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Review

Human-Cyber-Physical Systems for Energy Internet—A Review

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Abstract: As the research of HCPS in EI is ongoing, an increasing number of problems should be addressed, such as the leading role or aid function definition of humans, the coordination of humans with cyber and physical equipment, the state awareness of information handling, etc. Therefore, an increasing number of advanced techniques should be considered and adopted, such as IOT, AI and big data, etc., the main target of which is to improve the timely, digitalized, informationized and intelligent characters of the related tasks. This paper first introduces the applications of CPS in every industry, especially in the power grid and EI (Energy Internet), the introduction of which can be classified as a framework design, support technologies and algorithms, system function, power ancillary service, Energy Internet realization, etc. Then, this paper summarizes the related technologies of Human-Cyber-Physical Systems, which mainly include the areas of system design, theoretical analysis, technique development and application forecasting, which emphasizes its applications in EI. For the development of HCPS, it uses the human-in-the-loop concept and digital transformation as the future research and development directions, the performance of which can be largely promoted through these means. With the aid of HCPS, the optimal system performance of EI can be achieved more robustly, which finally evolves into an integrated and comprehensive modern power grid.

Keywords: CPS; HCPS; Energy Internet; human-in-the-loop

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1. Introduction

With the development of advanced computing, analyzing and control technologies—such as industry 4.0 and AI—data handling, analysis and application have become more important in assisting hardware operations; therefore, CPS and HCPS have drawn broad attention. The latter is the improvement of the former, but sometimes they have the same meaning. Based on the development of CPS, HCPS place more emphasis on intelligent systems and the leader function of humans in industry production.

Since humans step into modern industrial society, HCPS have undergone four stages, which are shown in Figure 1 ([1]):

(1) HPS: the production system was formed by humans and machines, which emphasized the human control of the machine, reduced the labor intensity and improved the production efficiencies through electrification and automation.
(2) CPS: the production system was made of an information system and machine, which emphasized the aid function of the information system in industry, which through sensor information gathering and actuator information feedback, improved the automatic level of the machine.

(3) CPSS: developed from CPS, the production system is made of an information system, physical system and society, which emphasized the complementary nature of the information system and society system, and through information relay, improved the intelligence level of machines (give it a fish). As CPSS is the transition of CPS and HCPS, it is not reviewed in detail in this paper.

(4) HCPS: based on CPSS, the production system is made of humans, cyber and physics, which emphasizes the leader role of humans in production. Based on the information relay and policies interaction, it can largely improve the system's intelligence level (teach him to fish).

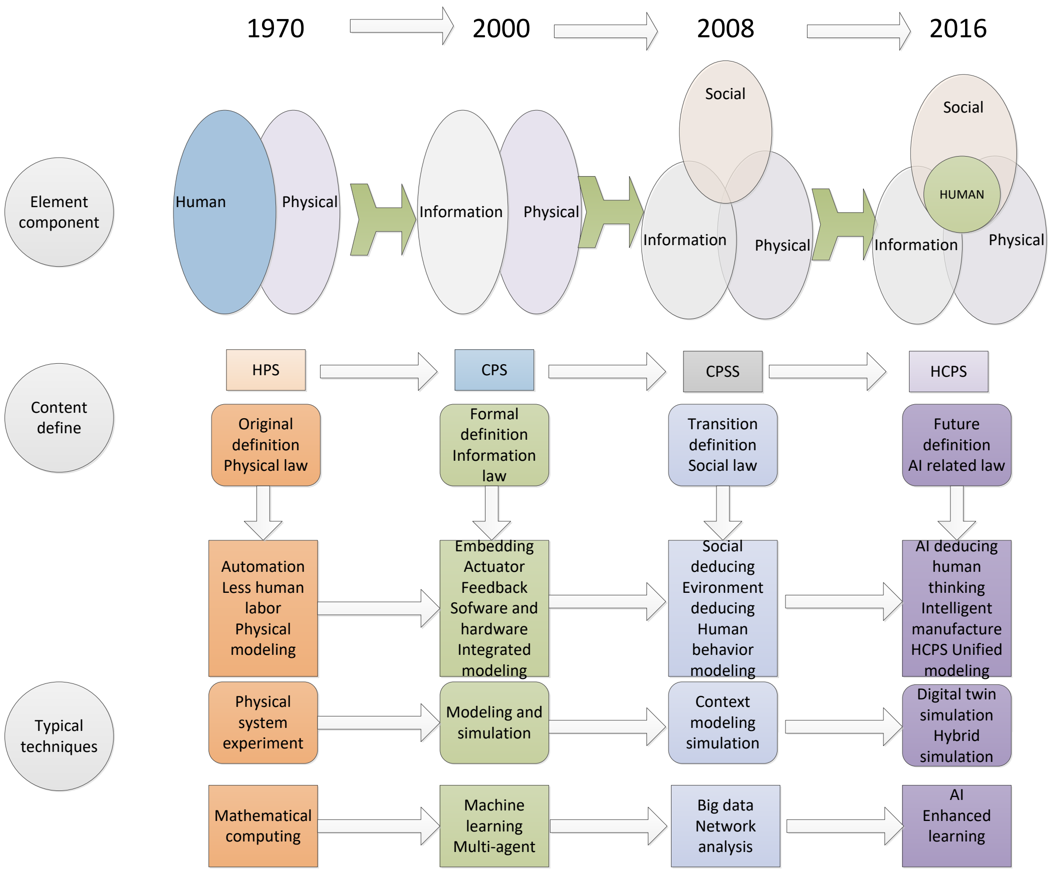

Figure 1. The development trend of HCPS.

In order to write this paper, following the steps of a systematic literature review [2], and searching with the keywords "Ei" (can be extended to "energy system" and "power grid"), "CPS", "HCPS", "digitalize transformation" and "human in the loop", we selected 112 papers from CNKI, Baidu Academy and IEEE. The cited paper number for CPS and HCPS research conducted between 2016 and 2023 is shown in Figure 2. From the figure, we can see that the main research years for CPS research are between 2018 and 2021; after and before this time range, the number of published papers is smaller, while the main research years for HCPS are between 2020 and 2023, which show the related research of HCPS is ongoing and can gradually substitute CPS.

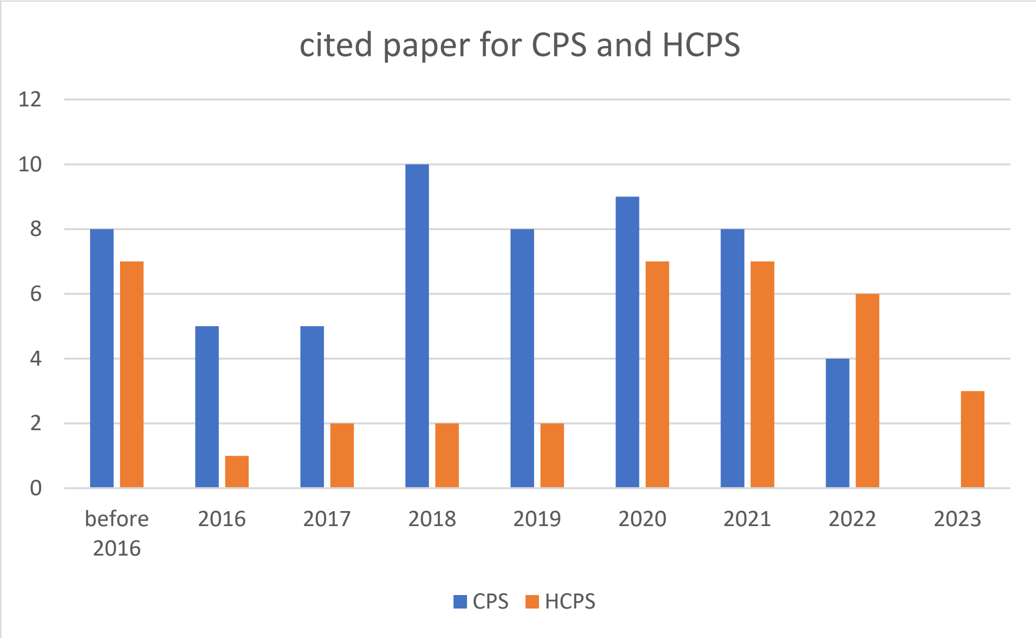

Figure 2. The cited papers of CPS and HCPS.

From Figure 3, we can see that about 40.1% of the cited papers are published in journals, about 58% of cited papers are published as conference papers and the others are doctorate theses; thus, the diversity and coverage of papers can be ensured.

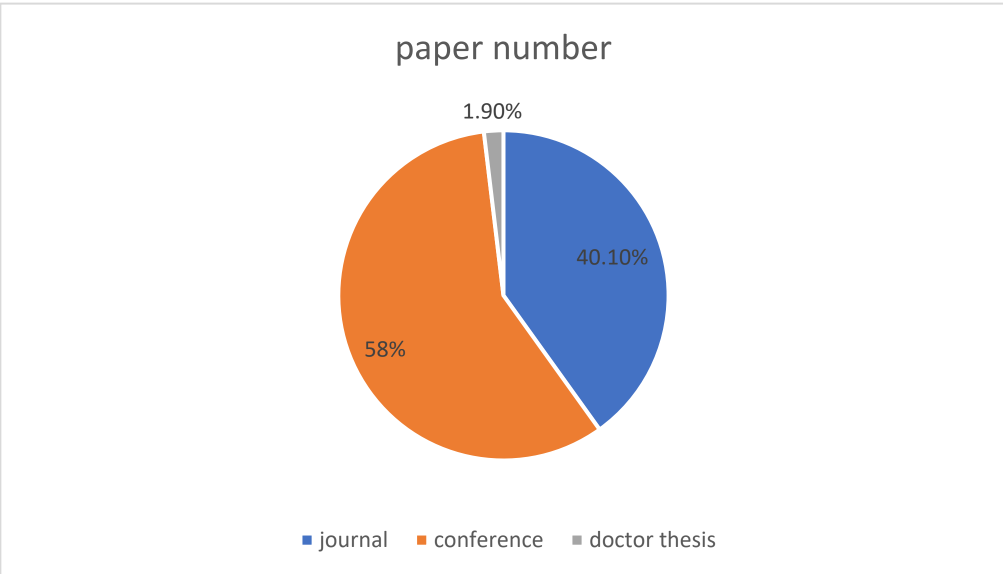

Figure 3. The published type of papers.

The contributions of this paper are shown in Figure 4. Based on the contributions, the subsequent structure of this paper is as follows: the 2nd section introduces the current development situation of CPS; the 3rd section introduces the current development situation of HCPS; the 4th section introduces the application of the related modern technologies in CPS and HCPS; the 5th section discusses potential HCPS realization in EI; the 6th section concludes the whole paper. The last section discusses the future development directions.

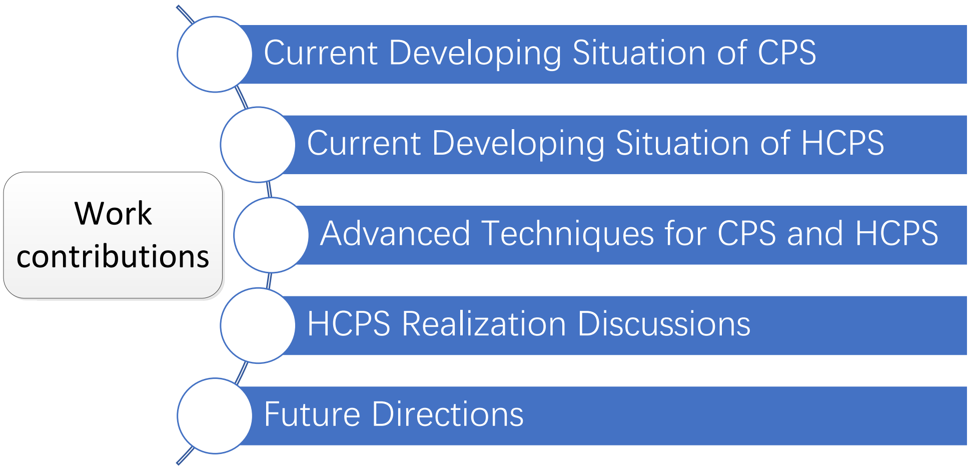

Figure 4. The contribution of this paper.

2. Current Developing Situation of CPS

As shown in Figure 5, CPS is the pioneer of HCPS, whose current research domains include industry, agriculture, aerospace, shipping, building, safeguarding, education, machine and software and hardware devices, energy, etc. As the paper focuses on the study of HCPS used in Energy Internet, the use of CPS in the power grid is elaborately studied compared to other industries; the further stage of HCPS in Energy Internet is also elaborately illustrated in the following sections.

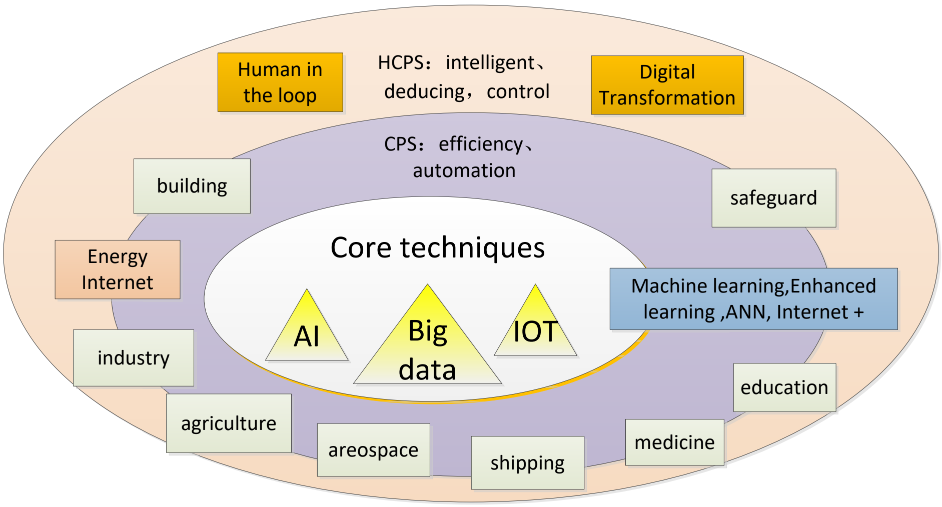

Figure 5. The domain of CPS and HCPS.

2.1. CPS on related Industries

The research of CPS in the related industries is shown as in Table 1, which includes theoretical analysis, industry, agriculture, aerospace, shipping, building, safeguarding, education, medicine, hardware/software, etc. Its application in the energy domain is described in Section 2.2.

Table 1. CPS on related industries.

Industry	Paper No.	Research Content	Main Object	Technique Detail

Theory analysis	[3]	Proposed a function level cyber-physical code design method.	Designed a function level cyber-physical code design method.	Using high-level combination algorithm.
	[4]	Reviewed the development of CPS, discussed the related safety factors with the CPS, brought challenges, and its effects in healthcare.	Undertook a development review.	Conducted safety factor analysis and challenge analysis.
	[5]	Proposed the basic concepts of CPSOS modeling.	Created system model equations, exchanged data through ultra-long distance.	Set up neural networks, sensing networks and action actuate networks.
	[6]	Proposed an initial design of a flexible and real-time CPS monitor tool.	Founded related framework and main comprised components, and further researched related demos.	Designed a real-time CPS monitor tool.
	[7]	Advanced five standards for the model performance evaluation, and the model performance based on CPS modelling was discussed.	Undertook the hybrid modeling method research.	Using physical and equation modeling and machine learning.
	[8]	Discussed whether the machine and human can realize collaborate control in the CPS system.	Realized collaborate control in the CPS system.	Updated the difference list between the abilities of human and machine
industry	[9]	Founded a pure simulation prototype on industry CPS.	Realized simulation integration of CPS and physic system.	Conducted firm ware and multi-physic control systems' collaborative simulation.
	[10]	Listed the faced challenges in CPS collaborative development.	Undertook the simulation demo in CPS design.	Using coherent management and collaborative simulation.
	[11]	Analyzed the need of industry 4.0 to CPS system and proposed detailed representation of CPS machine tool system.	Proposed a 4-layer framework.	Conducted detailed representation of CPS machine tool system.
	[12]	Proposed an intelligent sensor modeling and communication protocol based on digital twin.	Undertook intelligent collaboration in CPS.	Using digital twin.
	[13]	Focused on industry safety and control and proposed related schemes with digital twin system.	Realized industry safety and control.	Based on digital twin system.
	[14]	Proposed setting behavior models based on digital twin in IOB (Internet of Behaviors).	Increased the running efficiency and transparent extent of CPS, and improved the dynamic adjust abilities.	Using digital twin in IOB.
agriculture	[15]	Developed an electrical circuit model for adjusting soil's moisture in next generation of CPS irrigation.	Realized next generation of CPS irrigation.	Developed an electrical circuit model for soil's moisture.
aerospace	[16]	Proposed corresponding CPS interactive model to realize formation control and tracked the emergence of other robots and the static hurdles.	Realize formation control, orbit tracing and obstacle avoiding.	Set up CPS interactive model.

	[17]	Proposed an electromechanical event model and the co-simulation method based on CPS.	Illustrated related space and temporal information with this energy system, and proposed system modeling and handling method based on event response.	Founding unified model and top layer services across the domain of application and data resource.
	[18]	Proposed a mutation analysis tool for embedded software in CPS.	Realized mutation analysis in CPS environment and solved the extendable and precision problem.	Realized online software system management of satellite orbiting.
shipping	[19]	Proposed a next generation of ship IPS (integrated power system), which realized high information level of every physical equipment, and would evolve into CPS.	Realized patch handling and distributed deploying to obtain time efficiency and system extensibility.	Proposed a new type of key-value model.
building	[20]	Proposed a multi-agent technology and corresponding ZigBee protocol for intelligent building CPS system.	Set up intelligent building CPS system.	Realized wireless network user level CPS based on multi-agent technology.
safeguard	[21]	Proposed some performance extensions on DFD (Data Flow Diagram) and used it in UAV quad-rotor to analyze its safety.	Constituted effective information and physical defense system.	Using DFD (data flow diagram) on related CPS interaction.
	[22]	Proposed a safety threat quantization analysis method in ICPS (Industry CPS).	Founded the math model between physical factory and feedback controller.	Set up dynamic closed loop fusion model.
	[23]	Decide the boundary of the plane to distinguish grid fault and information attack based on CPS.	Distinguished the abnormal features of physical fault and information fault.	Proposed a distributed 2-dimensional plane mapping method based on local measured frequency and voltage.
education	[24]	Proposed a new task-oriented real and flexible method to teach CPS.	Using a new task-oriented real and flexible method to teach CPS.	Summarized five types of teaching methods and realized on demand use.
	[25]	Managed to create the CPS curriculum focusing on industry.	Made breakthrough on the gap between industry need and education output.	Taking institution cooperation.
medicine	[26]	Used CPS to non-intrusive measure the patients’ blood oxygen content and reduce the error probability.	Realized CPS medicine operation.	Modelled the context probability based on system status and developed a context sensing filter.
	[27]	Realized rapid binary vulnerability detect for healthcare CPS based on cycle semantic learning driven.	Improved the detect precision of robust properties.	Using the related technique with healthcare CPS.
	[28]	Used CPS related technologies to realize remote operation of medical robot to effectively resist COVID disease.	Resisted COVID disease.	Using CPS related technologies.
Hardware/software	[29]	The usage of the general accelerator and related software and hardware to provide key non-function demand for covering offline multi-core	Used proper virtual and self-organizing technologies for CPS.	Set up offline multi-core and chip multi-handling system framework.

		and chip's multi-handling system framework.		
	[30]	Described the role and function of True Time 2.0 software package in information packing simulation with the scheme of CPS handler and network protocol.	Undertook programming in CPS research by using toolbox to simulation and multi-module to initialization.	Designed the TrueTime tool.
	[31]	Proposed the fusion model of sensor element and hardware in CPS.	Adopted active resistor measurement and obtained higher measure precision.	Conducted multi-channel sensor interaction.
	[32]	Used CPS components to enhance the data quality and sensing precision of inertia sensors.	Developed physical coherent tools and algorithms of inertia measure units.	Using post-processing to reduce the noise and mistake of estimated physical value in the measurement.
	[33]	Designed the package scheme of sensor method by CPS.	Undertook on the optimal and package of function method.	Realized inter-layer calling between methods.

2.2. CPS on Electricity Power System

From Figure 6, we can see that the application of CPS in electrical systems includes the areas of framework design, support techniques and algorithms, system function, power ancillary service and Energy Internet realization, etc.

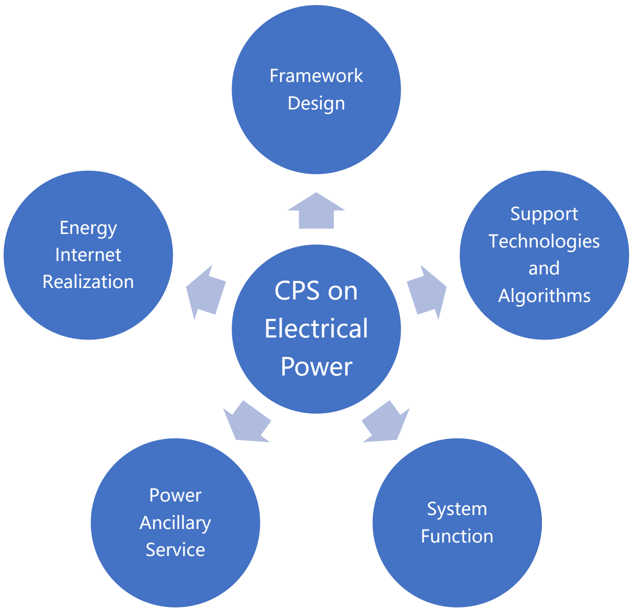

Figure 6. CPS application in electrical power system.

2.2.1. CPS on Framework Design

Framework design is the initial step of realizing CPS in power systems. In the power domain, it will embody the characters of opening, interconnection, peer, sharing, intelligent, economic and green for power CPS, which usually adopt the ideas of IOT, artificial intelligent and "Internet plus". The related research is shown in Table 2.

Table 2. CPS on framework design.

Industry	Paper No.	Research Content	Main Object	Technique Detail

CPS on Framework Design	[34]	Proposed the WECSs (Wind Energy Conversion Systems) concept, analyzed its function need, and further applied CPS to improve its performance.	Proposed the research trend for energy applications, so CPS could be potentially integrated with WECS.	Realized demand-side management and smart building.
	[35]	Proposed the UPIOT (Ubiquitous Power Internet of Things) concept.	CPS can deeply coordinate information and physical resources in UPIOT.	Using the techniques of computing, communication and control.
	[36]	Based on information and automation, and through deepening fusion of information system and physical system, electrical power system would gradually evolve into power CPS.	Researched the finite state automation model of electrical power components, and analyzed its state characters, state transfer rules and state transfer functions of related services.	The model was validated in the feeder terminal units.
	[37]	Proposed a multi-micro grid task model based on CPS.	Researched the CPS framework and model of multi-micro grid and set up the multi-micro grid CPS model based on multi-agent system.	Related demos verified the effect of proposed model.

2.2.2. CPS on Support Technologies and Algorithms

The realization of CPS is based on advanced technologies and algorithms, in which stochastic probability statistics and simulation modelling are the main development directions, which include many advanced technologies and algorithms, as shown in Table 3.

Table 3. CPS on support technologies and algorithms.

Research Topic	Paper No.	Research Content	Main Object	Technique Detail
Support Technologies and Algorithms	[38]	Proposed a distributed network method for CPS risk evaluation and defense policy making. Through network risk level analysis, it could promote the attack and defense precision.	Promoted the attack and defense precision.	Fulfilling the task based on stochastic game Petri model.
	[39]	In grid monitoring and operation, the key importance of interdependent of physical dynamics and communications in CPS was analyzed.	Information entropy estimation could be used in measuring its uncertainty and determined its communication need in monitoring.	ODEs (Ordinary Differential Equations) and PDEs (Partial Differential Equations) was used to describe the entropy evolution.
	[40]	Proposed that CPS standard can more objectively evaluate the effect of control behavior.	Realize optimal control and fulfill CPS standard at the same time.	Proposed a dynamic optimal CPS control method based on model predictive control in interconnect power grid.
	[41]	With the aid of cyber communication and handling, the SCPIFS (Security Control Plan Incorporating Frequency Stability) could ensure the safety and stability in both end of HVDC (High Voltage Discrete Current) tie-line and operate economically.	Ensuring that grid is within the limit of frequency stability domain.	With the aid of cyber communication and handling.

	[42]	Tested the performance of CPS based on exploring method.	Handled complex continuous method, expanded the big test input space, which was suited for black system.	Combined with the machine learning techniques to improve the search precision and effectiveness and expanded the test results in the form of information explanation.
	[43]	Introduced the related research of CPS power systems, it reviewed the development trend of info-attack means and summarized the modeling methods of CPS.	Had important theory and application value in the research of CPS power system.	Using relation matrix, graph theory, complex network theory, finite state machine, math programming and cell automation.
	[44]	Proposed that advanced ICT was the fundament of development power system into CPS network, which needed inter-connection and privacy preserve.	The CPS realization in power flow exchange needed the support of cyber interaction, to which ICT is the fundamental means.	Using ICT technologies.

2.2.3. CPS on System Function

The role of CPS is embodied in the system functions, which mainly lie in the system operation- and energy management-related services, as shown in Table 4.

Table 4. CPS on system function.

Research Topic	Paper No.	Research Content	Main Object	Technique Detail
CPS on System Function	[45]	Analyzed the CPS security modeling and its assessment in power grid.	IEMS (Integrated Energy Management System) was proposed, with the form of distributed EMS and cloud EMS.	Safety modeling and assessment were carried out.
	[46]	Proposed that as the state estimation was a basic function of energy managing system in the power grid, and the disturbing data might affect its performance.	CPS should consider the cyber security, and a sensitive analysis method for CPS was proposed.	Identifying its critical measurement.
	[47,48]	Proposed the need of HIL (Hardware-In-the-Loop) for CPS security testbeds to handle the power system blackout.	Have zero overruns and low latency in computing and transmitting.	The performance was verified by a synthetic grid model and IEEE related bus grid models.
	[49]	Proposed the function of EH (Energy Hub), and its reasonable location could make smooth and reliable operating of CPS in power grid.	A comprehensive EH location model was proposed based on CPS.	Using Matlab/Simulink to show its effectiveness improvement of EH in power utilization.
	[50]	Proposed the EISH (Energy Integrated Service Hub) concept, which can be seen as the integration of data center, energy store device, EV charge station, and gas network for cold and hot energy.	Make a reliable CPS in multi-energy system.	Consider the communication efficiency, data transmission delay, and energy transmission efficiency, and carried out the simulation using Matlab/Simulink.

2.2.4. CPS on Power Ancillary Service

The healthy realization of CPS lies in its ancillary services, which mainly consider simulations in safeguarding evaluations and preventive protection, as shown in Table 5.

Table 5. CPS on power ancillary service.

Research Topic	Paper No.	Research Content	Main Object	Technique Detail
CPS on Power Ancillary Service	[51]	Proposed that renewable energy and power market will increase the dimensions of distributed power generating problem.	Realized the intelligent training of grid control center's working staff, optimizing related factors such as in renewable energy, distributed generating and power market.	Fulfilling the target through CPS and edge intelligence.
	[52]	Analyzed the correlation of smart grid with CPS and based on the analysis of locating the key safe node in cyber-power fusion network, it proposed some effective safeguards.	Proposed some effective safeguards.	Fulfilling the task through modeling and simulation.
	[53]	Discussed the vulnerabilities of CPPS in community attack type. The related models included power level, information level and their function linkage in the condition of topo consistency and non-scale information network.	Analyzed the effect of different attacks and different information networks on the proceeding of cascade failure.	The proposed minimum load cutting model was illustrated as a linear programming model.
	[54]	Proposed that deep interaction of massive cyber-physical interoperation in DER (Distributed Energy Resources) and overall remote monitoring and control made grid attack easier.	A DER monitoring and control architecture of CPS was proposed, with standard communication protocols, such as IEEE 2030.5-2013 SEP2 (IEEE standard for Smart Energy Profile Application Protocol).	Related simulation showed 100% real-time performance and zero overruns.
	[55]	Proposed the PCPS (Power Cyber Physical System), which combining information flow and power flow.	A PCPS simulation platform based on ADPSS (the Advanced Digital Power Simulator) was proposed.	Related simulation results showed that this simulation could meet the needs of PCPS research.

2.2.5. CPS on Energy Internet Realization

CPS can be conveniently and economically used in EI, which introduces many new application scenes and research directions, as shown in Table 6.

Table 6. CPS on Energy Internet realization.

Research Topic	Paper No.	Research Content	Main Object	Technique Detail
CPS on Energy Internet Realization	[56]	Proposed EI-CPS (Energy Internet Cyber-Physical System) with deep couple of energy layer and information layer.	Proposed the future technique challenges of EI-CPS.	Paper analyzed core techniques in CPS, such as system modeling, data analysis and operation control and so on.
	[57]	Proposed a FPDU (Flexible Power Distribution Unit) based on CPS in Energy Internet.	FPDS (Flexible Power Distribution System) is further proposed, with the equipment combinations of iPower + Router, iPower + Switcher and iPower + Hub.	Included four key technologies, such as port plug and play, multi-port energy routing, hierarchical information communication and layered energy managing.

[58]	From system running perspective, existing problem of CPS in Energy Internet was systematic analyzed.	Proposed the key directions for future research with adaptive planning as the main view angle.	Adopted two-layer constraint for planning model, which combined with complex network construction and planning, and realized "source-network-load" collaboration.
[59]	Proposed access equipment concept in Energy Internet based on CPS.	Its overall framework, designing functions, core hardware and software components and future development directions are comprehensively studied and analyzed.	Undertook the techniques used in monitoring of and coordinating with the distributed energy devices.
[60]	Studied CPS in Energy Internet, which included the interaction between the cyber layer and physical layer and related flow matrix forming.	The influence of cyber data disturb (dislocation, delay and data error) in the proposed model was studied.	Corresponding simulation model was built and tested for its validity and influences.

With the development and innovation of information technologies, CPS are broadly used in a variety of industries, especially in the energy domain, which brings high effects and low operating costs, but the lack of high effective human leadership severely limits its further development; under this condition, HCPS are introduced, which brings revolutionary impacts to modern industry and EI, the performance of which can be largely promoted.

3. Current Developing Situation of HCPS

The current research on HCPS mainly includes the areas of system design, theoretical analysis, technique development and application forecasting. The application of HCPS to the power grid is just at the beginning. With the technique progression and theoretical innovation, the modern energy system exhibits more characters that deeply fuse with HCPS. The use of HCPS in Energy Internet will undoubtedly become a hot research topic.

3.1. HCPS Framework

The HCPS can be classified into four layers: physical layer, cyber layer, decision layer and fusion application layer, which correspond to the P(physical), C(cyber), H(human) and S(fusion) in HCPS, as shown in Figure 7. Most applications can obey this framework.

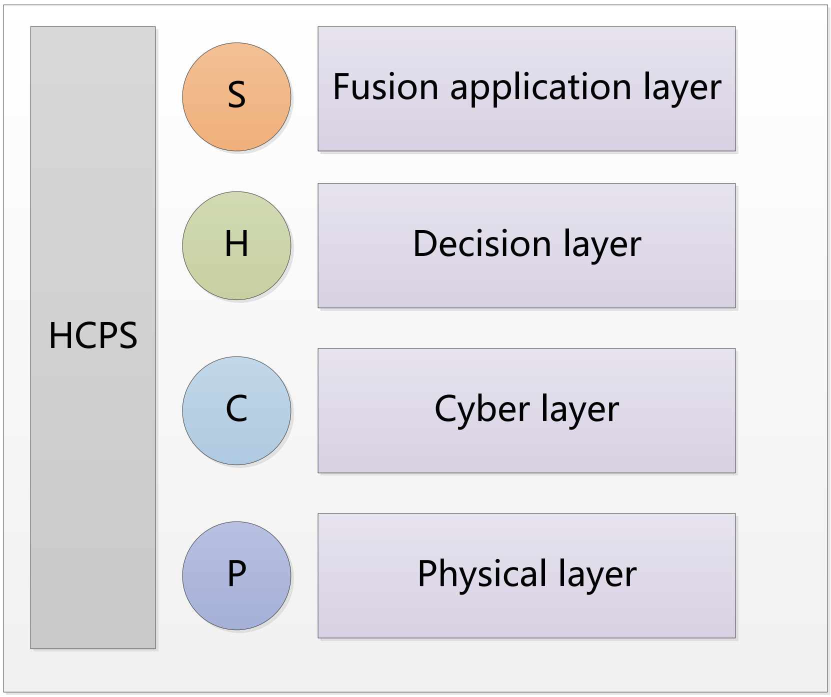

Figure 7. Framework of HCPS.

In the physical layer, the system obtains the data through sensors and the IOT, and executes the commands sent from the above layers. In the cyber layer, the system transmits and handles the local data to make up related policies that should be quickly issued to the physical layer. In the decision layer, the system makes the final policy with the aid of a human. In the fusion application layer, the system schedules the rules for the operation and management of the specific application.

3.2. Related HCPS Research

The related HCPS research is shown in Table 7.

Table 7. Related HCPS research.

Research Topic	Paper No.	Research Content	Main Object	Technique Detail
system design	[61]	Proposed a unified framework used for further understanding the intelligent properties of HCPS.	Provided a more real and rational industry 4.0.	Realizing "human as center" concept.
	[62]	Proposed a new HCPS framework, which can coordinate the task assignment between human and machine.	Proposed a new adaptive control and manage method for human-machine collaboration.	Undertook adaptive control, machine learning catered to intelligent shopping platform.
	[63]	Introduced HCPS into smart power plant.	Realized the cooperation of HCP and other elements of smart power factory.	Introduced HCPS into smart power factory.
theory analysis	[64]	Focused on the originality of HCPI, summarized its basic concept, research content and the application in ternary fusion intelligent.	Produced a new research era: HCPI.	Adopted Human-cyber-physical intelligent (HCPI).
	[65]	Treated HCPS highly fusion as the core features of intelligent society.	Realized collaboration management of intelligent society.	Using the main model and the method of collaborate computing.

	[66]	Treated HCPS swarm intelligent computing as the future research direction of AIOT.	Realized CHPS swarm intelligent computing.	Using self-organize, and self-adaption AIOT.
technique development	[67]	Proposed a HCPS like App which could detect dependencies between interventions for medical effect in healthcare domain.	Proposed a CPS App.	Used a physiological simulator to model the complex interactions of human's physiology.
	[68]	Proposed a distributed group assembly system based on swarm intelligence and swarm robots in HCPS.	Increased the flexible and response property in focus on market change.	Set up a distributed group assembly system based on swarm intelligence and swarm robots.
	[69]	Used machine learning algorithm to analyze the space and temporal data in the environment, and conducted intelligent modelling on the system and environment, which founding a unified safety HCPS framework.	Founded a unified safety HCPS framework combining dynamic authentic.	Hybrid modeling was used which combining space-temporal driven with model driven means.
	[70]	Extended the multi-simulation method, which will combine with multi-equations and data driven method to set up AI modeling normal form and improving the resistance of HCPS.	Found optimal decision sequences to ensure that the system resist in non-determined conditions, and continuous HCPS evolving.	Using RESILTRON framework, AI modeling, and Digital twin.
	[71]	Conducted similarity analysis on traffic data, and considered the related physical characters which can influence HCPS and ensured rational assignment of related tasks.	Ensured service assign accuracy and safety.	Comprehensively considered every side's data characters in HCPS and realized related features' cross domain fusion.
	[72]	Proposed a HCPS flexible manufacture system based digital twin's general visualize framework.	Realized product design and debug.	Constituting a digital twin C-P model using multi-source heterogeneous information.
	[73]	Proposed an intelligent and self-managed new generation wind rotor HCPS framework in the background of Industry 5.0.	Provide more precise and intelligent sensing and policing ability.	Through digital twin, the training speed and model precision was largely improved.
	[74]	Realized deep fusion of physical space and virtual space based on HCPS fusion and interaction, to solve the control problem of robots.	Proposed and set up digital-twin driven intelligent control system.	Realized HCPS fusion and interaction.
application model	[75]	Proposed a VCPS (Vehicular Cyber-Physical System) concept, whose performance is analyzed depended on different information transmission conditions with especially considered HF (Human Factors).	Minimized the system-wide total utility loss due to unsuccessful delivery of some services.	Formulated the basic HFSS problem (BHFSSP) using Integer Linear Programming (ILP) and proved its NP-Completeness.
	[76]	Proposed a novel platform and designed a related framework for human-in-the-loop application in robot aiding human operation.	Augmented human interaction with the physical world.	Set up a prototyping platform and a design framework for rapid exploration of a novel human-in-the-loop application.
	[77]	Digital twin was a potential method to realize intelligent interaction and information fusion in HCPS.	Realized real-time interaction and control and intelligent collaborating.	Classified CPS as four-dimensional scientific problems.

[78]	Ubiquitous computing in HCPS would form new type computing modes, and generate killer applications, and traditional industry would face massive technique challenges and innovation opportunities.	Realized high-speed development of operation system.	Using ubiquitous computing.
[79]	The crossing of AI and multi-disciplinary would produce new research directions: HCPS intelligent or ternary fusion intelligent.	Realized the organize fusion of physical space, information space and society space.	Taking HCPS intelligent or ternary fusion intelligent.
[80]	Fused the innovation algorithm with human and AI, utilizing the advantages of robot, and promoted the role of HCPS in art collaboration innovation.	Promoted the development of HCPS art collaboration innovation.	Focused on parallel art innovation based on CPSS intelligent fusion.
[81]	Applied CPS in IOT healthcare.	Realized the effective utilizing of fog/cloud level resources and minimized operation cost.	Utilized cloud resources utilizing in CPS.
[82]	Applied HCPS in smart home's related research.	Proposed a new deep learning training scheme and avoided privacy omitting.	Using HCPS related technology.

3.3. HCPS on Energy Internet

3.3.1. System Modeling

To deeply apply HCPS in EI, system modeling is a necessary step, and it can be seen as the basic framework of EI. Here, the system modeling of HCPS is introduced and is not limited to the power system.

From a common security scene, Erol Gelenbe et al. proposed an important and complex example of HCPS: the EMS (Emergency Management System) in fire alarms and evacuees [83], the performance of which could be optimized through a human–cyber interaction. The EMS could effectively protect the nature, property and valuable infrastructures, but also faces failures and malicious attack threats, the performance of which requires the correct and intelligent ICT operations. In this paper, a wireless sensor-assisted EMS was designed, and its performance was evaluated for facing the emergency of malicious attacks in alarm information delivery.

Based on another scene, Zamfirescu C. B. et al. proposed an anthropocentric cyber-physical system (like HCPS) that can potentially be used in power consumption with product manufacturing [84]; a human plays an important role in this highly automatic system. The related model demonstrated this system's performance in concrete application scenes, which could augment the human operator largely through using a combination of the physical component (PC), the computational/cyber component (CC) and the human component (HC).

In the following research, Qiao Ji et al. analyzed the characters of the modern power system [85], which included the characters such as openness, uncertainty, distribution and highly multi-flow coupling and so on. Its scale and complexity were continuously and largely promoted, but challenges also emerged in this new situation. The AI technique can effectively handle this problem, especially using the human-in-the-loop hybrid augmented intelligence method, which can be seen as the prominent character of HCPS.

From the above, we can see that the formal definition of HCPS is somewhat rare, but its components' formation can be definite, in which human leadership and CPS components with rapid automation are necessarily required as the basic roles to construct a high-performance EI.

3.3.2. Human-in-the-Loop

When applying HCPS in Energy Internet, its advances and challenges lie in one important feature: human-in-the-loop. Through this feature, the operating performance of HCPS can be greatly increased, which can response to grid faults quickly and non-sensibly. The following introductions refer to EI related energy systems, such as building energy systems, as shown in Figure 8.

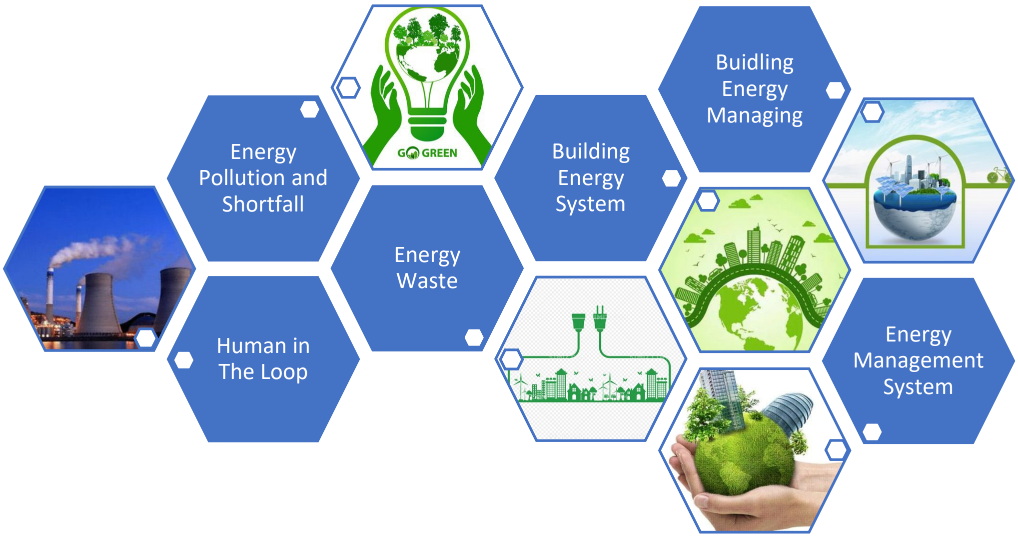

Figure 8. Scenes for human in the loop.

Conducting research for a specific scene, Sirajum Munir et al. studied energy waste in computer workstations with the function of human-in-the-loop [86], which improved the response accuracy and time delay. It used strategies such as the adaptive timeout interval, multilevel sensing of distraction and identified background processing. The detailed evaluation indicated that its energy waste can be significantly reduced through testing human gaze behavior.

Focusing on the building domain and facing energy pollution and shortfall problems, Mona Bisadi et al. proposed a new BEMS (Building Energy Managing System), in which IOT technology was utilized to solve the related challenges in building an energy managing domain with a human-in-the-loop CPS system as the support and auxiliary module [87], which could provide adaptive control over the building's energy consumption and promote productivity by influencing the staff's emotion state.

In the following research, from the game-theoretic perspective, Annika Eichler et al. adopted the human-in-the-loop concept in constructing building energy systems [88]. By using the technique of ADMM (the alternating direction method of multipliers), a great performance improvement can be obtained. The performance was demonstrated using an extensive numerical study.

Following the above research, Maximilian Schütte et al. proposed a building energy managing mechanism using human-in-the-loop control [89], which can minimize energy costs and occupants' discomfort, and the interest of the occupants in participating in the building energy management can be greatly promoted by adopting the team gain mechanism.

With a broader view, Shogo Shimamoto et al. proposed a stochastic and model predictive control combining model for EMS (Energy Management System) with the aid of human-in-the-loop [90]. Through using a discrete-time Markov chain and the related probability distribution computing of the temperature set point, the control problem could be simplified to a mixed integer linear programming method.

Human-in-the-loop not only increases the intelligence of HCPS, but also promotes its automatic running efficiencies and makes fault handling and recovery easier. Its realization should be based on the nature of the studied application scenes, adopting the most suitable techniques and further realizing the optimal schedule and application solutions.

3.3.3. Digital Transformation

To realize HCPS in an EI system, digital transformation is a necessary technique and becomes more important with the progression of ICT techniques.

In [91], Neumeyer X. et al. showed that the role of technology and digital literacy in the whole entrepreneurship can be important.

In [92], Neeley T. et al. proposed that in order to learn new digital transformation techniques, employees need to use a digital mindset, such as in an increasingly technology-intensive world.

In [93], Neumeyer, X et al. reviewed the critical gaps in the literature on managerial competencies and development and solved it using digital techniques.

In [94], Solberg E. et al. proposed that employees' digital mindset affects their participation in the digital transformation initiatives of their company, which provides opportunities for professional growth and competency abilities.

3.3.4. Technique Summary

As in mostly industries, the application of HCPS in Energy Internet is just at the beginning step, which lacks the integrated design and technique grounding of an entire system and a related technique plan. At the same time, most of the research on HCPS with the role of humans in the power system is in the preliminary stage, which does not clearly consider the real function and key location of humans. And the problem of how to realize related human role and tasks effectively and robustly, as well as how to establish the effective surveillance of human behavior, is still not settled. A more effective, more general and more safe HCPS whole system design, especially for Energy Internet, deserves further research.

4. Advanced Techniques for CPS and HCPS

HCPS are formed based on many modern techniques; the typical technologies include big data and the cloud, middleware, IOT, AI, digital twin and meta universe, etc., as shown in Figure 9, which can also be effectively applied in Energy Internet. With the maturity of HCPS, more techniques will be fused into the power system.

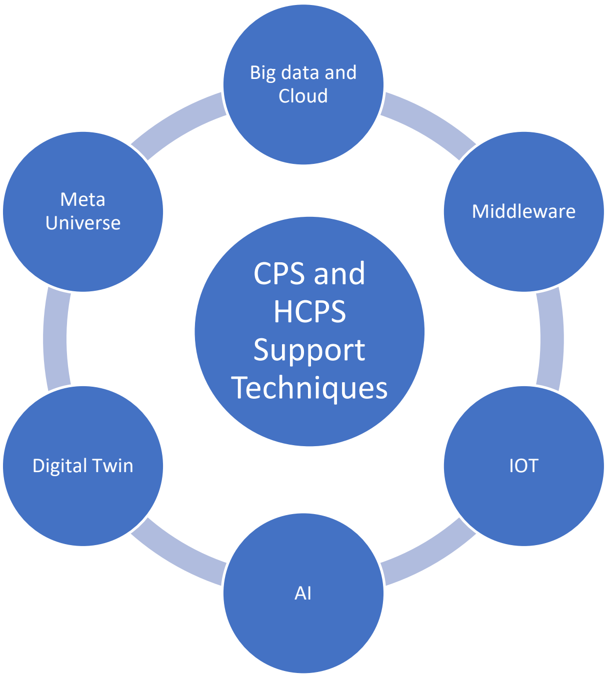

Figure 9. Support techniques of CPS and HCPS.

4.1. Big Data and Cloud

Big data and the cloud have been researched in CPS and are being extended to HCPS. Naiheng Zhang, in [95], establishes a cloud-based big data-driven robot modeling platform. An improved CPS definition based on the CPS framework was proposed, which used the cloud to solve the massive data handling problem. This paper proposed a structure modeling method and corresponding AADL language (Architecture Analysis and Design Language). The modeling of a smart robot factory was classified into three layers: cell level CPS, system CPS and system of system CPS, which could be properly used in the power generation, transmission and consumption of EI. In order to extend the model application ability of AADL in HCPS, the related components and the transfer of Simulink to AADL model components should be researched in detail.

4.2. Middleware

In the future, the database will be an important support module of HCPS, and middleware will be the key function in improving the system performance. Mi Jeong Park et al., in [96], proposed that a key intelligence of CPS will be ensuring high reliability in the frequent data transmission of the CPS nodes under extendable and dynamic computing environments. In order to effectively manage this type of data transmission, CPS require data center middleware to handle complex data distribution and storage. In order to support this high reliability, it may need continuous service in code modification. Thus, the dynamic software update can be effectively used in CPS-related applications, such as in EI energy management and maintenance. This paper proposed a dynamic update method focusing on the data center CPS application. The preliminary results showed that this technique can be used in CPS and HCPS applications to support highly reliable and seamless services.

4.3. IOT

The data collection and preprocessing of HCPS mainly rely on the IoT, which has become the foundation of modern energy systems. Its progress prompted the development of EI popularly utilizing HCPS. In [97], Shashank Shekhar proposed a dynamic data-driven cloud system. It is a new type of system that can effectively study and continuously enhance the related models of the cloud infrastructure. Through model analysis, it explored the cloud infrastructure by utilizing the correct source management policies and solving the cloud server with quality sensitive CPS/IOT tasks, such as in EI-related services. In this research, the dynamic data-driven cloud demo based on the cloud model and adaptive cloud resources management was proposed, the performance of which was evaluated and verified in a series of CPS/IOT applications. In [98], Li P. et al. proposed the IOT technique in smart building research with a transition from CPS to HCPS. Through using advanced techniques in the IOT domain, the energy efficiency can be largely promoted. In [99], Estrela, Vania Vieira et al. proposed the concept of the Health 4.0 Cyber-Physical System, using clouding computing, big data and the IOT as its main support techniques.

4.4. AI

The HCPS-related research listed above mainly use or can use AI related technology [66,73,80,82,100], which can be seen as the nervous system of HCPS, especially in EI; therefore, its performance should be paced with HCPS's demand. Through using AI within HCPS, the operating efficiency and optimal management ability can be largely improved, which can potentially map humans' abilities into the machine operation in EI system, so that complex handling work, such as troubleshooting, can be automatically solved. This feature is one prominent difference between HCPS and traditional CPS and is the source of the large performance promotion [1]. In [101], Roth Eatai et al. proposed an accurate model of the system's dynamics with AI control techniques in HCPS teleoperation. In [102], Yamagami M. used a combination of reactive (feedback) and predictive (feedforward) AI control algorithms in joint human-cyber-physical systems for manual trajectory tracking, the performance of which can be clearly improved.

4.5. Digital Twin

Since 2017, the fast development of the digital twin has provided a new key plan and possible technique route for the construction and fusion of HCPS [72,77] and its influence on HCPS with EI can be significant and obvious. Based on the entire sensing and high precision mapping of the physical world, and the deepening of the crossing innovation with AI, IOT and VR, the digital twin can provide a unified and convenient platform for the intelligent interconnect of HCPS with EI and provide highly effective and trusted channels for HCPS's deep fusion and collaborative interaction, such as in EI. In [103], Wang B. et al. introduced the human digital-driven HCPS, the key techniques and applications are of which are analyzed in detail. In [104], Chen Xiao et al. utilized the digital twin technologies in HCPS for next generation wind turbines towards industry 5.0.

4.6. Meta Universe

Based on the related features of the meta universe, such as open connect, peer mapping, high precision simulation and rapid human machine interaction, etc., HCPS becomes a necessary module suited for the further promotion of meta universe applications. Based on the meta universe, the EI system with HCPS will become more intelligent and vivid. Its running efficiency and simulation accuracy can be further improved, and the combination of the metauniverse with HCPS has a milestone meaning, which will generate many innovative techniques and application scenes. The typical example is EI running in the meta universe through the techniques of HCPS. In [105], Li Z. et al. established a super-metauniverse system (SMS) for the hyper cyber-world based on the big data platform, AI and IOT used in CPS, which can be further promoted to HCPS. In [106], Lie Z. proposed the concept of the man-machine-universe triadic methodology, which can be seen as the initial application of HCPS in the meta universe.

5. HCPS Realization Discussions

We did not find any projects that directly using HCPS in EI to date; however, we could find some potential projects in energy management, energy consumption and energy transmission that can use HCPS to promoted their energy utilizing efficiencies, as shown in Figure 10. If generalized to CPS and EI, the related examples can be seen in Section 2.2.5.

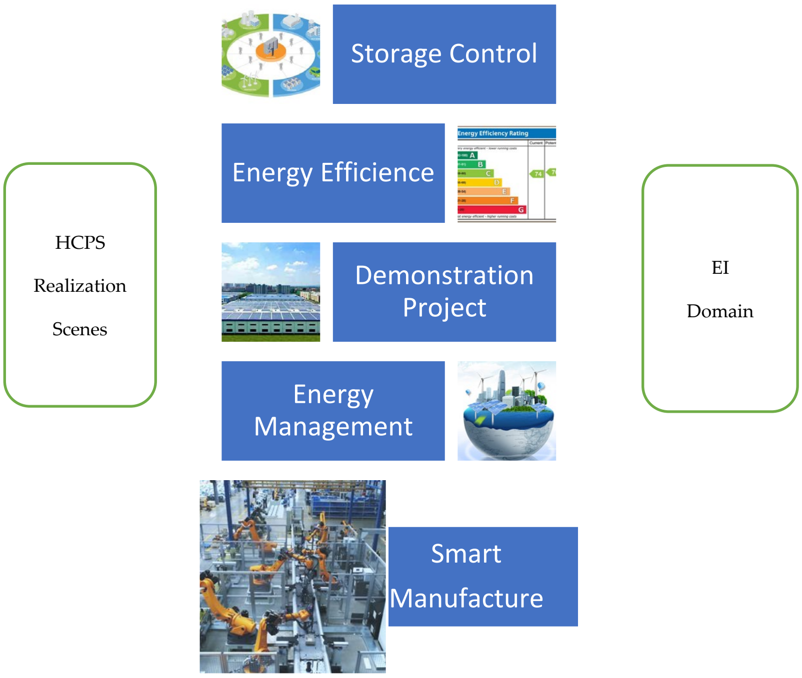

Figure 10. HCPS realization in EI.

In [107], Zhang Ning et al. studied the storage control strategy for Energy Hub in EI, which can further use HCPS to promoted the system's performance.

In [108], Chen X. et al. proposed an energy efficiency monitoring and management system to promote energy using efficiencies, with the support of similar techniques of HCPS, which paved the way for HCPS utilization in EI.

In [109], Volkwyn C. introduced the SAN XING garden project in 55 "internet + smart energy" demonstration projects, issued by the National Development and Reform Commission, which can further use HCPS to promote its performance.

As IOT and ICT techniques are the fundamental functions of HCPS, [110,111] can be seen as the candidate examples of the use of HCPS in energy management and energy harvesting.

In [112], Shahzad Y. et al. proposed the opportunities, applications, architectures and challenges in smart industries applying to EI (smart manufacture of EI), from which we can see that as the main performance improved the algorithms, HCPS could be the first new candidate technique utilized in this scene of EI.

From the above, we can see that although there are few initial projects with HCPS being used in EI, as the system and the related techniques mature, a large number of initial projects with HCPS in EI will emerge quickly in the next few years. Their combined actions will present the improvement trace of Industry Internet 5.0.

6. Conclusions

This paper reviewed the related research on CPS and HCPS, mainly applied in Energy Internet. From the research, we can see that the human function and its automation are the huge development hurdles needing to be overcome, but at the same time, can be the potential performance revenue sources in the development of HCPS, especially in EI, which shows its importance in HCPS. As time goes on, the AI technique may partly substitute the function of humans, and its occupied percentage of system function realization will become gradually larger.

With the maturity of ICT technologies in the energy system, especially with the evolution of AI, IOT and cloud computing, HCPS will play an increasingly key function in the EI operation, with its advanced automation and intelligence property, and pave the way for industry 4.0. We can see that, in the future, the HCPS combined with EI will frequently emerge in the digital twin and meta universe application scenes and will speed up the pace of social progress and technique progress.

As HCPS evolve, it should adopt the human center function, AI data handling, unified safeguarding, adaptive data gathering, unified identification and extended machine learning as its future development directions, just as is shown in Section 7. Furthermore, innovations can be found with the progress of HCPS. HCPS with EI will become a hot research topic in the near future.

7. Future Directions

Based on the technique level and development trends, further development directions of HCPS include (as shown in Figure 11):

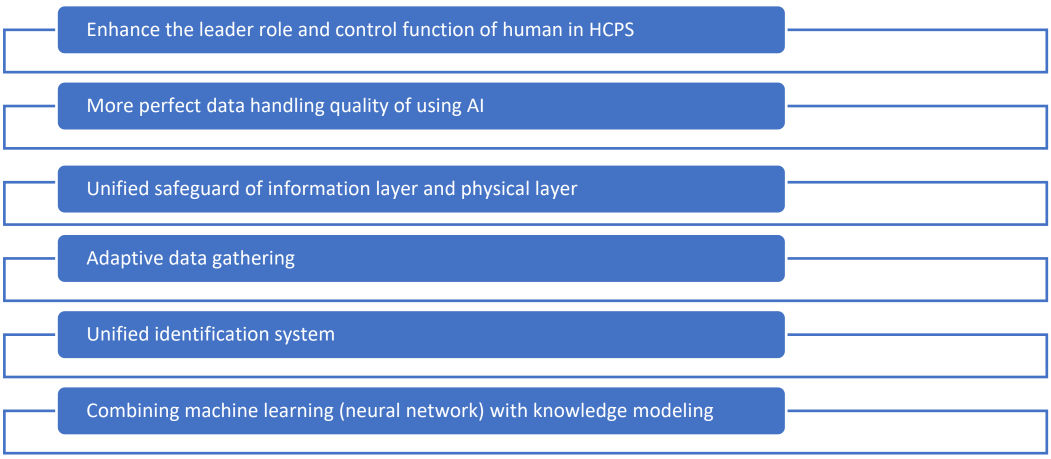

Figure 11. Future research directions.

(1) Enhance the leader role and control function of humans in HCPS. With the automation of HCPS, the problem with the need for human direction in fault and emergency situations becomes more complex and urgent. Humans should take the duty of directing, judging and control in HCPS; however, how to effectively use the knowledge of humans in HCPS cannot be effectively solved at present, such as in the EI domain, which requires the breakthrough of theory and techniques and the innovation of the concept. The leading role of humans in HCPS should be definitely ensured.

(2) More perfect data handling quality of using AI. The AI technique is rapidly developing, with its typical product, Chat-GPT 4.0, becoming a research hot spot in recent months, whose thinking level can match that of humans. When the related AI device and software can further enhance its deducing ability and human-like ways of thinking, it will and can largely improve the performance of HCPS, and finally, the performance of EI.

(3) Unified safeguarding of the information layer and physical layer. HCPS is a high fused system that tightly combines the physical layer with the information layer. An attack on one layer can be easily propagated to the other layer, such as the avalanche effect, which brought large challenges for the safeguard framework, simulation model and technique adoption, and this can be clearly observed in the EI system. It needs to set up a proper safe model, effectively utilize hybrid system safety

simulation software and generate highly effective and low delay safeguarding policies to ensure the entire performance of HCPS. On the bases of passive defense, active and self-adaptive intelligent safeguarding techniques are necessary.

(4) Adaptive data gathering. Based on the dynamic features of HCPS, the fault and emergency conditions may generate massive data, such as in EI. If the data cannot be gathered and handled in time, the operator cannot deeply mine the fault features, find timely resolutions and make highly effective safeguarding policies. Therefore, it needs to be based on the characters of the fault, activate the data gathering scheme when the fault occurs and modify the traditional sample policies and sample dimensions in time to ensure effective and reliable related data gathering, as well as correctly understand the fault from the system angle in order to win the time for fault handling and reduce the handling cost of HCPS operations.

(5) Unified identification system. EIs are required to achieve a cross-domain mass bidirectional interaction for both the energy and information flow, whereupon the corresponding HCPS requires an effective identity authentication and authorization system to realize efficient operations among regions, nodes and/or businesses. Distributed digital identity, as a rising type of digital identity which decouples identity registration, management and verification, with its multi-center grant and multi-center authentication mechanism, echoes the bottom-up construction of the EI. The adoption of distributed digital identity technologies, including DID (Decentralized Identifier) and VC (Verifiable Credential), may help to improve the overall performance of HCPS in EI with a wide range of complex scenarios.

(6) Combining machine learning (neural network) with knowledge modeling. Both techniques are broadly utilized in EI, but their interaction or integration are rare, which introduces some inherited shortcomings; for example, the neural network techniques cannot be effectively used in situations with less data, its result may not obey the physical laws, the parameters of modeling techniques need to be precisely estimated and its execution time may be long. Through the comprehensive utilization of the two means, the above problems can be effectively solved, which will open a new gate for high performance HCPS with its application in EI.

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Abbreviations

AADL	Architecture Analysis and Design Language
ADMM	The Alternating Direction Method of Multipliers
ADPSS	The Advanced Digital Power Simulator
BEMS	Building Energy Managing System
CC	Computational/Cyber Component
CPS	Cyber-Physical Systems
CPSOS	Cyber-Physical System of System
DER	Distributed Energy Resources
DFD	Data Flow Diagram
DID	Decentralized Identifier
EH	Energy Hub

EI	Energy Internet
EI-CPS	Energy Internet Cyber-Physical System
EISH	Energy Integrated Service Hub
EMS	Emergency Management System
EMS	Energy Management System
FPDS	Flexible Power Distribution System
FPDU	Flexible Power Distribution Unit
HC	Human Component
HCPI	Human-Cyber-Physical Intelligent
HCPS	Human-Cyber-Physical Systems
HF	Human Factors
HIL	Hardware-In-The-Loop
HVDC	High Voltage Discrete Current
ICPS	Industry CPS
ICT	Information Communication Technologies
IEMS	Integrated Energy Management System
IOB	Internet of Behaviors
IPS	Integrated Power System
ODEs	Ordinary Differential Equations
PC	Physical Component
PCPS	Power Cyber Physical System
PDEs	Partial Differential Equations
SCPIFS	Security Control Plan Incorporating Frequency Stability
UPIOT	Ubiquitous Power Internet of Things
VC	Verifiable Credential
VCPS	Vehicular Cyber-Physical System
WECSs	Wind Energy Conversion Systems

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