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The challenges in Singapore NEWater development: Co-evolutionary development for innovation and industry evolution

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A B S T R A C T

Co-evolutionary dynamism between innovation and institutional systems by transforming external crises into a springboard for new innovation is crucial for innovation and industry evolution in resource-constrained nations. This has been demonstrated by Japan's success in overcoming the energy crises in the 1970s and subsequent high-technology miracle in the 1980s. Similar to Japan's energy security, securing water is crucial for Singapore as approximately a third of the water supply is imported. This study traces the extensive stepwise endeavors Singapore undertook to address this problem. Initial attempts of learning from imported technology lead to the development of indigenous capabilities followed by export acceleration. This in turn has lead to a phenomenon observed and described as co-evolutionary "acclimatization", which has enabled the nation to successfully substitute 30% of water demand with technology-driven NEWater. This paper demonstrates the challenges faced in developing and disseminating these leading-edge technologies. The final result is "localizing" knowledge and creating local innovation using the knowledge from leading global firms thereby providing mutual benefits to competitors leading to the co-evolution between innovation and institutional systems. This co-evolutionary process provides new insights into innovation and industry emergence, particularly for inducing the economies at the bottom of the pyramid.

1. Introduction

Japan constructed a sophisticated co-evolutionary dynamism between innovation and institutional systems by transforming external crises into a springboard for new innovations [1]. This can largely be attributed to some unique institutional features of the nation including a strong motivation to overcome the fear of xenophobia, uncertainty avoidance, abundant curiosity, assimilation proficiency, and thoroughness in learning and absorption [2,3]. These underlying factors played a role in Japan's successful technology substitution for energy in the 1970s. This technology substitution was critical for Japan's survival given that its energy self-sufficiency rate was only 18% and it was 99% dependent on imported oil [4]. Importantly, this substitution was also enabled by trans-sectorial assimilation, learning and the utilization of core technologies. In addition, it involved long-term planning as well as appropriate and timely government intervention which contributed to the successful growth of Japan's high technology industry in the 1980s [5].

Similarly, the water security issue is one of the most crucial problems for Singapore's sustainability as it is dependent (33%)[1] on imported water. As a consequence of this, strategic options include increasing local catchment,

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[1] Figures as of Dec 2008 from "NEWater: From Sewage to Safe". Last assessed on 30 Oct 2010 http://www.adb.org/Water/Actions/sin/NEWater-Sewage-Safe.asp.

importing water, desalination and recycling water. Singapore has leveraged these options uniquely to develop NEWater (recycled water) by innovation. The production process of NEWater involves a comprehensive system of innovation conferred by a sophisticated combination of innovation in membrane technology and the optimal utilization under extremely subtle operating parameters, enabling technology substitution for conventionally treated water. Singapore's sophisticated level of information technology (IT) developed under the auspices of its unique institutional features, accelerated this substitution. Reduction in the cost of NEWater was critical for success, and this was triggered by the intensive research and development (R&D) efforts of leading firms such as The Dow Chemical Company and Asahi Kasei. The cost was reduced over time as a result of a virtuous cycle of successive R&D, learning effects and economies of scale. Today, NEWater systems (core technologies and operation/management know-how) are being exported globally and inspiring a new technopreneurial model in the 21st Century.

A total of five NEWater factories are in operation in Singapore (Table 1). The Bedok and Kranji NEWater factories were commissioned in 2003. A year later, the Seletar NEWater factory was commissioned. These NEWater factories are owned, operated and maintained by the government. The NEWater factories commissioned after 2004, such as the Ulu Pandan NEWater factory (commissioned in 2007) and the Changi NEWater factory (commissioned in 2010) are owned, operated and maintained by the private sector for a specific duration, typically between twenty and twenty-five years.

NEWater demonstrates leading-edge technologies developed through a comprehensive innovation system. A critical element of this innovation system is internalizing knowledge from leading global firms. As a result of this system of innovation, NEWater can inspire emerging economies in Asia, the Middle East and Africa by exporting the advanced NEWater systems which in turn further accelerates innovation and industry emergence leading to a sophisticated co-evolutionary dynamism that is scalable and transferable.

While this co-evolutionary phenomenon provides new insights to innovation and industry emergence, particularly in inducing the businesses at the bottom of the pyramid (BOP) [6], no previous research has attempted to elucidate, conceptualize and operationalize this unique dynamism in the context of Singapore. In this research, the development trajectory of NEWater in Singapore was analyzed along with the steps described above and technology leapfrogging was postulated [7]. While the dynamism enabling its technology leapfrogging was successfully elucidated, the conceptualization and operationalization of this dynamism is required for broad application.

Table 1
NEWater factories in Singapore.

Name of NEWater factory	Plant capacity (mgd)	Year commissioned
Bedok	18	2003
Kranji	17	2003
Seletar	5	2004
Ulu Pandan	32	2007
Changi	50	2010
Sum of Combined Capacity	122 mgd	

Table 2
Trend in NEWater dependency in Singapore (2003–2011) – %.

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011
NEWater dependency	1.7	3.7	5.3	9.0	16.4	22.2	24.6	27.4	30.4

This paper uses an empirical analysis utilizing diffusion [8–10], learning [11–13,22], and substitution [5,14–16] theories. It then does a cross evaluation and interpretation based on the analyses of the co-evolution [17,18] with institutional systems [5,19–22] and "acclimatization" [23] theories, in order to demonstrate that innovations emerging from research and development in NEWater improves the institutional systems which in turn induces further innovation.

Section 2 demonstrates an empirical analysis of the development trajectory. Section 3 analyses the transformation of imported technology into indigenous technology development. Section 4 elucidates the co-evolutionary acclimatization dynamism based on export acceleration. Section 5 briefly summarizes our new findings, policy implications and future research.

2. NEWater development trajectory[2]

2.1. NEWater dependency

Table 2 demonstrates NEWater (NW) dependency in Singapore over the period 2003–2011. The figures match the target as released by the Ministry of the Environment and Water Resources[3] that NEWater is targeted to meet 30% of the nation's water needs by 2011. Table 3 identifies the diffusion trajectory representing the trend in NEWater dependency toward 2011 using a logistic growth function

$$\pi(t) = \frac{\overline{\pi}}{1 + e^{-at+b}}$$

where $\pi(t)$: NEWater dependency; $\overline{\pi}$: its upper limit; t: time trend; and a, b: coefficients.

Fig. 1 compares the actual and estimated trend in NEWater dependency in Singapore over the period 2003–2011. By incorporating the quarterly trend (t_q) and quarterly total of used water into the estimated function, the quarterly trajectory ($\pi(t_q)$), and the quarterly NEWater production (based on capacity of production) over the period 2003–2009 were estimated.

2.2. Trend in learning

Using the quarterly production figures of NEWater (NW) and the trend in the fixed price of NEWater (p_n), (deflated

[2] Numerical analyses of this section largely depends on [7].

[3] Water for All, Ministry of the Environment and Water Resources website. Last assessed on 11 Feb 2011. http://app.mewr.gov.sg/web/Contents/Contents.aspx?ContId=960.

Table 3
Estimated trajectory for NEWater dependency in Singapore (2003–2011).

Coefficient	Estimated value	t-value	adj. R^2
π	31.0	26.7	0.994
a	0.76	11.0	
b	3.77	13.5	

by Manufacturing Product Price Index for manufactured goods), the dynamic learning coefficient ($\pi(t)$) was estimated using the following equation:

$$P_n = A\sum NW^{-\lambda(t)}$$

where A: coefficient; $\sum NW$: cumulative stock of NEWater production; $\lambda(t)$: dynamic learning coefficient; and t: time trend.

The dynamic learning coefficient $\lambda(t)$ can be depicted by the following equation as a function of time trend t [22]:

$$\lambda(t) = \sum_{t=0}^{n} a_i t^i = \left(a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + \ldots + a_n t^n\right)$$

Taking the logarithm, the following linear function was obtained:

$$\ln P_n = \ln A - \lambda(t)\ln\sum NW$$
$$= \ln A - \left(a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + \ldots + a_n t^n\right)\ln\sum NW$$

By using the backward elimination method, we obtained the following regression result with the highest statistical significance:

$$\ln P_n = 0.47 - \left(0.05 + 1.40\times10^{-5}t^3 - 4.85\times10^{7}t^4\right)\; adjR^2\; 0.938\; DW\; 1.27\; (3.61) - \frac{(3.04)}{(6.10)}(6.26)$$

The trend in the learning coefficient over the period 2003–2009 is illustrated in Fig. 2. Learning is measured from 2003, the year the first NEWater factory was commissioned. Learning took place as suggested by the increasing trend of the learning coefficient graph. The evidence of this learning is reflected by the commissioning of three NEWater factories – Kranji, Seletar and Ulu Pandan. These projects created many opportunities for the local firms to work alongside established players and in the process to pick up the know-how of the trade. Learning of the know-how with regards to NEWater factory construction, design, operation and maintenance reached its peak after the construction of the Ulu Pandan NEWater factory in 2007. Then, Ulu Pandan NEWater factory was the biggest NEWater factory in Singapore, with a plant capacity of 32 mgd. After the construction of the Ulu Pandan NEWater factory, know-how with regards to construction, operation and management of small and large NEWater factories had been acquired. It was timely to move forward from a period of learning dependence (prior to 2008Q2) to a period of indigenous capabilities development (after 2008Q3).

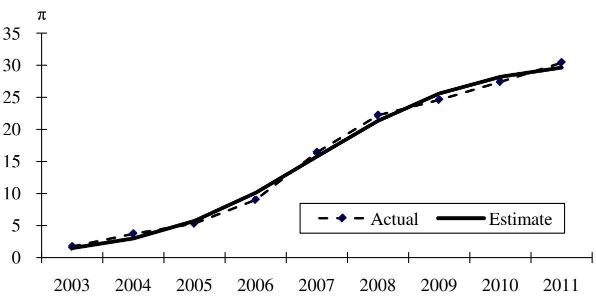

Fig. 1. Trend in NEWater dependency in Singapore (2003–2011): actual and estimated (%).

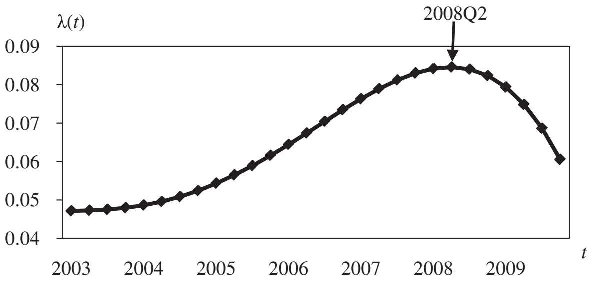

Fig. 2. Trend in learning coefficient (2003–2009).

2.3. Elasticity of NEWater substitution

The elasticity of NEWater (NW) substitution for conventional water (CW) was computed using the following equation:

$$\ln\frac{NW}{CW} = a + \sigma\ln\frac{P_c}{P_n}$$

where a: coefficient; σ: elasticity of NW substitution for CW; P_c: fixed price of CW; and P_n: fixed price of NW. Consumer Price Index and Manufacturing Product Price Index for manufactured goods were used as deflator of CW price and NW price, respectively.

Fig. 3 illustrates the trend in the NW and CW ratio over the period 2003–2009. The ratio reflects a steady increase reaching the target of satisfying 30% of the nation's water supply by 2011 (the 30% target corresponds to the NW/CW ratio of 43%).

The result of the analysis is summarized as follows and demonstrates a high statistical significance for the elasticity of substitution of NW for CW over the period examined.

$$\ln\frac{NW}{CW} = -4.96 + (7.64 - 1.48D_1 + 1.54D_2)\ \ln\frac{P_c}{P_n}$$

where D_1 and D_2: dummy variables (D_1: 07Q2-08Q2 = 1, others = 0; D_2: 08Q3-09Q4 = 1, others = 0).

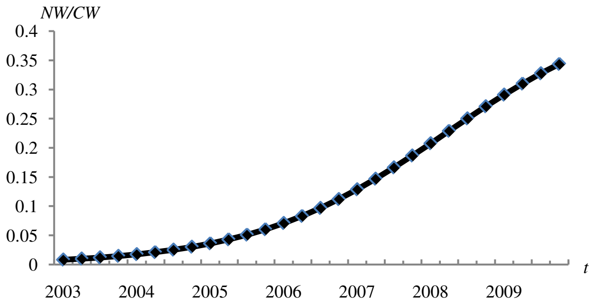

Fig. 3. Trend in the *NW* and *CW* ratio over the period 2003–2009.

The elasticity of *NW* substitution for *CW* for 2003 Q1 – 2007 Q1, 2007 Q2 – 2008 Q2 and 2008 Q3 – 2009 Q4 are 7.64, 6.16 and 9.18, respectively.

Fig. 4 demonstrates that this substitution can be attributed to the increase in relative prices (P_c/P_n) due to the *NW* price decrease through learning effects from imported technology up until the first quarter of 2007. While P_c/P_n changed to a decreasing trend as NEWater development shifted from an imported technology period to an indigenous technology period from the second quarter of 2007 due to relative increase in *NW* price, the *NW*/*CW* ratio continued to increase. A similar trend shows acceleration after the third quarter of 2008 due to the relative increase in *NW* price through higher functionality and a decrease in learning effects as NEWater development shifted to an export accelerating period based on indigenous technology development.

These sustainable substitutions demonstrate the substantial change from learning to indigenous technology development. It also shows further functionality development for export acceleration as a driver of *NW* substitution for *CW*. The level of elasticity of *NW* substitution for *CW* slightly decreased during the transition period from imported technology dependence to indigenous technology development. However, it also increased when there was an attempt at higher functionality for export acceleration.

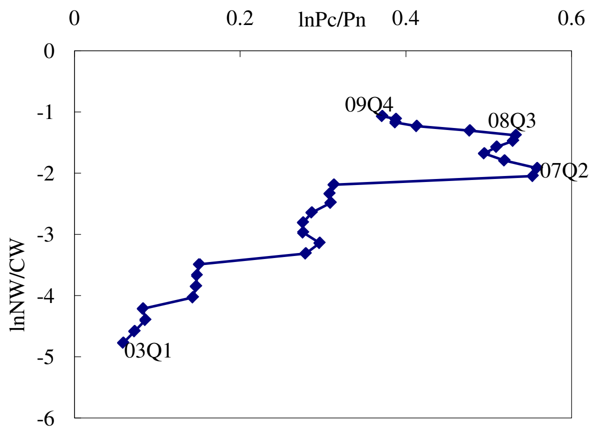

Fig. 4. Trend in the correlation between prices and volume of NEWater (NW) and Conventional Water (CW). (2003–2009).

3. Transformation from learning to indigenous technology

The foregoing analysis and data suggest four phrases in the ten-year transformation process. *Phase 1* was the gestation phase which began around 2000 and ended around quarter one of 2007. This phase was identified as the *imported technology dependent period*. *Phase 2* is the *transformation from learning to indigenous technology development period* which lasted for about a year. It started around the second quarter of 2007 and ended around the second quarter of 2008. Following the second phase was the *export accelerating period* which began around quarter three of 2008 and ended around 2010. The final phase began around 2010 and is known as the *co-evolutionary acclimatization period*.

3.1. Learning and absorption from imported technology

The first phase was triggered by the establishment up of the Bedok demonstration plant in 2000. Coupled with subsequent extensive learning, three advanced NEWater plants were commissioned: Bedok (2003), Kranji (2003) and Seletar (2004). The main components, such as the advanced membranes and ultraviolet disinfection units, were imported from established manufacturers. For example, Nitto Denko, a leading global manufacturer of membranes for water and wastewater treatment was the trusted supplier for reverse osmosis membranes (Table 4). Other established Japanese firms contributing their advance technology in reverse osmosis membranes include Asahi Kasei and Toray. Table 5 shows the country of origin of possible main suppliers of the main component and services for a NEWater factory. According to the author's sources, the Public Utilities Board (PUB) is constantly sourcing for reliable manufacturers to increase the pool of suppliers. By doing so, opportunities are indirectly created for local companies to learn from the manufacturers. In any NEWater project, the plant integrator has to interact and work closely with the component suppliers in order to design an efficient system. The technologies related to microfiltration and ultrafiltration processes are imported mainly from established industry players in Japan (Asahi Kasei), Europe (Siemens) and the United States (General Electric). The technologies used for the ultraviolet

Table 4
Advanced membranes introduced by leading Japanese firms[a] in Singapore NEWater factories.

NEWater Factory	Microfiltration /Ultrafiltration	Reverse Osmosis
Bedok (Demonstration Plant)		Nitto Denko (10)
Bedok	Asahi Kasei Chemicals Corporation (73)	Nitto Denko (32)
Seletar		Toray (24)
Kranji		Nitto Denko (40)
Ulu Pandan	Asahi Kasei Chemicals Corporation (191)	Nitto Denko (156)
Changi		Toray

Figures in parenthesis indicate capacity (thousand m^3/day).
[a] Japan's membranes occupy 50% of the world market.

Table 5
Country of origin for suppliers of products and services for Singapore NEWater factories.

Product/Service	Korea	Japan	US	Europe	Canada	France	Netherlands
Microfiltration /Ultrafiltration		*	*	*			
Reverse osmosis	*	*					
Ultraviolet disinfection			*	*	*		
Engineering -related services			*			*	*

disinfection process are imported mainly from established players in the United States (ITT Water and Wastewater), the United Kingdom (Hanovia Limited) and Canada (Trojan Technologies). Engineering-related capabilities and consultancy services are provided primarily by French-based companies (Suez and Veolia Environment), US-based companies (Black & Veatch and CH2MHill) and Netherlands-based company (Deltares).

During this period, there was intensive learning by local firms as illustrated in the upward trend in Fig. 4. One government initiative that facilitated this learning process was the setting up of the Environment & Water Industry Development Council (EWI) by the Ministry of the Environment and Water Resources (MEWR) in May 2006. This Council was tasked with spearheading the development of the environment and water industry in Singapore with the vision to develop Singapore into a 'Global Hydrohub' – a nation at the forefront of research and development; a nation with the capabilities in research and development, training, leadership, policy and implementation; a nation where experts all around the world can come together to interact and exchange knowledge in this area of water technologies. In order to become this hub, the Council adopted a three-pronged strategy – Capability Development, Cluster Development and Internationalization.

With innovation as the key driver of its strategies, the Capability Development Strategy of the EWI involved the establishment of a strong technology base through research and development (R&D). Consequently, through R&D, new technologies at the forefront of research must be developed. To accomplish this aim, human capital (expertise) is essential and therefore there is a need to build up research talent for the industry. PhD scholarships were put in place to groom experts in Environment and Water Technologies. These scholarships were funded by the National Research Foundation and administered through the EWI. To address the relevance of research to business at a national level, the Environment & Water Research Program was launched in 2006. The Program identified the areas of research and technological development needed to position Singapore as a global leader in water technologies and funds both basic and applied R&D projects with innovative and novel ideas that possess the potential for commercialization. Projects were funded through two schemes – the Innovation Development Scheme and the Incentive for Research & Innovation Scheme. The aim was to encourage public and private organizations to engage in innovative and collaborative projects, thus creating opportunities for local firms to learn the 'new'/'imported' technology, contributing to the upward learning trend in Fig. 2. Another initiative was aimed at attracting world-class industry players and international research institutes and agencies to set up and anchor their R&D centers in Singapore. In doing so, the foreign companies brought with them capabilities in the relevant areas that were imparted to the locals. Successful examples include the American Water Works Association (AWWA), Kiwa Water Research and Delft Hydraulics. Yet another initiative to create opportunities for learning was to encourage companies to base their test-bedding projects in Singapore. One successful example was the test-bedding of membrane distillation technology (Memstill) for seawater desalination at Senoko Refuse Incineration Plant. The technology was originally developed by a consortium in the Netherlands. Following successful trials in the Netherlands, the technology was brought to Singapore for test-bedding. This opened opportunities for locals working on the project to learn about the technology. Under the call to strengthen international R&D linkages, the local tertiary research institutions reached out to world-class players and have been successful in setting up joint centers of excellence based in Singapore. The Nanyang Technological University, for example, partnered with consultancy and research firm, DHI to form the DHI-NTU Water and Environment Research Centre and Education Hub. The National University of Singapore partnered with Dutch water specialist, Delft Hydraulic to form the Singapore-Delft Water Alliance to advance science and technology in the water sector. These centers of excellence house local and foreign expertise and create opportunities for locals to learn from their counterparts.

3.2. *Transformation to indigenous technology development*

Since the aim is to promote Singapore as a global hydrohub with capabilities to address water issues holistically, the Institute of Water Policy (IWP) was set up in June 2008. Located at the Lee Kuan Yew School of Public Policy of the National University of Singapore, the IWP serves as a platform to build up and train the next generation of Asian policy-makers and leaders. Over the years, the IWP has built up a team of experts, comprised of locals and foreign nationals to study various topics related to water. The areas of focus include water resources and sustainable development, water governance, urban water management and statistics and economics of water. The projects undertaken were water-related with a focus on Asian countries, such as India and China. The projects undertaken involved participants from other countries. This created opportunities for learning about the water industry in other countries and for testing the application of theories developed in countries at various stages of economic development.

In facilitating the transformation from the learning phase into the indigenous technology development phase, the EWI's Cluster Development strategy was to attract major international companies to anchor their operations (headquarters, engineering facilities or research and development centers) in Singapore. Working closely with the Economic Development Board of Singapore and the Public Utilities Board, the EWI was successfully attracted General Electric from the United States, Nitto Denko from Japan, Siemens from Germany and Veolia from France. When these companies anchored their operations in Singapore, they deployed experts from their home country and employed locals. This created opportunities for locals to learn from the experts. By 2010, the EWI witnessed the success of its Cluster Development Strategy. The WaterHub, a center of excellence, was constructed adjacent to the Ulu Pandan NEWater factory with the vision of being the leading hub for the global water industry. It is home to water associations such as the International Water Association and the Singapore Water Association (SWA), corporate research institutes such as Siemens and Konzen and the Centre for Advanced Water Technology. At the regional level, it aims to be the regional water knowledge hub for the water industry. Nitto Denko set up its R&D centre in the WaterHub in June 2008. The above efforts show the government's commitment to encouraging foreign investment in hydro-R&D by providing non-discriminative facilities.

Implemented simultaneously with the Capability Development Strategy and the Cluster Development Strategy was the Internationalization Strategy of the EWI, which aimed to help Singapore-based water companies 'internationalize' their businesses. Creating networking opportunities through trade missions and conferences and the signing of bilateral agreements on water research and consultancy projects proved to be effective methods. To date, bilateral agreements have been signed with the United Arab Emirates, Bahrain and India. Trade missions to the Middle East and China have been organized and local companies that have been invited to be part of the delegation led personally by the Minister for the Environment and Water Resource include Keppel Corporation, Hyflux Limited, Sembcorp Utilities and Salcon. In addition to trade missions, the annual Singapore International Water Week (SIWW) is an international conference that enhances Singapore's attractiveness at the global level. The SIWW is strategically held annually concurrently with the World Cities Summit as water management is often one of the integral issues faced by cities around the world regardless of the size and geographical location of the city. Both events aim to find sustainable solutions to common problems. Both conferences are well attended by ministers, policy makers, scientists and businessmen. This creates multi-disciplinary learning opportunities.

The process above describes learning and assimilation of spillover technology, which is dependent on learning that is shifted to indigenous development. This process is demonstrated in Ulu Pandan and Changi NEWater factories, which were commissioned in 2007 and 2010 respectively. Facilitating the transition was the introduction of the Public-Private-Partnerships (PPP) initiative to spur greater collaboration between the public and private sectors, in particular, the Design-Build-Own-Operate (DBOO) scheme. The Bedok and Kranji NEWater factories were built under the Design-Bid-Build (DBB) scheme, while the Seletar NEWater factory was build under the Design & Build scheme (Fig. 6). These three NEWater factories are owned, operated and maintained by PUB. With the experience gained from these three factories, PUB has established the viability of the reclamation of used water. By adopting the DBOO scheme for future water projects, it aims for greater private sector involvement, enhanced efficiency and keeping costs affordable. The fourth and fifth NEWater factories, Ulu Pandan and Changi respectively, were built under the DBOO scheme. Under the DBOO scheme, the concession company (private sector) is responsible for the design, construction and operations of the factory, typically for a period of 20–25 years. For Ulu Pandan NEWater factory, the concession company was Keppel Integrated Engineering. The DBOO contract was secured in 2004 to design, build, own and operate the plant of capacity 32 mgd, between 2007 and 2027. Sembcorp Utilities Pte Ltd won the 25-year DBOO contract (between 2010 and 2035) for the Changi NEWater factory of plant capacity 50 mgd.

The various procurement models mentioned in the above are illustrated in Fig. 5 through Fig. 7. A comparison of the models reveal that the DBOO model (Fig. 7) opens

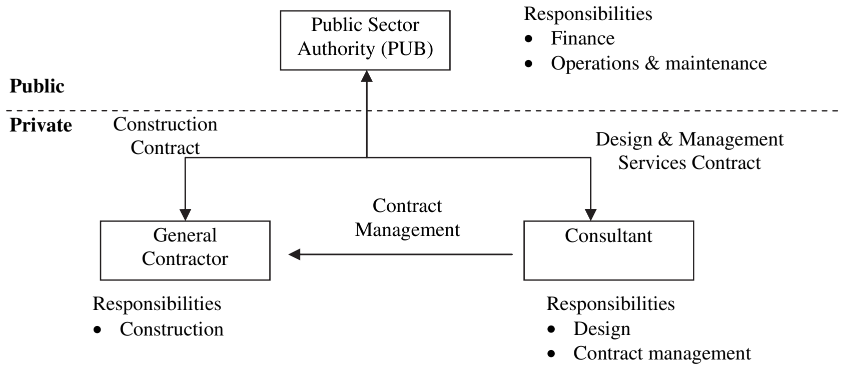

Fig. 5. The Design-Bid-Build model.

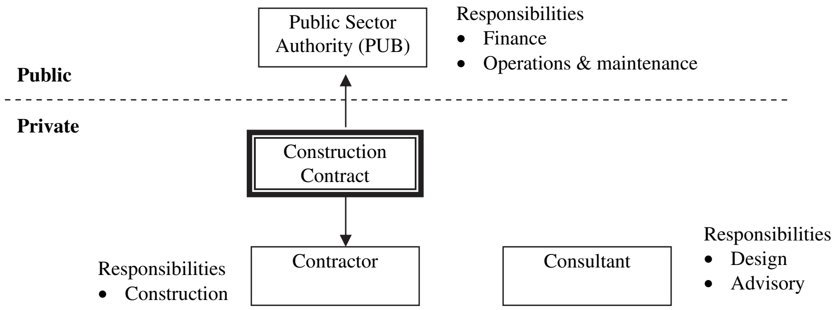

Fig. 6. The Design & Build model.

up opportunities as compared to DBB and D&B models, in the sense that local firms can participate in the projects as the EPC (Engineering, Procurement & Construction) contractor or O&M (Operations & Maintenance) contractor or working through the contractors as component suppliers or service providers. Core components that are required for such projects include membranes, pumps, pipes, valves, pressure vessels, chemicals, and contaminant detection equipment. Examples of services required include, and are not limited to, engineering, architectural, IT/computer monitoring, financial and project management services.

Because the technical specifications for DBOO projects are performance-based, it encourages the concession company (usually the private sector) to produce innovative and cost-effective solutions. The DBOO model created the opportunity for local firms such as Hyflux Limited, Salcon Pte Ltd, Keppel Integrated Engineering and Sembcorp Utilities Pte Ltd to bid for major projects that in turn created opportunities for them to develop indigenous capabilities from the spillover effects of the previous phase.

4. Export acceleration leading to co-evolutionary acclimatization

4.1. Export acceleration attracting global leading talents

Following the development of indigenous capabilities and the success of DBOO projects, firms began to internationalize their businesses, indirectly exporting their indigenous capabilities accumulated throughout the first two phases. This trend is supported by the figures reported from the annual SIWW. During the 2008 inaugural SIWW, S$367 million worth of deals was signed. During the 2009 SIWW, S$2.2 billion worth of deals was signed. During the 2010 SIWW, the figure was reported to exceed S$2.8 billion.[4]

The following is a detailed account of the export phase of three local companies – Keppel Integrated Engineering, Sembcorp Industries and Hyflux Limited.

[4] Singapore International Water Week Media Release, “Third Edition of Singapore International Water Week Hits New Highs”.

4.1.1. Keppel Integrated Engineering (KIE)

KIE is the main contractor for Ulu Pandan NEWater factory. KIE’s export acceleration phase is attributed to the NEWater and Waste-to-Energy projects secured from the Singapore Government in 2004 and 2005 respectively, which in term is supported by the the acquisition of Keppel Seghers Technology (formerly Seghers Better Technology) in 2002. The acquisition is important as it serves to establish the technology foundation for the group on which the KIE’s core competence in delivering environmental solutions is built on.[5] KIE currently has a strong portfolio of proprietary technologies. Even before the Ulu Pandan NEWater factory was commissioned in 2007, KIE was already exporting its indigenous capabilities overseas to Finland, Argentina and China. After the delivery of the Ulu Pandan NEWaster factory, KIE expanded its global presence and exported its indigenous capabilities to Alergia, Qatar, Sweden and the United Kingdom (Table 6). With the large numbers of overseas projects secured, the company was also prudent in maintaining its strong portfolio of proprietary technologies, so that it can continue to export innovative and sustainable environmental solutions. The Keppel Technology Advisory Panel established the Keppel Environmental Technology Centre in 2007 as a center of excellence to spearhead innovation in leading-edge environmental technology R&D, augment existing R&D initiatives and build strategic alliances with leading academic and industry partners. Since then, the KETC has worked closely with research partners and research institutes like the Singapore Institute of Manufacturing Technology and the Institute of High Performance Computing (both from the Agency for Science, Technology and Research), to harness external resources in complementing its own research base.

4.1.2. Sembcorp industries

Sembcorp Industries is the parent company of Sembcorp Utilities. Sembcorp Utilities was the local concession company that won the contract for the Changi NEWater factory. The successful delivery of the DBOO contract for Changi NEWater plant won the company the recognition as Singapore’s largest water management company. With a record of being a global leader in the provision of energy,

[5] Keppel Corporation Annual Report 2008.

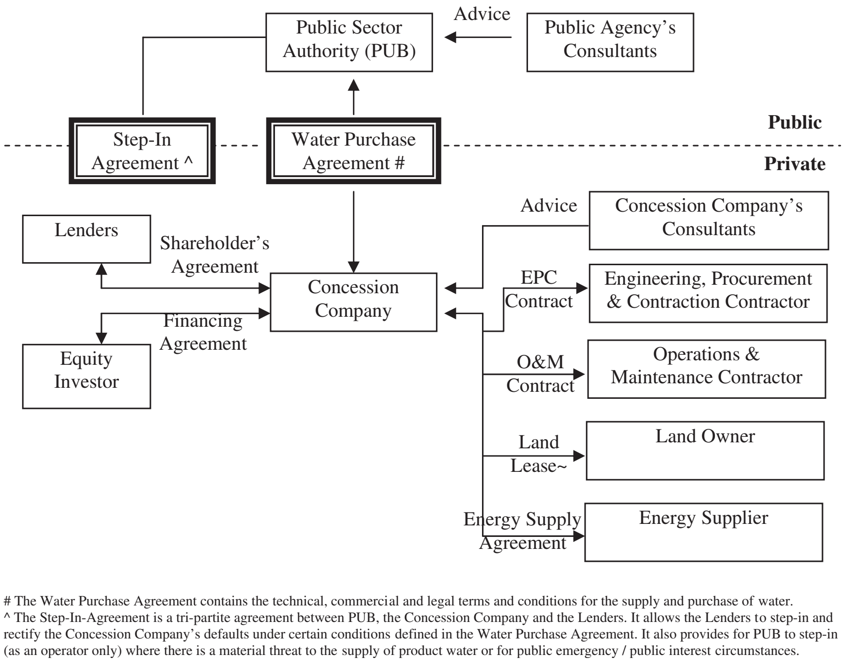

Fig. 7. The Design-Build-Own-Operate model.

water and on-site logistics and services, Sembcorp Utilities expanded the export of its indigenous capabilities from the United Kingdom, China and the United Arab Emirates to Indonesia, Philippines, South Africa, Chile, Panama, and The Caribbean (Table 7). The nature of the projects reflect the confidence of the customers in Sembcorp Utilities to deliver energy-efficient facilities capable of providing energy and water. The US$1 billion Salalah Independent Water and Power Plant in Salalah, Oman is one such example. The plant has a 490 MW[6] power capacity and 15MiGD[7] desalinated water capacity. This contract is significant to Sembcorp Utilities because it was the company's first project in the country.[8]

4.1.3. *Hyflux Limited*

Hyflux Limited was the main provider of microfiltration membranes for the Seletar NEWater factory. Its subsidiary, SingSpring (Pte) Ltd was the concession company for Singapore's first desalination plant, the Tuas Desalination Plant. The Tuas Desalination Plant was a DBOO project awarded under the PPP initiative. After building and developing indigenous capabilities as a microfiltration membrane manufacturer and as a main contractor and systems integrator for large-scale water treatment plants, the company accelerated the export of its indigenous capabilities to countries such as Algeria, Dubai and China (Table 8 and Table 9). Hyflux was chosen by Algeria Energy Company to design, build and run a seawater desalination plant in western Algeria. The contract was reported to worth US$468 million.[9] Hyflux is currently building the Tianjin Dagang Desalination Plant, China's largest membrane-based seawater desalination plant with a designed capacity of 100,000 m^3/day. Another successful "internationalization" deal for Hyflux was the S$95 million design and construction contract for a membrane-based seawater desalination facility for the Salalah Independent Water and Power Project in Oman.

4.2. *Co-evolutionary acclimatization*

The fusion of external knowledge acquired from export activities through joint export with countries possessing advanced technologies, institutional learning by the receiving party and the existing knowledge pool are expected to disseminate to various industries. This is the phenomenon known as co-evolutionary acclimatization. Indigenous Gross National Income (GNI) figures for Singapore[10] grew by S$71,865 million from S$110,671.3 million in 1999 to S$182,536 million in 2009. Given that GNI is equivalent to GNP (Gross National Product), and thus it is the result of the value-added generated by Singaporeans in Singapore (GSS) and value-added generated by Singaporean in Foreign country (GSF), the GNI figures generally support the co-evolutionary acclimatization phenomenon described.

[6] MW: Megawatt.
[7] MiGD: million imperial gallons per day.
[8] Sembcorp Industries Facts & Figures 2009.
[9] Milieu (March 2009) http://app.mewr.gov.sg/data/imgCont/943/2009_03.pdf. Last accessed on 12 Feb 2011.
[10] Yearbook of Statistics Singapore 2010.

Table 6
Projects contracted by Keppel Integrated Engineering during the export acceleration period.

Year Project was Secured	Project	Country	Value of project
2004			
	Ulu Pandan NEWater Plant	Singapore	
2006			
	Integrated solid waste management facility	Qatar	S$1.7 billion
	Upgrade existing wastewater treatment plant for InBev (the world's largest brewer)	Belgium	
	Kotka Energy WTE plant for municipal solid waste	Finland	$30 million
	WTE plant	China – Jiangyin	$13 million
	WTE plant	China – Changzhou	$13 million
	WTE plant	China – Tianjin	$13.5 million
	Project using Keppel's proprietary technology solution – UNITANK®	Argentina	US$1.3 million
	Tuas South WTE plant	Singapore	
2007			
	Expand an existing WTE plant in Moerdijk	The Netherlands	$35 million
	Waste treatment plant	China – Suzhou. Jiangsu Province; Zhongshan, Guangdong Province	$23 million
	Wastewater treatment and reuse plant	Algeria	$22 million
	Doha North Sewage Treatment Works (largest greenfield wastewater treatment and water reuse facility in the Middle East)	Ashghal, Qatar (awarded by the Public Works Authority in Qatar)	$1.5 billion
2008			
	A combined heat and power WTE plant [Keppel Seghers Belgium NV]	Sweden (owned by Amotfors Energi)	€34 million
	WTE plants	Europe – Honduras and Guadeloupe	$120 million
2009			
	Energy-from-Waste combined heat and power plant	United Kingdom (Greater Manchester Waste Disposal Authority)	$518 million
	WTE plant (largest in China)	China – Senzhen, Guangdong	
	WTE plant	China – Tianjin	$22.3 million
	WTE plant	China – Shandong	$30 million

WTE – Waste-to-Energy.

Table 7
Water capacity of water and wastewater treatment facilities constructed by Sembcorp Industries#.

Capacity of Treatment Facility	Year Facility will be Operational	Country of Treatment Facility	Number of Projects in the Country
2,000,000–3,000,000 m^3/day			
	2003	United Kingdom (Teesside)	1
	2005	China (Nanjing; Shanghai)	2
3,000,000–4,000,000 m^3/day			
	2006	United Arab Emirates (Fujairah)	1
	2006	China (Zhangjiagang)	1
	2008	China (Shenyang)	1
	2009	Singapore (Changi)	1
	2009	China (Tianjin)	1
5,000,000–6,000,000 m^3/day			
	2010	China (Yancheng; Zhumadian; Fuzhou; Qitaihe; Yanjiao; Xinmin)	6
		Indonesia (Batam; Talang Kelapa)	2
		Philippines (Subic Bay)	1
		South Africa (Nelspruit; Ballito)	2
		United Kingdom (Bournemouth)	1
		Chile (Santiago; Colina; Lampa; Antofagasta; La Negra)	5
		Panama (Lake Gatun)	1
		The Caribbean (Antigua; Bonaire; Curacao)	3
	2011	China (Qinzhou)	1
	2012	Oman (Salalah)	1

Sembcorp Industries was the developer, owner and operator.

Table 8
Export destination of Kristal™ membranes manufactured by Hyflux limited.

Country	Industry	Year deal was secured
Middle East & North Africa		
Algeria (Magtaa)	Seawater desalination	2008
Algeria (Tlemcen)	Seawater desalination	2006
Dubai	Sewage treatment	2005
Namibia	Textile wastewater	2002
Europe		
The Netherlands	Drinking water	Information not available
China		
Beijing	Ultra-pure water	2006
Guangdong	Desalination & wastewater	2005
Tianjin	Seawater desalination	2004
Southeast Asia		
Indonesia	River water treatment	2004
Malaysia	Brine regenerant recovery	2000
Malaysia	River water treatment	2000

Source: Hyflux Annual Report 2008.

Table 9
Designed capacities of water plants constructed by Hyflux Limited.

Designed Capacity (m^3/day)	Year deal was secured	Water plant
500,000 and above		
500,000	2008	Magtaa, Algeria [Desalination Plant]
100,000–499,999		
273,000	2002	Chestnut Avenue Waterworks [Potable Water Treatment Plant]
200,000	2006	Tlemcen, Algeria [Desalination Plant]
182,000	2009	Jurong Island, Singapore [Tuas Power Tembsus Multi-Ultilities Complex]
136,000	2003	Tuas, Singapore [SingSpring Desalination Plant]
100,000	2004	Tianjin Dagang, China [Desalination Plant]
Below 100,000		
80,000	2006	Langfang, China [Wastewater Recycling Plant]
68,000	2009	Salalah Independent Water & Power Project, Oman [Desalination Plant]
68,000	2009	Jurong, Singapore [Membrane Bioreactor Plant]
40,000	2002	Seletar, Singapore [NEWater Plant – Wastewater Recycling]
32,000	2001	Bedok, Singapore [NEWater Plant – Wastewater Recycling]

A phased trajectory leading to the development of co-evolutionary dynamism has been established as illustrated in Fig. 8. In this process, local companies and foreign industry players collaborate leading to the acquisition of external capabilities and assimilation of the external capabilities with local capabilities. The indigenous

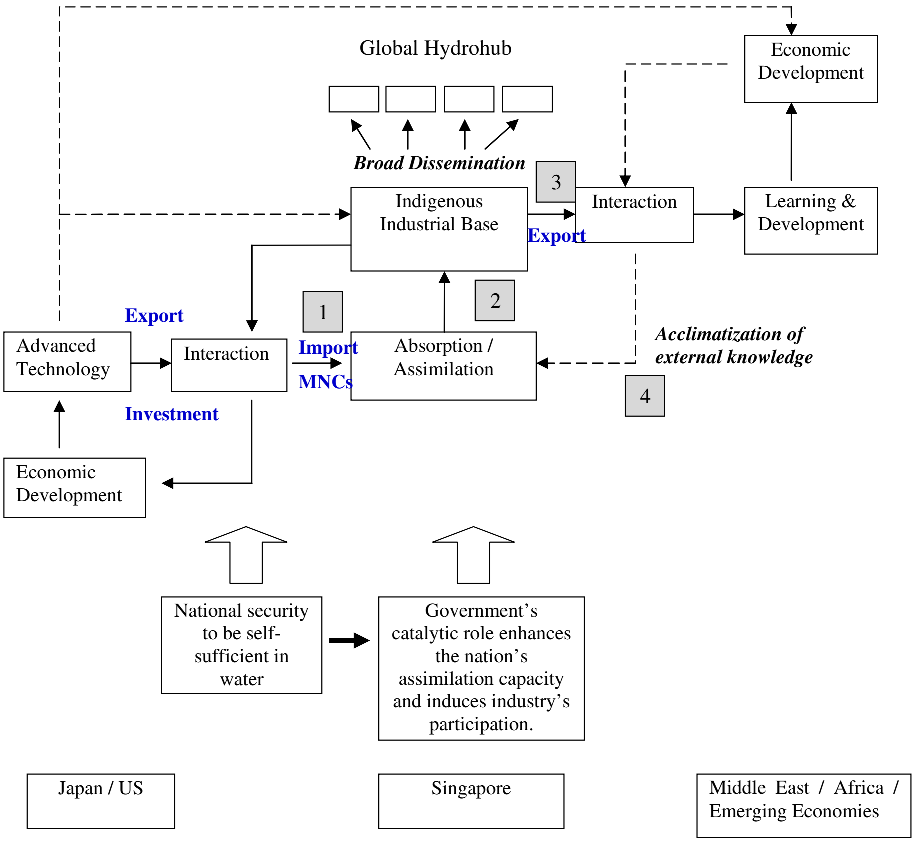

Fig. 8. Phased Trajectory Leading to Co-evolutionary Acclimatization.

capabilities developed are disseminated via local and overseas projects. The indigenous capabilities exported spur further innovation as the technologies have to be "acclimatized" to suit the recipient. Government stimulation in terms of pro-active policies and funding facilitate the acclimatization process.

The local firm, Hyflux Limited has plans to develop a new Hyflux Innovation Centre and the Hyflux Production Hub in the next three to five years. The company has also secured contracts in 2010 to construct a membrane bioreactor plant and a desalination plant on Jurong Island.

The co-evolutionary acclimatization phenomenon is also observed in another local firm, Keppel Integrated Engineering. The phenomenon is illustrated using the MEMSTILL project as an example. MEMSTILL® is a novel and low-cost desalination technology developed by a consortium which includes the Netherlands Organization for Applied Scientific Research and Keppel Seghers Belgium N.V., a wholly owned subsidiary of Keppel Integrated Engineering Ltd. The first bench scale test and first pilot plant test were conducted in Singapore. The second pilot testing was conducted in the Netherlands with improved materials and configurations to achieve significantly better results. The third pilot testing was also conducted in the Netherlands with the consortium deciding on a large demonstration plant planned in Singapore to further develop and commercialize the technology. A new design has been tested in Belgium and Spain.

Co-evolutionary acclimatization is also observed in the area of membrane bioreactors. Toray has a pilot plant located within the Ulu Pandan Water Reclamation Plant in Singapore. Asahi has its pilot plant located at Utrecht Water Reclamation Plant in The Netherlands. For both plants, a local firm, Keppel Seghers, designed, constructed, commissioned and operated the two membrane bioreactor pilot plants to test the technology that treats wastewater into industrial water quality in a single step. The advancement in the R&D work was a major attractive factor for Mitsubishi Rayon to start up a pilot plant at Bedok Water Reclamation Plant in Singapore. This illustrates the dynamic co-evolutionary acclimatization is not confined to geographic boundaries.

5. Conclusion

This paper analyzed Singapore's successive endeavors toward technology-driven water. It explained the successful accomplishment of innovation and industry emergence induced by overcoming the crucial constraints of water supply. The NEWater development and subsequent co-evolutionary acclimatization of world leading technologies were examined and this process explained. An empirical analysis of the diffusion, learning and substitution dynamism were conducted and results were cross evaluated and interpreted using theories of institutional systems, co-evolution and "acclimatization".

One noteworthy finding from this study is that Singapore has successfully moved from a constrained situation with limited capabilities in the water industry to a situation where it is now exporting capabilities worldwide. The need to be self-sufficient in water lead to the exploration of innovative ways of increasing water supply via existing (conventional) means and non-conventional means. NEWater is technology-intensive encompassing extensive R&D efforts in multi-disciplinary fields (such as nanomaterials and membrane manufacturing) fully integrated with sensitive systems engineering efforts. While the initial stage involved importing products and capabilities by engaging multinational industry players, a holistic government industrial policy was implemented to build up the necessary capabilities with the aim of becoming a Global Hydrohub. R&D centers were set up within tertiary education institutions where researchers concentrated on academic research which led to establishing Centres of Excellence to encourage interaction between private and public sectors, as well as academics and firms. Also successfully implemented was the initiative to attract major industry players to set up their R&D headquarters in Singapore. Through the government's PPP initiative, the opportunities for technology spillover and learning were enhanced. Knowledge was assimilated and transformed into the development of indigenous capabilities. With the indigenous capabilities developed, local companies won projects overseas, thus creating the opportunity for further knowledge transfer to other recipients.

These findings suggest the following policy implications for innovation and industry emergence, particularly in inducing businesses at the bottom of the pyramid. Firstly, the optimal combination of an industry's vigorous efforts and government's support and stimulation depend on the advancement of the system innovation. This is essential for success in the steps described above. These successive stepwise endeavors which began with learning from imported technology transitioned to indigenous technology development, which were then exported and finally lead to co-evolutionary acclimatization. Co-evolutionary acclimatization provides mutual benefits to competitors leading to global co-evolution between innovation and institutional systems. This dynamism could be scalable and effective in inducing businesses at the bottom of the pyramid. There is room for emerging economies to build up their indigenous capabilities for industries or technologies that are dependent on tacit know-how rather than patents. This is particularly applicable since the intellectual property regime in most emerging economies is not well enforced. The route to building up indigenous capabilities may not necessarily be through investment in R&D. Building clusters or partnerships may be a cheaper alternative than investment in R&D.

This paper, uses the Singapore's NEWater endeavor as an exemplar of how emerging economies can build up indigenous capabilities with long-term planning and appropriate and timely government stimulation efforts. Future research should focus on the generalization of this approach for application in emerging economies.

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