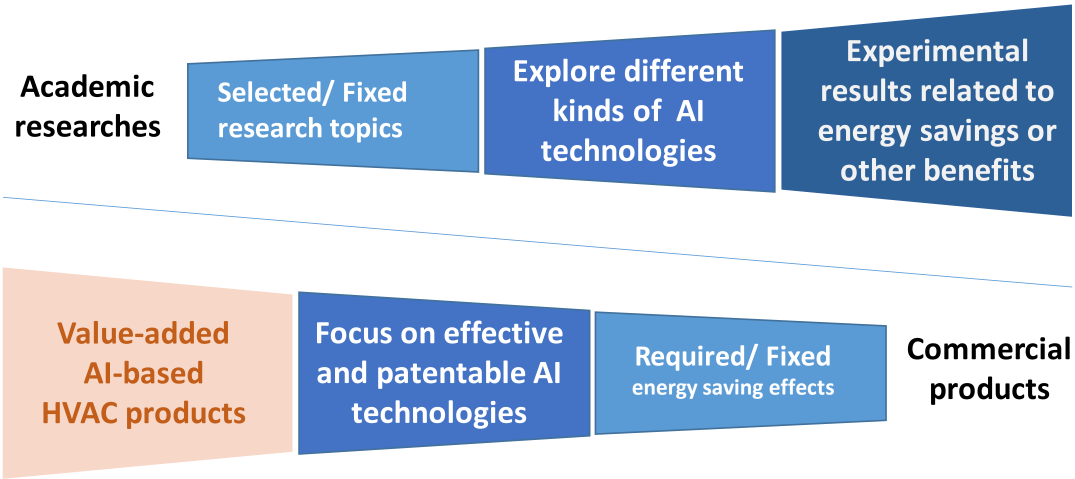


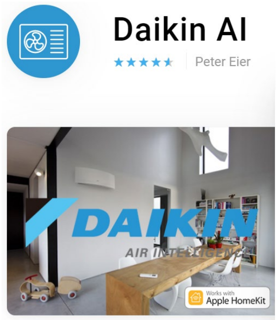
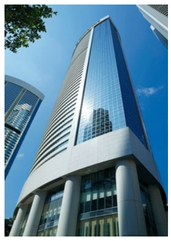
Figure 22. Difference in the thought processes governing academic research and commercial product development related to the use of AI technologies in HVAC systems.

Academic research focuses on specific topics, such as selected HVAC equipment applied in a specific type of building. The focus of research is typically the exploration of diverse technologies. The final result is usually the result of an experiment on energy savings, comfort improvements, or other benefits.

Specific targets related to energy consumption must be achieved in commercial product development. For example, an energy-saving effect must reach a specific percentage before a technology can be incorporated into a product. Patents for products are typically filed before product development. For a product to be patented, the AI technology used must be effective and patentable. Patentable innovations include new products, new processes, software, business methods, and some types of biological materials. By contrast, artistic creations, mathematical algorithms or models, abstract intellectual or mental concepts or processes, plans or schemes, and principles or theories cannot be patented. In addition to patentable subject matter, a successful patent filing requires the method to be novel, inventive, and useful. Moreover, the innovation must not have been used previously (known as prior art).

The final results for enterprise research and development are high value-added HVAC products. Table 13 lists the AI-based HVAC products investigated in this research.

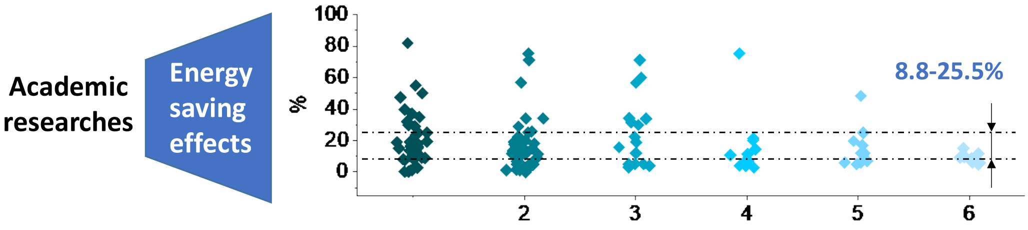
Table 13. AI-based HVAC products surveyed in this study.

	Daikin	Gree	IBM
		 55% energy savings	 30% energy savings
Johnson Controls	Google		LG
 50% cost savings	Cooling system  40% cost savings	Smart thermostat 	 30% energy savings
Midea	Siemens	Samsung	Panasonic
	 30% energy savings		 20% energy savings

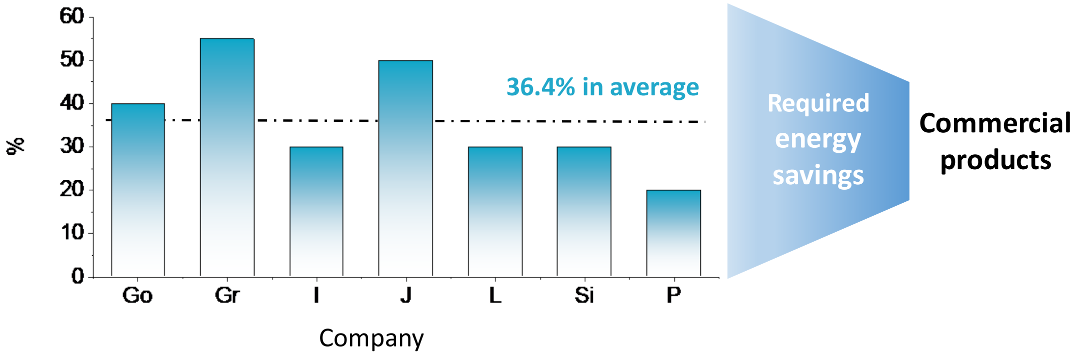
The products in Table 13 include air conditioners, chillers, and controllers for heating or cooling systems. Figure 23 presents a comparison of the energy savings of the AI methods used in academic research and the investigated commercial products.

As presented in Figure 23a, the six AI methods in academic research have average energy savings of 8.8–25.5%. Commercial products have average energy savings of 36.4%. Although these data are only claims by manufacturers and are not proven by a rigorous quantitative analysis, the aforementioned numbers still represent the energy savings expected from commercial products. These savings are 10% greater than those typically achieved in academic studies.

In accordance with the product development process presented in the lower part of Figure 23b, the energy-saving data comparison in Figure 23 indicates that companies must select AI methods with high energy savings and use relevant patents for enhancing energy savings to meet market expectations, such as expectations for AI-based HVAC products.



(**a**)



(**b**)

Figure 23. Energy savings of the (**a**) six AI methods used in academic research and (**b**) investigated commercial products.

5.5. Keys for Accelerating AI Commercialisation in HVAC Systems

A comprehensive investigation of more than 30,000 patents revealed that most patents are related to MPC (10,688), followed by the KBS/RS (3648) and MACS (2666), as shown in Figure 24. A patent application is an expensive procedure; thus, AI technologies involved in more patent applications are believed to be more effective by companies. Related technologies are also patentable and may be critical for research and development aiming to accelerate the commercial applications of AI.

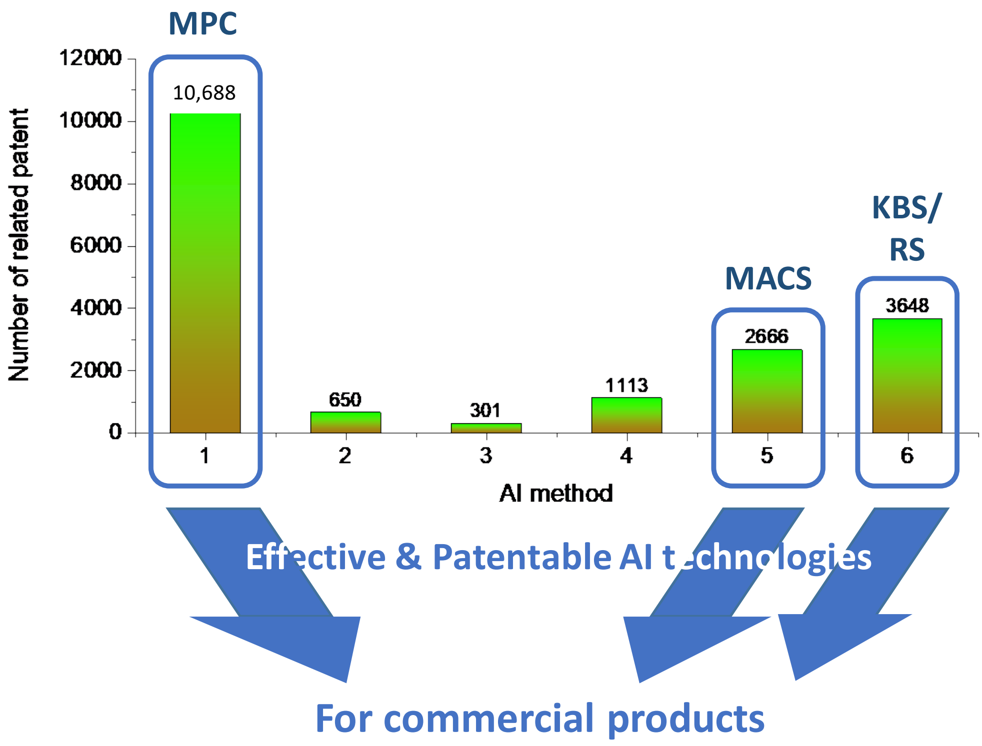


Figure 24. Effective and patentable AI technologies for commercial products by the number of related patents.

In addition to the number of patents, the number of citations of related patents was analyzed. Analysis of patent citations can be used to measure the quality of patents. The results of the aforementioned analysis are presented in Figure 25.

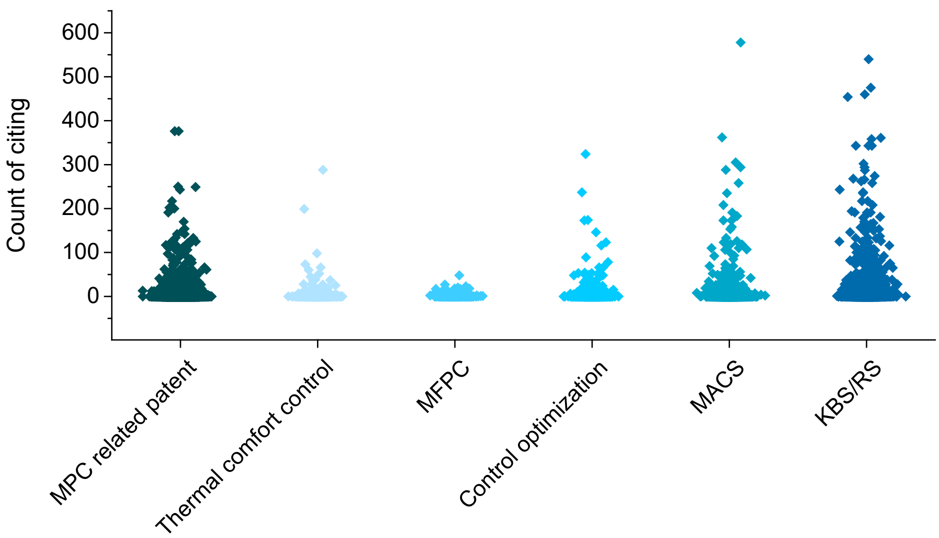


Figure 25. Analysis of patent citations with respect to the six AI methods.

A comparison of Figures 24 and 25 indicates that MPC, the MACS, and the KBS/RS are the methods that companies believe to be most effective. Most identified patents involved one of these three methods, and patents related to these three methods have high citation counts. Thus, AI-related patents with high quality are filed to protect high value-added AI-based HVAC products, and these patents typically include one of the three methods.

Considering the information depicted in Figure 22, the patent application content and innovations claimed by 11 companies indicate that high value-added HVAC products are associated with the following four elements:

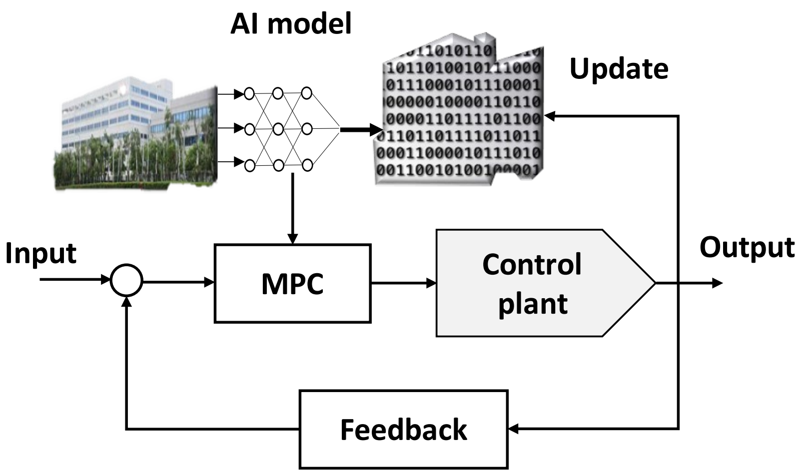
- Energy saving for sustainable development
- Cost savings
- Thermal comfort improvements
- Easy implementation.

These four elements are derived from the academic papers and innovations claimed by patents. Most studies in Table 1 describe how AI can save energy, reduce costs, and improve thermal comfort. However, as presented in Tables 2–12, some innovations emphasize easy implementation. Typically, few historical data are available for HVAC equipment in buildings. However, most AI technologies require historical data for training to build models or export rules to operate successfully. Therefore, innovation and invention must first focus on overcoming the historical data requirement to create sustainable air-conditioning systems.

This study linked the four elements and six AI methods with the patents from 11 companies. This produced the results of the final step. The process to apply AI for HVAC equipment to save energy, save cost, and improve thermal comfort is proposed. It is also noted that ease of implementation is also an important consideration for AI. The results are summarized in Tables 14–19.

Table 14. AI-enabled MPC technology for sustainable air-conditioning systems.

AI — Method 1. MPC



AI HVAC Product	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
	Information processing method	Fault diagnosis and Failure prediction	Air quality prediction model	Prediction-sharing model
AI patent	Multi-frame prediction	Accessory lifetime prediction		Plug-and-play control
	Data correction	Smart phone assisted ML		Smart user interface
	Hybrid ANN	Battery lifetime and cost calculator		Transfer learning

	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
	Spiking NN			Virtual data generation
	RBF NN			Simulation for testing control strategies
	Reliable data stream			Universal model
	Cascade model			
	Smart phone assisted ML			

Keys to accelerating commercialization

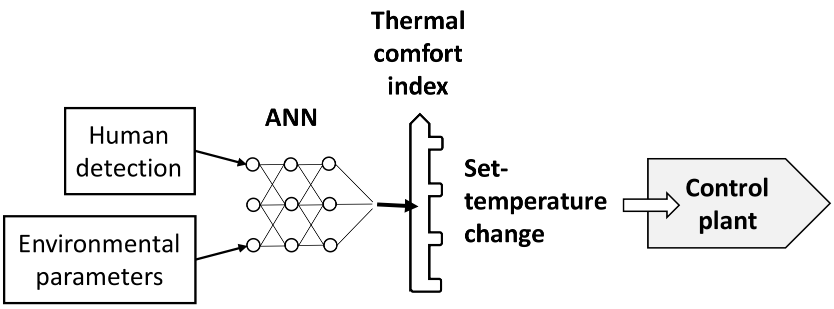
(1) High energy-saving effects; (2) easy-to-implement AI

Future research directions

(1) Smartphone-assisted prediction and energy-saving strategies; (2) novel NN designs; (3) transfer learning technology; 4) possibility of a universal model or work flow for different HVAC equipment in all types of buildings; (5) accessory fault and failure predictions; (6) explainable AI

Table 15. AI-enabled thermal comfort control technology for sustainable air-conditioning systems.

AI — Method 2. Thermal comfort control



AI HVAC Product	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
AI patent	Thermal image recognition		Thermal image recognition	Smart user interface
	Member discrimination		Voice recognition	
	Smart phone assisted ML		Member discrimination	
	Room allocation system		Smart phone assisted ML	
	Three-dimensional ventilation model		Clothing ROI detection	
	Signature-based thermostat control		Room allocation system	

	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
			Three-dimensional ventilation model	
			Air quality prediction model	
			Dust concentration control	
			Signature-based thermostat control	
			CNN/RBF NN	

Keys to accelerating commercialization

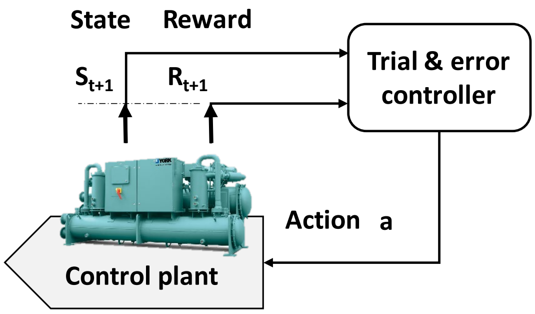
(1) Thermal comfort improvements by ventilation; (2) energy-saving effects; (3) smart user interfaces for thermal comfort sensing and control

Future research directions

(1) Coach mode to train humans to acclimate to slightly uncomfortable environments to save energy; (2) novel NN structure to sense human comfort levels

Table 16. AI-enabled MFPC technology for sustainable air-conditioning systems.

Method 3. MFPC



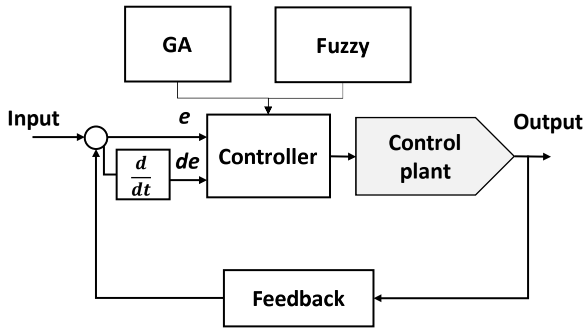
AI HVAC Product	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
AI patent	Reliable data stream			Reliable data stream
	Remaining value calculation			Remaining value calculation
	Information processing method			No need for history data or database
	Dual sensor measurement			

Keys to accelerating commercialization

(1) Energy-saving effects

Future research directions (1) Control stability of trial-and-error control; (2) novel RL networks that can quickly identify and correct prediction errors

Table 17. AI-enabled control optimization for sustainable air-conditioning systems.

AI	Method 4. Control optimization		
			
Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI

A total of 1113 patents use a GA, fuzzy logic, PSO, or other algorithms to adjust the parameters of PID controllers; however, no innovation is observed.

Keys to accelerating commercialization The technology development is relatively mature compared with other methods, and most existing commercial controller parameters have been optimized **Future research directions** Innovative mathematical theories may be developed; however, these mathematical theories cannot be patented

Table 18. AI-enabled MACS and distributed AI technology for sustainable air-conditioning systems.

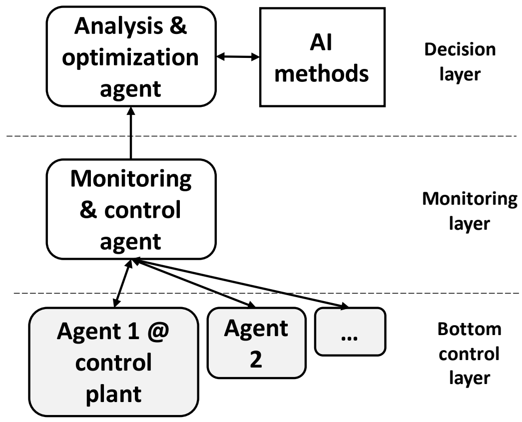
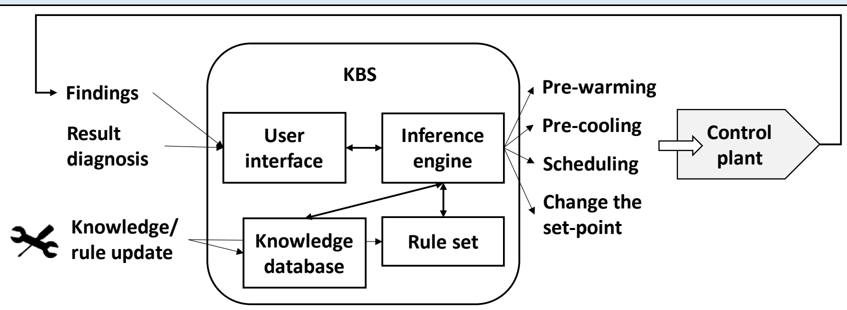
AI	Method 5. MACS			
				
AI HVAC Product	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI
AI patent	Signature-based thermostat control		Signature-based thermostat control	Internet communication and data acquisition
	Dual sensor measurement		Dual sensor measurement	5G network environment
				IoT
				M2M
				MTC
	Keys to accelerating commercialization (1) Easy to implement by continued development of the Internet, 5G, and IoT; (2) reduced energy usage while maintaining occupant comfort **Future research directions** Continue to develop high-performance AI chips deployed in the bottom layer			

Table 19. AI enabled KBS/RS-based control technology for sustainable air-conditioning systems.

AI	Method 6. KBS/RS			
				
AI HVAC Product	Energy-saving effect↑	Cost savings↑	Thermal comfort↑	Easy-to-implement AI

	Environment information obtaining method	Multi-energy resource management		Anonymous method to chat to and query database
AI patent	S-curve			Method for data correction
	Pattern recognition			
	Method for data correction			

Keys to accelerating commercialization

(1) Use of optimal prewarming, precooling, and chiller start–stop schedules to save energy; (2) for industrial applications, an energy-efficient program with a database or rules sets would be more reliable than would a control method that uses NN learning and is model agnostic

Future research directions

(1) Chat bots or novel query interface designs to facilitate access to the knowledge database; (2) development of knowledge extraction systems to reduce expert personnel requirements

Tables 14–19 present a summary of the technological development in MPC, thermal comfort control, MFPC, optimization, MACS, and KBS, respectively. Table 17 is particularly noteworthy. Because mathematical theories cannot be patented, mathematical innovation cannot be identified by analyzing patents. Thus, we can only infer that some HVAC products should be optimized using AI theory. The main theories are the GA and fuzzy logic. Moreover, although mathematical theories cannot be patented, the 1113 patents related to control optimization seem mostly claim mathematical theories as technical methods and propose energy-saving technical solutions. Therefore, the development of new mathematical theories is still recommended because of the limitations of patent applications. Further conclusions are presented in the next section.

6. Conclusions and Future Prospects

The following conclusions were obtained in this study by analyzing the data of 85 academic cases and 31,221 patents:

- Six methods of effectively applying AI for sustainable air-conditioning system were identified by the academic research results. Numerous patent applications were organized with an RDF, and the results were successfully linked to the six methods. Thus, we analyzed the six methods not only from academic data, but also from patent application statistics to verify the effectiveness of AI enabled technologies. The six methods were MPC, thermal comfort control, MFPC, control optimization, MAC, and KBS/RS-based control.
- According to an analysis of academic cases, as shown in Figure 9, the median energy savings of MPC were approximately 17.4%. MFPC had the highest energy savings of 25.5%, and the lowest energy savings were achieved by the KBS/RS (only 8.8%). However, differences in the number of cases investigated limit this conclusion. For example, we investigated 40 studies related to MPC but only 10 related to the KBS/RS. Thus, energy-saving ratio data can only be used as a reference and not as the main basis for comparison.
- The focus of this research was to understand the keys for accelerating the development of commercialization. Thus, patent analysis was conducted to compare the

aforementioned six methods. The RDF method was used to analyze more than 30,000 patents held by 11 companies. Patent applications are expensive; thus, methods related to more patents are the most promising for AI development.

- MPC is the AI technology most favored by enterprises for sustainable air condition systems. A total of 16,888 patents related to ANN and different NN architectures were identified, including the basic MLP method mentioned in academic papers and innovative methods such as BPNN, WNN, or the patent-protected spiking NN. The implementation framework of MPC is presented in Table 14. MPC implementations can learn from data to construct a system model. With ML, the control system can use the system input to make predictions automatically. Then, these predictions can be used to control HVAC equipment in advance to achieve energy savings for sustainable development.
- The KBS/RS is the second most favored AI technology by enterprises for HVAC systems. The implementation framework of the KBS/RS is presented in Table 19. For industrial applications, such as cooling systems in data centers, commercialized AI technologies involving KBS/RS-based control are typically used. Compared with MPC, in which an ANN is used to learn automatically and achieve predictive control, the KBS/RS constructs a database or infers a set of rules for controlling HVAC equipment. With a database to query or rules to follow, industrial control systems can save energy and have high reliability.
- The MACS is the third most favored AI technology by enterprises for sustainable air-conditioning systems. The implementation framework of the MACS is presented in Table 18. Because of the popularization of the Internet, 5G, and IoT, in addition to the development of high-performance chips, the MACS can be used to implement distributed AI on remote sensors and controllers. These intelligent devices can learn about occupants' room environments and reduce energy consumption in each room by automatically adjusting to an optimal level based on heat load conditions and air-conditioning capacity.
- Improving energy efficiency is key to accelerating the commercial applications of AI for HVAC equipment. According to academic research results, the six methods exhibited different energy savings (8.8%–25.5%). However, as summarized in Table 13, AI-enabled HVAC products should be able to achieve an average reduction in energy usage of 36.4%. Academic research results should be improved by at least 10% to achieve parity with industry products.
- Academic research results indicate an improvement in the PMV index of 15%–60% using AI methods. One special case used MFPC to predict and reduce comfort violation by 98%, resulting in 2% PPD. Most enterprise patents use smart interfaces to communicate with occupants, or use visual or thermal images to confirm heat sources or occupant locations. Ventilation control is then used to improve thermal comfort. In summary, academic achievements and industry innovations indicate that AI can improve occupant comfort by nearly 50%, communicate with occupants to confirm their comfort, and ultimately reduce occupant dissatisfaction to less than 3%.
- Energy cost savings are also a crucial factor in promoting commercialization. Academic research results indicate that cost savings of 6%–30% can be achieved using AI technologies in HVAC systems. Patent applications emphasize the need to increase the operating cost of additional devices when reducing energy costs. For example, HVAC equipment can be equipped with energy storage devices to store energy during off-peak electricity generation hours, and then use these energy storage devices during peak hours when electricity costs are expensive, to achieve the goal of reduced energy costs. The reductions in electricity should be considered alongside the lifetime cost of the battery lifetime; these two costs should offset each other.
- Patent innovation is key to the commercialization of AI for HVAC systems. Easy-to-implement AI technologies are required for HVAC systems. AI implementations

usually require substantial historical data for ANN training. However, HVAC equipment typically does not record data. To overcome this problem, patent innovations have proposed prediction-sharing models or universal models. Academic research and patents have proposed transfer learning to solve the training data problem. The objective is to design AI technology that is plug-and-play for HVAC control.

This study is the first usage of an RDF to analyze patents and compare them with academic research. The following 10 topics are proposed by innovative patents and suggested for future academic research:

1. Novel NN designs: Notable NN designs are spiking NNs and long short-term memory (LSTM).
2. Smartphone-assisted ML: Small air-conditioning systems used in small and medium-sized buildings are intended to provide a comfortable environment for occupants. Smartphone-assisted ML can communicate with occupants through their smartphones to predict loads and future energy consumption.
3. Transfer learning technology development: Large-scale air-conditioning systems used in all types of buildings may not have historical data for AI training. Transfer learning technology can transfer learning results for one building to another building, and help to make AI easy to implement.
4. A universal model: As AI becomes more commercially popular, multiple building usage records can be collected. If the industry can anonymously share these building data in an open manner for academic research, a universal model may be found.
5. Fault diagnosis and failure prediction, including accessory failure predictions: The failure of HVAC-related accessories, such as filters and belts, has not yet been studied in the literature; however, these failures affect the efficiency of air-conditioning devices. Academics should invest more time in the fault diagnosis of HVAC-related accessories.
6. Explainable AI (XAI): XAI can not only conduct predictions but also indicate the basis of its predictions; thus, XAI can improve the commercial applications of AI. Currently, XAI patent applications are rare; however, they are important for different types of applications, especially industrial applications, and are worthy of academic investment.
7. KBS interactive interface: The KBS/RS uses a database or fixed rules to query the AI control system. In the future, academic research can focus on KBS interactive interfaces or automatic rule inference systems that can reduce the requirement for expert personnel to establish a database or control rules.
8. High-performance AI chip: The high-performance chip is the foundation for realizing distributed AI in distributed air conditioners. This kind of chip can enable remote controllers to continue to work with no connection to a cloud server.
9. Stability of trial-and-error control: A total of 16 studies support the applications of MFPC, which exhibits high energy savings. However, the industry has not yet supported the development of this technology because the AI model itself is unpredictable. Because of the use of trial and error in MFPC, the control is relatively unpredictable. Methods for increasing the stability are a possible focus of future development.
10. Thermal comfort coach mode: Sustainable air-conditioning system design not only considers energy saving, but also personnel comfort. Current patent applications focus on thermal image recognition and ventilation control. A novel patent application relates to personnel clothing ROI detection. In the future, the development of the thermal comfort coach mode is recommended. This mode may be combined with behavioral change to increase acceptance by users. A slightly uncomfortable environment would further increase energy savings for sustainable development of human beings.

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Nomenclature

AHU	Air handling unit
AI	Artificial intelligence
ANN	Artificial neural network
BEMS	Building energy management system
BLE	Bluetooth low energy
BPNN	Back propagation neural network
CAV	Constant air volume
CNN	Convolutional neural network
CQ	Characteristic quantity
CSPF	Cooling seasonal power factor
DCAC	Data center air conditioning
DL	Deep learning
DT	Decision tree
GA	Genetic algorithm
GAN	Generative adversarial network
HVAC	Heating ventilation, and air-conditioning
IoT	Internet of things
KBS	Knowledge based system
LSTM	Long short-term memory
M2M	Machine to machine
MACS	Multiagent control system
MFPC	Model free predictive control
ML	Machine learning
MLP	Multilayer perceptron
MPC	Model-based predictive control
MTC	Machine type communication
NARX	Nonlinear autoregressive network with exogenous inputs
NLP	Natural language processing
NN	Neural network
PD	Proportional-differential
PI	Proportional-integral
PID	Proportional-integral-differential
PMV	Predicted mean vote
PPD	Percentage of people dissatisfied
PSO	Particle swarm optimization
RBF	Radial basis function
RDF	Resource description framework
RH	Relative humidity
RL	Reinforcement learning
RMSE	Root mean square error

RNN	Recurrent neural network
ROI	Resistance of insulation
RS	Rule set
SVM&R	Supporting vector machine & regression
TPH	Temperature, pressure, and humidity
VAV	Variable air volume
VRF	Variable refrigerant flow
WNN	Wavelet-based neural network

Symbol or Abbreviations

A	AI technique type
B	Building type
Ca	Carrier company
Da	Dakin company
Go	Google
Gr	Gree electric company
H	HVAC equipment type
I	IBM company
J	Johnson Controls
K_D	Differential constant
K_I	Integral constant
K_P	Proportional constant
L	LG electric company
M	Midea company
Pa	Panasonic company
R^2	R-squared value
Sa	Samsung company
Si	Siemens company

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