1

Technical Developing Pathway of Ecological Coal Mining

It is believed that since BCE 1000, human beings had already begun to conduct coal mining and its relative activities and in these early years, coal mining was small-scale, nonstandard, experience-based, and inefficient. Such coal mining behavior was relative feasible at that time mainly due to that the demand of coal was very small. However, things began to change since the eighteenth century along with the flare-up of the Industrial Revolution which was first began in Britain and spread around all the Europe and North America soon after. As it is known, one of the most important changes that the Industrial Revolution brings to the human beings on the technology perspective was the availability of coal to power steam engines and this great invention promoted the rapid expansion of the international trade by building the coal-fed steam for the railways and steamships. As a result, the demand on coal experienced an extremely rapid rising and the former coal mining technologies were dead out and then in 1880s the coal cutting machines were introduced which was the milestone of the modern coal mining and later in 1912, the surface coal mining also welcomed its new chapter by the invention of the steam shovels. It can be concluded that coal mining technologies directly affect coal mining quantity and quality, which in turn affect global energy supplies and, on another hand, coal mining has already made a series of environmental problems which are gaining more and more attention around the world and the environmental-friendly-oriented ecological coal mining technologies and methods are needed in urgent. In this chapter, for the purpose of better understanding of the developing pathway of coal mining from the technological paradigmatic development perspective, a general data analysis was conducted. Through this analysis, the main coal mining technology developing stages can be summarized clearly and using the S-curve-oriented prediction method, the main development direction for coal mining technologies in the following years can be identified.

1.1 Background Introduction

Coal is one of the most abundant, affordable, and readily combustible energy resources all over the world and is consumed more than 53 million tonnes of oil equivalent (mtoe) per year, with a proportion of 28.1% on current global primary

Innovative Approaches towards Ecological Coal Mining and Utilization, First Edition.
Jiuping Xu, Heping Xie, and Chengwei Lv.

energy [Ye et al., 2013, British Petroleum, 2017, WCA, 2017b]. Although renewable energy is developing in an increasing speed, its consumption only accounts for 10% of total global primary consumption. As a result, power generated by coal is still expected to dominate in the global energy structure. While the use of coal causes severe environmental problems, concerns about global energy supplies have grown over the past 15 years with rapid urbanization and industrialization of economy in developing countries; therefore, it is predicted that the demand for coal will remain stable in the short and medium term [WCA, 2017a].

The global coal reserves are 11.139 billion tonnes, with the reserves to production (R/P) ratio of over 153 [British Petroleum, 2017], indicating the huge potential of coal resource exploitation. The energy return on investment (EROI) has been found to be a useful measure to assess resource availability [Hall et al., 2014, Court and Fizaine, 2017]. This term is the ratio of the amount of energy delivered by a given process to the amount of energy consumed, and obviously the higher the EROI, the greater the net energy delivered to society for economic growth [Hall et al., 2014]. The long-term EROI estimates for global coal production show a rising trend, indicating that the global coal production is expected to peak between 2025 and 2045, which means that coal exploitation remains significant EROI potential [Court and Fizaine, 2017]. To directly assess future global coal production capacity, a technological diffusion model was developed and used to simulate the prediction of coal product capacity. It has been found that coal is anticipated to continue to make up a considerable share of global prime energy to meet the energy demands related to technological development.

Since the demand for coal exploitation will remain high in the future, there is also the danger of exacerbating the accompanying environmental problems, especially as majority of the known coal reserves will have to be mined underground [Griffith and Clarke, 1979]. However, traditional underground coal mining practices have caused serious environmental problems such as water aquifer pollution and land surface subsidence in Australia and China, which has brought social and health problems to these regions and their surroundings [Kapusta and Stanczyk, 2011]. Due to the current limitations of coal mining technology, 85% of the world's coal resources cannot be mined by conventional methods [PricewaterhouseCoopers, 2011]. Therefore, it is necessary to increase the research on coal mining practices with high technical efficiency and environmental friendliness.

With the rapid development of science and technology, there are more and more studies on the future of coal mining and many processes and technological innovations have been developed [Scott et al., 2010, Bise, 2013]. Especially, significant progress has been made in coal seam mining methods and other difficulties associated with severe inclinations, instabilities and complex geological structures, and key problems related to deep mine mining pressure control, gas and thermal pollution governance, and tunnel arrangements have been partially solved [Saghafi, 2012, Atay et al., 2014]. However, despite the remarkable development of coal mining technology in recent decades, there has been few paradigm investigations due to the absence of a systematic analytical framework.

The technological paradigm was first proposed by Dosi based on Kuhn's scientific paradigm theory and it has proven to be a reliable method for studying past trends and predicting future possibilities [Kuusi and Meyer, 2007, Ivanova and Leydesdorff, 2015]. Dosi also proposed a technology trajectory to track technology progress within the paradigm and the economic and technological trade-offs required. Subsequently, many studies have applied this method to elucidate the operation and dynamic development within the paradigm, and some useful results have been obtained [Rashid et al., 2013, Chen et al., 2015]. Motivated by previous studies, this chapter uses the technological paradigm theory to determine the coal mining technology road map, puts forward a coal mining technology paradigm, and reveals the long-term technological development dynamics, and thus provides guidance for future mining technology development and coal policy management.

In order to guide the research development direction of the potential coal mining technology paradigm, two steps were taken. Firstly, based on bibliometrics methods, a generalized data analysis system was developed to qualitatively analyze the keyword trend of coal mining technology publications and map the knowledge network. The Web of Science™ core collection was selected as the main database to search relevant literature on coal mining technology, then CiteSpace was used to analyze the textual data of relevant literature in the database [Chen, 2016]. These procedures could establish a coal mining technological paradigm that identifies production development trends and coal mining technologies that should pay attention to, which formed the basis of the proposed integrated coal mining development system.

1.2 Coal Mining Technology Development

In this section, to fully understand the long-term coal mining technological development dynamics and future trends so as to comprehensively review the development history of coal mining technology and to provide guidance for the development of mining technology in the future, an analysis approach based on literature mining is developed, which uses the data from the Web of Science database and the CiteSpace software to conduct cluster and identification analysis.

1.2.1 Literature Analyses

Scientific literatures are always the most important carrier of the critical and frontier discovery of research for most topics and research area and as for coal mining technology, this situation is absolutely true. However, it is difficult to conveniently and effectively to access and summarize the coal mining technology developing history and trend through the traditional literature analysis method which mainly due to that the relative knowledge and information are always embodied in the large amount of the published literatures. Literature mining has proven to be a useful method for elucidating major trends across time in published scientific literature and for the building of topic maps [De Bruijn and Martin, 2002]. In this section, a generalized data analysis system is developed from previous research to reveal the coal mining technological development trends.

1.2.1.1 Data Analysis System

The literature on coal mining technology has a long history of nearly 90 years, meanwhile considering the range and depth of research in this field, it is difficult to identify knowledge gaps or explore future research possibilities, thus, an effective analytical method is necessary. The citation indexing of scientific literature suggested by Garfield has proved to be useful in identifying similar research areas [Garfield and Merton, 1979]. A citation index is a comprehensive result based on journal articles, keywords, publication dates, and abstracts, according to which the impact of a citation in a specific field can be determined [Robinson-García et al., 2015]. Such a method has applied in many other areas. For example, Kajikawa et al. used a citation-based method to study the structural changes in sustainable biomass and bioenergy [Kajikawa and Takeda, 2008] and Liu et al. used keyword co-word networks to identify the intellectual emerging trends in the research on innovation systems [Liu et al., 2015]. The successful application of the citation indexing method prompts the authors to apply it to make a literature analysis of coal mine technology. As illustrated in Figure 1.1, a generalized data analysis system composed of four interrelated links (objective determination, data collection, data preparation, and data analysis) is developed conceptually. Keyword co-word analysis has been widely used to examine and understand knowledge development dynamics [Tian et al., 2008]. A quantitative and visual knowledge map can be formed by combining keyword-based bibliometric and network analyses [Choi et al., 2011, Kim et al.,

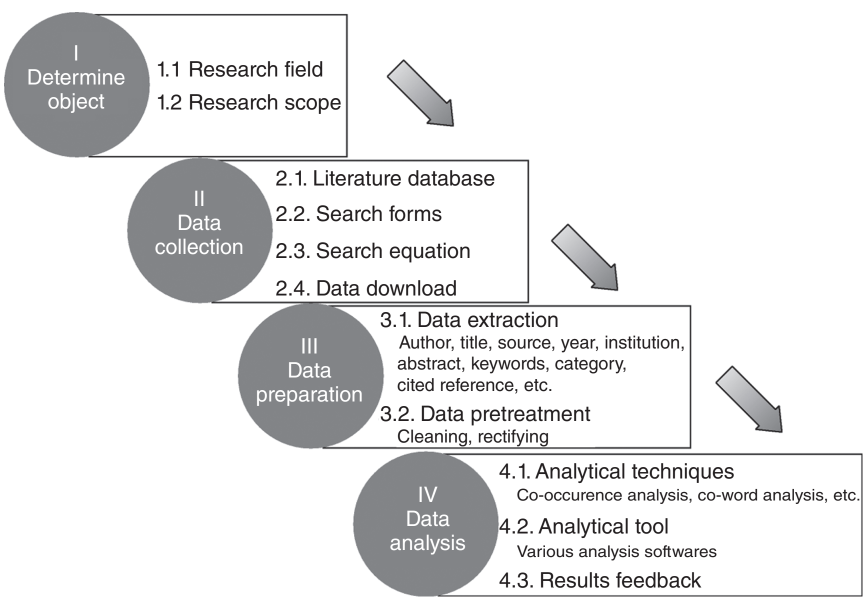

Figure 1.1 A generalized data analysis system.

Table 1.1 Selection criteria.

Search query:	TI = (coal mining) OR
	TS = (coal mining AND (method* OR technology* OR approach*
	OR systems* OR develop* OR trend*))
Language:	English
Publication type:	All document type
Time span:	1990–2017 *
Coverage:	Science citation indexes

Note that the WoS has no keywords for articles published prior to 1991. Our analysis of the changes in research frontiers and topics was therefore confined to post-1990 ISs research.

2016]. Therefore, a keyword analysis was carried out using scientific publication keyword co-word networks, for the sake of visualizing the global coal mining technological development dynamics and identify future trends.

The data acquisition module in the proposed analysis system inquired the Web of Science core collection database in January 2018 to identify the most relevant information. An advanced search was used, as shown in Table 1.1. When the search completed, articles, essays, book reviews, reviews, and editorial material were selected. After filtering, 3807 related articles were downloaded to form a text file, and then the CiteSpace analysis tool was used to identify all records and cited references to visualize the dynamics, patterns, and emerging trends of coal mining technology [Chen, 2016].

1.2.1.2 Knowledge Diagram

This chapter aims to reveal the development trend and research frontier of coal mining technology, thus a keyword co-word analysis was adopted. Keyword co-occurrence mapping is based on the keyword co-occurrence analysis method that explores theme variations across search fields by measuring the occurrence frequency of item pairs [Liu et al., 2015]. After standardization of similar or different words with the same meaning, CiteSpace was used to generate the keyword co-word network. As demonstrated in Figure 1.2, the simplified slice network generated by the minimum spanning tree (MST) algorithm consists of 790 nodes and 1021 links. The coal mining technology keywords knowledge diagram is then generated in the time zone view to focus on the evolution of knowledge over time, clearly showing how research was being updated and influences of mutual research [Chen et al., 2015]. As shown in Figure 1.2, the main keywords and associated frequencies are displayed along the time axis. Each node represents a different keyword, the size of each node denotes the co-occurrence frequency of the corresponding keyword, and each line indicates the co-occurrence relationship between the keywords.

As can be seen, coal miner (53) was a popular research focus around 1990, fully mechanized caving (13) became an important research topic from 1996, ecological and sustainable keywords have been prime research areas since 2004, and underground coal gasification (UCG) (94) has been focused on since 2006. After 2007,

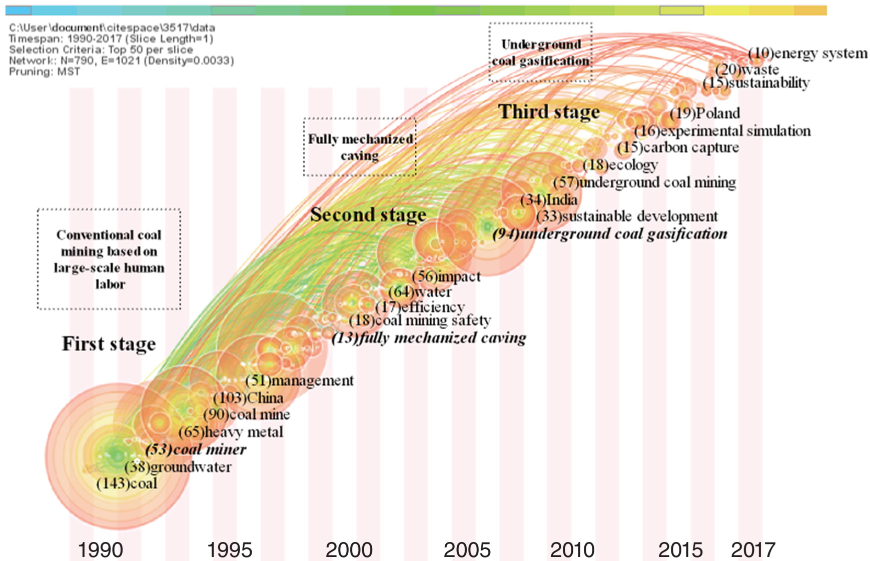

Figure 1.2 Timezone view for coal mining technology keywords diagram.

there was an obvious increase in renewable energy research with the appearance of keywords such as geothermal, solar energy utilization, and hydrogen production. Coal mining methods have also changed significantly over time, with opencast coal mining (11), long wall mining (14), and underground coal mining (57) appearing in sequence alongside some geographical focus such as China (103), United States (51), India (34), and Poland (19).

As can be seen from Figure 1.2, with the development history of coal mining technology, three main stages can be summarized. In the first stage, which lasted until early 2000, traditional coal mining based on large-scale human labor was the focus of research. After that, the second stage lasted for nearly 15 years took place, in which the fully mechanized caving technology was the most popular research topic, and in the third stage, from then to now, the UCG was the most important research area. Similar developing trends can be found in many other documents, not only in scientific literature, but also in reports or development plans. For example, a number of international conferences have discussed this issue and agreed that, a kind of clean coal technology, i.e. UCG, will be studied in many countries, such as Australia, New Zealand, India, Pakistan, Canada, Italy, the United States, and China [WCI, 2007, van der Riet, 2008]. In addition, the World Bank has reviewed clean coal mining technology from world experience and made implications for India and suggested that enough attention should be paid to UCG [The World Bank, 2008]. For China, one of the main coal producers, the government also encouraged to develop UCG in the future in the report of the 13th five-year plan for the development of coal industry [NEA NDRC, 2016]. Therefore, no matter from the results of literature mining, or the focus of relevant institutions, governments, and conferences, a common conclusion can be drawn that UCG will receive great attention in the future.

1.2.2 Three Periods of Coal Mining Technology

Technological innovation is essentially an iterative process with its push on industrial development and is triggered by the new market or service opportunities toward technological invention [Garcia and Calantone, 2002]. Technological innovation is in a cyclic process, where a new innovation is introduced for the first time and an improved innovation is reintroduced [Cheng et al., 2015]. This process is affected by multiple physical properties. With the increasing of those, a certain outcome point under the physical laws is obtained, namely S-curve [Cheng et al., 2015, Adner and Kapoor, 2016].

Additionally, from the systematic view, many other economic, social, institutional, and political factors can also be considered, and it may cause different technologies coexisting. Based on the accumulation of these factors, a technological paradigm can be naturally formed [Dosi, 1982]. Technology paradigm can determine the starting point and limit of new technology innovation cycles. Under the guidance of the specific paradigm, technological activities form the technological trajectory [Dosi, 1982]. As a result, technology evolution is a long-term series of technological paradigms, and each complete technological paradigm has an S-shaped curve (Figure 1.3). Based on the characteristics of different period, it could be roughly divided into three stages: competition, diffusion, and shift [Dosi, 1982, Christensen, 1992, 2013].

For the purpose of adequate appreciation of the long-term development of coal mining technology, it is necessary to explain the polymerization evolution of coal mining technology. Integrating literature analysis with S-curve theory of technology paradigm, coal mining technology paradigm can be divided into three stages:

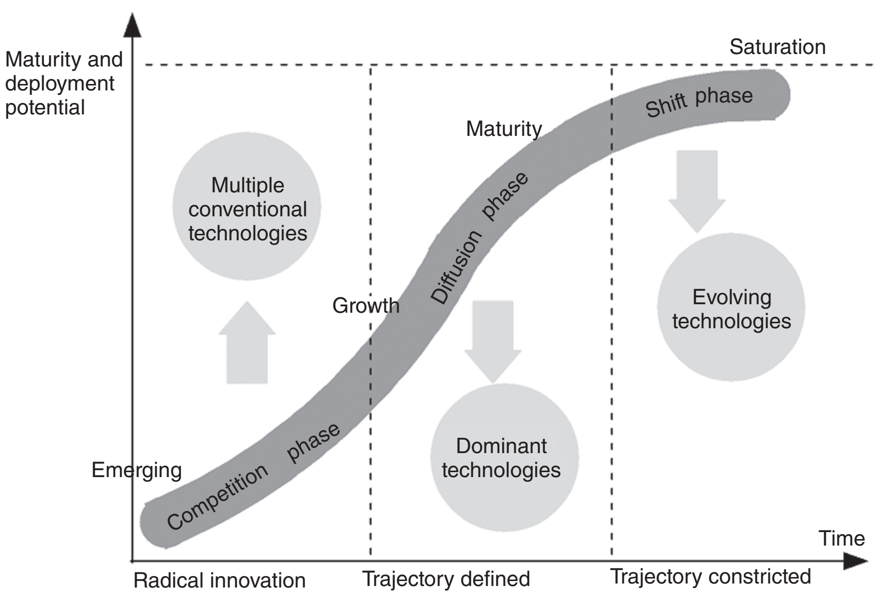

Figure 1.3 Three stages of the technological paradigm.

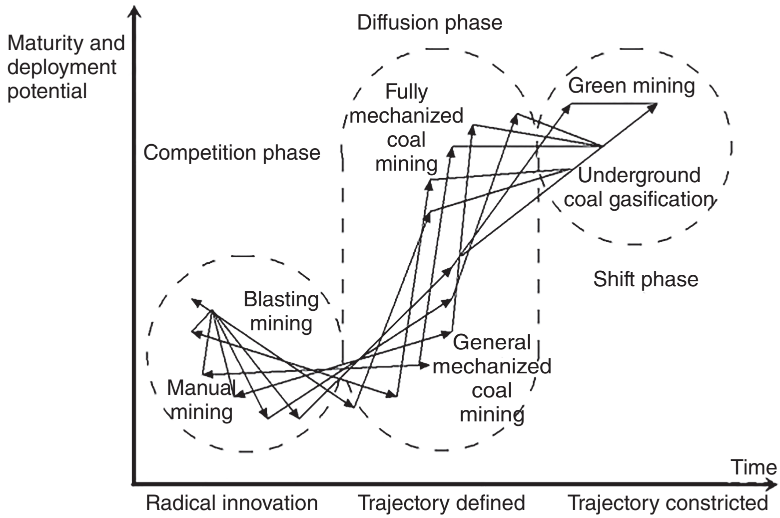

Figure 1.4 Technological paradigm for coal mining technology.

competition, diffusion, and shift, with each stage being characterized by different technologies, as described in Figure 1.4.

1.2.2.1 Competition Phase

Direct coal mining or manual mining is one of the oldest, most common, and versatile coal mining forms currently [Astakhov et al., 1990]. At first, coal mining was small scale, and coal was either buried on the surface or near the surface; consequently, drift mining and bell pit mining mainly depending on manual labor and the application of simple original equipment were the typical mining methods [Musson and Robinson, 1969]. Later, in order to satisfy the growing need brought about by the rapid development of international trade in the nineteenth century, the number of coal-fed steam engines for railways and ships were expanding. When coal became the major fuel supporting the industry, the demand for coal grew sharply and small-scale technologies were inadequate, consequently, coal mining developed from simple surface mining to surface and deep well mining. Even more important is that coal mining was implementing the machines, which greatly improve the production conditions. Taking an example, blasting technology was utilized for drilling and mining in horizontal tunneling lanes, which had a significant influence on the mining efficiency [Flinn et al., 1986]. Coal production reached 5 million tonnes in 1850. But manual labor remained the main mining technology as the machines were costly and unaffordable. Accident also occurred to coal mining and the miners were always in danger due to the worse working conditions and safety management.

1.2.2.2 Diffusion Phase

As mechanical and electrical technologies developed, safety production and high-efficient production were the requirements of the coal mining. The manual labor and the application of simple original equipment were gradually replaced by mechanized mining technologies. The coal mining machinery was specially designed to cut coal, the underground transportation adopted the conveyor, the ventilation adopted the fan, and the pumping equipment ensures the good gangue discharge. All of them improved the production efficiency and the overall safety production level of the coal mining [Stefanko, 1983].

Large complex systems were involved in modern coal mining, especially for underground coal mining with multiple production links, such as coal cutting, tunneling, transportation, ventilation and drainage, and surface production. But each mechanized working procedure was conducted as a separate production link and lacked comprehensive coordination. In order to integrate these procedures, fully mechanized mining technology occupied the modern coal mining, which lead to labor intensity reduction and safety improvement [Jinhua, 2006]. The United Kingdom was the first one to conduct fully mechanized coal mine equipped with self-advancing hydraulic supports in 1953, driving the development of various mechanized work faces and complete equipment packages in Germany, Japan, and China [Tian et al., 2006].

The stability of production became a new factor that restricted productivity after fully mechanized mining technology improved production efficiency significantly. In order to realize efficient production and reduce system risk, the stable automatic control production technology is adopted for the complete mining process. It had the ability to decrease the production staff needed down the shaft, further optimize the production system, increase mine safety, and save energy [Ralston et al., 2014]. At this time, information management had been employed to gather real-time production and supply information for fault prediction and disaster warnings [Guo et al., 2016].

1.2.2.3 Shift Phase

The efficient development and utilization of coal resources have played an important role in the world economic development; however, it meantime causes some issues such as environmental pollution and ecological damage and further limit sustainable development. With these problems reaching a critical level in the past few decades, the coal industry must move toward a new mode of sustainable development.

Latest studies have found that UCG technology provides a possible economic choice for extracting energy from coal resources while removing many environmental problems caused by deep mining [Son et al., 2016]. UCG technology converts in situ coal into a usable syngas to generate electricity or to produce liquid hydrocarbon fuels, natural gas surrogates, and valuable chemical products [Yang et al., 2016]. As is shown in Figure 1.5, UCG technology is realized by air and/or oxygen and steam injection into linked injection wells. The coal is then fired and a sequence of controlled chemical transformations takes place in the gasification channel, which is usually divided into three regions: oxidization, reduction and dry distillation, and pyrolysis [Samdani et al., 2016].

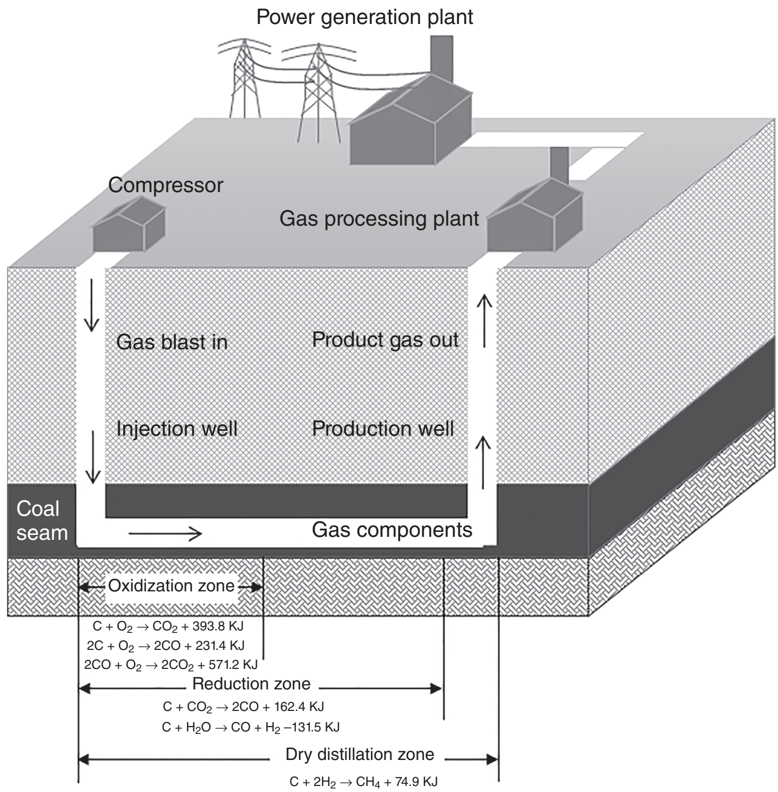

Figure 1.5 The UCG process.

In view of the process, UCG technology has many advantages over traditional coal mining and gasification technology [Su et al., 2016, Pei et al., 2016a]. First, laborer work underground is not needed and the general safety is improved. Second, when all the coal has been gasified, there is no need for surface gasifiers, consequently the surface footprints of the UCG plant are significantly reduced and related dust emissions and coal transport, treatment and storage costs are avoided. Third, UCG technology is capability to take advantage of coal seams which are so deep or so thin that they cannot be economically mined by conventional underground methods. According to the assessment, the United States, Australia, India, and China separately has over 5 million petajoules [PJ], 2.3 million PJ, 1.9 million PJ, and 2.2 million PJ of recoverable UCG syngas. With the application of UCG technology, there is a huge increase in the global recoverable coal reserves [PricewaterhouseCoopers, 2011, Su et al., 2016]. Based on the above advantages, UCG technology is recognized as a promising clean coal technology to help coal mining much securer, cleaner, and more economical. In addition to UCG technology, other potential technologies have also been come up to handle security and environmental issues. Qian presented a green coal mining technology system for China's coal industry which recommended taking measures to minimize the effects on the environment and develop an environmental-friendly recycling coal economy from the early stage of coal mining operations [Minggao, 2010].

1.3 Discussion

A paradigm is recognized as a comprehensive model that a specific scientific community must follow in a certain kind of scientific activities, which includes common world outlook, basic theory, paradigm, method, means, standard, etc. It was discovered through literature mining that the development of coal mining technology is on a trajectory that conforms to the S-curve of traditional technology paradigm, thus clarifying the paradigm of coal mining technology. Although there is few innovative coal mining technology paradigms from the literature analysis, latest researches pay attention to sustainable development, ecological sensitivity, energy system, renewable energy, and energy recovery and point out the direction of future technological innovation.

There is a need for a paradigm shift, which is a world view and behavior shared by a group of researchers engaged in a science. The term paradigm shift first appeared in The Structure of Scientific Revolution, the representative work of Thomas Kuhn. Paradigm shift, the fifth and final step in the Kuhn Cycle (Figure 1.6), is to break out of the original constraints and restrictions and to open up new possibilities by grafting on a higher level view such as a System Improvement Process [Thwink.org, 2014a, Ashkenazi and Lotker, 2014]. With coal expected to be a key driver of development, it will remain an important role in urbanization and industrialization [Thwink.org, 2014b]. However, exploiting and utilizing coal give rise to serious environmental issues. As coal occupies an important position, it cannot be abandoned. Therefore, the coal mine industry should keep a pace of sustainable development. UCG technology could assist in moving toward a path of coal industry sustainable development. UCG technology is a promising clean coal technology to help coal mining much securer, cleaner, and more economical with the ability to recover currently unmineable coal resources [Thwink.org, 2014a].

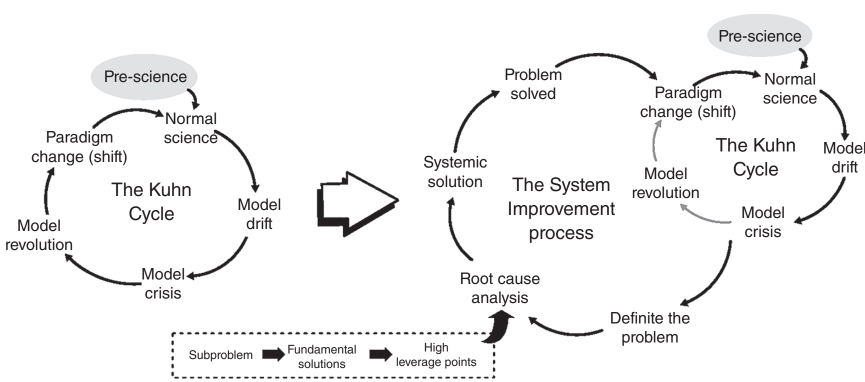

Figure 1.6 The Kuhn Cycle and the System Improvement Process.

Although this technology is still not satisfactory, it could be greener and more efficient when a paradigm shift happens.

Three main obstacles to achieve the UCG-based paradigm shift exist. First, realistic factors which are vital for complete UCG systems fall short of the requirement. Currently, the energy recovery rate is just approximately 30– 60%, at relatively low rate compared with open pit mining [Su et al., 2016]. Besides, the EROI index, which defines the relationship between the human-made capital energy required to produce energy and the amount of energy, is still unsatisfactory compared with other energy sources such as crude oil. Second, related environmental problems are caused as UCG technology involves geomechanical, hydrogeological, thermal, and geochemical process [Yang et al., 2007, Pei et al., 2016b]. Groundwater pollution is the most highlighted issue. A large number of pollutants, such as phenol, polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia, and sulfide, will be produced in the process of coal gasification. These pollutants diffuse and penetrate into the surrounding strata in the coal seam, which will pollute the surrounding groundwater. Moreover, underground caves are created in UCG technology and further rock and other materials cannot be supported; as a consequence, subsidence happens. Third, the desired syngas quality and composition are quite difficult to achieve [Imran et al., 2014, Pei et al., 2016b]. Syngas qualities have relations with the properties of the coal bearing strata, and the gasification conditions such as the size of the gasification cavities, the spacing, the moisture content, pressure, and temperature. Although hard technology can validly handle those obstacles [Pei et al., 2016b, Su et al., 2016], it is expensive and beyond capability of the developing countries which heavily rely on coal [Liu et al., 2007, Imran et al., 2014]. Therefore, integrating current technologies is more achievable option at present.

In order to realize sustainable and efficient coal mining and take full advantage of renewable energy, a more reasonable approach is necessary. Due to important role of UCG in future mining projects, an environmentally sustainable multiple energy comprehensive mining method based on ecological coal mining is proposed, graphically represented in Figure 1.7. Below are some highlights of the features for this approach.

As UCG technology causes carbon emissions, carbon capture and storage (CCS) technology is applied to capture these carbon emissions, and consequently the environment is improved [Asif and Muneer, 2007]. Combined UCG-CCS technology offers an approach to get better energy recovery from coal and avoid the hazardous environmental influences [Karki et al., 2010]. Specifically, after the UCG technology, there are large gaps deep underground which enable carbon emissions to be captured and stored [Khadse et al., 2007, Roddy and Younger, 2010, Tollefson and Van Noorden, 2012, Eftekhari et al., 2017]. When UCG is adopted at artificially high permeable areas such as depths underground greater than 700–800 m, carbon storage is considered to be attractive. Besides, Combined UCG-CCS technology is related to other carbon-intensive industries through the CO_2 pipeline grid, and power plants can utilize the UCG syngas with pre- and/or post-combustion capture.

For intra-regional self-supporting electricity supply for coal mining perspective, although wind and solar energy are widely applied to provide heating and cooling or

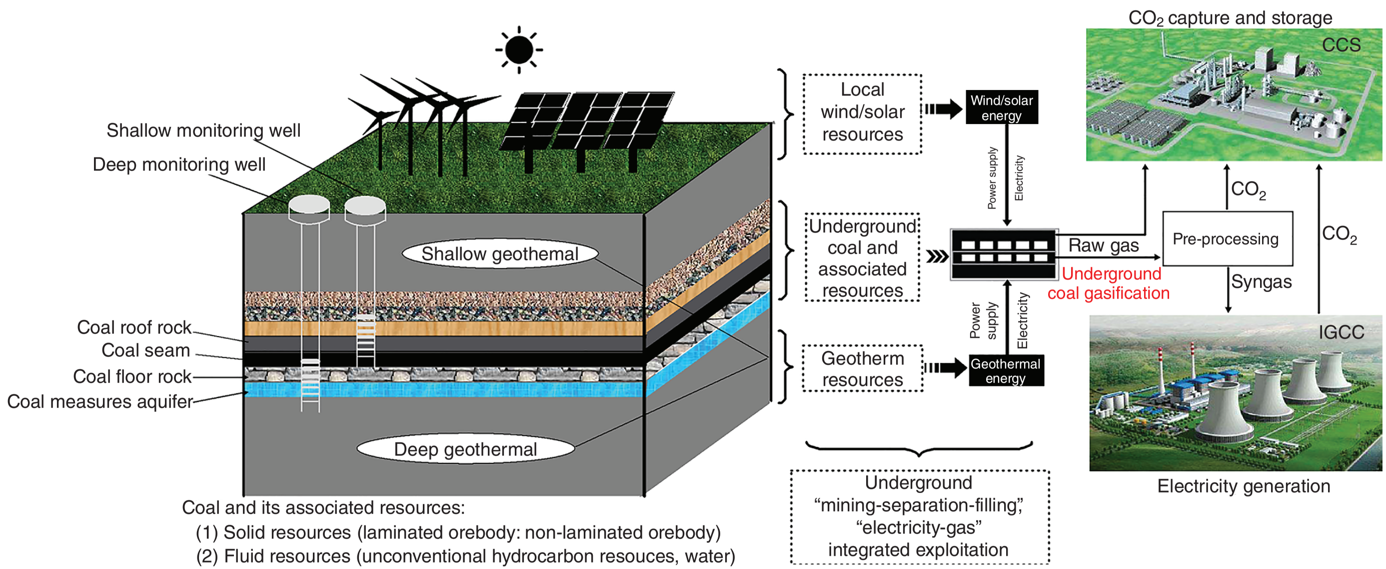

Figure 1.7 Ecological coal mining in the future.

to generate electricity, they are hardly employed in coal mining industry [Preene and Younger, 2014]. However, the integrated UCG system makes full use of the geology and geology conditions of the mine as well as the existing renewable energy sources, improving energy efficiency. Precisely, the integrated UCG system requires less or even no external power as it employs available intra-regional renewable energies to generate power [Wang et al., 2016, Hall et al., 2011, Ramos et al., 2015].

Moreover, the raw gas from UCG has too low energy content compared with generation standards, and requirement for pre-processing procedure is proposed for syngas separation and purification. This system is integrated with integrated gasification combined cycle (IGCC), which is able to save syngas transportation costs and reduce gasification and purification steps [Kintisch, 2007]. Besides, this system can add water monitor wells to monitor the underground water quality in case excessive concentration of groundwater pollutants occur.

To apply this integrated exploitation approach, it is vital to establish the regional polycentric energy systems which unite the scales and actors from different levels and areas [Kursun et al., 2015]. And this integrated exploitation method varies according to the particular geography and climate. In general, the exploitation approach eliminates the extreme environmental issues, ensures production stability, reduces energy consumption and ecological destruction, and realizes no coal on the ground [Lauber and Jacobsson, 2016].

References

Adner, R. and Kapoor, R. (2016). Innovation ecosystems and the pace of substitution: re-examining technology S-curves. *Strategic Management Journal* 37 (4): 625–648.

Ashkenazi, D. and Lotker, Z. (2014). The quasicrystals discovery as a resonance of the non-euclidean geometry revolution: historical and philosophical perspective. *Philosophia* 42 (1): 25–40.

Asif, M. and Muneer, T. (2007). Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews* 11 (7): 1388–1413.

Astakhov, A., Grübler, A., and Mookhin, A. (1990). Technology diffusion in the coal-mining industry of the USSR: an interim assessment. *Technological Forecasting and Social Change* 38 (3): 223–256.

Atay, M.T., Simonetti, B., and Coskun, S.B. (2014). Hybrid technology of hard coal mining from seams located at great depths. *Archives of Mining Sciences* 59 (3): 575–590.

Bise, C.J. (2013). *Modern American Coal Mining: Methods and Applications*. SME.

British Petroleum (2017). *BP Statistical Review of World Energy*. British Petroleum.

Chen, Y., Chen, C., Liu, Z. et al. (2015). The methodology function of cite space mapping knowledge domains. *Studies in Science of Science* 33 (2): 243–253.

Cheng, J.T.S., Jiang, I.-M., and Liu, Y.-H. (2015). Technological innovation, product life cycle and market power: a real options approach. *International Journal of Information Technology & Decision Making* 14 (01): 93–113.

Choi, J., Yi, S., and Lee, K. (2011). Analysis of keyword networks in MIS research and implications for predicting knowledge evolution. *Information & Management* 48 (8): 371–381.

Christensen, C.M. (1992). Exploring the limits of the technology S-curve. Part one: Component technologies. *Production and Operations Management* 1 (4): 334–357.

Christensen, C. (2013). *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business Review Press.

Court, V. and Fizaine, F. (2017). Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions. *Ecological Economics* 138: 145–159.

De Bruijn, B. and Martin, J. (2002). Getting to the core of knowledge: mining biomedical literature. *International Journal of Medical Informatics* 67 (1): 7–18.

Dosi, G. (1982). Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. *Research Policy* 11 (3): 147–162.

Eftekhari, A.A., Wolf, K.H., Rogut, J., and Bruining, H. (2017). Energy and exergy analysis of alternating injection of oxygen and steam in the low emission underground gasification of deep thin coal. *Applied Energy* 208: 62–71.

Flinn, M.W., Ashworth, W., and Pegg, M. (1986). *History of the British Coal Industry: 1946–1982: The Nationalized Industry*, vol. 5. Oxford University Press.

Garcia, R. and Calantone, R. (2002). A critical look at technological innovation typology and innovativeness terminology: a literature review. *Journal of Product Innovation Management* 19 (2): 110–132.

Garfield, E. and Merton, R.K. (1979). *Citation Indexing: Its Theory and Application in Science, Technology, and Humanities*, vol. 8. New York: Wiley.

Griffith, E.D. and Clarke, A.W. (1979). World coal production. *Scientific American* 240 (1): 38–47.

Guo, X., Wang, R., and Wu, Z. (2016). Research and application of WebGIS in coal mine information management system. *International Conference on Advanced Design and Manufacturing Engineering*.

Hall, C.A.S., Lambert, J.G., and Balogh, S.B. (2014). EROI of different fuels and the implications for society. *Energy Policy* 64: 141–152.

Hall, A., Scott, J.A., and Shang, H. (2011). Geothermal energy recovery from underground mines. *Renewable and Sustainable Energy Reviews* 15 (2): 916–924.

Imran, M., Kumar, D., Kumar, N. et al. (2014). Environmental concerns of underground coal gasification. *Renewable and Sustainable Energy Reviews* 31 (31): 600–610.

Ivanova, I.A. and Leydesdorff, L. (2015). Knowledge-generating efficiency in innovation systems: the acceleration of technological paradigm changes with increasing complexity. *Technological Forecasting and Social Change* 96: 254–265.

Jinhua, W. (2006). Present status and development tendency of fully mechanized coal mining technology and equipment with high cutting height in China. *Coal Science & Technology* 42: 1–4.

Kajikawa, Y. and Takeda, Y. (2008). Structure of research on biomass and bio-fuels: a citation-based approach. *Technological Forecasting and Social Change* 75 (9): 1349–1359.

Kapusta, K. and Stanczyk, K. (2011). Pollution of water during underground coal gasification of hard coal and lignite. *Fuel* 90 (5): 1927–1934.

Karki, N.R., Jha, D.K., and Verma, A.K. (2010). Rural energy security utilizing renewable energy sources: challenges and opportunities. *IEEE Conference*, India, pp. 551–556.

Khadse, A., Qayyumi, M., Mahajani, S., and Aghalayam, P. (2007). Underground coal gasification: a new clean coal utilization technique for India. *Energy* 32 (11): 2061–2071.

Kim, W., Khan, G.F., Wood, J., and Mahmood, M.T. (2016). Employee engagement for sustainable organizations: keyword analysis using social network analysis and burst detection approach. *Sustainability* 8 (7): 631.

Kintisch, E. (2007). Carbon emissions. Report backs more projects to sequester CO_2 from coal. *Science* 315 (5818): 1481.

Kursun, B., Bakshi, B.R., Mahata, M., and Martin, J.F. (2015). Life cycle and energy based design of energy systems in developing countries: centralized and localized options. *Ecological Modelling* 305: 40–53.

Kuusi, O. and Meyer, M. (2007). Anticipating technological breakthroughs: using bibliographic coupling to explore the nanotubes paradigm. *Scientometrics* 70 (3): 759–777.

Lauber, V. and Jacobsson, S. (2016). The politics and economics of constructing, contesting and restricting socio-political space for renewables-the German renewable energy act. *Environmental Innovation and Societal Transitions* 18: 147–163.

Li, J., Chen, C. (2016). *CiteSpace*. Press of Capital University of Economics and Business.

Liu, S.Q., Gang, J., Mei, M., and Dong, D. (2007). Groundwater pollution from underground coal gasification. *International Journal of Mining Science and Technology* 17 (4): 467–472.

Liu, Z., Yin, Y., Liu, W., and Dunford, M. (2015). Visualizing the intellectual structure and evolution of innovation systems research: a bibliometric analysis. *Scientometrics* 103 (1): 135–158.

Minggao, Q. (2010). On sustainable coal mining in China. *Journal of China Coal Society* 35 (4): 529–534.

Musson, A.E. and Robinson, E. (1969). *Science and Technology in the Industrial Revolution*. Manchester University Press.

NEA NDRC (2016). The 13th five-year plan for the development of coal industry.

Pei, P., Korom, S.F., Ling, K., and Nasah, J. (2016a). Cost comparison of syngas production from natural gas conversion and underground coal gasification. *Mitigation & Adaptation Strategies for Global Change* 21 (4): 629–643.

Pei, P., Nasah, J., Solc, J. et al. (2016b). Investigation of the feasibility of underground coal gasification in North Dakota, United States. *Energy Conversion and Management* 113: 95–103.

Preene, M. and Younger, P.L. (2014). Can you take the heat? The geothermal energy in mining. *Mining Technology* 123 (2): 107–118.

PricewaterhouseCoopers (2011). Industry review and an assessment of the potential of UCG and UCG value added products. www.lincenergy.com/data/media-news-articles/relatedreport02.pdf (accessed 25 May 2021).

Ralston, J., Reid, D., Hargrave, C., and Hainsworth, D. (2014). Sensing for advancing mining automation capability: a review of underground automation technology development. *International Journal of Mining Science and Technology* 24 (3): 305–310.

Ramos, E.P., Breede, K., and Falcone, G. (2015). Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. *Environmental Earth Sciences* 73 (11): 6783–6795.

Rashid, A., Asif, F.M.A., Krajnik, P., and Nicolescu, C.M. (2013). Resource conservative manufacturing: an essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner Production* 57 (20): 166–177.

Robinson-García, N., Jiménez-Contreras, E., and Torres-Salinas, D. (2015). Analyzing data citation practices using the data citation index. *Journal of the Association for Information Science and Technology* 67 (12): 2964–2975.

Roddy, D.J. and Younger, P.L. (2010). Underground coal gasification with CCS: a pathway to decarbonising industry. *Energy & Environmental Science* 3 (4): 400–407.

Saghafi, A. (2012). A Tier 3 method to estimate fugitive gas emissions from surface coal mining. *International Journal of Coal Geology* 100 (10): 14–25.

Samdani, G., Aghalayam, P., Ganesh, A. et al. (2016). A process model for underground coal gasification: part two growth of outflow channel. *Fuel* 181: 587–599.

Scott, B., Ranjith, P.G., Choi, S.K., and Khandelwal, M. (2010). A review on existing opencast coal mining methods within Australia. *Journal of Mining Science* 46 (3): 280–297.

Son, N.L.H., Anh, N.H., and Dong, H.N. (2016). Review of underground coal gasification technologies. *International Conference on Green Technology and Sustainable Development (GTSD)*, IEEE, pp. 69–73.

Stefanko, R. (1983). Coal mining technology: theory and practice.

Su, F.-q., Hamanaka, A., Itakura, K.-i. et al. (2016). Evaluation of coal combustion zone and gas energy recovery for underground coal gasification (UCG) process. *Energy and Fuels* 31 (1): 154–169.

The World Bank (2008). Clean coal power generation technology review: worldwide experience and implications for India.

Thwink.org (2014a). Kuhn Cycle. http://www.thwink.org/sustain (accessed 25 May 2021).

Thwink.org (2014b). A model in crisis: can civilization bypass the model revolution step or not? http://www.thwink.org/sustain/articles/018_ModelInCrisis/index.htm (accessed 25 May 2021).

Tian, Z.L., Zhang, C.W., and Li, J.H. (2006). Present status and tendency of fully mechanized coal mining equipment. *Coal Technology* 25: 1–2.

Tian, Y., Wen, C., and Hong, S. (2008). Global scientific production on GIS research by bibliometric analysis from 1997 to 2006. *Journal of Informetrics* 2 (1): 65–74.

Tollefson, J. and Van Noorden R. (2012). Slow progress to cleaner coal. *Nature* 484 (7393): 151–152.

van der Riet, M. (2008). Underground coal gagfication. *Proceedings of the SAIEE Generation Conference*. Midrand, South Africa: Eskom College.

Wang, W., Wang, Y., Song, W., and Shi, G. (2016). Evaluation of infrared heat loss of dust-polluted surface atmosphere for solar energy utilization in mine area. *International Journal of Hydrogen Energy* 41 (35): 15892–15898.

WCA (2017a). Environmental protection. http://www.worldcoal.org/coal/uses-coal/coal-electricity (accessed 25 May 2021).

WCA (2017b). Coal & electricity. http://www.worldcoal.org/coal/uses-coal/coal-electricity (accessed 25 May 2021).

WCI (2007). Coal Meeting the Climate Challenge. *Technical report*. World Coal Institute.

Yang, D., Koukouzas, N., Green, M., and Sheng, Y. (2016). Recent development on underground coal gasification and subsequent CO_2 storage. *Journal of the Energy Institute* 89 (4): 469–484.

Yang, L., Liu, S., Yu, L., and Jie, L. (2007). Experimental study of shaftless underground gasification in thin high-angle coal seams. *Energy and Fuels* 21 (4): 2390–2397.

Ye, R., Xiang, C., Lin, J. et al. (2013). Coal as an abundant source of graphene quantum dots. *Nature Communications* 4 (1): 94–105.