Assessing the Comprehensive Effects of Digital Investment on Energy Internet Industry

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Abstract. Quantitative analysis of the impact of digitalization on the energy, environment and economic comprehensive benefits of the energy Internet has important theoretical and practical value. Based on the perspective of industrial chain, this paper adopted the method of System Dynamics theory to describe the key role of digital technology investment in upstream energy production, midstream energy transmission and downstream energy consumption of the energy Internet industry. It identified digital technology investment and other key factors that affect the efficiency of the Energy Internet, clarified their feedback relationships. On this basis, it built a system dynamic model including energy producers, energy service provider and the end user subsystems to quantitatively simulate the comprehensive impacts of the Energy Internet industry under the change of the proportion of different types of digital technology investment. The simulation results show that digital technology investment plays a key role in improving the comprehensive benefits of the energy Internet; Under the scenario of high proportion of digital technology investment, it is estimated that by 2025, digital investment of energy internet will provide nearly 0.72 million jobs for Chinese society every year, and the installed capacity of clean energy power generation will increase to 1.76 billion kilowatts, which can reduce carbon dioxide emissions by 5.7 billion tons in total. Increasing the proportion of digital technology investment can significantly improve the comprehensive benefits of the energy Internet and strongly support the development goals of China's 14th Five Year Plan.

Keywords: digital technology investment; system dynamics; energy internet; comprehensive impacts evaluation

1. INTRODUCTION

The National Development and Reform Commission, the Energy Bureau jointly with the Ministry of Industry and Information Technology issued *The Guiding Opinions on Promoting the Development of "Internet +" Intelligent Energy* for the first time put forward the concept of energy Internet in February 2016, the "Opinions" pointed out that the energy Internet is a new form of energy industry development, which is the deep integration of the Internet and energy production, transmission, consumption and energy market. In 2022, China issued the policy document *Opinions on Improving the Institutional Mechanisms and Policy Measures for Energy Green and Low-Carbon Transformation*, which explicitly proposes to promote the integration of the Internet, digitalized intelligent technology and the power system, and to build a smart energy system with a high proportion of distributed renewable energy sources. With the

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development and utilization of renewable energy and the application of the Internet, the energy Internet has been paid attention to more and more scholars, who believe that it is an effective way to solve the current energy development problems. Dong (2014) and Fan (2016) argue that the energy internet is based on smart grid, clean energy as the dominant, compared with the traditional energy development systems, the construction of energy Internet brings multiple benefits to society, environment, economy and resources [1]. First of all, the energy Internet can promote large-scale clean energy power generation grid-connected [2]. and improve the consumption capacity of clean energy, reducing the pollution caused by fossil energy to the ecological environment; Yang (2021) discusses the contribution of regional energy Internet construction to carbon emission reduction from the perspective of real-time electricity price [3], Feng (2021) constructed a system dynamics model of business model transformation of energy internet under the perspective of carbon neutrality, and the study showed that the innovation of energy industry business model brought by energy internet is the key to the clean and sustainable development of energy industry. The study shows that the innovation of energy industry business models brought by the energy Internet is the key to the clean and sustainable development of energy industry [4]. Secondly, the energy internet helps to improve energy efficiency and reduce energy consumption; based on the analysis of inter-provincial panel data from the three major regions of China's central and east-west from 2014-2018, Li (2022) found that the construction of the energy internet can significantly improve the energy efficiency of energy-consuming industries [5]. Finally, the development of energy internet can lead to social and economic development; Yang (2015), from the perspective of user demand, argued that the main value of energy internet stems from the improvement of energy utilization efficiency, asset utilization efficiency and market allocation efficiency brought by intelligence [6], Xu (2021) qualitatively explored the mutual promotion between energy internet and socio-economic development in the context of "double cycle" [7]. Yu (2021) argued that the development of the energy Internet promotes the modernization of the energy industry system, which is important for the realization of high-quality economic development [8]. Theoretically, the new generation of digital technologies represented by big data, Internet of Things, and artificial intelligence can play a key supporting role in the comprehensive benefits of the energy Internet [9, 10] In terms of the application of big data In the application of big data, through the collection of big data cleaning, storage, and analysis and mining to realize the information asset sharing of the energy Internet, assisting the energy Internet multi-source system synergistic operation, can improve the management level of the energy Internet [11-13]. In the application of Internet of Things technology, it is possible to improve the management level of energy Internet by using the Internet of Things technology. In the application of Internet of Things technology, with the help of intelligent sensing devices, distributed cloud computing platform and user application software to respond to user needs in real time, the Internet of Things technology is used in the energy Internet, which can help to realize the efficient integration of the power system and information resources [14]. At the same time, IoT technology improves the reliability of information, enhances the trust between the upstream and downstream of the industry, and ensures the efficient operation of the energy Internet industry [15]. Artificial intelligence technology application mainly through deep learning, intelligent simulation, support vector machine and other technologies to accurately predict the grid load to achieve the energy Internet system optimization, overhaul and diagnosis and energy scheduling, to ensure the efficient operation of energy Internet [16-18].

According to the data of *the Annual Report on the Development of National Energy Internet in 2021* released by Tsinghua University's Institute of Energy Internet Innovation, as of December 2020, the total market capitalization of China's energy internet stocks reaches 6.79 trillion yuan. The data released by the State Grid shows that the investment for grid intelligence from 2009-2020 is 384.1 billion yuan, accounting for 11.1% of the total investment in the grid. However, the impact of the energy Internet, which is mainly characterized by the application of digital technology, on the economy and environmental benefits has not yet been fully studied. The theoretical mechanism of how the penetration of digital technology affects the assessment of the effects of the energy Internet is not yet clear. Traditional energy Internet assessment models mainly include econometric models based on energy-environment-economy (3E) and computable general equilibrium (CGE) models. Chen (2020) takes the Yangtze River Delta (YRD) region as an example, constructs an evaluation model of the degree of coordination of energy-environment-economy (3E) development, and studies the coordinated development of the 3E system under the conditions of open economy [19]. Wang (2021) argued that the development of energy internet is the key to promote clean energy utilization, improve energy efficiency, and reduce the cost of energy use, and constructed an evaluation model for the development of energy internet with three dimensions: energy, environment, and economy [20]. Zhang (2021) and Xu (2020) constructed an econometric model to study the evaluation model of coordinated development among economy, environment, and energy by utilizing 2003-2017 Chinese inter-provincial panel data [21, 22]. Guo (2018) constructed a computable general equilibrium model to study the coordinated relationship between energy prices and the 3E system [23]. Li (2018) used the Delphi method to establish an index system for assessing the development of the energy Internet based on rough set factor analysis, and concluded that technological maturity, the development trend of smart grids, and the innovation ability of enterprises are the key factors for evaluating the construction of the energy Internet [24]. Qin (2021) screened evaluation indicators from four dimensions of technology, society, economy, and engineering, and used fuzzy hierarchical analysis and cloud modeling to assess the comprehensive benefits of energy internet [25]. The current study only reveals the impact of the development and construction of the energy Internet on economic and environmental benefits, etc., and its modeling fails to adequately respond to the intermediate mechanism of the comprehensive benefits of the energy Internet. Jiang Han et al. (2019) constructed a system dynamics model for the assessment of the comprehensive benefits of regional energy Internet based on the feedback relationship between the factors related to the regional energy Internet, to explore the comprehensive benefits of the regional energy Internet construction and its key influence path. However, the existing studies have not introduced the factors of digital technology penetration into the assessment model, and cannot effectively assess the specific impacts brought about by the penetration and application of digital technology. This will largely ignore the important role of Internet digital technology in the value creation of the energy industry; Chen (2021) qualitatively discussed the important impact of digital technology on the low-carbon benefits of the energy Internet [26], but still lacks a detailed quantitative analysis. Most of the current research focuses on the overall benefits brought by the energy Internet, and few scholars study the role and impact played by digital technologies on the upstream and downstream of the energy Internet industry. Obviously, this will seriously constrain the energy Internet industry to carry out long-term investment layout and industrial planning, and restrict the high-quality development of energy Internet. Therefore, how to assess the potential benefits and impacts of digital technology in the energy Internet industry with scientific evaluation methods, the relevant research needs to be promoted urgently.

This paper applies the principle of system dynamics to analyze and study the key influencing factors of digital technology in generating the benefits of the energy Internet industry and the feedback relationship between them, and on this basis constructs a system dynamics model of the energy Internet that includes the subsystems of energy producers, energy service providers, and energy end-users. The model covers the application of digital technology in energy producers, energy investors, energy end-users and other participants, and studies the role of digital technology mechanisms to realize the simulation analysis of the comprehensive benefits of digital technology affecting the energy Internet. Based on the constructed system dynamics model, the impact of digital technology on the benefits of energy Internet is explored under different degrees of digital technology application, and the validity of the model is examined to provide effective policy references for the planning and recommendation of energy Internet.

2. MODLE CONSTRUCTION

System dynamics is a theory that studies the overall behavioral characteristics of a system by analyzing the feedback relationships of variables within the system. It has significant advantages in dealing with highly nonlinear, high-order, multivariate and complex large systems. Its modeling process consists of five steps: determining system boundaries, subsystem delineation, mapping feedback loops, mapping flow diagram construction, and model testing.

The application of digital technology throughout the energy generation, transmission and use of various links, under the influence of the value creation of the energy Internet is a complex dynamic evolutionary system, the influencing factors are complex and variable and interact with each other. Therefore, this paper analyzes the causal mechanism of digital technology-driven energy Internet benefits by constructing a system dynamics model for evaluating the comprehensive benefits of energy Internet.

2.1System boundaries

This study intends to construct a systematic model of the comprehensive benefits of digital technologies affecting the energy Internet, and analyze the dynamic changes of the comprehensive benefits created by each participant in the energy Internet under the weight of different digital technology investments. From the perspective of energy production, energy transmission and energy consumption, the model boundary of the system is limited to energy producers, energy service providers and energy end-users; according to the three-phase plan for the development of the smart grid released by the State Grid, a more complete smart grid system will be constructed in China from 2016 to 2020; with reference to the information released by the State Grid, China's energy Internet system will be 2025 Initial completion. Therefore, the simulation time of the model is set as 2015-2025 (2015 is the base year), in which the test boundary of the model is 2015-2020, the predictive simulation boundary of the model is 2020-2025, and the simulation time span is set as 1 year.

2.2Subsystem division

Based on the industrial connectivity perspective, we analyze the key role of digital technology in the upstream, midstream and downstream of the energy Internet industry. The system dynamics model constructed in this paper contains three subsystems: energy producers, power grid enterprises, and energy end-users. The application of digital technology in energy producers mainly includes photovoltaic power generation and storage system, wind power generation technology, digital power plant, intelligent hydropower plant, etc.; in the energy service side, intelligent power transmission, transformation and distribution are realized through sensors, Internet of Things, and other technologies; in the energy end-users' side, with the popularization of smart meters, the information on users' power consumption is collected and fed back to realize the personalized power consumption plan and incentives to reduce energy consumption and save power consumption. In order to reduce energy consumption and save electricity expenditure. The model framework is shown in Fig 1. The model contains the following assumptions:

(1) Assuming that the energy market environment is stable, the enterprises involved in the upstream and downstream of the energy Internet industry will not make changes to their current decisions if the external environment remains unchanged. According to market data compiled by the Prospect Industry Research Institute, currently, China's power transmission and distribution is monopolized by the State Grid and China Southern Power Grid, and the State Grid is the main enterprise in China's smart grid construction. Therefore, it is reasonable to adopt the proportion of investment in grid intelligence in the State Grid to replace the proportion of investment in grid intelligence in the whole industry.

(2) Intelligent investments for power supply investments are entirely devoted to photovoltaic power generation, intelligent hydroelectric power plants and wind power generation technologies.

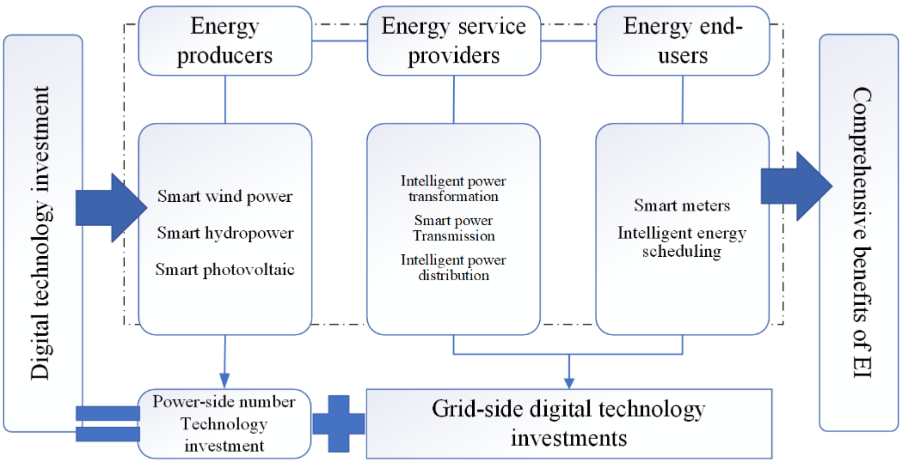

Figure 1 Model frame drawing

2.3Feedback loop diagram

Based on the model boundaries, a Feedback loop diagram is constructed for the energy producer subsystem, the energy service provider subsystem, and the energy end-user subsystem.

1) Feedback loop diagram of energy producer subsystems

The energy producer subsystem Causal Loop Diagram, shown in Fig 2, consists of a main feedback loop, which are:

a) Power supply investment → (+) share of distributed renewable energy power generation investment in power supply investment → (+) investment in clean energy power generation → (+) installed capacity of distributed renewable energy power generation → (+) distributed renewable energy power generation → (+) reduction of fossil energy consumption → (+) reduction of carbon dioxide emissions from alternative fossil energy sources.

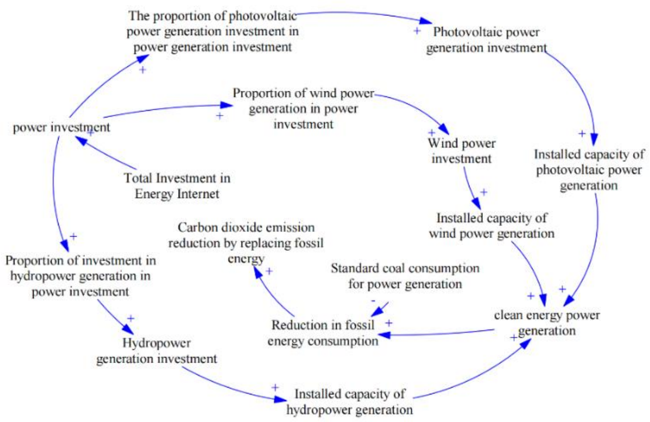

Figure 2 Feedback loop diagram of energy producer subsystem

2) Feedback loop diagram of energy service provider subsystems

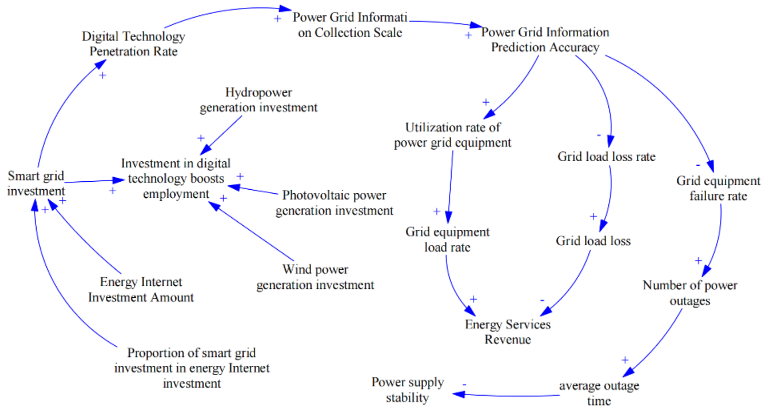

Figure 3 Feedback loop diagram of energy service provider subsystem

The Energy Service Provider Subsystem Causal Loop Diagram, shown in Fig 3, consists of three main feedback loops, which are:

a) Share of grid intelligence investment in energy internet investment → (+) Grid intelligence investment → (+) Digital technology penetration → (+) Grid information collection scale → (+) Grid information prediction accuracy → (+) Grid equipment utilization → (+) Grid equipment load factor → (+) Energy service revenue

b) Share of grid intelligence investment in energy internet investment → (+) Grid intelligence investment → (+) Penetration rate of digital technology → (+) Scale of grid information collection → (+) Accuracy of grid information prediction → (-) Failure rate of grid equipment → (+) Number of outage accidents → (+) Stability of power supply.

c) Share of grid smart investment in energy internet investment → (+) Grid smart investment → (+) Amount of digital technology investment → (+) Number of jobs driven by digital technology investment

3) Feedback loop diagrams of Energy end-user subsystem

The energy end-user subsystem Causal Loop Diagram, shown in Fig 4, consists of two main feedback loops, which are:

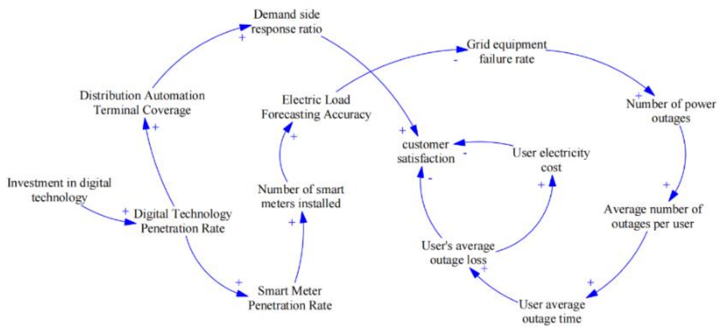

Figure 4 Feedback loop diagram of energy end user subsystem

a) Amount of investment in digital technology → (+) penetration rate of digital technology → (+) penetration rate of smart meters → (+) number of smart meter installations → (+) accuracy of electricity load forecasting → (-) failure rate of grid equipment → (+) number of power outage accidents → (+) cost of electricity to customers.

b) Digital technology investment → (+) digital technology penetration → (+) distribution automation terminal coverage → (+) demand-side response ratio → (+) user satisfaction.

2.4Flow diagram construction

The flow diagram of the model is constructed based on the drawn feedback relationship diagram, as shown in Fig 5. The system flow diagram contains major variables such as total investment in energy internet, investment in grid intelligence, investment in digital technology to enhance the number of jobs, CO2 emission reduction from alternative fossil energy sources, installed capacity of hydropower generation, installed capacity of wind power generation, installed capacity of photovoltaic power generation, and power generation from clean energy sources.

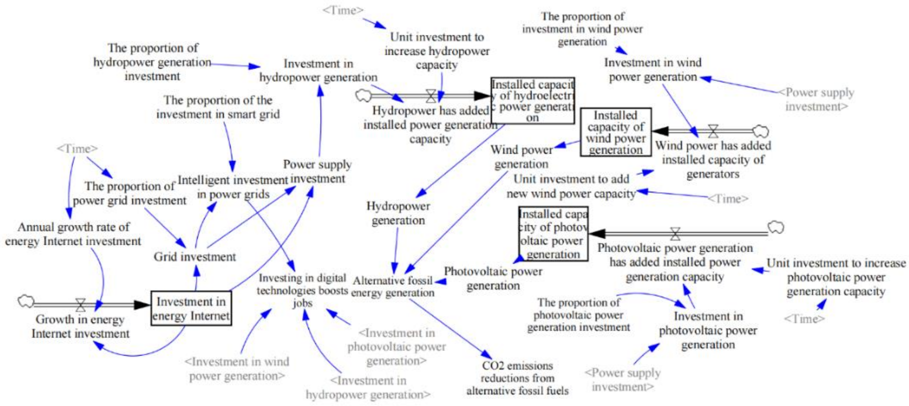

Figure 5 Flow diagram of Digital technology investment affects the comprehensive benefits of the energy Internet industry

During the construction of the model, data were obtained from databases such as the China Electricity Council, *the National Statistical Yearbook*, and *the Energy Statistical Yearbook*. *The 2016 Guiding Opinions on Promoting the Development of "Internet Plus" Smart Energy* opened the beginning of the construction of China's energy Internet. According to the three-phase plan for smart grid development released by the State Grid Corporation, the total investment in the three-phase plan is expected to exceed 400 million yuan, of which the investment in intelligent digital technology accounts for about 20%; the number of fully non-agricultural employment driven by each billion yuan of output value in the electric power infrastructure industry is 796, and the number of fully non-agricultural employment driven by each billion yuan of output value in the production and supply of electric power industry is 640 [27]. The carbon dioxide emission factor is 1.0659 kg/(kw-h) [28]; the endogenous variables of the model include variables such as energy internet investment, annual growth of energy internet investment, amount of clean energy investment, clean energy power generation, and the share of investment in grid intelligence. The model equations are fitted to solve the parameters with the help of polyfit function in MATLAB, and the main variables and specific parameter settings, as shown in Table 1.

Table 1 Data sources and parameter setting

Parameter	symbol	Data sources
EI investment	I^{EI}	the Annual Report on the Development of National Energy Internet in 2021
Proportion of investment	P	State Grid Intelligent Planning General Report
Power investment	I_G	the Energy Statistical Yearbook.
Grid investment	I_E	State Grid Intelligent Planning General Report
Installed capacity	C	the Energy Statistical Yearbook.
Clean energy generation	G_{cln}	the Energy Statistical Yearbook.
Employment benefit	β	Ye Ziwang (2020)

factor		
Employment benefit factor	cf_{coal}	Chen Weian (2012)

3. Empirical studies

3.1Model testing

In this paper, the model validity is tested by observing the size of the absolute average error between the fitted value and the true value of the main variables in the model, including the amount of investment in the energy Internet, power supply investment and power grid investment from 2015 to 2020. The results of the error test are shown in Table 2, in which the absolute average errors of energy Internet investment amount, power supply investment and grid investment are 2.94%, 4.86% and 4.48%, respectively, and the average errors are less than 5%; they are within the acceptable range. This shows that the simulation model constructed in this paper for the comprehensive benefit of digital technology impacting the energy Internet can more effectively grasp the changing law of the comprehensive benefit of digital technology impacting the energy Internet and its interrelationship.

Table 2 Error checking

Year	Investment in the energy Internet			Power investment			Grid investment		
	Fitted value	Actual value	Error	Fitted value	Actual value	Error	Fitted value	Actual value	Error
2015	8576	8576	0	3939.81	3936	0.1%	4636.19	4640	0.08%
2016	8774.11	8840	0.75%	3314.86	3409	2.76%	5459.25	5431	0.52%
2017	8181.85	8239	0.69%	2922.56	2900	0.78%	5259.3	5339	1.49%
2018	7775.22	8161	4.73%	2965.47	2787	6.4%	4809.75	5374	10.5%
2019	8057.46	8259	2.44%	3498.55	3283	6.57%	4558.91	5012	9.04%
2020	9268.49	10189	9.03%	4628.69	5293	12.56%	4639.81	4896	5.23%
Average error			2.94%			4.86%			4.48%

3.2Scenario design

The model starts with the construction of a more complete smart grid system in China in 2015 and runs until the end of 2025. In order to study the impact of the comprehensive benefits of the energy Internet under different degrees of digital technology application, and to explain more clearly the social, environmental, and economic benefits brought by digital technology, this paper uses scenario analysis. Table 3 shown the settings of the three scenarios. Scenario 1 (Baseline Scenario): In the Baseline Scenario, the development model is stabilized and the proportion of investment in digital technology remains unchanged; Scenario 2: The proportion of investment in digital technologies increases, with investment in grid intelligence accounting for 40% of grid investment, and investment in hydropower, wind power, and photovoltaic power accounting for 25%, 40%, and 10% of power supply investment, respectively; Scenario 3: The proportion of investment in digital technology increases dramatically, with grid intelligence investment accounting for 60% of grid investment, and the proportion of investment in hydropower, wind power, and photovoltaic power accounting for 30%, 50%, and 15% of power supply investment, respectively

On this basis, the simulation results for each year of 2021-2025 under different scenarios are compared with the results of the baseline scenario, respectively, as a means of exploring the impact of digital technologies on the comprehensive benefits of the energy internet.

Table 3 Simulation scenario setting

Parameter	Scenario 1	Scenario 2	Scenario 3
Proportion of investment in grid digital technology	20%	40%	60%
Proportion of investment in hydropower digital technology	22%	25%	30%
Proportion of investment in digital technology for Photovoltaic power generation	9%	10%	15%
Proportion of investment in wind power digital technology	32%	40%	45%

3.3Analysis of results

In order to study the comprehensive benefits generated by energy Internet under different levels of digital technology application, this paper analyzes the impact of digital technology on the comprehensive benefits of energy Internet by simulating three scenarios, i.e., the number of jobs driven by digital technology with different digital technology investment weights, the amount of installed clean energy, the amount of electricity generated by clean energy, and the amount of carbon dioxide emission reduction.

1)Number of people employed as a result of digital technology development

Fig 6 demonstrates the impact of digital technologies on the number of jobs driven by the energy internet for different digital technology investment ratios. The ratio of digital technology investment gradually increases from Scenario 1 to Scenario 3, and the simulation results show that the digital technology

Investment in will lead to an increase in employment. Employment increases by 35% and 79% from the base case when the share of investment in grid intelligence is increased to 40% and 60%, hydropower to 25% and 30%, photovoltaic to 10% and 15%, and wind to 40% and 50%, respectively.

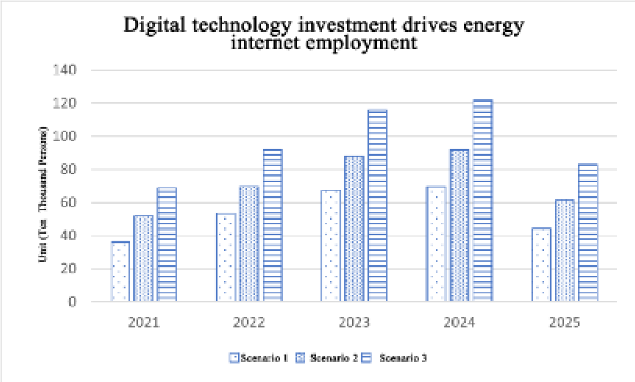

Figure 6 Digital technology investment drives energy internet employment

2)Clean energy installations

Fig 7, Fig 8 and Fig 9 illustrate the increase in installed clean energy for different percentages of investment in digital technologies. The simulation results show that different weights of digital technology inputs increase the installed capacity of wind, hydropower, and photovoltaic power generation. The simulation results show that the installed capacity of wind power will reach 420 million kilowatts, hydropower will reach 390 million kilowatts, and photovoltaic capacity will reach 460 million kilowatts, and the total amount of installed clean energy will reach 1.28 billion kilowatts by 2025 under the baseline scenario, and the total amount of installed clean energy will increase by 10.3% and 37.5% under Scenario 2 and Scenario 3, respectively.

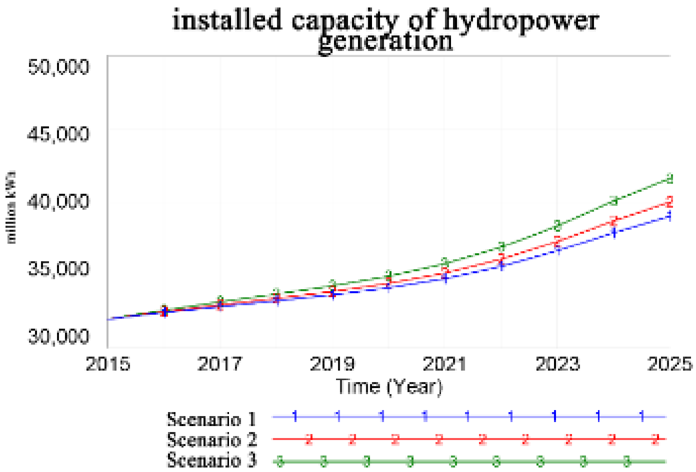

Figure 7 Digital technology investment to increase the installed capacity of hydropower generation

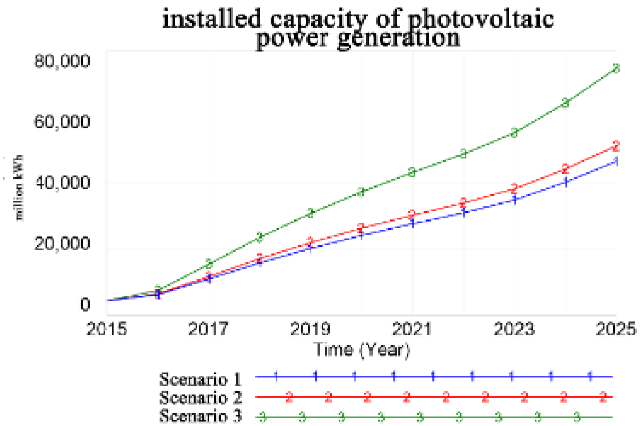

Figure 8 Digital technology investment to increase the installed capacity of photovoltaic power generation

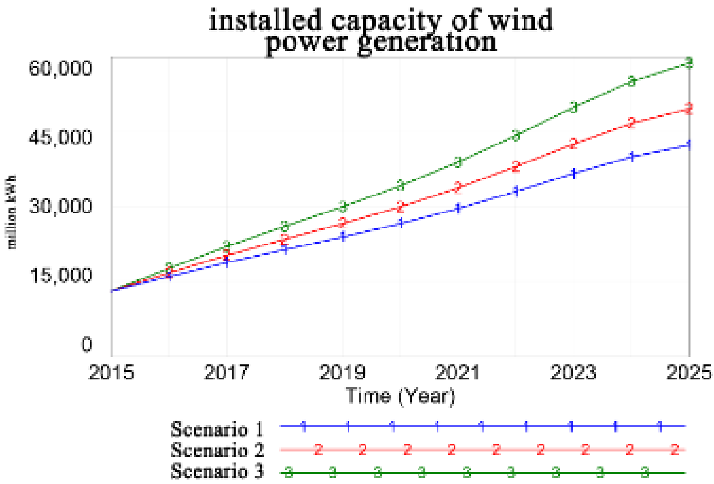

Figure 9 Digital technology investment to increase the installed capacity of wind power generation

3)Alternative fossil energy CO2 emissions

Fig 10 illustrates the impact of digital technologies on the carbon dioxide emission reduction benefits from the energy internet for different proportions of digital technology inputs. The simulation results show that alternative CO_2 emission reductions by 2025 under the baseline scenario would be 440 million tons. The simulated CO_2 emission reductions under Scenario 2 and Scenario 3 are 480 million tons and 570 million tons, respectively, representing an increase of 9.1% and 29.5% compared to the BUA scenario.

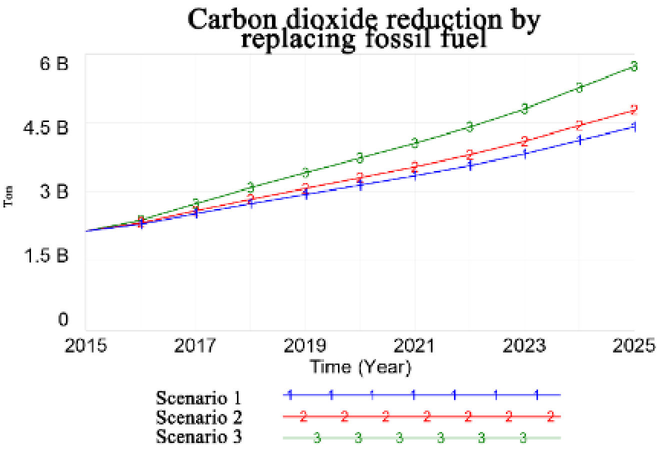

Figure 10 Carbon dioxide reduction by replacing fossil fuel

4. Conclusion

Digital technology is widely used in all aspects of energy production, transportation and consumption, providing safe and reliable technical support for the smooth operation of the energy Internet, promoting the development of clean energy, creating new energy consumption patterns, and contributing to the coordinated development of energy producers, energy service providers and energy end users. The role of digital technology in the value creation of the energy Internet is affected by many factors, in order to accurately portray the role and mechanism of digital technology in the comprehensive benefits of the energy Internet, this paper, based on the principle of system dynamics, constructs a system dynamics model of the impact of digital technology on the comprehensive benefits of the energy Internet, and analyzes the impact of digital technology on the comprehensive benefits of the energy Internet by sorting out the application mode of digital technology among the participating enterprises in the whole industry chain of the energy Internet. By sorting out the application mode of digital technology among the participating enterprises in the whole industry chain of energy Internet, analyzing the impact of the increase in the proportion of inputs on the number of employed people, the installed capacity of distributed renewable energy, the power generation capacity of clean energy, and the carbon dioxide emission of alternative fossil energy, the intrinsic mechanism of the role of digital technology in the energy Internet as well as the impacts on the economy, society, and the environment have been researched; and optimization simulation is carried out by means of the constructed system dynamics model, which provides a basis for the investment and construction of energy Internet. The simulation results of the model data show that: 1) digital technology plays a key role in energy producers, energy service providers and energy end-users, and the input of digital technology has changed the way of creating benefits in the energy Internet, which greatly promotes the development of the energy Internet. 2) the development of digital technology brings new employment opportunities for the society, and it is expected that the application of digital technology in the energy Internet will bring 400,000 employment opportunities to the society every year, which will help the society to develop. 3) The application of digital technology in the energy Internet contributes to the grid connection of clean energy power generation. billion tons, helping China to achieve the development goal of carbon neutrality.

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