The energy cost of water independence: the case of Singapore

Lenouvel Vincent, Lafforgue Michel, Chevauché Catherine and Rhétoré Pauline

ABSTRACT

Finding alternative resources to secure or increase water availability is a key issue in most urban areas. This makes the research of alternative and local water resources of increasing importance. In the context of political tension with its main water provider (Malaysia), Singapore has been implementing a comprehensive water policy for some decades, which relies on water demand management and local water resource mobilisation in order to reach water self-sufficiency by 2060. The production of water from alternative resources through seawater desalination or water reclamation implies energy consumptive technologies such as reverse osmosis. In the context of increasing energy costs and high primary energy dependency, this water self-sufficiency objective is likely to be an important challenge for Singapore. The aim of this paper is to quantify the long-term impact of Singapore's water policy on the national electricity bill and to investigate the impact of Singapore's projects to reduce its water energy footprint. We estimate that 2.0% of the Singaporean electricity demand is already dedicated to water and wastewater treatment processes. If its water-energy footprint dramatically increases in the coming decades, ambitious research projects may buffer the energy cost of water self-sufficiency.

Key words | desalination, rainwater harvesting, Singapore, sustainability, urban water-energy nexus, water reclamation

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INTRODUCTION

In the context of increases in water scarcity and pollution, population and economic growth and urbanisation, finding alternative resources to maintain or increase water availability is a key issue in most urban areas worldwide. In several countries, cities are increasingly competing with other users to access common conventional freshwater resources. If appropriate, allocation rules at the river basin scale, as well as the reduction of water wastage and inefficiencies, may help to maintain the urban water supply. Conversely, they may fail where rules or agreements cannot be reached or where water resources are insufficient. In that context, the research of alternative and local water resources to ensure water self-sufficiency is an important consideration in many urban areas (Rygaard *et al.* 2011).

Alternative and local sources frequently mobilised in urban areas form three types:

- **Urban rainwater collection:** rainwater collection is implemented at several scales. At the building scale (rooftop harvesting, etc.), the water collected is mainly used for non-potable purposes and few treatments are generally needed. On a large scale (aquifer recharge, natural or artificial reservoirs, etc.), rainfall may supply drinking water and treatment is needed.
- **Desalination:** desalination relies on seawater or brackish water contained in aquifers or estuaries. As population increase concentrates on coastal areas, desalination is of increasing interest in many cities.
- **Urban water reuse:** the interest in urban water reuse lies in its reliability and availability, in its location within the boundary of the city water system and in the proportional relationship existing between water consumption and wastewater availability. Reuse projects generally aim at providing low-quality water for non-potable uses. Other projects provide high-quality water for specific industrial uses or drinking purposes (Jimenez & Asano 2008). This implies the need for stringent standards as well as a complex treatment process.

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The use of alternative resources has positive impacts on water supply reliability, conventional water withdrawal reduction or avoidance of important investment costs and conflicts associated with large-scale hydraulic infrastructure. However, it also creates many drawbacks. Sanitary issues frequently arise due to the potential decrease in water quality, generally related to salinity or microbiological issues. Lack of public acceptance has resulted in the failure of several reuse projects worldwide (Po *et al.* 2003). Finally, the treatment associated with water reuse or desalination projects increase significantly the energy requirements of the water sector. Energy supply reliability being a strategic issue in urban areas, the potential benefits from water independence may be offset by the increase in energy dependency.

The aim of this paper is to quantify the long-term impact on energy consumption of a well-known water self-sufficiency policy, relying on the three above-identified alternative water resources in Singapore. The following section provides a comprehensive snapshot of the unique Singaporean water situation. The subsequent section presents the general methodology used to estimate the energy cost in the water sector in the long term. The section after that displays the associated results, while the subsequent section discusses the main findings.

DESCRIPTION OF THE SINGAPORE WATER SITUATION

Located at the extreme south of Malaysia, Singapore is a city-state of 716 km^2 with approximately 5.4 million inhabitants in 2013 (SingStat 2014a). Singaporean territory is composed of numerous small islands surrounding a larger island, which comprises most of the population and economic activity. The small size and the density of the city make Singapore unable to supply domestic demands in water and energy with local natural resources. Singapore has historically relied on its harbour to access primary energy (mainly natural gas) and on the 1 km distant Malaysian mainland to access freshwater. Singapore thus faces a double dependency regarding water and energy (Lafforgue *et al.* 2013a).

Independent from Malaysia since 1965, the reduction of Singapore's water import from Malaysia is one of the main national challenges, and water infrastructure has been developed to meet this goal for 50 years by the Public Utilities Board (PUB) (Segal 2004; Lee 2005; Tortajada 2006; Suzuki *et al.* 2010; Tortajada *et al.* 2013). Freshwater has been imported from the Malaysian state of Johor through a framework of different international agreements signed in 1927, 1961 and 1962. The 1927 and 1961 agreements are now finished, the latter since 2011. The 1962 agreement guarantees the supply of 415 Mm^3 of freshwater per year to Singapore until 2061, by which time Singapore aims to have reached water independence. In order to achieve this ambitious objective, Singapore has, for some decades, implemented a water policy based on both supply and demand management.

On the demand side, Singapore's authorities have made considerable efforts to achieve a dramatic increase in drinking water network efficiency, with unaccounted-for-water (UFW) maintained at around 5% since the mid-1990s.

Furthermore, Singapore combines different management approaches to reduce per capita water demand from 175 litres per capita per day (lcd) in 1994 to 152 lcd in 2012. This has been done by increasing the block water tariff, public information and awareness, mandatory labelling measures on water device efficiency or subsidies for technical change in households. The decreasing trend in water consumption is expected to continue and the Singapore authorities' target is to reach 140 lcd by 2030 (Puah 2011; Tortajada *et al.* 2013), although total water demand will increase due to future population growth (Lafforgue *et al.* 2013a). Figure 1 synthesises the recent evolution in UFW and per capita consumption.

On the resource side, the Singaporean policy relies on the so-called *4-tap policy*. The first water *tap* relies on imports from Johor, Malaysia. Since 2011, Singapore has the right to take up to 415 Mm^3/y from the Johor River. However, the Malaysian *tap* is generally assumed to provide 40% of Singapore water demand, corresponding to 250 Mm^3/y. Drinking water is produced from freshwater thanks to conventional water treatment processing. Although water from Malaysia is still the first national *tap*, Singapore adopted an early comprehensive policy increasing the use of local resources.

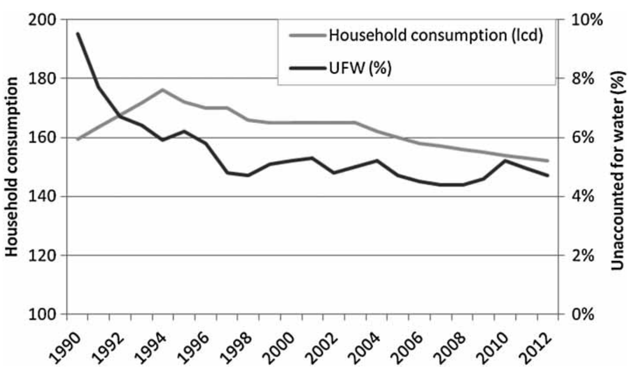

Figure 1 | Trends in per capita water consumption and unaccounted-for-water.

The second water *tap* relies on rainfall (30% of water demand). Indeed, Singapore receives 2,344 mm of rainfall annually (National Environment Agency 2014). At the time of independence, surface water was contaminated by pollution from slums or polluting farming activities located on riverbanks. One of the city's major achievements was to tackle these problem early, rehousing families from the waterfront in new areas with proper sewer systems. Slum residents and backyard industries were resettled to create wellhead and source water protection areas. Pig farms were progressively phased out in the early 1990s (Chia *et al.* 1988) while development of the harbour and industrial activities were concentrated in the southwest part of the island, away from the main watercourses.

In the meantime, Singapore has increased its rainwater and run-off storage capacity through the construction of large reservoirs in the centre of the island or at river mouths. Reservoir numbers have increased (14 in 2005 to 17 reservoirs today) and storage capacity now exceeds 150 Mm^3 (Lee 2005; Harley 2012). With the recent building of the Marina Barrage and Punggol and Serangoon reservoirs, the drainage area covers roughly two-thirds of the national territory. This closes a cycle of large investment geared towards large-scale rainwater harvesting. The second water *tap* is unlikely to increase significantly in the near future.

The third water *tap* has relied since 2003 on water reuse – an initiative named NEWater – that provided 18% of Singaporean water demand in 2012. (Wastewater has been reused since 1966 in Singapore. Industrial water (IW) has been produced from the effluent from a wastewater treatment plant located on the west side of Singapore. The reclamation process relies chiefly on chemical clarification, sand filtration and cascaded aeration (PUB online 2014). IW has been steadily replaced by NEWater in most of the industrial west side of Singapore and only 25 Mm^3/y have been provided through a specific network supplying oil and chemical industries in Jurong Island, representing 4% of national demand. IW is excluded from analysis in this paper.) NEWater mostly meets IW demand, freeing up drinking water for domestic consumption. Water is reclaimed mainly via conventional activated sludge processes and is further treated in NEWater plants through microfiltration, reverse osmosis (RO) and ultraviolet (UV) technologies. NEWater meets high quality standards (Mong-Hoo & Seah 2013) and benefits from an important communication campaign to increase public acceptance. NEWater is the first cornerstone of Singapore's water self-sufficiency policy, and with more than 110 Mm^3 sold to industries in 2012, it meets 32% of industrial and commercial demands (SingStat 2014b). The Singapore authorities aim to meet an increasing share of industrial needs by increasing NEWater production capacities and extending the NEWater distribution network. In addition, up to 2% of the produced NEWater is today blended with rainfall water in reservoirs before being treated and sent to the drinking water distribution network. The objective of Singapore is to increase steadily the share of NEWater in the drinking water network (PUB online 2014).

The fourth water *tap* relies on seawater desalination with the commission of two desalination plants in 2005 and 2013, with a water production capacity of, respectively, 50 and 115 Mm^3/y. Based on microfiltration and RO, these plants have surplus capacity to meet future water demand and anticipate the reduction in water imports from Malaysia. Seawater desalination is the second cornerstone of the Singaporean water independence policy. The current situation in terms of treatment capacities and supply sources is summarised in Table 1.

The *4-tap* policy induces a shift from conventionally treated Malaysian freshwater to Singaporean local resources. As a result, seawater desalination and water reclamation via NEWater production will increase. Both processes are energy consumptive and the objective of water self-sufficiency is likely to increase the energy dependence of Singapore. This strategic choice has already driven up the energy footprint of water production and

Table 1 | Share of different water sources in Singapore's water supply system (2013)

Tap	Capacity (Mm^3)	Production (Mm^3)	Share in water supply (%)	Energy footprint (kWh/m^3)	Trend
Malaysia	415	250	40	0.25	Decrease
Rainfall harvesting	NA	200	30	0.25	–
Seawater	165	50	8	4.10	Increase
NEWater	195	110	18	0.95	Increase
Industrial water	45	25	4	NA	NA

NA: not addressed.

treatment processes up to 2% of overall Singapore electricity demand (see Appendix, available online at http://www.iwaponline.com/wst/070/290.pdf). Reducing the energy footprint of water processes is currently of great importance on the city-state's agenda (Bocquet 2013). The trends in water production, electricity consumption and price are presented in the Appendix and demonstrate that energy is a key issue.

In the following section, we present the methodology used to assess the energy cost of the *4-tap* policy for the next 15 years.

METHODOLOGY

This section depicts the methodology used to reconstitute the energy footprint of the *4-tap* policy until 2030. To do so, we present our hypotheses and calculation methods related to water demand projection, water supply evolution and the energy requirement of water processes based on the literature or on official Singaporean sources such as:

- PUB;
- Singapore Department of Statistics (SingStat);
- Ministry of the Environment and Water Resources (MEWR);
- Ministry of National Development (MND);
- National Population and Talent Division (NPTD);
- Energy Market Authority (EMA).

Growth in population and water needs

As shown in Figure 2, Singapore's population has grow continuously since its independence, from 1.5 million in the early 1960s to 5.4 million today. The population will reach 6.7 million by 2030 (NPTD 2013).

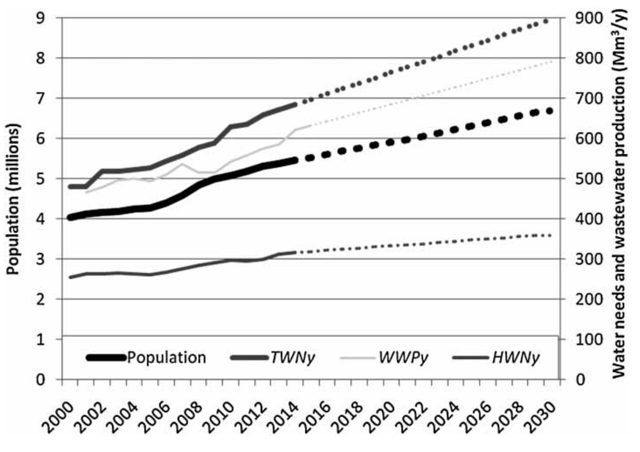

Figure 2 | Trends in population growth and total water demand.

Along with the rise in living standards (GDP per capita rose from S$1,600 in 1965 to S$63,000 in 2011), per capita water demand rose from 75 lcd in 1965 to 175 lcd in 1994. Because of the water conservation policy undertaken since the 1990s, per capita consumption has steadily decreased since and is planned to reach 140 lcd in 2030 (MEWR & MND 2009). Assuming a homogeneous 4.8% hypothesis for UFW until 2030, corresponding to an average value over the last 10 years, we reconstitute household water needs (HWN) for year y following the equation below, with pcd_y the yearly per capita demand.

$$HWN_y = (population_y \times pcd_y)/(1 - UFW)$$

Singaporean authorities assume that industrial and commercial water needs (IWN_y) will increase with economic growth and will represent 60% of overall water demand in 2030 (PUB 2013). We retain this hypothesis to draw a trend from 2012 to 2030, reconstituting industrial demand. Furthermore, we assume 4.8% for UFW into the non-drinking water network to obtain IWN_y and thus the total water needs in Singapore (TWN_y).

We finally reconstitute wastewater production (WWP_y) based on 2001–2013 data available on the MEWR website. During this period, WWP increased from 467.2 to 585.0 Mm^3. These data allow the estimation of a trend ratio between the produced wastewater and the total water sold in Singapore.

Singapore aims at supplying an increasing share of the water demand with reclaimed wastewater. The objective is to supply 50% of the total demand by 2030 with NEWater.

Reconstitution of energy requirements in the water sector

Based on PUB publications, Nam *et al.* (2002), Plappally & Lienhard (2012), Yeshi *et al.* (2013) and PUB sources, we assume the following energy requirement to produce the different Singaporean water *taps*:

- Malaysian water and large-scale rainwater harvesting (including 2% of NEWater blended in rainwater reservoirs): 0.25 kWh/m^3. (No value could be found in the literature or PUB reports, so this figure is a hypothetical value reflecting the overall energy cost of Malaysian water and rainwater. Since Malaysian water flows towards Singapore in pipes, partially due to a relatively regular downward slope, we assume energy costs to be chiefly related to water treatment. This hypothesis has to be confirmed.)

- NEWater for uses such as industry: average 0.95 kWh/m^3 (range: 0.7–1.2 kWh/m^3).
- Seawater desalination: average 4.1 kWh/m^3 (range: 3.9–4.3 kWh/m^3).
- Wastewater treatment: from 0.52 to 0.89 kWh/m^3, according to the wastewater treatment plant (energy generation from sludge digestion is not accounted for).

Moreover, transportation and distribution energy requirements are not addressed. Drinking water from Malaysia is produced mainly at the Johor River waterworks, 40 km away from Singapore. Due to Johor relief, water transport from Malaysia does not imply crossing any major height difference and the associated energy footprint is likely to be low.

ANALYSIS AND RESULTS

Projected baseline for energy footprint in the water sector

For the purposes of projection of energy needs in the Singapore water sector, the following assumptions have been used for a baseline scenario 'H0':

- Constant water production energy requirement per cubic metre for each *tap*, as mentioned earlier.
- PUB water demand projections for 2030, as in Figure 2.
- PUB water source projections for 2030.
- No new desalination plants will be built before 2030, although the two existing desalination plants will be used at full capacity by 2030.

As a result, the current energy footprint of Singapore water production processes reaches around 430 GWh/y. Treated wastewater represents 575.0 Mm^3 in 2012 and the estimated energy consumption for wastewater treatment, 410 GWh. The overall water energy footprint exceeds 840 GWh for 2012.

Figure 3 presents the increase in energy needs in the water production process. Total energy consumption for the water production and wastewater treatment is foreseen to increase up to 1,850 GWh in 2030. This represents more than a two-fold increase from the 2012 level. The average energy requirement per m^3 for water treatment will double from 0.66 to 1.31 kWh/m^3 due to the technical shift towards desalination and re-use. Wastewater treatment energy requirements may increase in the framework of the

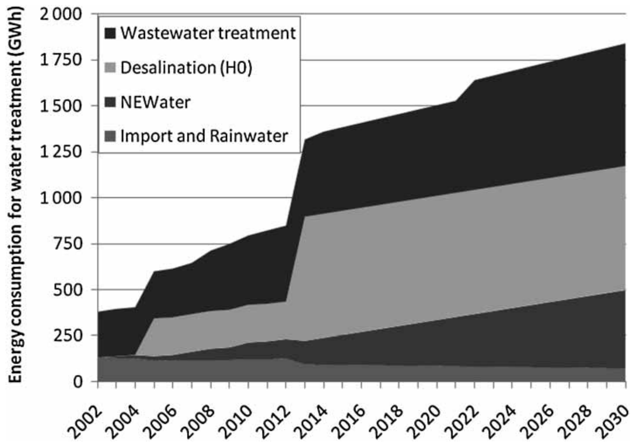

Figure 3 | Projected energy consumption for water production processes in Singapore (baseline scenario H0).

Singaporean deep tunnel sewerage system (DTSS), due to a shift towards more compact and high-performing plants (phase 1 of DTSS was implemented since 2008 with the commission of the Changi wastewater treatment plant while we assume that DTSS phase 2 will be implemented in 2022 with the commission of the Tuas plant).

Singapore electricity demand amounted to 42.6 TWh in 2012. Following our reconstitution, water production and treatment represent currently 2.0% of national electricity demand. Only 3.4% of Singaporean energy is produced from local energy sources such as municipal solid waste and solar panels, while 84.3% is produced from imported gas and 12.3% from other imported fossil fuels.

Singapore's gas supply is secured through international agreements and Singapore harbour's top rank position. It nonetheless remains heavily dependent on foreign imports and volatile energy prices. In the 2005–2012 period, electricity demand rose by an average of 3.3% a year as gas and electricity prices increased by, respectively, 5.0 and 8.2% per year (EMA 2012). The Singapore water sector is coping with increases on two fronts: an increase in energy demand and an increase in energy prices.

Projected impact of Singapore initiatives to reduce energy footprint in the water cycle

In view of this trend, Singapore is seeking ways to reduce energy dependence in the water sector, while continuing to pursue its aim of water self-sufficiency. Local authorities have launched several initiatives to this end – initiatives undertaken in partnership with other national institutions under the umbrella of the Environmental & Water Industry

Program Office (EWI), but also in partnership with universities and the private sector. The goals are three-fold: 'Cost Competitiveness, Water Quality and Additional Resources'.

The main initiatives are as follows:

- Reduce desalination energy needs (S$4 million grant from the EWI program to a private operator (Siemens)).
- Increase drainage surface by up to 90% (various salinity plants to produce water from brackish estuaries).
- Reduce water reclamation and NEWater production costs, replacing part of the activated sludge process (aeration and final clarification) and pre-treatment for RO (microfiltration or ultrafiltration) by membrane bioreactor (MBR) in NEWater plants. As discussed in the Appendix (available online at http://www.iwaponline.com/wst/070/290.pdf), the planned MBR capacity of 66 Mm^3/y will mitigate the energy consumption of the water sector by 2.8% compared to the 2011 level.

Moreover, PUB has increased the integration of energy systems in water facilities through the following measures:

- Increased optimisation of biogas production from sludge digestion in wastewater treatment plants.
- Production of energy by a 411 MW CCG turbine in the 2013 desalination plant.
- Introduction of cross-subsidies between water and electricity.

We assess hereafter the impact of the Singaporean policy addressing the energy requirements of desalination plants (scenario H1). The desalination energy requirement targeted by PUB is 1.5 kWh/m^3 in the mid-term and 0.75 kWh/m^3 in the long-term (Puah 2011). (To achieve this, Singapore and its partners have invested in breakthrough innovation relying on electrodialysis or ion exchange as well as biomimetics. RO will not be further used. This hypothesis is quite optimistic but corresponds to the Singaporean pathway.)

In scenario H1, we first assume a steady decrease in desalination energy requirement from 4.1 towards 1.5 kWh/m^3 in the 2017–2030 period. We secondly assume that NEWater production will totally rely on the MBR-RO-UV process by 2030. This shift implies a 0.4 kWh/m^3 energy abatement (see Appendix). This abatement is integrated in the wastewater treatment curve in Figure 4.

As a result, total energy consumption for water treatment could rise by 50% between 2012 and 2030. However, the overall energy footprint would be latterly stabilised around 1,250–1,300 GWh/y. This stabilisation is mainly driven by increases in desalination energy efficiency.

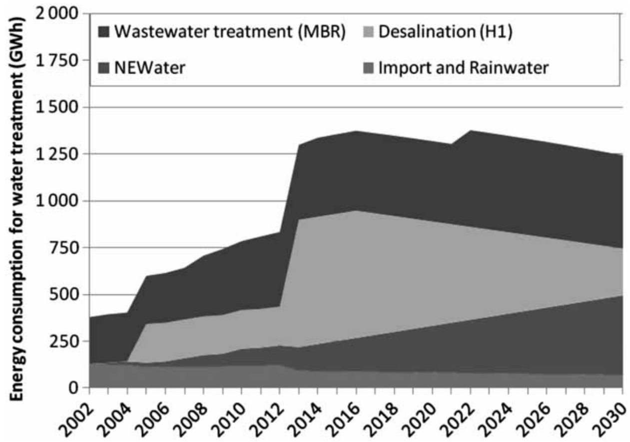

Figure 4 | Projected energy consumption for water production processes in Singapore (scenario H1).

LIMITATIONS AND POSSIBILITIES

These findings have been obtained on the basis of official and/or published data. The estimates could be fine-tuned using additional data, including operating data on energy used for pumping or water treatment processes. Moreover, the assumption that desalination plants will operate at full capacity must be confirmed.

A task still to be performed is to determine energy costs for different pumping requirements (pumping of water from Malaysia; pumping to the distribution system; stormwater and wastewater pumping; pumping of water for industrial uses) and the gains or losses achievable by replacing some of the water from Malaysia by a more local supply source. Other existing or new technologies that Singapore is planning to use to reduce its water dependency have also to be integrated (e.g., variable salinity plants).

Finally, the energy sector, in combination with the water sector, should be addressed as a real opportunity for energy savings and production (micro hydroelectricity, waste heat from power plant for desalination, sludge digestion heating or sludge drying). To date, biogas production recovers nearly 30% of the overall wastewater treatment energy requirements (Yeshi *et al.* 2013), which represents 86 GWh for 2012 or 10% of the water-energy bill. Yeshi *et al.* (2013) suggest this amount could be increased to 50%.

CONCLUSION

This paper deals with the impact of the change in the water sector in the instructive case of Singapore, which includes most of the water-energy issues that may face cities in the near future. The city has built a demonstration hub of world renown in the water sector – a hub that trials and develops technologies of the future with the potential to serve as an example for other parts of the world. In particular, Singapore is exploring how to manage growing demand in the context of water scarcity and volatile energy prices, and has thus been forced to optimise both its water demand and its energy costs.

Faced with the prime objective of reducing its dependence on Malaysia for water, Singapore has taken steps to address this situation. It has developed facilities to harvest and store rainwater, as well as a system providing extensive retreatment of wastewater and stormwater, primarily for use in industry but also in part for potable water (NEWater project). In conjunction with seawater desalination, this system has helped to make the island more water self-sufficient, but it is both costly and energy intensive. With virtually no local energy sources, Singapore is now tackling the challenge of cutting energy usage for water treatment needs. To that end, it has launched some ambitious research and development programmes exploring ways of reducing energy requirements for desalination, and ways of adopting a more integrated approach to water and energy. This latest initiative might extend to considering the use of combined water and power production systems.

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