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Assessing the impacts of nuclear desalination and geoengineering to address China's water shortages

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HIGHLIGHTS

- China will have enough nuclear power by 2030 to eradicate water scarcity.
- Nuclear desalination would be affordable even for the poorest Chinese households.
- It emits hundreds of times less CO2 than the STNWTP and coal desalination.
- Nuclear desalination should be used to supply water to the coastal demand centers.
- Water supply from STNWTP should be limited to remote provinces.

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ABSTRACT

Critical assessment of mega-projects is emerging as a much-needed discipline in an era when, in many places, resource demands exceed environmental capacity. This techno-economic study, using the Desalination Economic Evaluation Program developed by the International Atomic Energy Agency, shows that by 2030, China will have the capacity to produce 23.1 billion m^3 of water annually, at \$0.86/m^3, as a co-product of electricity generation through nuclear power, provided that the country favors desalination over water diversion. We calculate that the resulting water production and supply chain needed to eradicate absolute scarcity for 0.16 billion people will cost between \$0.99/m^3 and \$1.79/m^3, and we prove that this will be affordable, even for the poorest inhabitants. We then compare both coal and nuclear desalination with the currently planned South–North Water Transfer Mega-Project and show that, while the short-run cost of water diversion is lower, critical vulnerabilities and future resource demands favor nuclear desalination.

1. Introduction

In China, several provinces, especially in the North and East, experience moderate to severe water shortages, affecting municipal, industrial, and agriculture needs. The total national shortage in 2030 is forecasted to be nearly 200 billion m^3 with more than 25% for domestic needs [1]. Water-use efficiency, recycling and conservation programs have been implemented to save water, but they have not addressed the shortage issue in its totality.

Cross-region water diversion projects have been undertaken to address lack of water. In particular, the South-to-North Water Transfer Project (STNWP), presented in Fig. 1, aims at diverting about 27 billion m^3 of water from Yangtze River and Danjiangkou reservoir to water-scarce Northern provinces. This project, expected to cost more than \$30 billion for the Eastern and Central routes, and to require 530 MW of energy generation for pumping capacity, will not increase the total quantity of water available to the nation.

Its costs, scale, and impacts warrant a framework to alternative, possibly unconventional, approaches. One such alternative is the use of seawater to address fresh water needs through desalination. Desalination can play a major role for coastal cities, communities where fresh water access costs are high, or where the average electricity consumption to produce one cubic meter of water is higher than 6 kWh (see SI–S2 for calculation details). China already uses desalination through coal-fired plants. However, today, the country has 69 desalination facilities producing, in total, around 400,000 to 500,000 m^3 per day — not even reaching the scale of a single Middle Eastern desalination plant [2]. At the same time, China is massively developing nuclear power. Hot steam from nuclear reactors can be used for desalination. The purpose of this study is to determine if and under what assumptions, in the long term, nuclear desalination can prove itself to be more appropriate to China than water

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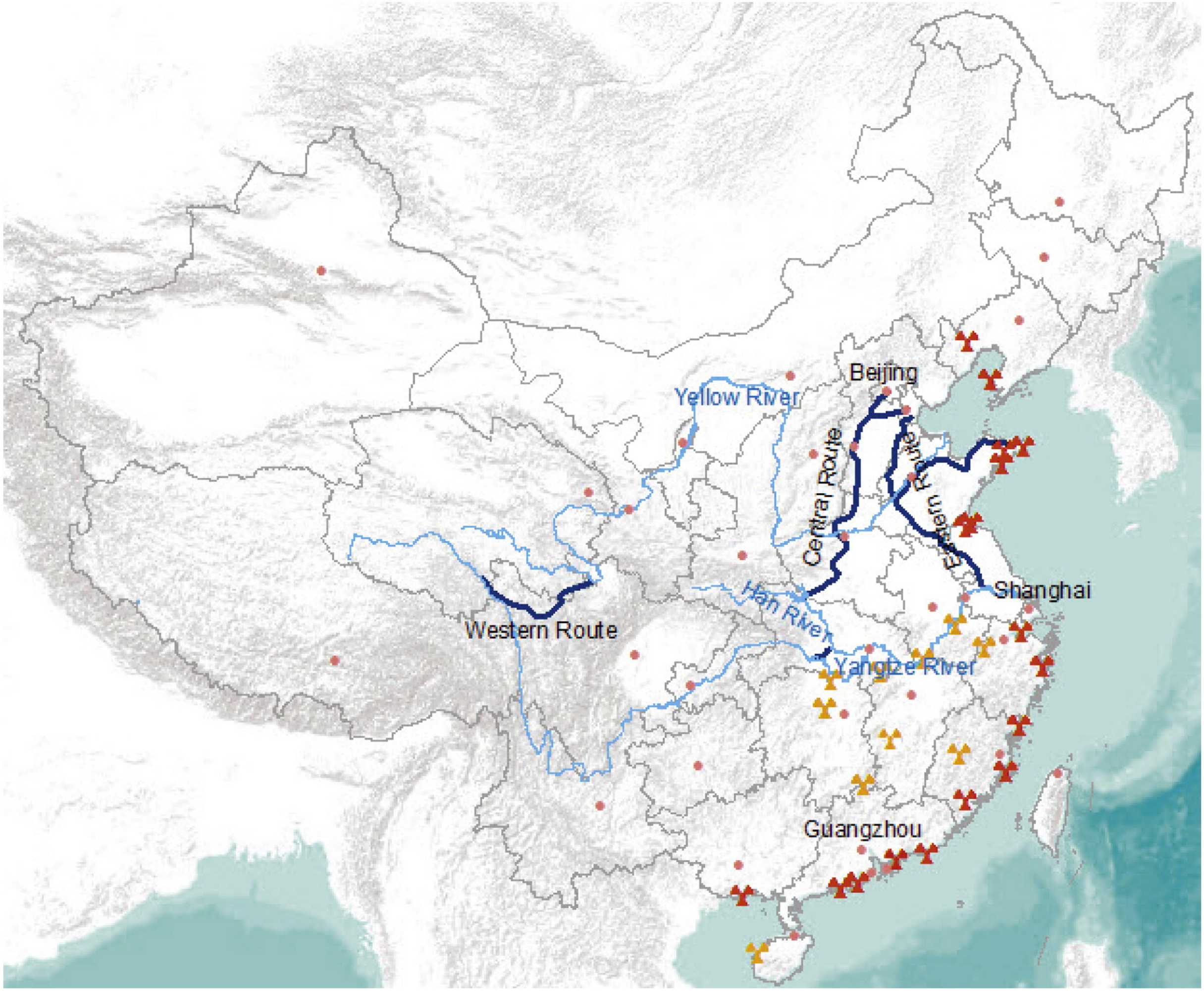

Fig. 1. Chinese nuclear fleet by 2030 [3–5] and Eastern, Central and Western routes of the South-to-North Water Transfer Project [6]. The three routes are drawn in dark blue. Red crosses represent nuclear plants hosting reactors appropriate to nuclear desalination in 2030, while yellow crosses indicate not appropriate nuclear plants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

diversion projects and coal desalination. The choice of a 2030 horizon results from a trade-off between the need of a period of time long enough to expect substantial evolution in the Chinese nuclear fleet, and the uncertainty of long-term planning.

1.1. Past research

The literature addressing water scarcity in China is extensive but not comprehensive; several studies have been conducted on water desalination in China but with no detail on nuclear desalination [7–9], on nuclear desalination but not from a Chinese perspective [10–15], and on novel reactor technologies to perform desalination in China but not on how to develop a desalination industry to address shortage in its totality [16–20]. Zhang et al. [7] and Zhou and Tol [8] described the technical and economic characteristics of different desalination processes and their implementation in China. However, the limiting impact of the Chinese power industry on water production had not been evaluated until now. The present study focuses on one type of desalination's power supply: steam extraction from nuclear reactors. The power output of the 2030 Chinese nuclear fleet is considered, leading to an accurate evaluation of the maximal production capacity of fresh water, the geo-location of future water-scarce provinces and desalination plants, and the affordability of desalinated water for domestic and industrial needs in the 2030 Chinese context. This paper provides a specific framework to assess nuclear desalination impact: the eradication of *absolute scarcity* by 2030, as defined later in this paper. Finally, previous studies mentioned other solutions to water shortage in China that could compete with nuclear desalination, particularly STNWTP, but no research was executed prior to the present study on the development of an interdisciplinary framework to evaluate and quantify nuclear desalination assets and drawbacks compared to other, similar in objectives but not in means, solutions.

1.2. Data sources and methods

In this study, the technical configuration, performance and economic assessments of building a desalination plant and coupling it to a nuclear reactor have been performed with the Desalination Economic Evaluation Program (DEEP) model developed by the International Atomic Energy Agency (IAEA) [21,22]. DEEP's calculation methods and inputs have been modified and adapted to the characteristics of the present study. The project's data come from World Nuclear Association, DEEP, IAEA's Power Reactor Information System (PRIS) and Advanced Reactors Information System (ARIS) for the nuclear and desalination technical and economic sections; from Zhou and Tol [23], Gleick [11], IAEA [24] and DEEP for the water transportation section; from the World Nuclear Association, Nicobar Group, University of South China (USC) and Google Maps for the nuclear facility location section; from China Water Risk [25] regarding China's current and future water situation; and from the Chinese Bureau of South-to-North Water Transfer Planning and Designing for the

STNWTP. Costs and prices are given in 2013 US dollars, and the conversion rate between Chinese RMB and US dollars is 0.16. Formulas and equations used to perform the calculations can be found in the Supporting Information document.

2. Methods

2.1. Selection of the appropriate desalination technology

Desalination technologies differ on the energy consumption intensity, the form of energy required, the flexibility in the choice of plant's location, and the quality of water produced. The existing technologies are divided into two broad categories: membrane separation and thermal process [26]. The three commercial seawater desalination processes as identified by the IAEA, which are proven and reliable for large-scale production of desalted water, are: MSF (Multi-Stage Flashing) and MED (Multi-Effect Distillation) for distillation processes; RO (Reverse Osmosis) for membrane processes [27].

Nuclear desalination is the principle of coupling on-site a nuclear reactor and a desalination plant in order to produce fresh water. The coupling point is the cogeneration steam turbine, used to produce electrical energy and bleeds steam for process heat. The electrical energy required by the desalination plant can also be supplied by the on-site nuclear reactor [28]. Because RO uses electricity from the grid, it does not suit nuclear co-generation's characteristics. MSF and MED can be coupled to a nuclear reactor to perform water desalination through steam extracted from the nuclear facility.

The advantage of MED is its low energy consumption compared to other thermal processes, because the vapor produced in each stage is used to heat up the feed water in the next effect. Compared to MSF, this not only reduces the energy required for distillation but also the overall electric power consumption [26] (see SI–S2). MED is the most suitable process for nuclear desalination, and thus it is the technology considered in this study.

2.2. Assessment of China's technical ability to perform nuclear desalination in 2030

Water desalination is assumed to be powered by reactors of the 2030 nuclear fleet as planned by the Chinese government in 2013 to address future electricity needs [3,4,29,30]. No additional nuclear reactors have been considered for specific desalination purposes in this study. The Chinese nuclear fleet in 2013 consists of 17 reactors in operation on six different sites, for a total electricity net generation of 13.9 GWe. By 2030, the total nuclear net capacity should reach 104.9 GWe with 101 reactors [3,4] (Fig. 2). The 84 additional reactors to be built by 2030 will be spread over 30 sites.

Inland and island nuclear plants, as well as plants whose decommissioning is scheduled before 2045, have not been considered in this study as calculations show that their use for desalination purpose is not economically attractive. According to these criteria, 18 nuclear power plants have been identified as appropriate to nuclear desalination by 2030 (Fig. 1), hosting 66 reactors in total, with a net total capacity of 66.4 GWe: Fuqing, Ningde, Zhangzhou, Ling Ao, Lufeng, Taishan, Yangjiang, Fangchenggang, Lianyungang, Tianwan, Hongyanhe, Xudabao/Xudapu, Haiyang, Hongshiding (Rushan), Shidaowan, Qinshan, Fangjiashan and Sanmen.

This study deals with the assessment of the capacity and construction and operation costs of 66 desalination plants. It is assumed that each desalination plant will be built as close as possible to a nuclear reactor and coupled with it. A desalination plant can be built either during or after the construction of a nuclear plant [31]. All desalination plants are supposed to be built by 2030.

2.3. Nuclear desalination technical and economic characteristics in China in 2030

The main nuclear parameters that influence desalination production capacity are the power capacity and thermal efficiency of nuclear reactors. They depend on the nuclear technology considered. The 66 reactors identified gather ten different nuclear technologies.

To determine the ideal water desalination plant size to be powered by each of the 66 nuclear reactors, the available heat, related to the nuclear technology, is calculated. The theoretical quantity of water that can be produced by the maximum quantity of heat is reduced by a 15% margin, rounded down to meet standard capacities of water plants. This margin is equivalent to the average reserve margin advocated by institutions' standards [32]. The number of reactors and maximum total production related to each nuclear technology is shown in Table 1 (see SI–S2 for calculation details).

A nine percent water desalination plant's forced outage rate is additionally considered, assuming that scheduled outage for maintenance will be performed along with nuclear reactor's scheduled outages. Therefore, the water production capacity allowed by the 66 MED

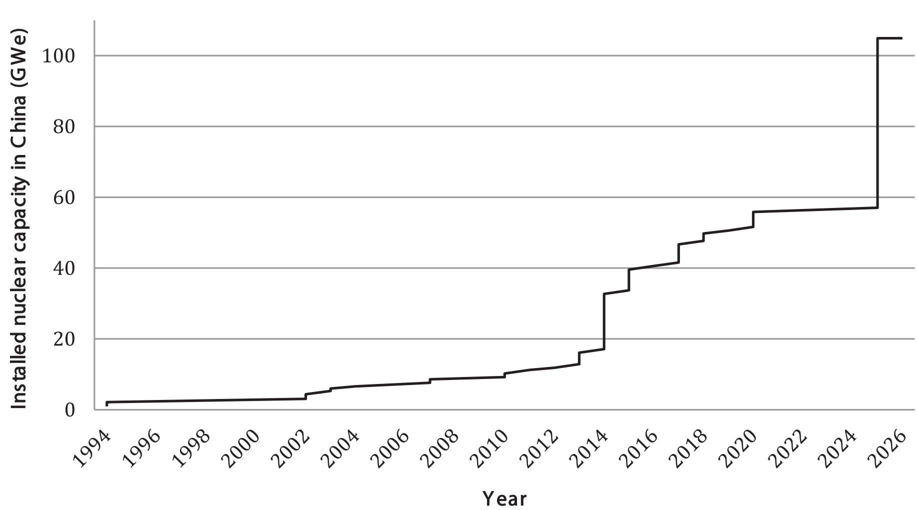

Fig. 2. Nuclear capacity expansion in China by 2030 (Gigawatt-electric). For the nuclear reactors whose starting year is not known yet but is planned to be built before 2030, it is assumed to be 2025. This assumption does not impact the results.

Table 1
Composition, including maximum theoretical production capacity (millions of cubic meters per year), of the fleet of nuclear reactors suitable for desalination purposes by 2030 [30]. See SI–S15 for nomenclature.

Reactor technology	Number of reactors in 2030	Maximum annual water production
		million m^3/y
EPR-1700	4	2233.8
CAP1400	4	2014.8
VVER 1200	2	927.1
AP1000	10	4307.0
ACP1000	2	773.8
VVER V-428	4	1533.0
CPR1000 (+)	30	10,840.5
ACPR1000 (+)	6	2146.2
CNP-600	2	511.0
ACP100	2	80.3
Total capacity	*66*	*25,367.5*

desalination plants, which would be built near the 18 nuclear sites, is 23.1 billion m^3 per year (see SI–S5).

The total investment to build 66 water desalination plants is $80.7 billion dollars. Considering a discount rate of six percent [33], the annual cost is $8.9 billion over the 25 years of the water desalination plants' lifetime. An additional cost, accounting for the reduction in sellable electricity from the nuclear plants due to steam extraction and water desalination plant electricity use, $11.0 billion per year.

The resulting final specific water production cost is $0.86/$m^3$. The calculated cost of producing one cubic meter of water is shared as follows: 32% ($0.28) of fixed charge, 13% ($0.11) of O&M costs, and 55% ($0.47) due to loss of electricity generation because of steam extraction.

To this production cost, water transportation must be added. The cost of transporting water from production plants to demand centers depends on China's quantitative and geographical distribution of water needs. The method used to calculate water transportation costs in this study is described in SI–S8.

3. Results and discussion

3.1. Relevance of nuclear desalination in 2030

3.1.1. Identification of a metrics

The average inflation rate in China over the past ten years equals 3.1% [34]. Logic suggests that water production costs should be compared with forecasted water prices to assess the affordability of nuclear desalination by 2030. However, beyond inflation, water price in China has continuously been rising these last years due to political reforms [35]. In Beijing, the average water price was multiplied 30 times between 1991 and 2004, while the inflation raised prices about two times only. During the year 2005 alone, the price increased by 20% [36]. Nevertheless, government contributions are still too low to fill the gap between the true cost of service and the revenue from users [37], which suggests that additional reforms will be enforced in the near future, making the water price landscape even more confusing. Because of the preponderance of political reforms over market laws to set water prices in China, it is almost impossible to forecast 2030 water tariffs.

Instead, the high uncertainty on future water prices and the Chinese government dominance on this matter, which in this case should be favorable to population because the primary goal will not be water utilities profit, suggest that nuclear desalination be evaluated on the basis of its relative cost and benefits to population. The “five-percent rule” [38] advocates that water purchase must be equal or lower than five percent of households' income to be affordable. Therefore, if water production and supply costs from nuclear desalination show themselves to be lower than five percent of poorest households' income, then political reforms should likely favor nuclear desalination, as primary goal is not profit but affordability. This metrics is more stable than the 2030 water tariffs projection as it does not rely on unpredictable variations of future prices.

In 2030, ten provinces (Beijing, Tianjin, Hebei, Shanghai, Shanxi, Shandong, Henan, Liaoning, Jiangsu, Ningxia) will experience renewable water resources per capita per annum below 500 m^3 [25], which is the threshold for *absolute scarcity* [39,40]. We conducted a study to evaluate the quantity and costs of producing and supplying desalinated water to the ten capital of provinces identified above in order to eradicate absolute scarcity by 2030. The economic viability of nuclear desalination is evaluated using the five-percent rule. The calculation method to assess economic viability of nuclear desalination is detailed in the case of Beijing below, but the same method was used for all cities.

The objective of absolute scarcity eradication in China through an appropriate supply to these ten provinces, represented by their capitals, provides the framework needed to accurately assess the characteristics and impact of nuclear desalination in China by 2030.

3.1.2. Eradicating absolute scarcity by 2030 through nuclear desalination

In 2013, the minimum monthly wage in Beijing in January 2013 is $229 [41], that is $2748 per year. The average annual wage increase in China is considered to be 14.3% according to the trend of the last ten years [42]. Therefore, the five-percent rule will confirm the relevance of nuclear desalination only if the production and supply cost of 500 m^3 of water per person per year in 2030 in Beijing is below $1703.

As of 2013, renewable water resource in Beijing is 145 m^3/capita/annum [25]. Beijing's population in 2013 is 20.7 billion, and in 2030 it will be about 30 million. In a “business-as-usual” scenario, the renewable water resource per capita per annum in 2030 will therefore be 100 m^3 per year. This section of the study aims at evaluating the economic impact of supplying an additional 400 m^3 of water per capita per year in Beijing, using nuclear desalination, in order to reach the 500-m^3 absolute scarcity threshold for households. This represents an additional supply of four times that of a “business-as-usual” scenario.

The costs of water production and supply from Chinese desalination plants to Beijing in 2030 (Fig. 3) depend on the quantity of supply per person per day. Supplying each of the 30 million inhabitants of Beijing with 400 m^3 of water per year from desalination means a quantity of water of 1.1 m^3 per day. According to Fig. 3, the average cost of supplying 1.1 m^3 per person per day to Beijing in 2030 is $1.18/$m^3$.

The cost of producing and supplying 500 m^3 of water per year per capita in Beijing, including 400 m^3 from desalination with an average cost of $1.18/$m^3$, will cost to each Beijing's inhabitant $630 annually. This amount equals about 1.85% of the minimum annual salary in Beijing, which is affordable according to the five-percent rule.

The same cost simulation was performed to eradicate absolute scarcity in the capitals of the nine other water-scarce provinces; results are presented in Table 2. The total additional water supply to eradicate absolute scarcity in these cities, hosting 0.16 billion inhabitants in total, is 134 million m^3 per year, which is less than 0.6% of the total quantity of fresh water that will be available through nuclear desalination by 2030.

Calculations show that eradicating water scarcity through nuclear desalination in these ten capitals at risk will be affordable for every Chinese household by 2030 according to the five-percent rule. The five-percent rule also shows that water tariffs by 2030 in all water-scarce capitals could be increased well above inflation's sole effect without jeopardizing Chinese households' ability to afford water.

In case of pure water needs – for special industries for example – water production cost in 2013 will be around $5/$m^3$ due to treatment. Because MED produces pure water, nuclear desalination costs are already below water market price in China [24].

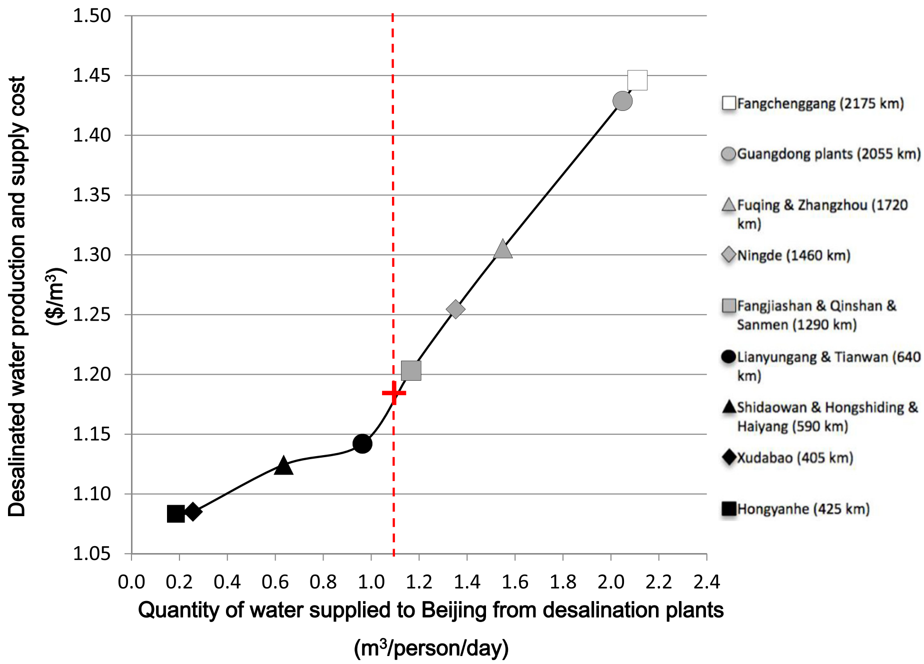

Fig. 3. Desalinated water production and supply average cost (US dollars per cubic meter) in 2030 as a function of quantity of residential water supply per person per day in Beijing. The red cross indicates the point (1.1; 1.49) of the curve corresponding to the eradication of absolute scarcity. Markers represent minimum quantities of water for which the capacity of an additional water plant is required (small quantities are supplied by nearby plants and cost increases when production from additional, further plants are required). The length in brackets indicates the distance in kilometers between the additional desalination plant considered and Beijing [3,5]. See SI–S11 for the technologies of nuclear reactors for each plant, and Table 1 above for maximum annual water production capacity powered by each technology. Calculation of water production and transportation costs is detailed in the Supporting information document. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Comparison between nuclear desalination and two other projects with similar objectives: coal desalination and South-to-North Water Transfer Project

As of 2013, although China Guangdong Nuclear Power has commissioned a small 10,080 m^3/day desalination plant [43], there is no desalination plant coupled with nuclear reactors in operation in China. To address its water shortage, the country has conducted two main initiatives in addition to improving water use efficiency: the South-to-North Water Transfer Project, and water desalination using energy from coal-fired plants. Beijiang's desalination and power plant in Tianjin, with state-of-the-art MED and coal-fired technologies, is the most advanced and largest plant of this kind in China, with a production capacity aiming at reaching 400,000 m^3/day of water [44].

CO_2 emissions and water production specific costs have been evaluated for nuclear desalination, STNWTP, and coal desalination. The hypotheses and data used for this comparison are presented in SI–10. Calculation shows that nuclear and coal desalination will produce water for \$0.86/m^3, and that transportation cost will range from \$0/m^3 to \$0.93/m^3 to supply all water-scarce provinces. Water production and supply will cost \$0.49/m^3 in the case of STNWTP, but this project will not be able to supply the following capitals of water-scarce provinces: Taiyuan (Shanxi), Shenyang (Liaoning) and Yinchuan (Ningxia), accounting in total for 21.6 million people who will experience absolute scarcity

Table 2
2030 water production and supply costs from nuclear desalination to the capitals of the ten water-scarce provinces by 2030; ratio between poorest households' income and water expense on an annual basis.

Capital (Province)	Water production and supply costs from nuclear desalination (\$/m^3)	Ratio between poorest households' water supply cost and income
Beijing	1.18	1.85%
Tianjin	1.18	2.03%
Shijiazhuang (Hebei)	1.15	2.35%
Shanghai	1.10	2.18%
Taiyuan (Shanxi)	1.45	3.13%
Jinan (Shandong)	1.01	2.42%
Zhengzhou (Henan)	1.13	1.97%
Shenyang (Liaoning)	0.99	1.88%
Nanjing (Jiangsu)	1.01	1.93%
Yinchuan (Ningxia)	1.79	3.48%

Green cells indicate cases where the five-percent rule validates the affordability of nuclear desalination supply. Projected water needs come from [25], wage and annual wage increase from [41] and [42], calculation of water production and transportation costs is detailed in the Supporting information document.

in 2030. As a seasonal supply mean, STNWTP's water availability will also be substantially reduced during some periods of the year. The water quality will be high enough in the three cases to be considered as *potable* and therefore meet domestic needs, but STNWTP's water is not pure enough to meet industrial needs. Therefore, in the latter case, a cost to purify water must be added to supply more quality-demanding water needs.

Total CO_2 emissions have been calculated over each alternative's lifetime (25 years for coal and desalination plants, 50 years for STNWTP), and then come down to equivalent emission quantity per year. Powering water production through nuclear desalination will annually emit 25,000 tons of CO_2, whereas the CO2 emissions will add up to 110 million tons per year with coal desalination, and 4 million tons per year for STNWTP. A carbon tax of $8/t-$CO_2$ [45] would annually cost $32 million in the case of STNWTP and $0.9 billion in the case of coal desalination, more than two thousand times the case of nuclear desalination. The social and environmental impacts of nuclear and coal desalination mostly lie in their potential effect on coastal marine's life. STNWTP will have a substantial impact on fluvial life, but the high social consequences of this project reside in the resettlement of 300,000 people [46], and the potential drying-out of South China, which has already endured searing droughts in 2000, 2007 and 2009 [47], which could be accentuated because of water transfer toward Northern provinces.

4. Conclusion — relevance of the development of a nuclear desalination industry in China by 2030

Through the use of an interdisciplinary framework, the viability of nuclear desalination in China by 2030 and its predominance over coal desalination and STNWTP have been confirmed in all cases but far-from-coast Chinese regions such as Ningxia. While coal desalination should not be part of the solution undertaken to solve Chinese water shortages, because it is not consistent with China's commitments toward sustainability, water diversion projects should be used at a smaller scale and in specific cases. Rather than providing water to coastal cities, STNWTP, rooted in river springs in the middle of the country, should be dedicated to supplying remote provinces like Ningxia and Gansu, which are too far from the coast to receive affordable fresh water from desalination plants.

In the longer term, desalination could be performed using high temperature nuclear reactors like the HTR-PM (High Temperature Reactor-Pebble bed Module), whose yield would be higher than conventional reactors thanks to its novel technology. The use of nuclear heating reactors like the Chinese NHR-200 (200-MWt Nuclear Heating Reactor) is a mean to produce free steam, because the electricity-related cost would only result from electricity consumption by the desalination plant and not from the reactor's thermal efficiency decrease. This could reduce by half the water-production specific cost according to the calculations presented in this study. On the other hand, NHR-200 uses a novel technology; therefore the cost induced by building a reactor and its fuel cycle may be higher compared to well-known pressurized water reactor technologies that will still compose most of the Chinese nuclear fleet in 2030. Finally, desalination through solar power, although at its early days, may become predominant by 2030, considering the already favorable context for this energy in China in 2014.

Next steps should involve the creation of an international working group between China and any other states willing to set up a nuclear desalination program, to favor the pooling of technical knowledge and the efficient use of available funds. To achieve this project, the public must be informed and the investors must be convinced. This requires the systematic and publicly-available evaluation of assets and drawbacks presented by nuclear desalination and other types of energy as well as geoengineering projects – including risk assessment and cautious cost evaluation of each option in each country's particular context – as presented in this study. In addition to China, India, the Republic of Korea and Pakistan, which all demonstrate simultaneously a lack of water and the ability to use nuclear energy for desalination [48], could represent a potential long-term market for nuclear desalination providing that such a methodological evaluation is performed in those countries.

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Appendix A. Supplementary data

A complete description of the calculation methods and data used in this study is attached in the SOM. Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2014.12.028.

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