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Comprehensive Utilization of Seawater Resources Based on Ocean Energy

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Abstract: This paper presents a tidal current power generation system with desalination and hydrogen production using concentrated seawater electrolysis and proposes a comprehensive utilization method of marine energy and seawater resources. Tidal turbines can provide sufficient power for islands and offshore facilities, whereas seawater desalination plants can assure adequate freshwater supply to the islands. However, concentrated seawater, a by-product of seawater desalination, is usually treated as waste and discharged back to the ocean. Thus, it becomes a source of pollution and causes the wastage of enriched chemical resources, such as hydrogen, chlorine, and sodium. This study investigates the technologies for hydrogen and caustic soda production by concentrated seawater electrolysis using the tidal current power generation system. By this means, marine energy resources can be used efficiently and seawater resource can be adequately recycled, and offshore hydrogen supply stations may be established in the near future.
Keywords: tidal current energy; marine chemical energy; comprehensive utilization of seawater; hydrogen production; caustic soda production

1 Introduction

According to the different forms, ocean energy can be divided into tidal energy, tidal (ocean) current energy, wave energy, salt difference energy, temperature difference energy, etc. The estimated reserves of these ocean energy types are as high as 2.1×10^6 TWh/a [1]. It is far beyond the sum of all kinds of energy (power) used by human beings. In addition, there are other types of ocean energy, such as offshore wind energy, marine biomass energy, and ocean geothermal energy. The ocean energy mentioned above are renewable and clean. Moreover, there is a significant amount of “ocean (water) chemical energy” in seawater. The effective use of this energy and the “recycling” of seawater is a new topic of scientific research, and some technical problems are investigated herein. Specifically, this article focuses on a novel, research-worthy plan for the utilization of ocean energy, seawater desalination, and comprehensive utilization of seawater resources (i.e., seawater desalination using ocean energy). Besides obtaining valuable freshwater resources, the power of the ocean energy can be further used for hydrogen production by electrolysis and alkali production. Alkali manufacturing is the process of using the concentrated by-product (i.e., brine) for obtaining hydrogen, chlorine, soda ash, caustic soda, and other chemicals directly from seawater. The main objective of this study is to propose a new method for the comprehensive utilization of marine energy and seawater resources.

The desalination of seawater is a practical choice, which is potential to solve the shortage of freshwater resources in coastal (offshore) areas and has important social significance and economic value. The industry of

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seawater desalination has significantly evolved. Ocean energy can be used for seawater desalination and supply freshwater to the coastal areas or water-free islands and reefs. As such, the integration and expansion of marine renewable energy and seawater desalination technologies are required. The cost of seawater desalination is expected to be reduced further. The accumulation of sodium chloride in the concentrated brine after desalination is very similar to the concentration of sodium chloride in the electrolytic salt process solution. Domestic and foreign research institutions and enterprises such as the Zhejiang University, Guangzhou Institute of Energy Research, and Chinese Academy of Sciences have conducted long-term and extensive work in the field of ocean energy power generation by scrutinizing tidal and wave energy. Power generation equipment and technology are in their development stage. However, simultaneously using the electricity generated by ocean energy and the concentrated brine produced by seawater desalination to complete the electrochemical production process that usually consumes a large amount of electricity by inland manufacturers is currently conceptual. Neither research nor technology implementation has been accomplished in this area. Consequently, this study focuses on the analysis of the process, its costs, and the production of hydrogen by electrolysis and other chemicals using marine energy for power generation and residual brine (usually abandoned back to the sea). The feasibility and efficiency of this method are evaluated herein for its potential economic and social benefits.

2 Feasibility analysis

China is a country that lacks freshwater resources. Out of more than 660 cities in the country, more than 400 cities lack water, and 108 of which have severe water scarcity [2]. The lack of water resources has become an important factor that restricts social and economic development. The use of seawater desalination technology to obtain freshwater is not affected by time, space, and climate, and provides stable municipal and industrial water supply for coastal areas in a reasonable price. However, with the implementation of large-scale seawater desalination plants with reverse osmosis membrane, the discharge of its by-product (i.e., concentrated seawater) might attract national attention. Concentrated seawater not only has high salt content but it also introduces some chemical substances during the seawater pretreatment process. If not handled properly, it affects the environment and causes pollution [3]. Its impact is especially severe on the ecological conditions of semi-enclosed and enclosed sea areas. Therefore, the Chinese government gives great importance to the comprehensive utilization of seawater. It is clearly stated in the *Opinions on Accelerating the Development of Seawater Desalination Industry* (Guobanfa [2012] No. 13) that “a combination of seawater desalination treatment and comprehensive utilization of resources” should be implemented. When the goal of desalination of 6×10^6–8×10^6 t/d is achieved in 2020, the output value of the concentrated seawater resources will reach more than 37 billion yuan. Moreover, seawater desalination serves as a source of minerals and greatly contributes to the protection of the marine environment. For example, a 1×10^5 t/d seawater desalination device discharges approximately 6×10^4 t of the concentrated seawater daily, and its salt content constitutes approximately 6×10^3 t. If salt is extracted as a by-product, the cost of seawater desalination can be reduced by 20% [4]. The amount of concentrated seawater, which is discharged by the device, reaches approximately 2.19×10^7 t yearly, of which the total amount of chemical resources exceeds 2×10^6 t. In summary, the direct disposal of concentrated seawater into the sea will cause the waste of resources and pollution of the sea. In contrast, the exploitation of desalinated seawater is not only an extension of the comprehensive utilization of seawater resources but also it is technically feasible and creates potential value.

3 Comprehensive utilization scheme of seawater resources based on tidal energy or ocean current energy

The terms “tidal current energy” and “ocean current energy” refer to the kinetic energy of the seawater flowing in the horizontal direction. However, they are formed by different processes. The former is concentrated near coasts and islands and is characterized by high velocity and energy density. The latter is common in the open ocean and is characterized by small velocity and substantial energy total. Tidal current energy and ocean current energy are distinguished by their strong regularity and insignificant impact on the marine environment. Therefore, they are suitable for large-scale development [5]. Comprehensive utilization of seawater resources by tidal current power generation on different coastal areas and islands is of great practical importance and is convenient for local energy extraction by means of the sea.

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3.1 Ways of the utilization of seawater resources based on tidal current energy

3.1.1 Desalination based on tidal power generation

For most islands located far away from the mainland, the lack of freshwater resources is a common problem. Conventional desalination is intrinsically dependent on the availability of electric power, whereas long-distance power transmission on island is often limited. These islands tend to have natural tidal energy or ocean current energy. Therefore, an effective solution to the problem of freshwater on islands is the transformation of the kinetic energy of tidal (ocean) current into the electricity using the power generation equipment. The desalination device can be used later to obtain freshwater.

3.1.2 Treatment of concentrated brine using tidal power generation

As mentioned before, the concentrated seawater obtained by desalination and discharged directly into the sea not only pollutes the surrounding sea area but also causes the wastage of resources. Seawater is rich in sodium chloride, which is an important raw material for the preparation of caustic soda. Hydrogen and chlorine are the by-products of caustic soda preparation and have high economic value. Hydrogen is especially valuable as the energy source for hydrogen fuel cells and hydrogen fuel cell vehicles. The core of the chloralkali industry is electrolysis. It is estimated that during the chloralkali production process, the electric energy consumed by the electrolysis process accounts for 53.2% of the total energy consumption. Many caustic soda plants have introduced their own small-scale power plants, which not only meet the needs of the electricity consumption for the production process but also reduce the production costs [6]. However, most of the self-contained power plants are thermal power plants. They have significant negative impacts on the surrounding environment in the process of power generation. As such, power consumption has gradually become a limiting factor affecting the production of caustic soda. Tidal current power generation and chloralkali industry can be united because it is practical to use concentrated seawater in the chloralkali production. In the near future, the development and utilization of tidal current energy should be combined with power generation, desalination, and chloralkali production within the same site to create a comprehensive utilization system for marine energy.

3.2 Flow analysis of comprehensive utilization of seawater resources based on tidal current energy

Fig. 1 is the flow chart showing the comprehensive utilization of seawater resources. Freshwater, solid alkali products, hydrogen, chlorine, concentrated hydrochloric acid, and other products are obtained by a series of treatment processes for raw seawater intake. During the process, tidal current power generation equipment produces electricity. First, the pretreated seawater is desalinated using the reverse osmosis membrane method, and the concentrated seawater with the NaCl concentration of 6%–8% is obtained [7]. The reverse osmosis membrane method has the advantages of low investment and low energy consumption [8]. Second, the refined concentrated seawater is obtained by electrodialysis of concentrated seawater. In industry, caustic soda, chlorine, and hydrogen are usually prepared by electrolysis of the saturated sodium chloride solution [9]. Therefore, it is necessary to refine the concentrated seawater to increase the content of sodium chloride in the solution. Electrodialysis is a mature technology of seawater concentration [10], and it can improve the accumulation of sodium chloride in the concentrated seawater to meet the requirements of alkali production.

Finally, caustic soda, chlorine, and hydrogen are produced by electrolysis of the saturated sodium chloride solution. During the electrolysis process, the refined concentrated seawater enters the ion-exchange membrane electrolyzer from the anode side. Subsequently, some freshwater left from the desalination process is added to the cathode side. After electrolysis, the diluted brine and chlorine are obtained at the anode side, whereas the electrolyte and hydrogen are produced at the cathode side. The anodic saltwater and chlorine gas are cooled in a titanium cooler and separated into gas and liquid. The hypochlorite in the fresh brine can be removed by the dechlorination process and reused in the concentrated seawater refining process. After the chlorine gas is cooled and dried, it can be liquefied and stored. Additionally, hydrochloric acid can be synthesized with hydrogen generated at the cathode. The chlorine gas can be used for the power supply and hydrolysis process. Hydrogen can be pumped into a high-pressure hydrogen storage tank, where it can be stored after drying. Furthermore, it can be used for hydrochloric acid production process. In addition, the solid caustic soda can be obtained by evaporating the electrolyte at the cathode.

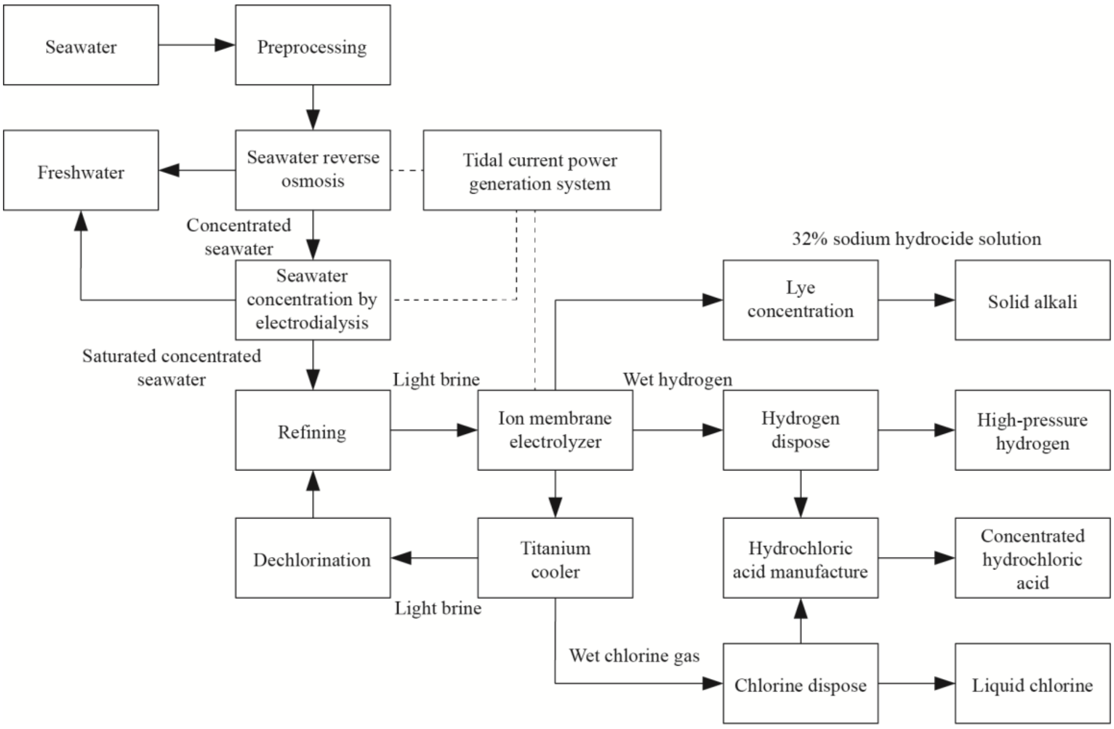

Fig. 1. Flow chart of comprehensive utilization of seawater resources.

3.3 Economic analysis of the operation

This study tests a desalination equipment with a capacity of 2.5×10^3 t/d and an operation time limit of 10 years to evaluate the process costs. The desalination process proposed herein is a widely used reverse osmosis membrane method so that its operating costs are the same as that of the conventional desalination equipment. Equipment operation costs consist of fixed costs and operating costs. The fixed costs of desalination equipment include depreciation, financial, and other expenses. The operating costs mainly include electricity, maintenance, membrane replacement, pharmaceutical, labor, and other costs [11].

There are several similarities between offshore wind power generation system and tidal power generation system in terms of investment, operation, and maintenance. Therefore, this study uses the electricity price of on-grid offshore wind power to estimate the electricity price of on-grid tidal current power. According to [12] and the *Notice of the National Development and Reform Commission on Adjusting the Benchmark Feed-in Price of Photovoltaic Power Generation and Onshore Wind Power* (Specified Price from National Development and Reform Commission from 2016, No. 2729), the benchmark feed-in price of offshore wind power is 0.85 yuan/kW·h. According to the calculation of operating costs in [11], the cost of desalination is 12.4 yuan/t under the designed conditions.

After desalination, the concentrated seawater is concentrated by electrodialysis. The electricity consumption for this process is 170 kW·h/t [13] and is calculated by converting the concentrated seawater into sodium chloride. If the electricity price is 0.85 yuan/kW·h, the electricity cost of the sodium chloride production is 144.5 yuan/t. At present, the price of raw salt in the chloralkali industry is approximately 250 yuan/t, and hence, the cost of raw material can be reduced to some extent by using the concentrated seawater as a stoste for the chloralkali production.

The desalination equipment with a capacity of 2.5×10^3 t/d can produce up to 3×10^3 t of the concentrated seawater daily. As a result, it is necessary to fully use the concentrated seawater, so that the amount of produced caustic soda reaches 5×10^4 t/A. The power consumption per ton of caustic soda produced by ion-exchange membrane electrolysis is 2340 kW·h, steam consumption is 0.9 t, and sodium chloride consumption is 1.6 t. By combining the cost of electricity and sodium chloride, the energy consumption cost per ton of caustic soda is 2310 yuan [14]. The total cost per ton of caustic soda is approximately 2594 yuan based on the time limit of 10 years, whereas the equipment depreciation and operation costs should also be considered.

In this study, a comprehensive utilization method of marine chemical energy based on tidal (ocean) current power generation is proposed. The cost of desalination is 12.4 yuan/t, and the cost of caustic soda production is

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2594 yuan/t. According to [11] and [14], the cost of desalination and caustic soda production is 8.808 and 1281 yuan/t, respectively, under normal operating conditions.

If the costs of conventional desalination and caustic soda production processes are compared with those of the concentrated seawater, the cost gap lies in the price of electricity. It is expected that with the development of technology and industry expansion, the costs of power generation and its economic value using the proposed mode will be significantly diminished.

4 Downstream application of seawater resources

Saturated saltwater can generate hydrogen, chlorine, and caustic soda by electrolysis, which are important chemical raw materials. Caustic soda is the main product of the chloralkali industry and is known as the “mother of the chemical industry.” Chlorine and hydrogen also play a key role in the development of the chloralkali industry.

Caustic soda is widely used in detergent, soap, papermaking, printing, dyeing, textile, medicine, dyestuff, metal products, basic chemical industry, and organic chemical industry. The demand for domestic caustic soda is stable, whereas the downstream consumer market is still dominated by traditional industries, such as alumina, papermaking, printing, dyeing, and chemical fiber [15].

Chlorine is a principal joint product of the chloralkali industry and is widely applied. It is an important disinfectant for tap water and is used as the main raw material for the production of bleaching powder and bleaching agents. Chlorine is extensively used in the electronic industry for VLSI manufacturing. Downstream products of chlorine are also quite abundant. With chlorine as a source, epichlorohydrin can be produced by chlorohydrination, polyether and tetrachloroethylene can be produced downstream, and tetrachloroethylene can be produced as a refrigerant. Chloropropene, epichlorohydrin, phosgene, diphenylmethane diisocyanate (MDI), and polyurethane can be later produced in cooperation with the chemicals from other production lines. Trichloroethylene can be produced for direct selling [16].

Hydrogen is widely used in oil refining and fuel cells. It improves the yield of light oil and oil quality. In 2017, China’s total refining capacity reached 7.7×10^8 t, while the hydrogen consumption was approximately 6.16×10^6–1.078×10^7 t [16]. Fuel cells have great commercial value and potential usage in transportation, energy, military, aerospace, and other industries. Hydrogen fuel cells are predominantly made of fuel cells and can be utilized for hydrogen fuel cell vehicles, distributed generation, emergency power, and other emerging industries [17].

Additionally, hydrogen also has great effect on naval and civilian bases at distant seas. The China Aerospace Science and Technology Corporation (CASC) has recently established the first civil–military integration hydrogen energy engineering technology research and development center in China. According to the marine energy desalination, ice making, gas making, seawater kinetic and chemical energy resource utilization scheme proposed herein, the system combining power generation, desalination, and hydrogen production will be installed on several Chinese islands and reefs, where automation, mobility, unmanned charging, and water- and gas-filling are provided. This not only promotes research and application development of high-tech equipment in the fields of renewable marine energy and hydrogen energy utilization but also safeguards Chinese maritime safety, rights, and interests.

5 Conclusions

The combination of tidal current power generation with desalination and chloralkali production allows for the better utilization of available marine resources. Additionally, it reduces dependence on land-generated energy and permits the establishment of related industries on islands and at sea. Moreover, such tidal current power generation system can utilize various tidal energies; it provides important economic value, and adds a new driving force for the industrialization of tidal power generation.

Freshwater obtained from the desalination process can serve for the chloralkali production, provide domestic water for an island, and be stored at a freshwater supply station to recharge arriving vessels. The utilization of concentrated seawater within the same site not only reduces the environmental pollution caused by the by-products of desalination but also reduces the costs of the chloralkali production and provides economic benefits.

Hydrogen energy is recognized as a kind of clean energy and the most promising secondary energy of the 21st century, and obtaining hydrogen from the ocean is one of the imminent goals of the hydrogen industry. By utilizing the marine chemical energy scheme proposed herein, high-purity hydrogen can be produced which allows for the construction of offshore hydrogen refueling stations.

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References

[1] Ronger H H, Bart'hel F, Cabrera M, et al. Energy resources [M]. New York: United Nations Department of Economic and Social Affairs, World Energy Council, 2000.

[2] State Development and Reform Commission, State Oceanic Administration, Ministry of Finance of the PRC. Special plan for seawater utilization [R]. Beijing: State Development and Reform Commission, State Oceanic Administration, Ministry of Finance of the PRC, 2005. Chinese.

[3] Ahmed H, Muneer H. Impact of desalination plants fluid effluents on the integrity of seawater, with the Arabian Gulf in perspective [J]. Desalination, 2005, 182: 373–393.

[4] Zhao H, DiaoY Q. Preliminary study on the use of nuclear energy seawater desalination [J]. Ocean Science, 2002, 26(7): 18–21. Chinese.

[5] Sun Z F. Development status of marine energy utilization technology at home and abroad [C]. Haikou: Deep Sea Energy Conference, 2015. Chinese.

[6] Liu Q Z. Energy consumption and energy saving technology in electrolytic caustic soda production[J]. Chlor-Alkali Industry, 2002 (8): 1–8. Chinese.

[7] Ma B H, Bai Y H. Analysis of salt production from concentrated seawater after seawater desalination [J]. Journal of Salt and Chemical Industry, 2013, 42(4): 25–26. Chinese.

[8] Wang H T, Li B A, Liu B. Review of the status quo and new technology of seawater desalination technology [J]. Journal of Salt and Chemical Industry, 2014, 43(6): 1–4. Chinese.

[9] Chang X B, Zhong J Y, Wang J F. Efficient utilization technology of ion membrane alkali light brine [J]. Chlor-alkali Industry, 2017, 53(1): 8–11. Chinese.

[10] Liu D Y, Song J. Application and development of concentrated seawater salt by electrodialysis [J]. Salt Science and Chemical Engineering, 2018 (3): 11–13. Chinese.

[11] Gao D S. Comparative study on technical and economical characteristics of seawater desalination methods in northern China [D]. Dalian: Dalian University of Technology (Master's thesis), 2013. Chinese.

[12] Zhang J L, Wang Y Q. Analysis on the development plan of offshore wind power region in China [J]. Wind Energy, 2018 (6): 62–68. Chinese.

[13] Wang C Q, Tian F C, Liu J R. Study on electrodialysis and halogenation process of concentrated seawater [J]. Journal of Salt and Chemical Industry, 2015, 44(11): 39–43. Chinese.

[14] Jiang X J. Financial analysis of the annual production of 500 000 tons of ionic membrane caustic soda in Dongying association [D]. Qingdao: Ocean University of China (Master's thesis), 2009. Chinese.

[15] Deng K, Zhang D M. Analysis of China's chlor-alkali industry development status and future competition characteristics [J]. Chlor-Alkali Industry, 2013 (11): 5–19. Chinese.

[16] Zhao X J, Yuan W. Analysis of chlor-alkali industry technology and product optimization and utilization [J]. Chlor-Alkali Industry, 2018 (9): 7–11. Chinese.

[17] Liu G Z. Fuel cell technology and its application in chlor-alkali industry [J]. Chinese Chlor-Alkali, 2016 (6): 1–5. Chinese.