Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.24702

173 (2020) 123–132
January

Identify competitive advantages and disadvantages of seawater desalination industry in China using the diamond model

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Received 3 January 2019; Accepted 14 July 2019

ABSTRACT

Seawater desalination, a technology that can tap new source of water and increase water supply, has been increasingly supported and incentivized with various policies and regulations in China. However, the quantitative targets set by Chinese government have never been met and seawater desalination industry (SDI) is developing slowly when compared to the rapid advancement of desalination technology. Why has the SDI been developing slowly, even with strong support and incentives by the government? In this study, a diamond model is proposed to comprehensively analyze the industrial competitive advantages and disadvantages. The results show that the SDI has already achieved certain market competitiveness in technology research and development, equipment manufacturing and engineering construction in China. According to the relative analysis results, the weak market competitiveness, disconnection of technology with the market and the shortage of the industry chain are the main factors responsible for the slow development of SDI in China.

Keywords: Seawater desalination industry; Diamond model; Competitiveness

1. Introduction

China has been listed by the United Nations as one of the 13 poor water countries [1]. More than 400 cities have insufficient water supply and 110 have been suffering from serious water scarcity [2]. The average annual water deficit in northern China is 46.9 billion m^3, while the water shortage in southern China is 6.7 billion m^3 [3]. As an important complement and strategic reserve of water resources, seawater utilization is an important way to relieve the water stress [4]. The development of seawater desalination industry (SDI) is of great significance to alleviate the shortage of water resources in coastal areas and islands in China, promote the utilization of brackish water in the central and western China, optimize the water sources and ensure the sustainable utilization of water resources [5].

The research on seawater desalination (SD) technology in China began in 1958, while the research on SDI started in 1996 [6,7]. Some studies showed that China's SD has the foundation and conditions for industrialization development: it has been technically developed and economically acceptable, and formed an emerging high-tech industry [8–11]. In addition, SDI has been strongly supported by the Chinese government. As early as 2005, the Chinese government published the first guiding document Special Planning of Seawater Utilization, which clearly pointed out that SDI water production capacity shall reach 0.8~1 million m^3/d in 2010 [12]. In order to further promote the development of SDI, the State Council released Opinions on Accelerating the Development of SDI in 2012, which listed the development of SDI as a national policy for the first time [13].

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This article was originally published without an Acknowledgment. This version has been corrected.
Please see Corrigendum in vol. 175 (2020) 420 [10.5004/dwt.2020.25482].

1944-3994/1944-3986

Since then, numerous agencies predicted the SDI would enter a golden age, but the SDI development for the last three decades has been much slower than predicted. Fig. 1 demonstrates the cumulative water production capacity and annual growth rate of SDI in China. Though the total water production capacity has been increasing, the annual growth rate has dropped below 20% since 2010. The total water production capacity was 0.59 million m^3/d in 2010 and 1.01 million m^3/d in 2015, both of which did not meet the annual targets. During the same period, wastewater reclamation, reuse, water transfer and rainwater harvesting developed rapidly. The lack of specific regulations to implement the national policy of SDI put great pressure to SDI industrial chains. Although there was huge water shortage in China and desalination systems grew rapidly, SD systems grew relatively slowly. For 2014, the desalination water production was about 27 million m^3/d [14], but SD water production was only 0.94 million m^3/d, only accounting for 3.48% of the total desalination water production.

To understand why SDI developed slowly, it is crucial to comprehensively analyze the competitive advantages and disadvantages of SDI in China. However, literature mainly focused on a specific perspective of SDI such as technology, economy or environment. Overall competitive advantages and disadvantages assessment of the industry are pressingly needed. We contribute to literature by using the diamond model to comprehensively explore the competitive advantages and disadvantages of SDI in China. The diamond model has been widely used in various fields, which mainly focused on holistic industrial competitiveness [16–21].

The remainder of this paper is organized as follows. Section 2 provides a framework of diamond model for the SDI. Section 3 describes the data sources. Section 4 introduces the diamond model to determine the competitive advantages of SDI. Section 5 identifies the industrial competitive disadvantages of SDI. Finally, Section 6 concludes the study and provides suggestions for future development of SDI in China.

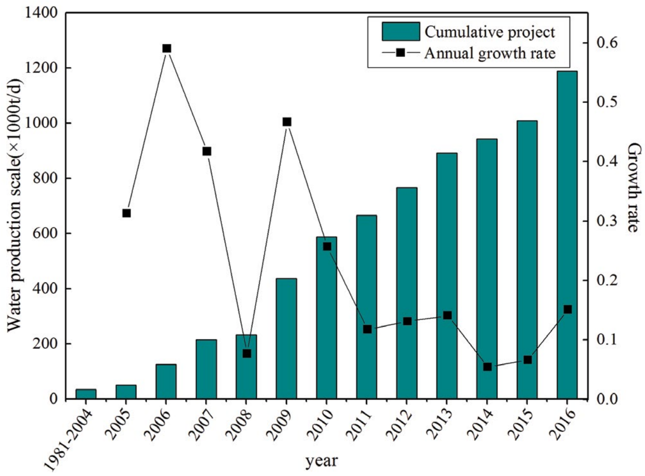

Fig. 1. Capacity growth of seawater desalination in China [15].

2. Methods

2.1. Michael porter diamond model

"Competitive strategy (CS): techniques for analyzing industries and competitors", "Competitive advantage (CA): creating and sustaining superior performance" and "Competitive advantage of nations (CAN)" are commonly known as Porter's competition trilogy, published in 1980. CS mainly involved in the analysis of the industry and competitors outside the enterprise [22]. CA was published in 1985 and mainly discussed the internal value activities and cost drivers of the enterprise [23]. Based on an economic analysis of the company's internal activity costs and external industry structure, Porter further expanded to analyze the impact of regional industrial clusters and national policies, and then finally published the book of CAN in 1990, which built a new paradigm of national competitiveness [24]. This new paradigm is the Michael Porter diamond model.

A bridge between the theoretical literatures in strategic management and international economics could be built by Porter's CAN [25]. Using the diamond model, one can explain why particular countries succeed in particular industries [26]. In addition to explaining how some industries succeed, this model is also a tool for predicting future directions of specific industries. It can even predict if an industry can flourish and become more competitive when an opportunity arises [24]. The diamond model is based on four specific attributes (factor condition, demand condition, related and supporting industry, firm strategy) and two exogenous variables (government and chance). These attributes and exogenous variables interact in a diamond shape, from which the diamond model is derived.

The diamond model has been widely used and questioned. Criticisms on the diamond model include the scale of analysis, the factors used in the model and reasoning [25]. Nonetheless, it did play an irreplaceable role as a tool to systematically analyze industry competitiveness.

Porter's diamond model has been employed in various countries to examine industry competition in domestic and global market for both industry and national levels [27,28]. It was firstly used to study the competitiveness of International Tourism in China in 1999 [29]. Since then, it has been used in many industries in China, such as cultural industry, financial industry, wine industry, water industry and so on [30–33]. For example, Wu et al. [16] adopted the diamond model to comprehensively analyze the competitiveness of China's coal industry, and discovered that this industry suffers from excessive capacity, low coal price and substitute of clean energy, and so on. They also found the support of government policy and national strategies will greatly promote the recovery of this industry. Each key factors in diamond model has an important impact on the comprehensive competitiveness of this industry. Through the analysis tools of diamond model, Wang et al. [34] found that factor and demand conditions were the most important determinants of exhibition location in the conference and exhibition industry by investigating the industrial present situation and future development in Taiwan.

2.2. Diamond model in SDI in China

As far as we know, the diamond model has only been used to analyze regional SDI in Shanghai, China [35].

This study is aimed to integrate the knowledge of SDI in China by introducing the diamond model to comprehensively analyze the competitive advantages and disadvantages of SDI in China. While applying Porter's "Diamond" framework to SDI in China, the competitive analysis of SDI is determined by four attributes and two exogenous variables (Fig. 2). The four attributes include:

- Firm strategy, structure and rivalry: The conditions governing how companies are created, organized and managed, as well as the nature of domestic rivalry.
- Demand conditions: The market demand characteristics of SD products.
- Related and supporting industries: The presence or absence in the SDI of supplier industries and other related industries, whether they are nationally or internationally competitive.
- Factor conditions: Production factors, such as natural resources, desalination technologies and infrastructure.

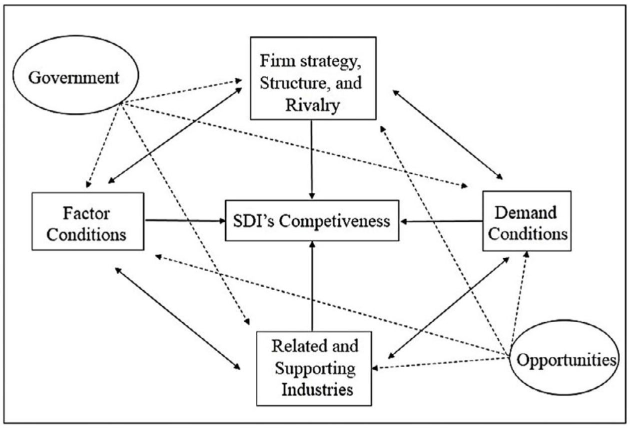

Fig. 2. Diamond framework of Chinese Seawater Desalination Industry [24].

These four attributes have bidirectional effects and form a diamond-shaped system. In addition to the four attributes, there are two exogenous variables: government and opportunities, which constantly affect the development of the four attributes. Opportunities are beyond our control but the influence of government cannot be ignored. Therefore, this study will combine these two variables to analyze the four attributes.

2.3. Data

The data of SD are either obtained directly from our national survey or from literature and reports by various institutes and organizations, such as the National Development and Reform Commission [12], the State Council [13], State Oceanic Administration People's Republic of China [15]. The data types and sources are summarized in the appendix. Table 1 shows the number of SD projects and associated water production capacity. The social, economic, water resources and patent data are obtained via various agencies and organizations such as Ministry of Environmental Protection of the People's Republic of China [36], The National Development and Reform Commission [37], Beijing Water Authority [38], Tianjin Development and Reform Commission [39], the Ministry of Water Resources of the People's Republic of China [3], The Network of China Water [40] and Patent Cloud Web [41].

2.4. Competitive advantages of SDI in China

2.4.1. Firm strategy, structure and rivalry

2.4.1.1. Firm strategy and structure

Firm strategy, structure and rivalry in the industry are mainly reflected in size of business, strength of monopoly power and intensity of market competition. The theory of competitive advantages mainly embodies competitive advantages of enterprises in market [42]. To materialize

Table 1
Number of projects and water production capacity of seawater desalinated projects in China [15]

Year	Number of projects		Water production (m^3/d)		Annual growth rate
	New	Cumulative	New	Cumulative	
1981–2004	28	28	35,270	35,270	–
2005	8	36	16,047	51,317	0.31
2006	8	44	73,944	125,261	0.59
2007	11	55	89,620	214,881	0.42
2008	4	59	17,840	232,721	0.08
2009	15	74	203,604	436,325	0.47
2010	12	86	150,785	587,110	0.26
2011	7	93	78,255	665,365	0.12
2012	2	95	100,300	765,665	0.13
2013	8	103	125,465	891,130	0.14
2014	11	114	51,075	942,205	0.05
2015	7	121	66,620	1,008,825	0.07
2016	10	131	179,240	1,188,065	0.15

Table 2
Patents owned by domestic enterprises in SDI [40]

Field	Enterprises	Patent type		
		Invention	Utility model	Appearance
Membrane	Origin water	63	7	0
	KeenSen	7	15	2
	Vontron	76	48	0
Equipment manufacturing	Dongfang Electric	747	317	12
	Shanghai Electric	348	117	211
	China Electric Environmental Protection	97	140	0
Key accessories (tube, high-pressure pump, etc.)	Lianyungang Zhongfu Lianzhong composites	83	73	2
	Nanjing New Core Composites	11	10	0
	China nanfang pump	41	62	14

competitive advantages, enterprises obtain monopoly profits through corresponding advantages of resources or market structure [43]. Different economic entities can obtain this advantage by applying for patents to grasp the exclusive right to produce and sell related products [44].

With the possession of different patent ownership, some domestic enterprises are strongly competitive in the fields of desalination engineering, equipment manufacturing and system integration, and key material development (shown in Table 2). As a carrier of technological innovation, patents have gradually supported SD enterprises achieve their self-competitiveness. Leading enterprises started to dominate China's SDI, some of which are shown below.

- Origin water has successfully developed a SD reverse osmosis membrane with high performance through its independent innovation. This broke the monopoly of SD membrane technology by a handful of foreign companies for a long time.
- Dongfang Electric's Zhonghe SD Engineering is the only enterprise in China that has the capability of design, manufacture, installation, commissioning and operation of multiple effect distillation (MED) desalination equipment. In 2011, two large-scale low-temperature multiple effect distillation (LT-MED) independently designed and developed with a capacity of 4,500 m^3/d, was successfully commissioned by the company.
- China Nanfang Pump is the largest manufacturer of stainless steel stamping and welding centrifugal pumps. It has developed a large number of pumps for membrane SD, which has been widely used in various SD projects. It gradually became a leading enterprise.

2.4.2. Rivalry

With the rise of alternative water supplies such as water reclamation and water transfer (for example: South-to-North water diversion, SNWD), water market is becoming increasingly competitive. Since the first phase of SNWD Middle Route project started to transfer water in 2014, the total water supply reached 5.85 billion m^3. The project benefited 18 large and medium-sized cities such as Beijing, Tianjin, Shijiazhuang and Zhengzhou. It provided new water sources and changed water supply pattern in northern China. In addition, water reclamation has received strong government support to address the water stress [45].

For example, the SNWD and reclaimed water resources have become important water sources for Beijing public water supply. In 2017, the SNWD provided 70% of public water supply in Beijing and reclaimed water reached 1.05 billion m^3. In the process of technology development, market competition has two sides: creativity and destructiveness [46]. The competition in water market has promoted SD technology upgrading through creativity. It drove market share from low-tech enterprises to high-tech enterprises through destructiveness and promoted technology upgrading through reallocation effect.

2.4.3. Demand conditions

Tong et al. [1] found that the spatial distribution of water shortage in China is significant using standard hydrological indices (Water stress/scarcity index, WSI, m^3/person/y). As shown in Fig. 3, Chinese water shortage gradually increases from South to North and the provinces with absolutely water scarcity are mainly located in Northern coastal areas. Apart from the lack of water in the land area, there are 489 islands with an area of over 500 m^2 in coastal areas, of which more than 200 islands do not have fresh water storage and supply facilities disclosed by the official reports of China. In addition, some of these islands have suffered from severe over-exploitation of groundwater, resulting in seawater intrusion and serious deterioration of water quality [47]. Though, it can be seen that the shortage of fresh water in China's coastal areas has long existed.

In order to solve the status of water shortage, SD projects has been gradually established in nine coastal provinces. The end-users of SD water in China are mainly divided into two categories: industrial and domestic. The industrial users mainly need SD water for high quality industrial boiler makeup water, food, biological, pharmaceutical and electronics industries, and other high-purity water purpose [15]. The Northern coastal provinces are dominated by large scale industrial desalination projects, mainly in water intensive industries in Tianjin, Hebei and Shandong. The Southern coastal provinces are dominated by desalination projects

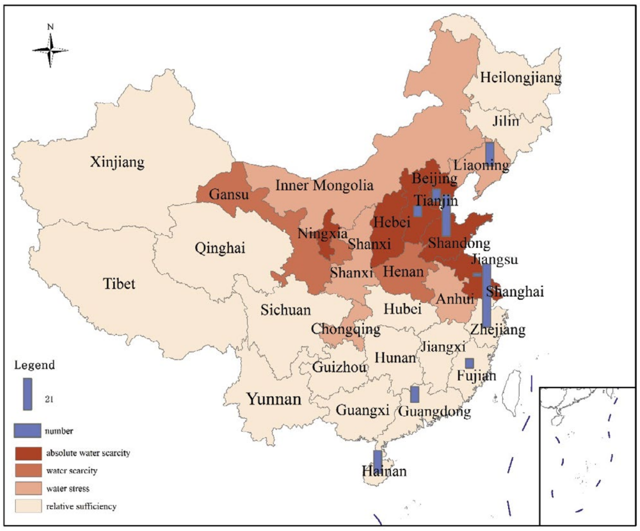

Fig. 3. Distribution of water shortage and seawater desalination plants in China [1].
Note: Water stress/scarcity index evaluation criteria developed by the United Nations is: local water resources defined as relative sufficiency with WSI > 1,700 m^3/person/year; water stress with 1,000 m^3/person/year < WSI ≤ 1,700 m^3/person/year; water scarcity with 500 m^3/person/year < WSI ≤ 1,000 m^3/person/year; absolute water scarcity with WSI ≤ 500 m^3/person/year; and the data of Figure 3 came from literature [1]. Due to the different caliber of statistics, the three regions of Taiwan, Hong Kong and Macau are not counted in the figure.

for public water supply in islands of Zhejiang, Fujian and Hainan (Fig. 3).

However, with the development of industrialization and urbanization, water consumption will continue to grow and the conflict between water supply and demand will become even more prominent. It is estimated that water demand per capita of the four northern provinces (Tianjin, Hebei, Liaoning and Shandong) in northern coastal areas of China will reach 350 to 400 m^3 and the water shortage will reach 27.3~39.3 billion m^3 [12]. Therefore, the demand for SD water will be very large due to the huge water vacancy and the existing foundation of SD projects.

2.4.4. Related and supporting industries

The SDI is to desalinate seawater with a complete industrial chain system including related technology research and development, raw material production, equipment manufacturing, engineering design and construction, production and operation procedures [5]. Starting from the source of seawater, the SDI is divided into “core layer”, “support layer” and “related layer” according to the industrial classification for national economic activities (GB/T4754-2017) of Chinese national standards [48].

In the entire industrial chain of SDI, the upstream is the water treatment equipment manufacturing focusing on SD technology, the middle reach is the engineering operation management and the downstream is applications of SD products (Fig. 4). SDI leads electricity, heat production and supply industry, equipment manufacturing industry, material industry, chemicals manufacturing, wiring and pipeline construction and other industrial technological innovation.

Water treatment equipment manufacturing was an important entry point to the SDI industrial chain in China. With the continuous improvement of reverse osmosis composite membrane technology, nano-filtration membrane technology, electro-dialysis technology, energy recovery technology, energy saving and integration technology, functional adsorption technology, other related materials as well

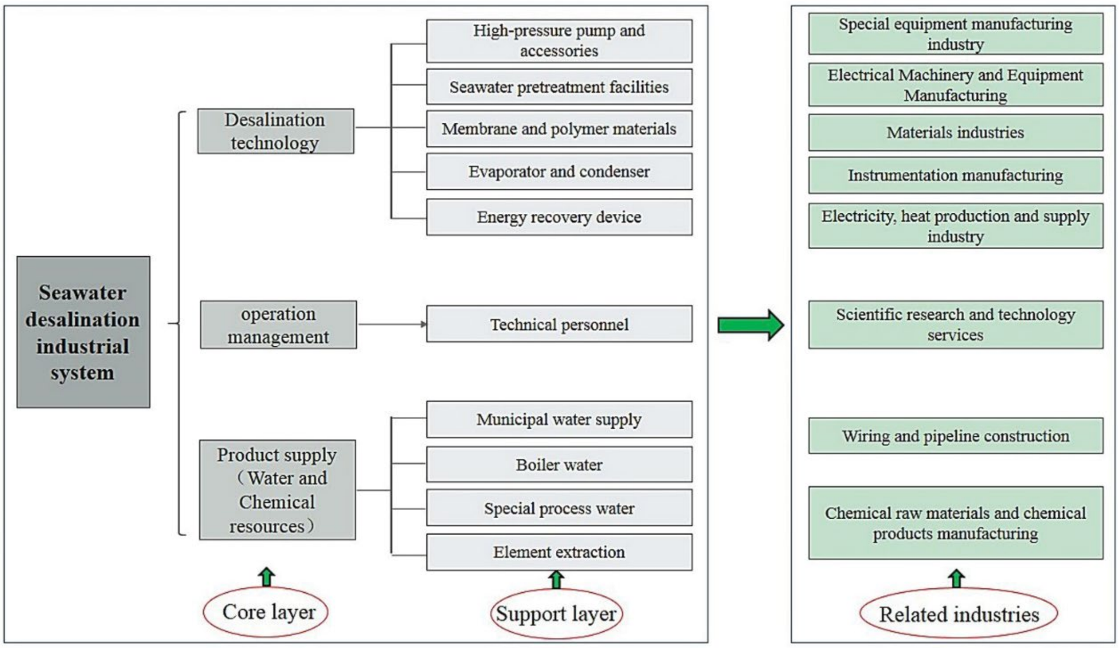

Fig. 4. Constitution of seawater desalination industrial system.

as manufacturing industry, SDI gained increasing support from the industrial chain [45]. After more than 50 years' exploration, manufacturing reverse osmosis and distillation equipment have become the most competitive parts of SDI industry chain in China.

2.4.5. Factor conditions

2.4.5.1. Nature resource

China has four major sea areas, namely the Bohai Sea, the Yellow Sea, the East and South China Seas, with a coastline of more than 18,000 km and rich seawater resources [49].

Intakes and drainages of seawater mainly distributed in the eastern waters of Liaodong Peninsular, the South China Sea coastal area and the Bohai Bay. Most of the seawater intakes are located in industrial and urbanized areas and ports [50].

The physical and chemical properties of seawater in different seas are highly relevant to desalination projects. As shown in Fig. 5, the proportion of China's good seawater quality (Grade I and II) monitoring points showed an ascending trend, rising from 62.7% in 2010 to 73.4% in 2016. The ratio of inferior grade IV seawater quality showed a downward trend, which has been higher than 16% over six years from 2010 to 2015 year, down to 13.2% in 2016. The overall seawater quality in China showed slightly improvement, which means that the competitiveness of SD may increase due to the reduction in the costs of seawater pretreatment.

2.4.5.2. Technologies

The research on SD started in the 1950s in China. The study on electro-dialysis started in 1958 and the research on reverse osmosis and distillation began in 1965. In 1984, the Institute of Seawater Desalination and Multipurpose Utilization, a national scientific research institute, was established in Tianjin, which is specialized in seawater utilization technology and development strategy. The institute made a major breakthrough in key SD technologies. Multi-stage flash (MSF), MED, and RO are the three main technologies for SD. MED, ED, MSF and RO technologies are applied in China's SDI, accounting for 12.2%, 1.5%, 0.8% and 85.3% of desalination plants, respectively (Fig. 6a). Among them, RO and MED account are for 68% and 31% of the national desalination capacity, respectively (Fig. 6b). Chinese research and development of distillation and reverse osmosis is relatively advanced. Thus, China now is one of the countries among the USA, France, Japan and Israel that have the capability to independently research and develop advanced desalination technology.

2.4.5.3. Infrastructure

The application of SD in industry, however, started much later than the research of SD technology in China. For membrane technology, the first 200 m^3/d ED desalination plant was established in 1981 in Yongxing Island of Xisha, Hainan. In 1997, a membrane unit was used to build the first seawater reverse osmosis (SWRO) desalination plant in Shengshan Island in Zhoushan. The desalination capacity of this plant was 500 m^3/d and imported technologies and equipment were used primarily [51]. Origin water, Motimo and Toray Bluestar companies started to manufacture desalination equipment domestically since then.

For distillation, the first study on LT-MED started during the Tenth Five-Year Plan period and a LT-MED demonstration project of 3,000 m^3/d was established in 2004. Since then, desalination equipment has been imported from France and Israel. In 2006, China independently developed 3,000 to 12,500 m^3/d LT-MED device to provide boiler makeup water for a power plant. In 2007, China successfully signed a contract to export domestically manufactured LT-MED desalination equipment for Indonesian power plants. This indicates that China can independently design and manufacture LT-MED devices [52].

In 2009, the first SD plant with a capacity of more than 100,000 m^3/d was completed in Tianjin [53]. The scale of SD projects in China has been gradually increasing. Presently, the largest desalination project is the thermal desalination project of SDIC Tianjin North Boundary Power Plant with a capacity of 200,000 m^3/d. By the end of 2016, 131 desalination plants have been completed in China, mainly in 9 provinces along the coast (Table 3).

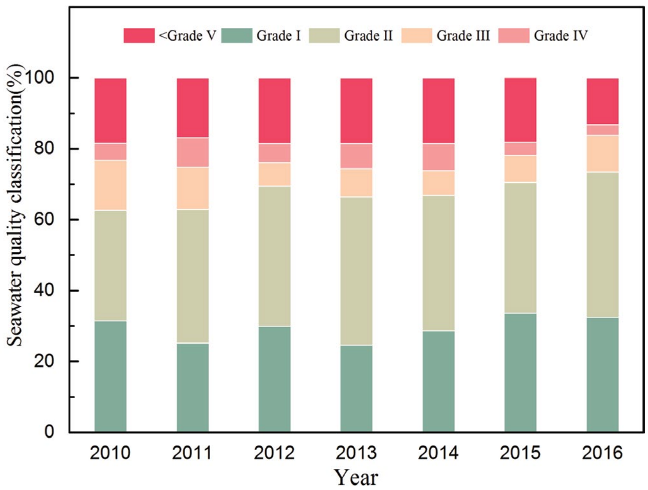

Fig. 5. Coastal seawater quality in china [35].

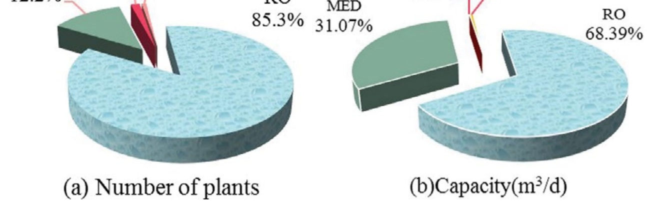

Fig. 6. (a) Number of plants and (b) capacity of seawater desalination plants with various technologies in China [15].
Note: MED – Multiple-effect distillation, ED – Electro-dialysis, MSF – Multi-stage flash and RO – Reverse osmosis.

Table 3
Regional distribution of China's seawater desalinated capacity [15]

Provinces	Number of SD plants	Capacity (m^3/d)	Capacity ratio (%)
Liaoning	15	87,664	7.38
Tianjin	8	317,245	26.70
Hebei	7	173,500	14.60
Shandong	27	282,005	23.74
Jiangsu	2	5,100	0.43
Zhejiang	41	227,795	19.17
Fujian	6	11,031	0.93
Guangdong	10	81,140	6.83
Hainan	15	2,565	0.22

2.4.6. Competitive disadvantages of SDI in China

2.4.6.1. Weak market competitiveness

Although China's SD technology has gradually been advancing, RO technology is still the main technology used in SD projects. After more than 50 years' development, China's membranes are primarily characterized by RO membrane and hollow fiber membrane [54]. There are many factors that affect the investment and operation costs of RO desalination projects, including engineering processes, energy consumption, equipment, and raw water [55]. Membrane was fouling and degradation increase the operation cost, which are the bottlenecks restricting the RO applications [56].

Though the coastal seawater quality was improved recently, seawater pollution is still severe in China, which increases SD cost. As shown in Table 4, the cost of SD is generally higher than that of urban public water supply and other alternative water supplies such as recycled water and SNWD water. Energy consumption accounts for 1/3–1/2 of the total SD cost [57]. Highly influenced by the international energy market and China's energy policy, energy prices are often not controlled by SD plants. Thus, it is tough to reduce cost of energy consumption of SD.

With the development of alternative water supply such as long distance water transfer (for example SNWD) and wastewater reclamation, water stress is no longer a key driver of SD. Compared with desalinated seawater, the cost of municipal water supply is not too high. Simultaneously, the construction of reservoirs, pipeline, diversion projects, and other infrastructures of municipal water are subsidized. For example, the total investment in the construction of a water distribution network in a suburb of Shanghai, China is about 3.2 billion yuan, of which the total amount of subsidies from the municipal financial resources is about 1.07 billion yuan, and the average subsidy ratio is as high as 33% [59]. Therefore, they are not completely accounted for in water price. However, desalinated seawater does not enjoy the "policy dividend", because it has not been included in China's overall water resources planning [60]. Water prices in China do not fully reflect costs of water production and scarcity of water resources. Subsidies to conventional water supplies further weaken the competitiveness of SDI.

Therefore, the cost dilemma of SD in the short term is difficult to solve. Due to the restriction of long-distance transportation of pipeline network, SD is expected to be important supplement of industrial water and the strategic reserve of water resources in coastal cities, to break through the value orientation of the existing water supply market in the future.

2.4.6.2. Disconnection between technology and market

SDI has a complex industrial chain. The key factor that determines whether the industrial chain can develop steadily and continuously is market demand. China's SD is mainly applied to provide industrial water and municipal water, accounting for 66.61% and 33.05% respectively. For industrial water, SD is applied mainly in thermal power generation, chemical, petrochemical, and steel manufacturing industries (shown in Fig. 7). The maximum SD plant capacity for industrial water is about 800,000 m^3/d. For municipal water, use of SD is limited by infrastructure construction, desalination costs, public acceptance and policy.

Though national and provincial policies are "strongly supportive", most policies lack the specific incentives for SD. Due to the weak market demand and the lack of specific incentives, the SD technology and market is disconnected. Many desalination plants cannot sell their produced water due to weak demand [55]. The disconnection between technology development and market demand will eventually limit the future SDI investment [61].

2.4.6.3. Poor resources integration ability

Though synergies and agglomeration between SDI and supporting industries emerging in China, an integrated SD industrial chain has not been established yet [54]. Some key links such as water treatment equipment manufacturing are missing.

Enterprises engaged in SD equipment manufacturing are generally of small scale [62]. Therefore, it is difficult to form

Table 4
Water prices in different cities [36–39,56]

Cities	Municipal water price	Industrial water price	Recycled water price	South-to-North water price	Seawater desalination costs
Beijing	3.64	8.15	<3.50	2.33	
Tianjin	4.00	6.65	<4.00	2.16	5.00–8.00
Qingdao	1.80	2.20	<1.70	2.04	

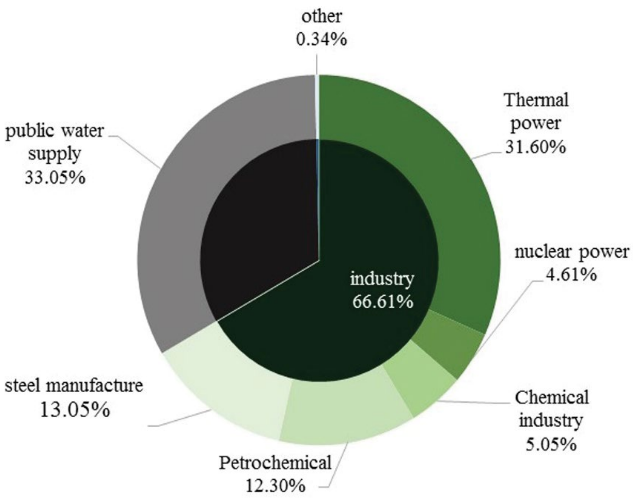

Fig. 7. Project scale of seawater desalination plants with various technologies in China [15].

a strong brand effect. Many SD's equipment still have to be imported and most SD raw materials need to be imported. These have severely restricted the industrialization of SD technology.

For example, Chinese enterprises have successfully developed high-performance SD RO membrane through independent innovation. However, most commercial membrane materials still rely on imports. As shown in Table 5, 100% of ultrafiltration membranes for SD pretreatment rely on the imports. The RO membranes that have been manufactured domestically occupy only 10% of market share. 50–70% of raw membrane materials are imported [63].

Desalination products include desalinated water and extracted chemicals. China has been able to extract sodium, potassium, bromine and magnesium from seawater. However, the technological process of comprehensive utilization of these chemicals is outdated and there is a gap between the quality of domestic and foreign products. It is in urgent need of technology and equipment upgrading [64].

Unlike the internationally desalinated water used mainly for public water supply, China's desalinated water is mainly used for industrial water supply. Water supply management and infrastructure construction in China limited the SD development. The incompleteness of SD industrial chain leads to weak industrial resource integration.

3. Conclusions

To understand why SDI developed slowly, this study employed Porter's diamond model to comprehensively analyze competitive advantages of SDI. Based on the analysis, the following conclusions can be reached.

The competitive advantages include four aspects. (1) Abundant seawater resources, desalination technology, equipment manufacturing capability, and 131 desalination projects provide foundation of SD. (2)The gap between water supply and demand creates a huge demand on SD. (3) A small number of enterprises control the market can form economies of scale and rivalry in the same industry can promote the upgrading of SD technology. (4) Related and supporting industries provide a relatively complete production chain for the independence of SD technology in China. These factors and the support of government policy provide favorable opportunities and initial impetus for the development of SDI.

The competitive disadvantages include the following. (1) Compared with other water sources, the high cost of desalinated seawater results in weak market competitiveness. (2) Weak demand of SD products lead to a disconnection between SD technology and market. (3) Due to the lack of some key links and reliance on foreign equipment and materials, SD forms a weak resources integration capability. These competitive disadvantages may be responsible for the relatively slow development of SDI in China.

The development history of SDI in China in the last several decades showed it is facing tremendous challenges. Competitive SDI not only help mitigate the impact of water stress but also ensure water security. Whether SDI can continue to play a significant role in ensuring China's water security in the future highly depends on how Chinese government responds to the challenge. To promote SDI in the future, the following factors need to be taken into account: (1) advance desalination technology to reduce costs; (2) promote infrastructure construction to increase demand on SDI products; and (3) strengthen SDI industrial chain so that SDI can be supported by upstream and downstream industries.

Table 5
Source of membrane products used in seawater desalination [59]

Product source	UF	RO	Raw materials
Import	100%	90%	50%–70%
Made in China	–	10%	30%–50%

Acknowledgements

This project is supported by the special fund from the State Key Joint Laboratory of Environment Simulation and Pollution Control (Research Center for Eco-environmental Sciences, Chinese Academy of Sciences) (Project No. 18K02KLDWST).

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Appendix

Table A1
Data used in the study classified by the attributes

Attributes	Data	References	Used in text
Firm strategy, structure, and rivalry	Patent owned by domestic enterprises	[41]	Table 2
	Water prices	[37–40,57]	Table 4
Demand conditions	Distribution of water shortage and SD plants	[1,15]	Figure 3
Related and supporting industries	Source of membrane used in seawater desalination	Literature [62]	Table 5
Factor conditions	Related data of seawater desalination project	[15]	Figure 1,6,7 and Table 1
	Regional distribution of seawater desalination capacity		Table 3
	Coastal seawater quality	[36]	Figure 5