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The role of energy to solve water scarcity in Qatar

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ABSTRACT

Qatar's significant wealth in natural gas and oil brings the country to the highest income per capita worldwide. The drastic economic and social development gained by these revenues modernizes the country's infrastructure and improve the population living standards in all aspects. Qatar gross domestic product income, in billion dollars ($B) increased from $B 115.270 in 2008–$B 202.45 in 2013. Meanwhile, Qatar faces real challenges due to very limited natural freshwater resources. Water scarcity creates water and food security problems. The viability of agriculture food productions is continually decreasing. Agriculture in Qatar depends mainly on groundwater, which is over-exploited, depleted, quality deteriorated, and becoming less suitable for agriculture, and its usage, in general, can be seized soon. Qatar's abundant energy is used to generate desalted seawater to satisfy 99% of municipal water needs. The possibility of treating wastewater treatment to be used for agriculture purposes is discussed here, along with the interdependent relation between water, energy, and agriculture (and thus food). This paper outlines and discusses Qatar energy resources, demands, and consumption; as well as water resources, demands, consumption, and security. Detailed consumed energy in desalting seawater and treating wastewater are presented.

Keywords: Water resources; Groundwater; Wastewater; Desalination; Natural gas; Agriculture

1. Introduction

Qatar is a small peninsula, (11,586 km^2), on the northeast coast of the Arabian Peninsula. It has 563-km coast length, single land border with SA southwest of the country while the rest is surrounded by the Arabian Gulf and is separated from Bahrain by a strait in the Gulf. Qatar's total population increased from less than 0.05 million (M) in 1960 to 1.447 M in 2008 to 1.774 M in 2012 to 2.2 M in 2013, Fig. 1. The 2011 population included 98.8% living in urban areas, and 1.2% in rural areas [1].

Qatar's gross domestic product (GDP), in billion dollars ($B) increased from $B 31.02 in 1970 to $B 115.270 in 2008 to $B 192.402 in 2012 to $B 202.45 in 2013, Fig. 2a, [2]. The GDP is the market value of all officially recognized final goods and services produced within a country in a year. Qatar has the highest GDP per capita, estimated by $108,458 in 2012, Fig. 2b. This is more than double that of close by countries such UAE ($49,012) and Kuwait ($39,889), and three times of SA ($31,275), Oman ($29,166), and Bahrain ($28,744). GDP per capita is used to indicate the country's material standard of living.

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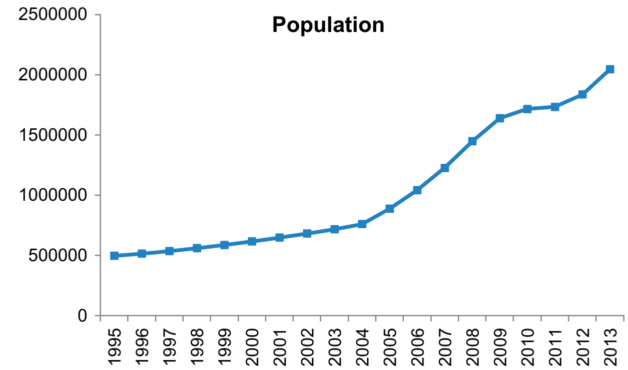


Fig. 1. Qatar historic population increase in millions of people [1].

The International Monetary Fund (IMF) [3], reported that Qatar's nominal GDP is estimated to be $B204.81 in 2013 and is projected to be $B212.67 in 2014 and $B224.56 in 2015. The nominal hydrocarbon GDP increased from $B66.58 in 2010 to $B112.44 in 2012 (almost doubled in two years), estimated to be $B111.03 in 2013, and is projected to be $B106.19 in 2014 and $B103.11 in 2015. Fig. 2a shows the GDP history in Qatar [2]. The reported GDP per capita in current prices, Fig. 2b, was $58,406.46 in 2013 (472% of the world average), and was $61,232.27 in 2011.

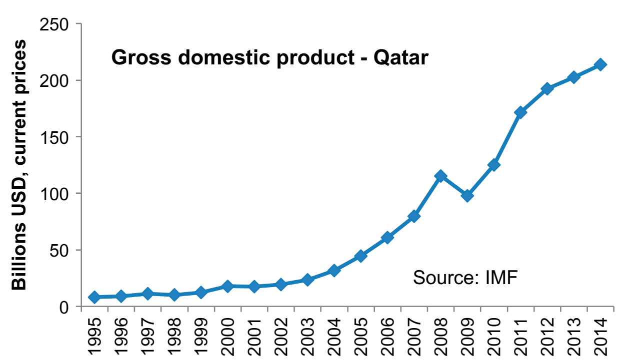


Fig. 2a. Qatar's GDP history in billions of US dollars [2].

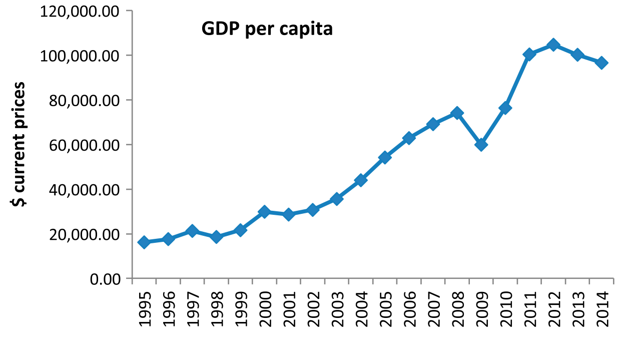


Fig. 2b. Qatar's GDP per capita with the current prices [2].

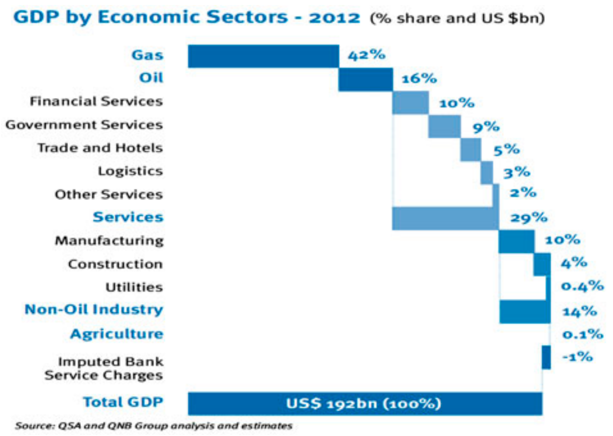


Fig. 2c. GDP by economic sectors—2012 (% share and US $B) [2].

Qatar's export value was reported in 2012 as $B133.72, including $B116.2 from petroleum export, and import value is $B30.79 [5]. Its earnings from the hydrocarbons sector accounted for about 60% of the total government revenues over the past five fiscal years. The distribution of its GDP in 2012 is given in Fig. 2c.

Qatar's proved crude oil reserves are in excess of 25 billion (B) barrels (bbl) and proven natural gas (NG) reserve exceed 25 trillion cubic meters (TCM), more than 13% of the world total and third largest in the world [5]. According to Qatar Statistics Authority and Qatar National Bank (QNB) Group estimates, the oil and gas sector was responsible for 57.8% of Qatar's total nominal GDP in 2012, see Fig. 2c.

Oil and NG revenues have made Qatar the world's highest per capita income with significant economic and social transformation gained by these revenues. The country's infrastructure is modernized, and the population living standards are improved. Nearly all citizens have full and secure access to water and sanitation facilities. Also, investment in health care increased the primary health care access to everyone [6]. Life expectancy increased considerably because of increase in living standards and quality health care provisions. Unemployment is one of the major concerns in the region, but with adequate policies of Qatarisation, unemployment decreased markedly over time (3.9% in 2001 to 0.5% in 2010). The adult literacy rate increased from (90.2%) in 2001 to (96.3%) in 2010, i.e. an annual increase of (0.7%), and is expected to reach 100% soon.

1.1. Qatar NG resources

Qatar has huge NG resources, about 24.682 TCM in 2013 [7], Fig. 3. Worldwide: Qatar reserve is the third after Russia (48.676 TCM) and Iran (33.780 TCM). Qatar is the second largest NG exporter, exporting nearly 121.76 Bm^3 in 2012, and first in exporting liquefied natural gas (LNG) since 2006. It also has the highest capacity of LNG facilities, 77 million tons per year (Mt/y) and are produced by two companies: Qatargas (42 Mt/y) and RasGas (35 Mt/y), fourth largest dry NG producer in 2012, (after United States, Russia, and Iran). Qatar's NG marketed production is 157 Bm^3, and NG export of 128.71 Bm^3. In 2010, Qatar exported nearly six times as much LNG as Russia. In 2011, it accounted for 31% of the world's LNG exports.

Data on Qatar NG productions are given as [5]: gross production increased from 90,887 Mm^3 in 2008 to 183,698 Mm^3 in 2013 (about doubled in 5 years, and about 4.8% of world production), marketed production increased from 76,981 Mm^3 in 2008 to 177,602 Mm^3 in 2013, flaring gas decreased from 3,597 Mm^3 in 2008 to 741 Mm^3 in 2013, and reinjection decreased from 4,758 Mm^3 in 2008 to 2,650 Mm^3 in 2013 [5]. NG consumption increased from 11.11 Bm^3 in 2002 to 43.21 Bm^3 in 2012, almost tripled in 10 years.

Qatar NG export increased from 56,780 Mm^3 in 2008 to 128,710 Mm^3 in 2012. NG consumption in Qatar is on the rise. The consumption of 43.21 Mm^3 in 2012 is more than 30% that in 2011. Qatar NG consumption compared to production is shown in Fig. 4a. Most of Qatar energy demands are met with NG, and the majority of its LNG production is exported. Fig. 4b shows Qatar's NG export compared with other exporting countries. Qatar's growing NG production has increased its output of condensates

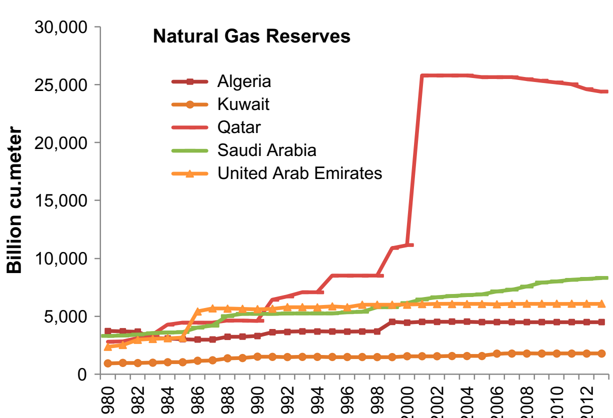


Fig. 3. Qatar and regional countries proven NG reserve in billion cubic meters (BCM) [7].

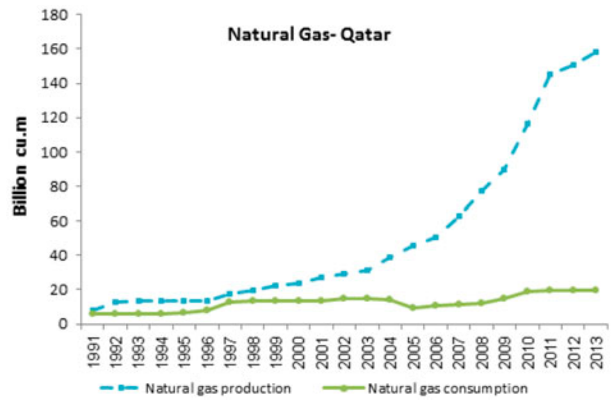


Fig. 4a. History of Qatar's NG production and consumption in billion cubic meters (bcm) [7].

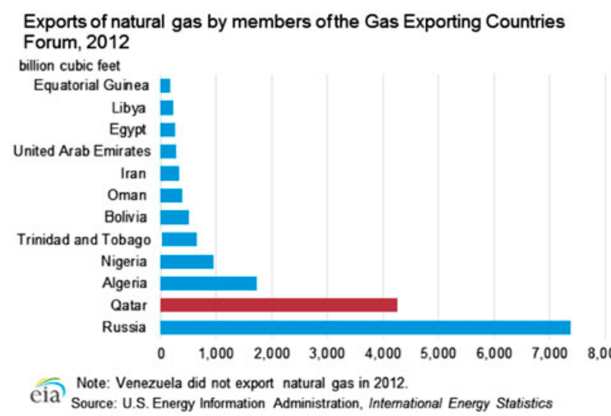


Fig. 4b. Rating of Qatar in exporting NG in billion cubic feet among members of gas exporting countries [7].

and NG plant liquids, which are valuable byproducts of NG production. The NG ratio of the consumed to produce ratio in 2012 is about 24%, and the export to produce is 76%.

1.2. Qatar oil

Qatar's proven crude oil reserve is 25.244 B barrels (bbl) in 2013, the 9th largest reserve in OPEC and 13th largest in the world. Comparison of Qatar's crude oil reserve with other Gulf Cooperation Countries (GCC) countries is shown in Fig. 5a. Crude oil production ranged between 0.8428 Mbbl/d in 2008 and 0.724 Mbbl/d in 2013.

Crude oil export ranged from 0.703 in 2008 to 0.599 Mbbl/d in 2013. The 2013 Qatar's output of petroleum products (in 1,000 bbl) was 113.3 including 38 of gasoline, 21.6 of kerosene, 22.3 of distillates, 6.3 of residuals, and 25.2 of others [4].

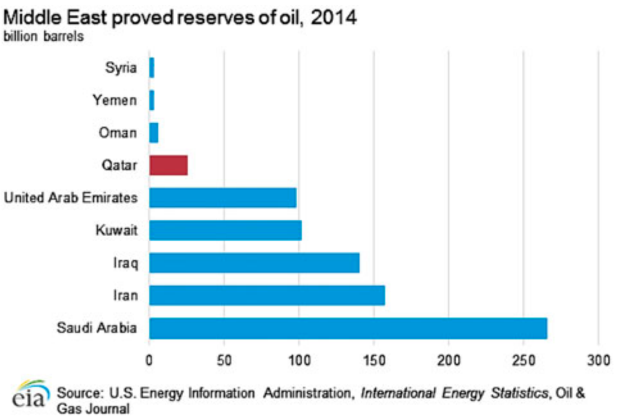


Fig. 5a. Qatar crude oil reserve in billion barrels compared other Middle East countries [7].

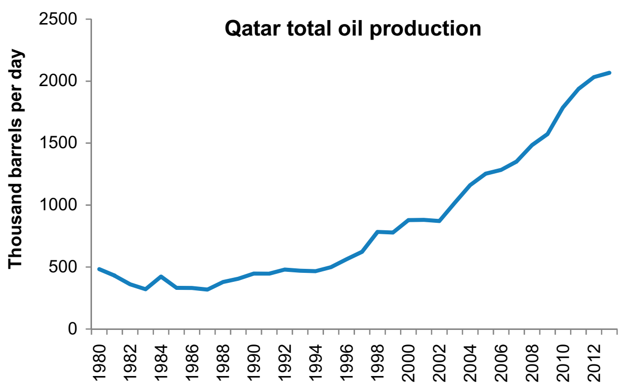


Fig. 5b. Qatar's total oil production in thousand barrels per day [7].

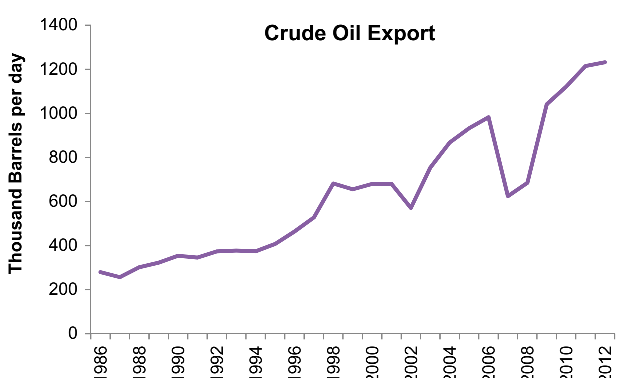


Fig. 5c. Qatar's total oil export [7].

Petroleum products' exports (in Mbbl/d) was 0.096 in 2008, 0.249 in 2009, 0.322 in 2010, 0.509 in 2011, and 0.465 in 2012. Qatar's exports of crude oil and its petroleum products (in Mbbl/d) are 0.801 in 2008, 0.896.0 in 2009, 0.9081 in 2010, 1.097 in 2011, and 1.053 in 2012. Besides crude oil production, there is non-crude liquids (oil) production resulted from the robust NG production, which produces many heavier hydrocarbons in addition to NG. The non-crude liquids production was estimated to be half of Qatar's total oil supply in 2012 (EIA), and its condensate production could surpass 0.8 Mbbl/d by 2015 and reach nearly one Mbbl/d by 2016, (EIA). The Qatar condensate reserves are estimated by more than 22 Bbbl by QNB, (EIA). Fig. 5b shows the historic oil production, including the crude and non-crude oil production. Qatar's oil consumption increased from 0.104 Mbbl/d in 2008 to 0.1260 Mbbl/d in 2012, Table 1.

Table 1
Qatar's oil consumption by type in 1,000 bbl/d [5]

	2008	2009	2010	2011	2012	2013
Gasoline	22.3	24.7	25.1	26.9	31.5	29.6
Kerosene	18.4	19.7	24.9	31.1	33.1	57.5
Distillates	36.3	36.3	38.9	44.1	38.7	39.6
Residuals	–	–	–	–	–	
Others	26.8	27.5			22.7	20.3
Total	103.8	108.2	118.3	124.9	126	147

Qatar's total crude oil and petroleum products increased from 0.896 Mbbl/d in 2009 to 1.11 Mbbl/d in 2013. Qatar's total oil export increased from 1.319 Mbbl/d in 2008 to 1.842 Mbbl/d in 2012, Fig. 5c. Its refinery capacity increased from 0.20 Mbbl/d in 2008 to 0.339 in 2012.

1.3. Qatar electricity

The demand on electric power (EP) rose significantly in recent years, as other energy demands. Qatar has the highest EP consumption per capita in the GCC and among the highest in the world. Qatar's per capita consumed EP was 16.833 kW h per capita per year (kW h/y Ca) in 2013, compared to 16.183 kW h/y Ca for Kuwait, 11.89 kW h/y Ca for UAE, and 8.55 kW h/y Ca for SA. The total consumed EP increased from 16,906 GW h in 2007 to 28,242 GW h in 2011 [7].

All Qatar's power plants (PPs) use NG as fuel. The PPs capacity was increased due to the increase in demand. This capacity increased from 7,830 MW in 2010 to 8,756 MW in 2013 and is expected to reach (according to various estimates) 15,000 MW in 2015. This capacity is more than enough to meet the demand. The peak demand was around 6,000 MW in 2013. In 2012, the generating capacity had a surplus of about 2,500 MW, or nearly 30% [8]. Three of the five powerplants in Qatar are producing electricity and desalted seawater (DW), and are called cogeneration power desalting plants (CPDP).

According to the KAHRAMAA statistical book [9], the generated EP increased from 13,232 GW h in 2004 to 34,668 GW h in 2013, and the maximum demand, increased from 2,520 MW in 2004 to 6,000 MW in 2013. Meanwhile, the DW production increased from 178 Mm^3 in 2004 to 465 Mm^3 in 2013 with a maximum daily production increase from 0.544 Mm^3/d in 2004 to 1.38 Mm^3/d in 2013 [9]. The history of EP production, and installed capacity is given in Figs. 6a and 6b, respectively.

1.4. Qatar prime energy production and consumption

The difference between the prime energy produced and consumed by NG and oil given by Fig. 7, respectively, represents the main income to Qatar. Although the production is about six times the consumption, there is a trend of decreasing this difference.

Qatar total energy production in terms of 1,000 equivalent barrels of oil per day (1,000 beo/d) increased from 3,504.8 in 2009 to 5,441.6 in 2013. Meanwhile, Qatar total energy consumption in 1,000 boe/d increased from 898.7 in 2009 to 1,328.5 in 2013, OAPEC 2014.

Qatar's energy production and consumption in terms of Quadrillion Btu from 2006 to 2012 are given as [7].

	2006	2008	2010	2011	2012
Production (quadrillion Btu)	4.476	5.9071	8.1008	9.528	
Consumption (quadrillion Btu)	0.9506	1.1438	1.1335	1.4867	

The big jump in prime energy production (in Quadrillion Btu) from 4.4760 in 2006 to 9.528 in 2011 (almost doubled in 5 years) is due to two factors. The first is the Qatar's Oryx gas to liquid (GTL) plant became fully operational in early 2009. At full capacity, the Oryx project uses about 330 MMcf/d of NG feedstock from the Al Khaleej field to produce 30,000 bbl/d of GTL products. The second is the Shell Pearl GTL project uses 1.6 Bcf/d of NG feedstock to produce 140,000 bbl/d of GTL products as well as 120,000 bbl/d of NG liquids and liquefied petroleum gasses. These are abrupt changes that cannot continue.

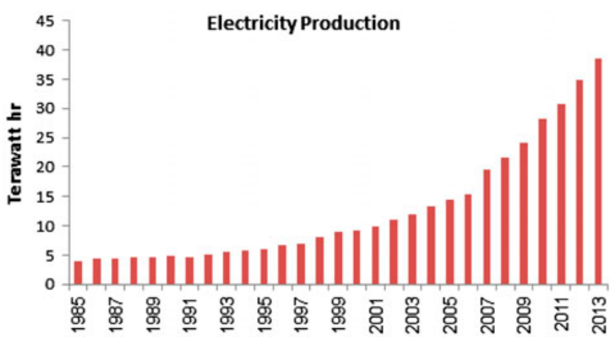


Fig. 6a. Qatar's electricity production tetra watt hours.

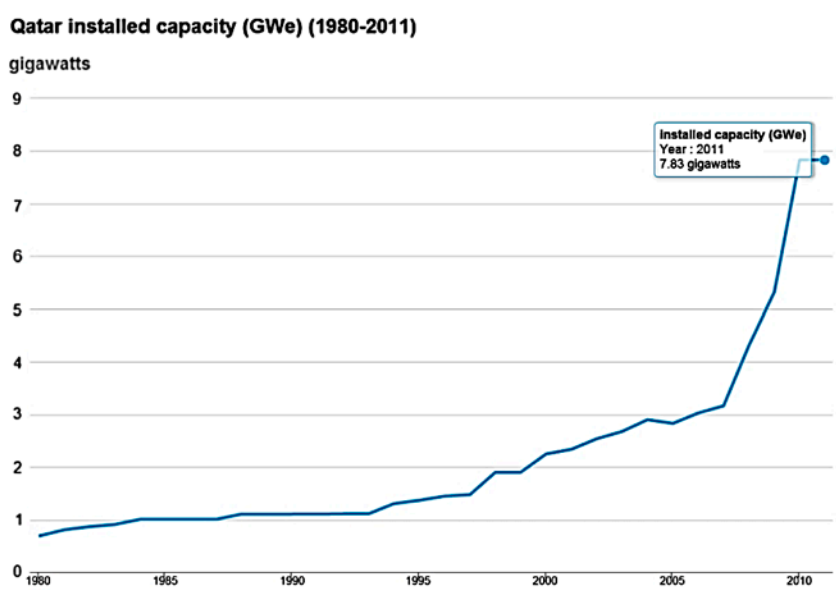


Fig. 6b. Qatar's installed EP plants in GW capacity [7].

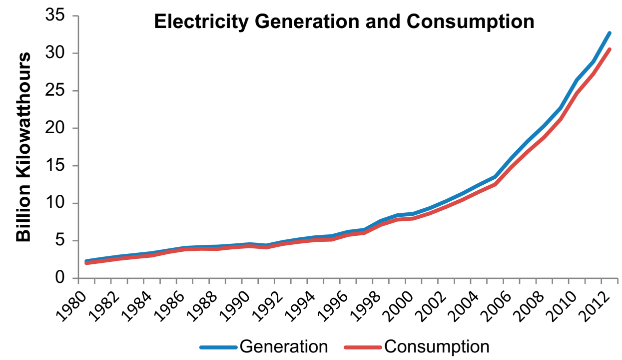


Fig. 7. Electricity generation and consumption between 1980 and 2012 [7].

Meanwhile, the consumption is continually rising at an alarming rate. The prime energy consumption increases from 1.1335 in 2010 to 1.4865 Quadrillion Btu (31% in one year). The total electricity generation and consumption is shown in the Fig. 7.

Qatar's huge oil and NG reserves give the wrong notion that primary energy is almost free, with no incentive to conserve. This is clear from the fact that Qatar's prime energy consumption per capita is among the highest in the world (17.419 ton of oil equivalent per capita (toe/y Ca) in 2012), compared to 10.408 toe/y Ca for Kuwait, 7.353 toe/y Ca for Bahrain, 6.738 toe/y Ca for SA, 1.143 toe/y Ca for Jordan, and 0.312 toe/y Ca for Yemen.

This is a wrong attitude as oil and NG resources are finite, will deplete, and their savings increase their export and economic returns. Energy conservation is necessary everywhere, as more energy consumption leads to more negative impact on the environment, more economic loss, and less sustainability. High demands on electricity are already causing NG shortage in all GCC, except Qatar, for the time being. Fast population growth means more consumed energy, and the rate of energy consumptions is more than its rate of production in all GCC, maybe with exception of Qatar for the time being again, and this cannot be hold more in near future.

Qatar succeeded in raising the value of its energy exports by liquefying the most of its NG production for cheap export and refined more of its crude oil production. Qatar should invest more in clean energy like solar energy. Kahramaa's first solar power facility, to be set up in Duhail over 100,000 m^2 area, is expected to be operational by 2016 with a generation capacity of 15 MW. Kahramaa has targeted a generation capacity of 200-MW solar power at 60 sites across the country by 2020, tallying to roughly one million m^2 of space [10].

1.5. Qatar water resources

Despite acute freshwater shortages, nearly 100% of the population has full access to clean drinking water and sanitation facilities. This is a great achievement. Qatar energy wealth is utilized effectively in water infrastructure (from production to distribution) to alleviate the natural water resources shortages. DW provides 99% of municipal water demands, but at the expense of consuming huge amounts of fuel energy and cost. Energy is also used in collecting and treating wastewater before its disposal. Therefore, sustaining water security depends on the availability of fuel energy and funding of the water desalting projects.

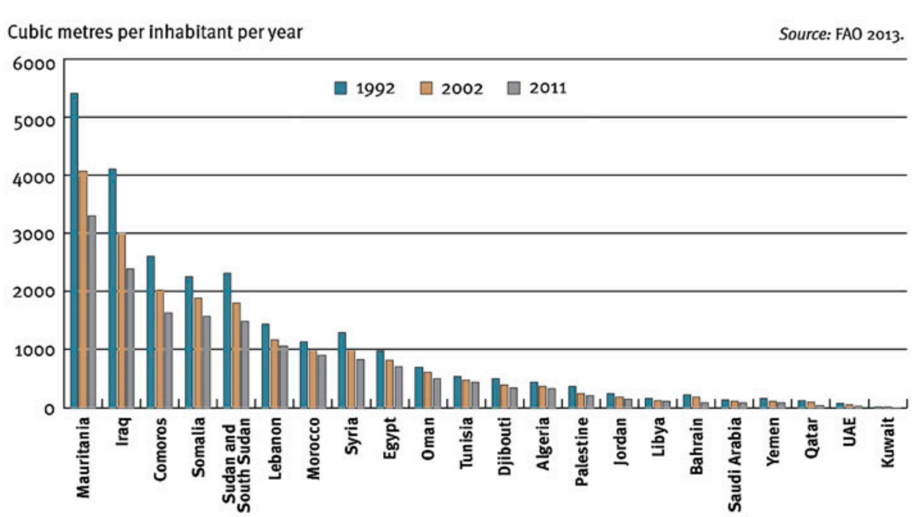
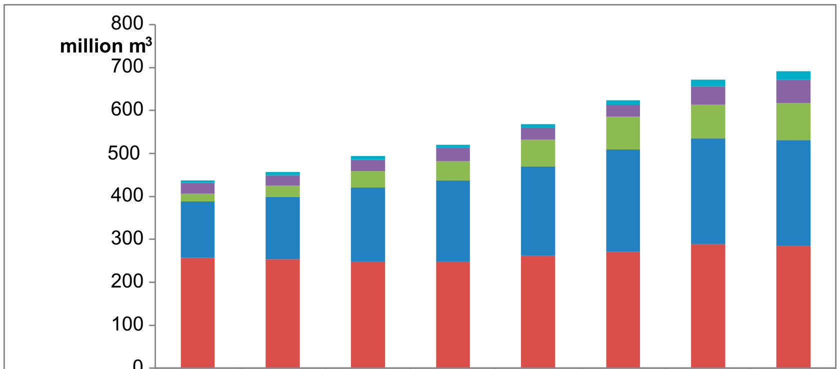


Fig. 8a. Total renewable water resources, 1992, 2002, and 2011 in m^3/y Ca [11].



	2006	2007	2008	2009	2010	2011	2012	2013
Industry	6.10	6.80	8.60	7.18	7.58	9.58	14.66	19.18
Commercial	24.60	24.80	26.20	30.90	27.90	29.10	42.58	54.38
Government	18.39	26.23	38.77	45.07	62.33	75.68	79.11	86.67
Households	130.62	144.55	172.57	188.52	209.08	238.17	246.32	245.50
Agriculture	257.69	254.05	248.15	248.89	261.16	271.45	288.76	285.28

Fig. 8b. Disaggregated water consumption from 2006 to 2013 [13].

Qatar, as most of the GCC, is an arid land and is one of the world poorest countries in natural freshwater resources. Fig. 8a shows that the Kuwait, UAE, and Qatar are the water poorest in the GCC [11]. The data collected by the Ministry of Environment (MoE) show that the total water withdrawal in 2011 was 771.33 Mm^3/y. The freshwater withdrawal includes 414.382 Mm^3/y (53.6% of total withdrawal) originated DW, and 257.2 Mm^3/y (32.4% of total withdrawal) from groundwater (GW) abstraction. The reuse water originated from treating wastewater (WW), sometimes called treated sewage (TSE) as shown in Fig. 8b is 107.986 Mm^3/y (14.0% from total withdrawal). Besides the very limited water for agriculture, the land for agriculture (64 thousand hectares area) is also limited, out of 1,161 thousand hectares of the total area of the country.

Due to the dramatic increase in population, the DW increases from 178 Mm^3 in 2004 to 465 Mm^3 in 2013. Furthermore, water consumption increased in the industrial sector from 42.5 Mm^3 in 2012 to 70.6 Mm^3 in 2013 as a result of two new intensive petrochemical production lines that came on stream in 2013 [12]. These figures exclude seawater that is used for cooling and returned directly to the sea. The groundwater (GW) extraction for irrigation remained constant from 2008 to 2012 due to the slow agricultural expansion and/or abandoning of agriculture farms resulted from GW increased salinity. Water share from desalination is increasing, while the GW remains constant as shown in Fig. 8c. Increasingly, the government realizes the potential of reusing treated wastewater (TWW) for several applications. However, there is still huge scope for improvement.

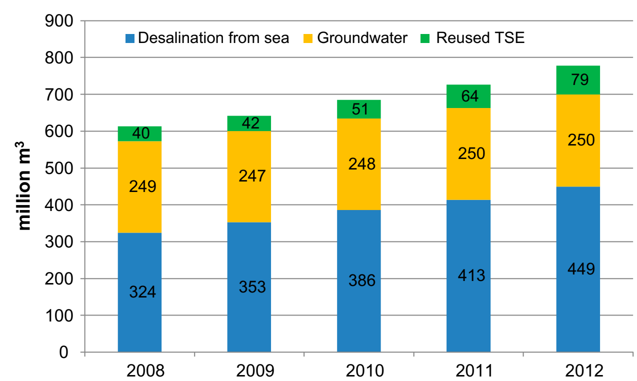


Fig. 8c. Water uses and water losses in 2011; data sources: MoE, Kahramaa, Ashghal [13].

1.6. Natural water resources

1.6.1. Rainwater

The annual precipitation rate is very low, about 74 mm per year (mm/y) and the evaporation rate is very high (2,000 mm/y). So, rainwater is not considered as a natural freshwater resource, although very low amount of rainfall is seeped to groundwater (GW).

1.6.2. Groundwater (GW)

GW may be considered the only natural freshwater resource, although it is over-extracted, quality deteriorated, and its usage as freshwater can be terminated in a few years. The GW replenishment rate is 58 Mm^3/y while its abstraction rate reached 257.2 Mm^3/y in 2012 as reported by Nagy [13] and 400 as reported by Sadik [14].

The 58 Mm^3/y replenishment rate of GW and 2.1 M population in 2014 give per capita average natural water resource less than 29 m^3/y Ca; and this was 450 m^3/y Ca in 1970, 218 m^3/y Ca in 1980, 103 m^3/y Ca in 1990, 85 in 2000, and becomes 29 in 2012. This is far below the worldwide average of 6,000 m^3/y Ca, and the recognized water poverty line of 1,000 m^3/y Ca [15]. In 2012, the GW withdrawals were estimated by Sadik [14], as 400 Mm^3/y, including 236 Mm^3/y for agriculture, 8 Mm^3/y for industry, and 156 Mm^3/y for domestic uses. However, there are other sources that provide different values as 250.45 in 2011 including 230.05 for agriculture, 0.18 for industrial, 9.6 for domestic, 10.38 for municipal, and 0.24 for KAHRAMAA [13]. Sadik [14], compared the water withdrawal in the GCC as percentage of annual freshwater resources (2009) in Table 2, and showed that Saudi Arabia (SA) suffers the biggest gap between renewable supply and demand.

Qatar's GW withdrawals from 1976 to 2009, as well as the number of wells, are shown in Fig. 8a. Fig. 8b shows the area underlain by freshwater (<1,000 ppm, parts per million) and good brackish water (2,000–3,000 ppm) in North Qatar, 1971–2008 [15]. Table 3 shows Qatar GW abstractions and its usage in 2009.

Table 2
Water withdrawal in the GCC as percent of annual freshwater resources (2009) [14]

Country/sub-region	All uses (%)	Agriculture use (%)
Bahrain	344.8	155
Kuwait	4,500	2,500
Oman	92.3	82
Qatar	689.6	407
Saudi Arabia	987.5	869
United Arab Emirates	2,666.6	2,213
GCC	740	633
Yemen	171.9	156
GCC and Yemen	549.3	472

The works on many farms in Qatar and UAE have been stopped [16], and [17]. About 8,000 farms have been abandoned (or near abandoned) out of 24,000 farms in Abu Dhabi, western region of the UAE, and Al Ain in UAE. Concerns have been growing about the depletion of GW and deteriorating quality.

The fossil GW is a finite and irreplaceable once being mined. Mining GW may be beneficial in the short term, but it is a real loss in the long term as this water should be considered as the country's national wealth. Over-exploitation beyond the replenishment rate drastically reduces the area underlain freshwater of less than 1,000 ppm salinity, and good brackish water of 2,000–3,000 ppm as shown in Fig. 9b. This figure gives the history of the areas underlain by fresh and brackish water in North Qatar brackish water.

The GW total dissolved solids (TDS) distribution in 2009 is given in Fig. 9c. The TDS in GW is obtained by measuring the specific conductivity of the GW. Historical TDS map from 1971 to 2003 is given in Fig. 9b, and in 2009 is given in Fig. 9c.

The GW TDS distribution in 2009 is given in Fig. 9c. The TDS in GW is obtained by measuring the specific conductivity of the GW. Historical TDS map from 1971and 2009 is given in Fig. 9d.

Fig. 9b indicates that between 1982 and 2008, the total area underlain the freshwater (TDS < 1,000), suitable for irrigation, has been reduced to nearly 20% of its original area (from 1,278 to 275 km^2); the area underlain good brackish water (of TDS between 1,000 and 2,000 ppm) has been reduced by nearly 45% (from 1,785 to 1,025 km^2), and the area underlain brackish water (of TDS 2,000–3,000 ppm) has been reduced by 20%. Table 4 shows the changes in an area underlain by freshwater and low salinity brackish water from 1971 to 2009. Based on current GW abstraction, freshwater will completely disappear in 2018 [15]. The freshwater lens, accumulated in northern-central part of Qatar, has declined in the area, which represented 15% of the country's area in 1971 to become 2% in

Table 3
Qatar 2009 GW abstractions and its usage [15]

Well site use	Rate (m^3/d)	Rate (Mm^3/d)	Percentage of total (%)
Farm	866,435	226	90.9
Municipal	35,677	9.3	3.7
Domestic	38,114	9.9	4.0
Industrial	13,070	3.4	1.4
Total	953,296	248.7	100

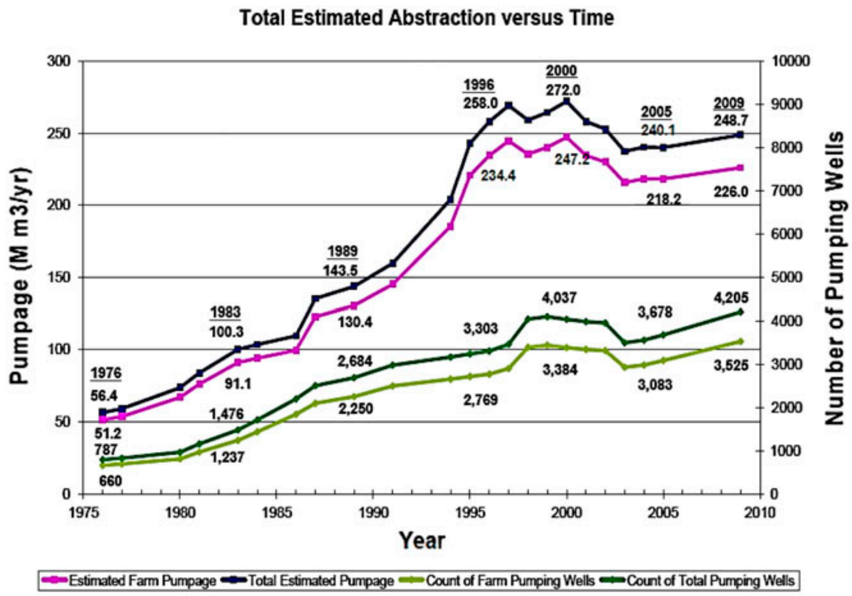


Fig. 9a. Qatar farming and total GW abstraction, and a number of wells from 1977 to 2009 [15].

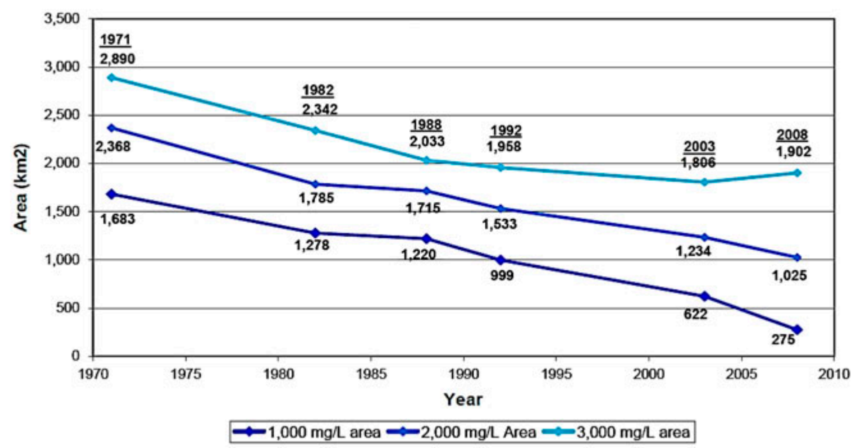


Fig. 9b. Area underlain by freshwater (<1,000 ppm) and good brackish water (2000–3,000 ppm) in North Qatar, 1971–2008 [15].

2008. The freshwater lens in 2009 was approximately 11% of its size in 1971 and continues its shrinkage as indicated in Table 4.

It is noticed that water with TDS between 1,500 and 3,500 ppm could be harmful to plants exceeding above 3,500 ppm is unsuitable for irrigation. Deterioration of water quality forces the abandonment of some farms.

The depletion of freshwater from GW aquifer should be considered by authorities as a serious issue. The GW aquifers should be viewed as a strategic resource to sustain various water uses, conserve ecosystems and provide emergency reserves in case DW production is stopped. Dependence on DW alone could be risky. The GW could be recharged with potable water quality to sustain its usage. This idea starts to be applied in both Kuwait and UAE. Strong measures are adopted in Saudi Arabia to reduce extractions in order to keep the GW sustainable. The GW is mostly used for agriculture. GW management is needed through monitoring and pricing mechanisms and improving irrigation efficiency. The irrigation efficiency can be improved by using modern pressurized irrigation systems, micro-irrigation, and automated irrigation scheduling systems to increase water productivity; while shifting from low value vegetables

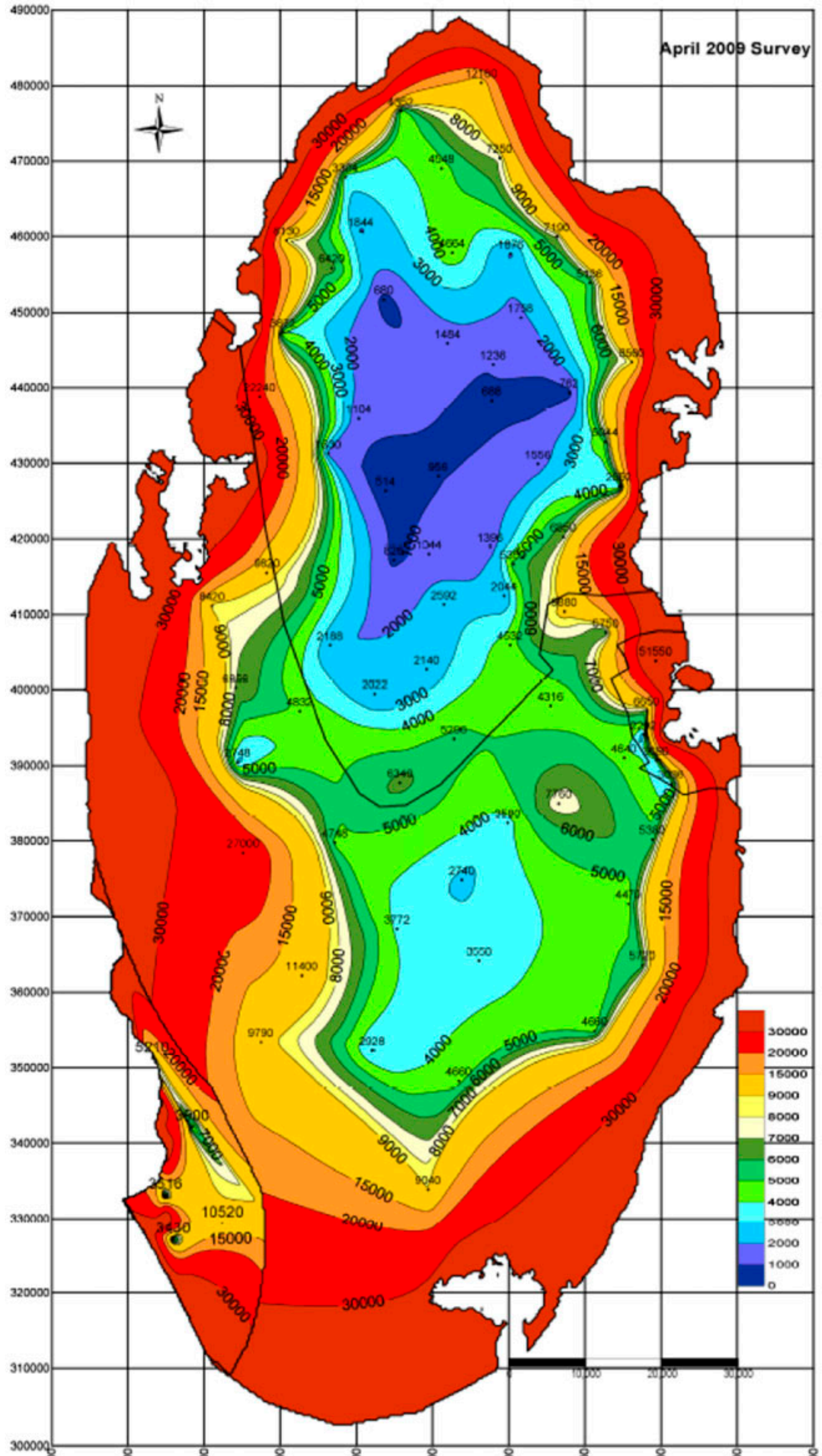


Fig. 9c. TDS is concentration map, [15], Reused with permission.

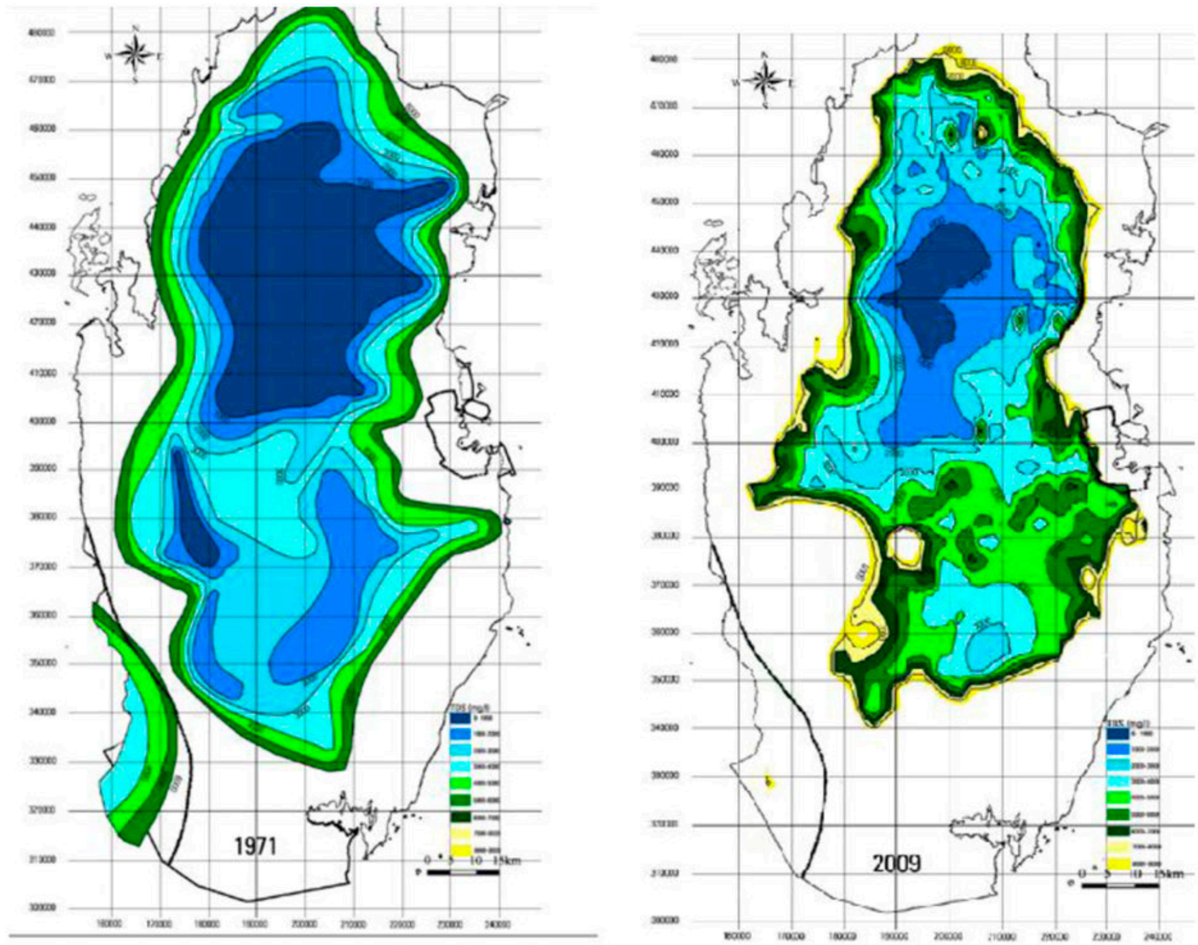


Fig. 9d. Historic TDS in groundwater map between 1971 and 2009, [15], Reused with permission.

Table 4
Changes in an area underlain by freshwater and low salinity brackish water, 1971–2009 [15]

	TDS < 1,000 mg/l	TDS < 2,000 mg/l	TDS < 3,000 mg/l
1971 area (km^2)	1,683	2,368	2,890
1971% of country area	15%	21%	25%
2009 area (km^2)	186	897	1,782
2009% of country area	2%	8%	16%
2009% of 1971 area	16%	43%	66%
Projected year to reach zero area	2018	2037	2056
Year remaining	4	13	42

grown in open fields to high value vegetables grown in greenhouses. This practice is started in many farms in Qatar.

1.7. Qatar water consumption

Qatar water withdrawal (771.33 Mm^3/y in 2011) is far beyond its natural freshwater resources (58 Mm^3/y or 7.5% of total withdrawal). In 2011, the water withdrawal included about 250 Mm^3/y of GW, and 414.382 Mm^3/y of DW [13]. For the 2011 population of 1.91 M, then, the per capita total daily consumption was 953 liters per capita (l/d Ca), accounting the total withdrawals and water losses which is one of the highest in the world. Severe water shortage with very high consumption impacts national development

Table 5a
Qatar's main power and desalting plants capacity up to 2010 [20]

Desalination plant	Power plant capacity (MW)	Total capacity (m^3/d)	Total capacity (MIGD)	Starting date
Ras Abu Fontas A	497	318,226	70	1980
Ras Abu Fontas B	609	150,000	33	1995
Ras AbuFontas B1	377	240,000	53	2002
RasAbuFontas B2	567	136,000	30	
RasLaffan A	756	181,843	40	2003
RasLaffan B	1,025	272,760	60	2006
Meisieed	2007			2009
RasGirtas	2,730	286,400	63	2011
Satelites	184			1983
Total	8,752	1,450,229	349	

while endangers water and food securities, and the environment. The DW is mainly produced by consuming the available NG as fuel that runs the co-generation power-desalting plants (CPDP). Qatar desalting capacity in 2013 was reported as 1.78 Mm^3/d, one of the 10th highest in the world, Global Desalination Capacity [18], while it was 1.47 Mm^3/d in 2010 as given in Table 5a. Other non-conventional water resource in Qatar, besides DW, is the recycled TWW. Water consumption in the country is increasing at alarming rates. The DW production (accounts for about half of Qatar's water usage and 99% of municipal water) is very costly and energy intensive process. Moreover, the desalting plants occupy a large land area on the seacoast [19].

The US is considered to have one of the highest daily consumed water per capita (575 l/d Ca) in the world, ahead of France (287 l/d Ca), United Kingdom (149 l/d Ca). Qatar's consumed municipal water is about 62% of DW, after deducting the network loss, and the industrial and utility consumptions from the DW. The DW production in 2014 is estimated to be 1.2 Mm^3/d (or 438 Mm^3/y). The reported network losses reached more than one-third of total production in 2006, declined to 28% in 2010, but still higher than the target of 18% [4]. The water consumptions by industrial and utilities reached 43.16 Mm^3 in 2012 (about 10% of the DW production), and includes (in Mm^3) 13.821 for power and utilities, 11.31 for refining, 7.864 for petrochemicals, 7.45 for LNG/NG, 2.463 for mining, minerals, and others, 0.04 for support services, 0.315 for oil and gas (E&P), and 0.0087 for transport, storage, and distribution. So, the municipal water consumption is 354 l/d Ca. The high consumption per capita is mainly attributed to the high government subsidization, high leakage in the water distribution net and public unawareness of the value of water.

1.8. DW

The role of DW is expected to grow in Qatar due to growing of population, urbanization and industrialization, and depletion of GW. Desalination plants (DP) in Qatar (by the end of 2010) had a cumulative capacity of 325 million imperial gallons per day (MIGD) or almost 1.5 million cubic meters per day (Mm^3/d). Table 5a shows the main power and desalting plant's capacity up to 2010. Table 5b shows the capacity of the several desalination types in m^3/d in Qatar in 2011, and thermal desalting system (multi stage flash (MSF) and ME-TVC) is more than 90%, and the seawater reverse osmosis (SWRO) is less than 3.2%. Fig. 10a shows the capacity distribution in Qatar and SA.

In Qatar, DW represents 99.9% of the municipal water, and the balance 0.1% is GW. About 80.5% of the thermal DP are MSF type, and the balance (about 19.5%) is multi effect-thermal vapor compression type (ME-TVC). The main desalting plants, MSF and ME-TVC used in Qatar are combined with PPs to obtain their thermal energy input (steam extracted from turbines). The combined DP with PP is called cogeneration power desalting plants (CPDP).

The small capacity of reverse osmosis (RO) in Qatar (170,497 m^3/d) is divided by 48% for seawater

Table 5b
The capacity of the desalination types in m^3/d in Qatar in 2011 [21]

ED (electrodialysis)	140
Other/unknown	15,002
RO (reverse osmosis)	170,497
MED (multi-effect distillation)	353,931
MSF (multi-stage flash)	1,460,715

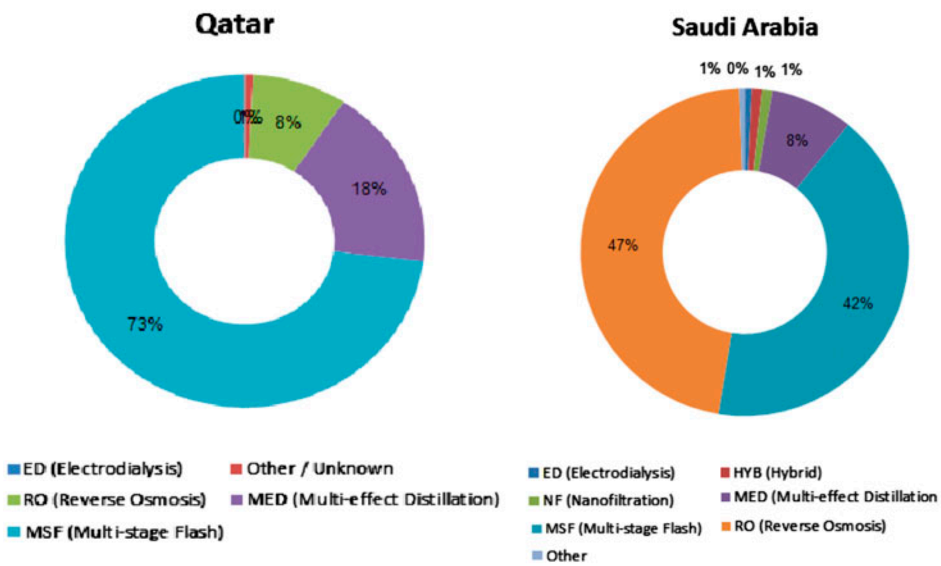


Fig. 10a. Percentages of the different desalination types in Qatar and SA [21].

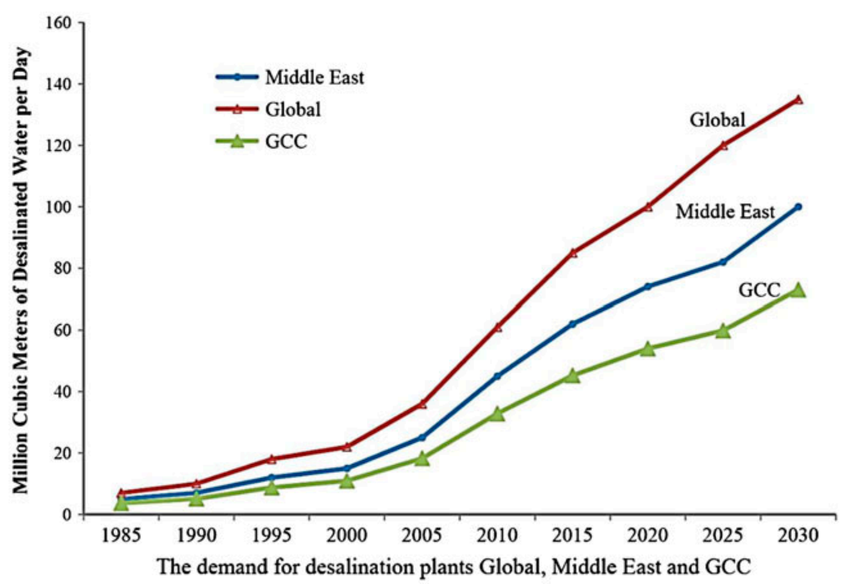


Fig. 10b. Current and expected demands for DW in the GCC, Arab countries, and world [24].

and 52% for brackish water. The electro-dialysis (ED) is mainly for brackish water RO. The share of SWRO in desalting plants in Qatar is less than 3.2% of total capacity, while this ratio increased to become 47% in SA because it is more energy efficient compared to thermal desalination methods, Fig. 10a. Recently, Qatar decided to build Umm Al-Houl CPDP plant, which will have 60 MIGD of SWRO, and 76.5 MIGD of MSF units.

An example of the latest CPDP in Qatar is the RasGirtas plant located in Ras Laffan Industrial City, Qatar. The plant's EP capacity (2,730 MW) is produced by eight gas turbines and four steam turbines (ST). The plant was commissioned on May 2011, and it cost 3.9 \$bn. It is fully operated with DW production of 286,000 m^3/d (63 MIGD). It uses 10 ME-TVC desalting units. Also, two MSF desalting units of 18 MIGD each (total 160,000 m/d) are to be built in Ras Abu Fontas by the end of 2015. The capacity of this plant is almost 10% of Qatar's total DW production. The power required for running the facility will be supplied from the 597 MW RAF B2 PPs.

Table 6
The 2012 estimated daily desalted water production in the GCC [19]

Country	Thermal + SWRO + BW (m^3)	Thermal processes (m^3)	SWRO (m^3)	Thermal processes energy cost ($B/y)	SWRO processes energy cost ($B/y)
SA	13,530,973	5,426,131	5,479,792	4.753	1.200
UAE	9,753,024	7,411,069	2,209,065	6.492	0.484
Kuwait	2,134,253	1,461,136	275,254	1.280	0.060
Qatar	1,944,195	1,771,638	155,160	1.552	0.034
Oman	1,626,149	417,990	988,888	0.366	0.217
Bahrain	1,398,064	756,967	582,667	0.663	0.128
Total	30,386,658	17,244,931	9,690,826	15.107	2.122

The extensive use of MSF and ME-TVC in the GCC is due to their high reliability, as any shortfall in production cannot be afforded. The MSF and ME-TVC main problem is the extensive use of energy. Both use thermal energy in the range of 265 MJ/m^3, besides pumping energy of 4 kW h/m^3 for MSF and 2 kW h/m^3 for ME-TVC. This is very high compared to the energy consumed by seawater reverse osmosis (SWRO), which consumes pumping of 4–6 kW h/m^3, but needs extensive feed seawater pre-treatment. A small-scale RO plant was built by Qatar Electricity and Water Company (QEWC) as part of a trial in Dukhan, treating high salinity water with a capacity of 750 m^3/d. In 2003, QEWC acquired another Dukhan Desalination RO desalting plant of 9,000 m^3/d, which was previously owned by Qatar Petroleum [25].

All brackish water plants are small capacity, and using RO spiral wound membrane systems using spiral wound membranes, except one opened in 2014, that has 35,000 m^3/d. Qatar's annual DW production increased from 178 Mm^3/y in 2004 to 373 Mm^3/y in 2010 [9], (almost doubled in 6 years or 14% annual increase) and is expected to reach 438 Mm^3/y in 2014. This is based on 6.5% average annual increase [18].

Fig. 10b shows the demand projection of DW in GCC, Middle-East, and worldwide. Table 6 gives all GCC estimated DW production in 2012 as 26.937 Mm^3/d. These include 17.245 Mm^3/d thermally operated plants used only in the GCC, namely, MSF, and multi effect-thermal vapor compression (ME-TVC), and 9.690 Mm^3/d by SWRO [21]. Table 6 also gives the annual cost in billion dollars per year ($B/y). Fig. 11 gives the top 10 DW producer countries with their capacity and shows that became one of those 10 highest DW producers in the world [18].

DP in Qatar are vulnerable to unforeseen conditions such as oil spills that can force desalting plants to shut down. This factor, besides the inefficiency of the used desalting methods, threatens the water security or requires large investments to ease

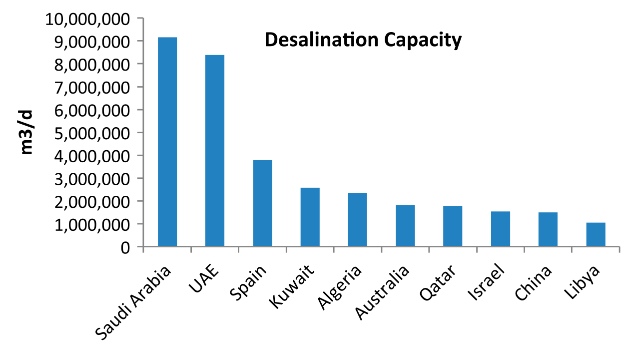


Fig. 11. The top 10 seawater desalination countries by online capacity [18].

shortages. The continuous growing water demands are met by building more desalting plants, and more NG consumption. The desalination plant's capacity reached 325 MIGD, or 1.478 Mm^3/d in 2010, reported to be 1.9 Mm^3/d in 2013, and still there are plans to invest heavily in further desalination facilities.

KAHRAMAA invested in the water storage construction activity, undertaking $B2.8 reservoir project capable of holding seven days of DW as a backup for DW supply. The 1.9 B gallon 8.65 Mm^3 facilities will include a network of reservoirs connected by 183 km, 2.5 meters wide pipeline linking the Ras-Laffan desalination facility in Qatar's North and the Ras Abu Fontas plant in the south.

It is questionable that building more desalting plants are a sustainable solution to face the rising water demands in view of the substantial economic burden, negative environmental impact, and high fossil fuel cost, even it is abundant now.

Most GCC follow the same approach of adding more seawater desalting plants, which is energy intensive and of high capital cost to meet rising water demands. Producing DW reduces pressure on water resources, while negatively affecting air and marine environments.

1.9. Wastewater and its treatment processes

Qatar's municipal wastewater (WW) has to be treated before its disposal into receiving water or land to lower its harmful compound concentrations. Qatar's WW treatment plants (WWTP) are built and operated by the Public Work Authority (Asghal), with the goal to treat WW to avoid (or reduce) its bad effects on receiving surrounding. The harmful contaminants include organic materials, pathogens, nutrients, and synthetic chemicals. The high content of organic matters or nutrients can lead to O_2 depletion in receiving water or eutrophication [22]. Eutrophication is the process by which a body of water acquires high concentration of nutrients, especially phosphates and nitrates that promote excessive growth of algae. As the algae die and decompose, high levels of organic matter and decomposing organisms deplete the water of available oxygen, causing the death of other organisms, such as fish, (i.e. the natural aging of water bodies).

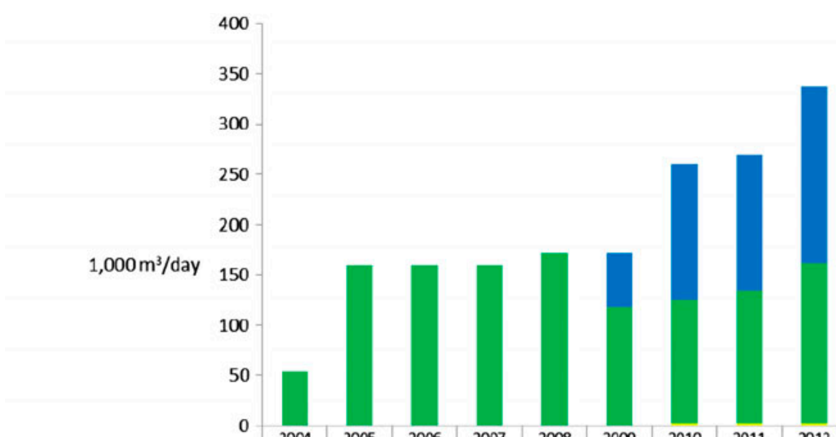
Qatar has the following WWTP with (capacities): Doha West (135,000 m^3/d), Doha South (112,000 m^3/d), Lusail (60,000 m^3/d), Doha industrial area (12,000 m^3/d), Alkhor (4,860 m^3/d), and Al Thakhira (30,000 m^3/d); total capacity of (352,860 m^3/d) [18]. Doha North would be the largest WWTP, under-construction to treat 439,000 m^3/d [25] and thus the total capacity would be 701,860 m^3/d soon.

Nagy [13] reported that all present WWTP of 335,000 m^3/d total capacity are treating WW to tertiary level, with 175,500 m^3/d of dis-nitrification, i.e. nitrogen (N) removal, and phosphorous (P) removal, 159,400 m^3/d for just disinfection, and 2,000 m^3/d for secondary treatment, Fig. 12.

Parts of Qatar's treated WW (TWW), called TSE, are reused in agriculture and aquifer recharge. The WW treatment (WWT) process is complex, and biological treatment has many details, not to be fully discussed here. The influent and effluent water qualities different treatment processes in Doha West WW plant are given in Table 7.

In this section, we limit our discussion of energy requirements for wastewater treatment processes. The energy consumed in collecting WW can be near zero for gravity-fed systems, or may be high if large volumes of water are conveyed for long distances or to high elevation. When sewers, say, are below ground, WW is pumped to a higher elevation with the energy consumed. Pumping stations for untreated WW (sewage) must be capable of handling some solids, grease, grit, and stringy material. No data are available on Qatar's WW collecting system, except it was connected in 2004 to almost 100% of Mesaieed and Doha housing, 67% in Al Rayyan, and 54% in Wakra [24]. A typical consumed average energy for collecting WW is 150 kW h per MG (0.04 kW h/m^3) depending on topography, system size, and age [26].

Energy consumed in the WW treatment (WWT) processes depends on WW constituents and TWW's final TWW quality. Treatment levels are commonly known as: primary, secondary, tertiary, and advanced or quarterly; and each has its uses. The final WWT level is determined by the water body or land where



	2004	2005	2006	2007	2008	2009	2010	2011	2012
Tertiary treatment (N + P removal)						54.0	135.0	135.0	175.5
Tertiary Treatment (Disinfection)	54.0	160.0	160.0	160.0	172.0	118.0	123.0	131.8	159.4
Secondary treatment						0.1	2.2	2.2	2.0

Fig. 12. Design capacity per treatment type of urban wastewater treatment plants in Qatar [13].

Table 7
Doha South Sewage Treatment Works, Doha, Qatar (4 July 2013)

Sample point Sample type	Standard [a]	Inlet Grab	Inlet anaerobic tank outlet Grab	Anoxic tank outlet Grab	Aerobic tank outlet Grab	Balancing tank (clarified water) Grab	Sand filters Grab	Cl contact tank outlet[b] Grab
Ambient T (°C)		40	40	40	40	40	40	40
Sample T (°C)		35	34	35	33	35.5	35	35.5
pH	6–9	7.18 (7.2[c])	6.92	7.05	7.10	7.35	7.16	7.16(6.8[c])
BOD_5 (mg/L)	10	156C						1[c]
COD (mg/L)	150	395[c]						19[c]
TDS (mg/L)	2,000	1,643[c]						
TSS (mg/L)	50	166[c]						0.3[c]
Conductivity (μS/cm)		1,643	2,173	2,330	2,375	2,145	2,076	2,093
Salinity (mg/L)		806	1,065	1,142	1,164	1,048	1,017	1,028
Chloride (mg/L)	0.1							
Fluoride (mg/L)	15							
TKN, N	35							4.6[c]
Ammonia, NH_4	+15							
Phosphate, PO_4^{3-}	30	8.5[c]						1[c]
Sulfate, SO^{4-}	400							
Sulfide, S^{2-}	0.1							
FC (MPN/100 mL)	2.2							0[c]
DO (mg/L)	>2							7.1[c]
Aluminum (mg/L)		0.037	0.003	<0.001*	<0.001*	0.005	<0.001*	<0.001*
Arsenic (mg/L)		0.001	0.002	0.002	0.002	0.002	0.002	0.001
Boron (mg/L)		0.208	0.243	0.251	0.251	0.253	0.243	0.234
Cadmium (mg/L)		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Chromium (mg/L)		0.002	<0.001*	<0.001*	0.001	<0.001*	<0.001*	<0.001*
Cobalt (mg/L)		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Copper (mg/L)		0.005	0.001	0.001	0.002	0.001	0.002	0.002
Iron (mg/L)		0.330	0.313	0.331	0.335	0.284	0.269	0.259
Lead (mg/L)		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Manganese (mg/L)		0.021	0.043	0.043	0.040	0.040	0.001	<0.001*
Mercury (mg/L)		0.004	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Nickel (mg/L)		0.004	0.003	0.003	0.003	0.003	0.003	0.003

(Continued)

Table 7 (*Continued*)

Sample point		Inlet	Inlet anaerobic tank outlet	Anoxic tank outlet	Aerobic tank outlet	Balancing tank (clarified water)	Sand filters	Cl contact tank outlet[b]
Sample type	Standard [a]	Grab	Grab	Grab	Grab	Grab	Grab	Grab
Zinc (mg/L)		0.006	0.010	0.009	0.007	0.011	0.012	0.008
Oil and grease (mg/L)	10							
Phenols (mg/L)	0.5							
TOC (mg/L)	75							

[a]Qatar Ministry of Environment (undated).
[b]Post-ultrafiltration.
[c]Average results as reported by Doha South STW.
*Concentration was below detectable limit. The detectable limit for ICP-MS is 1 ppb (0.001 mg/L) to 5 ppm (5 mg/L).

the TWW is to be disposed to, or reuse application requirements if the WW is to be reclaimed. Reclaimed TWW is a water source that should be seriously considered in arid areas.

The WW constituents [27,28] include:

(1) Organics, carbon (C) based, and oxygen (O_2) and hydrogen (H_2) concentration that are usually determined by biochemical oxygen demand (BOD). The BOD is the amount of oxygen required to transfer the carbon content to carbon dioxide and water. Also, chemical oxygen demand (COD) and total organic carbon (TOC) are used to find some carbon contents.
(2) Solids that can be dissolved or suspend in wastewater, and known as: total solids (TS), total suspended solids (TSS), TDS, total volatile solids, and total fixed solids.

Nutrients, such as N and P can accelerate eutrophication. N is present in many forms (NH_4^+, NH_3, NO_3^-, NO_2^-, Org-N) and certain parameters include several species (Tot-N), and similar for phosphate (Org-P, PO_4^{3-}, HPO_4^2) [23].

Eutrophication is the process by which a body of water acquires a high concentration of nutrients, especially phosphates and nitrates. They promote excessive growth of algae. When the algae die and decompose, high levels of organic matter and the decomposing organisms deplete the oxygen in water, causing the death of other organisms, such as fish, (i.e. the natural aging of water bodies). Typical sewage composition with components' concentrations (in mg/l) are: TS (300–1,200), SS (100–350), TOC (80–290), BOD_5 (110–400), total nitrogen N (20–85), ammonia NH_3 (12–50), nitrate (0), nitrite (0), and total P-phosphorous macronutrient (4–15) [23].

The organic matters, (C based, O_2, and H_2), can also be attached to N, P, and other molecules. Removal of organic matters is necessary since they cause O_2 reduction in the effluent recipient. Treatment of organic compounds (with C) is to convert C to common gasses like carbon dioxide (CO_2) and N, by making dissolved O_2 available. Since direct measuring the amount of organic material is difficult, the amount of O_2 required to degrade them are used (BOD) instead as given before. Degradation is carried out by micro-organisms consuming O_2. The BOD value is a measurement of the amount of O_2 consumed by the micro-organisms during a five-day period (BOD_5) or a seven-day period (BOD_7) [23].

Organic matter and ammonia are "oxygen-demanding" substances. They are usually destroyed or

Table 8
Major contaminants in wastewater and unit operations, processes, and treatment systems used to remove them [29]

Contaminant	Unit operation, unit process, or treatment system
Suspended solids	Screening and comminution (shredding)
	Grit removal
	Sedimentation
	Filtration
	Flotation
	Chemical polymer addition
	Coagulation/sedimentation
Biodegradable organics	Activated sludge variations
	Fixed film reactor: trickling filters
	Fixed film reactor: rotating biological contactors
	Membrane bioreactors (MBRs)
	Lagoon variations
	Intermittent sand filtration
	Physical-chemical systems
	Natural systems (land treatment)
Dissolved solids	Membranes
Pathogens	Chlorination
	Hypo-chlorination
	Bromine chloride
	Ozonation
	UV Radiation
Nutrients	
Nitrogen	Suspended-growth nitrification and denitrification variations
	Fixed-film nitrification and de-nitrification variations
	Ammonia stripping
	Ion exchange
	Breakpoint chlorination
	Natural systems
Phosphorus	Metal salt addition
	Lime coagulation/sedimentation
	Biological phosphorus removal
	Biological-chemical phosphorus removal
	Natural systems
Nitrogen and Phosphorus	Biological nutrient removal
	Natural systems

converted to other compounds by bacteria if there is sufficient oxygen present in the water, but the dissolved O_2 needed to sustain fish life is used up in the break down process.

The existence pathogens like bacteria or viruses in the discharge streams can cause diseases in species close to WW stream and disinfection is necessary to avoid that. High concentrations of nutrients, N and P can lead to massive algae growth, and synthetic chemicals may have toxic, adverse effects on ecosystems.

Meanwhile, WWT can be extended for reuse (reclamation). In arid countries, reclaimed TWW can be water sources for unlimited usage if proper treatment is applied. Table 8 lists the contaminants of major interest in WW and the treatment processes applicable to their removal [29].

1.10. WW treatment processes

The common processes and equipment applied in WW treatment are shown in Fig. 13.

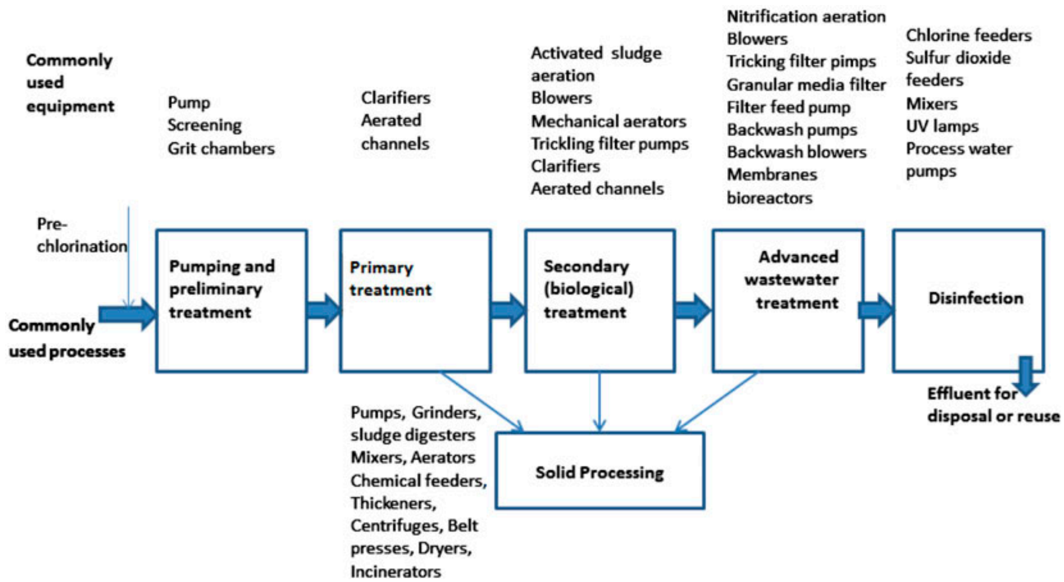


Fig. 13. Commonly used processes and equipment in wastewater treatment, adapted from [29].

1.11. Primary treatment

In primary treatment, sewage screening and clarifications are performed to remove (and shred) large floating objects, such as rags, cans, bottles, and sticks that may clog pumps, small pipes, and down-stream processes. It also includes sedimentation of some of the suspended solids and organic matters by gravity in large settling basins. As WW enters these large tanks, it slows down, and the suspended solids settle at the bottom. The settled masses, called the primary sludge, are collected and can be removed continuously or at intervals. Odors at the primary treatment stages are bad, and odor control can be included in the primary treatment.

Beside screening and settling by gravity to remove solid particles and organic matters, air dissolved floatation (DAF) can be used to remove small particles that can be entrapped by air and float to the water's top surface, where they are removed. A grit chamber can be introduced between the screen and the settling tank to remove sand, grit and cinders, and small stones settle to the bottom. Grit and gravel removal is important, especially in cities using combined sewer systems. The effluent from primary treatment ordinarily contains a considerable amount of organic matter. Some chemicals may be added to assist with solids removal. Primary treatment can reduce the BOD of the incoming wastewater by 20–30% and the TSS by some 50–60%.

1.11.1. Secondary treatment

Bacteria in the water consume, naturally, soluble organic contaminants (e.g. sugars, fats, organic short-chain carbon molecules, etc.) and bind much of the less soluble fractions into floc if O_2 exists. This results in new bacterial cells, CO_2, and other by-products. So, O_2 is added to WW to grow micro-organisms (mainly bacteria) in water and rapidly metabolizes soluble and colloidal organic pollutants, and this is the basis of the biological WWT, i.e. consuming organic matter by micro-organisms that include bacteria, viruses, algae, and protozoa. The secondary treatment consumes the largest share of used energy in the TWWP, about 30 to 60% of the total energy used. The two most common conventional methods used to achieve secondary treatment are attached growth processes (known as fixed film) and suspended growth (known as activated sludge) processes, generally followed by sedimentation.

In the suspended-growth system such as activated sludge processes, WW flows around and through free-floating micro-organisms, gathering into biological flocs that settle out of the WW. The settled flocs retain the micro-organisms, meaning they can be recycled for further treatment. In the attached growth (or fixed film) system, the microbial growth occurs on the surface media, such as stone or plastic media, with WW passes over along with air to provide oxygen. Trickling filters and rotating biological contactors (RBC) are two common examples. A trickling filter is simply a bed of media (typically rocks or plastic) through which WW passes. The media ranges from three to six feet deep and allows large numbers of micro-organisms to be attached and grow. New facilities may use beds made of plastic balls, interlocking sheets of corrugated plastic, or other types of synthetic media. Bacteria, algae, fungi, and other micro-organisms grow and multiply, forming a microbial growth or slime layer (biomass) on the media. In the treatment process, the bacteria use O_2 from the air and consume most of the organic matter in the WW as food. RBC consists of a series of circular disks rotating through the WW flow, partially submerged. These disks, usually plastic, are the media where the biofilm develops and eventually sloughs off. Attached growth processes are effective at removing biodegradable organic material from the WW.

The activated sludge method is widely used in large WWTPs of 1 MGD capacity or more. Trickling filters (one of the attached growth methods) are simple and reliable systems for small to medium sized. Nitrification is also used, as advanced treatment, to reduce ammonia toxicity in the effluent, as well as the dissolved oxygen demand on the receiving waters (due to the oxidation of ammonia). Another type of advanced treatment system is activated sludge process combined with solid filtration by membrane bioreactor (MBRs). The MBRs filters are immersed in the reactor, and the water flows from the outside through the membrane and into the annular space. Aeration in the activated sludge reactor provides oxygen to the microbial population and scours the membrane filter surface. MBRs are designed for and operated in small spaces and have a high removal efficiency of contaminants such as N, P, bacteria, biochemical oxygen demand, and TSS.

The second treatment can include removal of nutrients; N, P, or both N and P, or considered in the tertiary treatment as the case in Qatar. Not all biologic treatment methods are aerobic processes. In some cases, (e.g. when organic concentrations are very high) anaerobic bacteria are used.

The *tertiary treatment* improves the quality of the second treatment effluent by removing the residual suspended solids that were not removed by the secondary, often by using granular medium filtration or micro-screens. The tertiary treatment can include disinfecting methods to kill off pathogens by the use of chlorine, ozone or UV radiation; and reducing the N and P content of the effluent, as well as some final solid removal.

Disinfection is a final step before discharging the TWW to the environment, to reduce the number of micro-organisms. The most commonly used disinfection method is chlorination. Also ultraviolet (UV) light and ozonation can be used instead of chlorine.

More advanced treatment is applied if the treated WW is to be reused for agriculture or aquifer recharge. Advanced TWW by using RO is applied for TWW to be recharged in aquifers in Kuwait and UAE. Aquifer recharge is used to prevent degradation of GW and to generate additional water source via bioremediation of WW, beside using the recharge water as strategic storage.

1.12. Recycled TWW

If the treated municipal WW is to be reclaimed, additional treatment is needed to suit the usage purpose, (e.g. agriculture, aquifer charge, or unlimited usage). Reclaimed water can be used for freshwater augmentation. Table 9 shows that the treated amount

Table 9
Water withdrawal, wastewater produced, treated wastewater, and reused TWW [31]

Countries	Total water withdrawal (10^9 m^3/y)	Total WW produced (10^9 m^3/y)	Volume of treated WW (10^9 m^3/y)	Volume of Treated water reused (10^9 m^3/y)
Saudi Arabia	23.67 in 2006	0.73	0.652	0.166
Bahrain	0.3574	0.0449	0.076	0.0163
Egypt	68.3	3.76	2.971	0.7
United Arab Emirates	3.998	0.5	0.454	0.248
Iraq	66	0.575	0.098	0.0055
Libya	4.326	0.546	0.04	0.04
Jordan	0.941	0.117	0.111	0.102
Kuwait	0.913	0.25	0.239	0.078
Oman	1.321	0.098	0.037	0.0023
Qatar	0.55	0.444	0.066	0.043
West Bank & Gaza	0.418	0.05	0.03	0.00544
Yemen	3.4	0.074	0.046	0.06

of the total withdrawal is limited in the GCC [31]; and more WW should be treated and reused.

Reclaimed WW is a guaranteed valuable water resource. It increases with population increase, can be a high percent of municipal water (up to 80% in Israel), and should be fully utilized in all the arid GCC. The cost of treating the tertiary WW after both N and P removals to potable quality for unlimited use excluding drinking is much less than the cost of DW. So, it is desirable to treat all generated WW and reuse it. Nevertheless, Qatar for example, lacks the infrastructure to deliver reclaimed water to potential users. Investments are needed to extend collection and treatment networks. A public campaign for the acceptance of recycled water is needed.

Qatar's reclaimed TWW accounts for only 14.9% of total water withdrawal. TWW supply is currently more than demand, and about 40% of TSE effluent is discharged into septic lagoons. About one-third of Qatar's municipal WW is currently treated (≅354,000 m^3/d or 129.4 Mm^3/y) and partially recycled. The recycled TWW is used for the irrigation of few crops and landscaping. Extending the WW treatment of tertiary level of limited usage for irrigation to quaternary level (of potable water quality) using RO can open the door for extensive use of reusing municipal TWW. This can improve the water security by not being completely dependent on the DW production, which is vulnerable to oil spills, operation interruption, and so on.

Technically proven WW treatment processes already exist to produce water of almost any desired quality. The feasibility of using reclaimed water for irrigation is usually evaluated based on several factors including: salinity, trace elements, and water infiltration rates. Long-term soil exposure to reclaimed water results in increased deposits of N and P, while potassium, calcium, magnesium, and sodium tend to be more variable. Agriculture water reuse becomes an established water practice in several water-stressed countries of the Arab region. It saves polluting the environment from the untreated WW discharge. The nutrients in treated WW can reduce the need for applying chemical fertilizers, thereby reducing costs and potentially adverse effects associated with fertilizers. While costs vary according to quality and transportation expenditure, one m^3 of treated effluent costs \$0.66 in Kuwait to bring TWW to potable condition, while one m^3 of DW costs by thermal system is above \$3/m^3. However, health risks from consuming produce from untreated or inadequately treated WW should be evaluated. Also, GW can be polluted from infiltration of contaminated irrigation water.

2. Energy for water

Energy is needed for GW pumping from wells, water conveyance, WW collection, treatment, and distribution, and desalting sea or brackish water. Pumping energy from wells depends on the water depth in the well. Energy for water conveyance depends on moving distance, topography of the water network, pipe diameter, and friction. Energy consumed by WW and desalination will be given later in detail.

2.1. *Groundwater extraction and its specific energy requirement*

The 2014 UN world water report [32], estimated typical energy required for pumping GW around 0.1 and 0.5 kW h/m^3 for 36.5 m, and 122 water depths, respectively. This energy is used to overcome both gravity for elevation and friction in water piping. A simple example of how to calculate the consumed pumping energy for one m^3 of water extracted from well at 36 m below surface (≅360 kPa) to deliver it to a tank having 20-m water height (≅200 kPa), and for 200-kPa friction by using a pump of efficiency (η) 65% and motor (η) 90% is:

$$\text{Consumed electric power (EP)} = [1 \times (360 + 200 + 200)/(0.65 \times 0.9)]/3600 = 0.36 \text{ kW h/m}^3$$

3. Energy consumed by wastewater treatment processes

A brief overview of WW treatment processes was given before to help in estimating its consumed energy. The conventional treatment steps in the WWTP are [30].

3.1. *Wastewater treatment energy consumption*

Energy is consumed in collecting wastewater (WW), WW conveyance to the WWTP, WW treatment processes, and TWW discharge (or distribution). The energy consumed in collecting WW can be near zero for gravity-fed systems, or can be high if large volumes of water are conveyed for long distances or to high elevation. No data are available on Qatar's WW collecting system, except it was connected in 2004 to almost 100% of Mesaieed and Doha housing, 67% in Al Rayyan, and 54% in Wakra [24].

Energy consumed in WWT processes depends on the initial WW constituents, end level of TWW, types of the equipment used, and size of the plant. EP is mainly used in the WWTP by the aeration processes, solid treating, and pumping.

An overview of consumed energy for different plant sizes and plant types is given in Table 10a [26]. The consumed EP varies by the WWTP size, and WW treating method (i.e. trickling filter, activated sludge, advanced WW treatment with and without nitrification). The specific energy consumption (SEC) decreases by increasing the WWTP size [33]. A typical average of SEC in medium size plant for tertiary treatment is 0.44 kW h/m^3. This gives an estimation EP equal to 56.67 GW h for Qatar's WWTP of present capacity 352,860 m^3/d; and 116.69 GW h for the 701,860 m^3/d capacity after adding the Doha North WW plant soon. The above figures are just rough estimations, as different values of SEC estimations are reported in the literature. Menendez [33] reported that the large WWTP in the US has average SEC of 0.32 kW h/m^3, Table 10a.

Table 10b shows that, as example, for standard activated sludge WWTP of 3,785 m^3/d (1 MGD) capacity, the SEC is 0.594 kW h/m^3, for 37,850 m^3/d (10 MGD) capacity, the SEC is 0.32 kW h/m^3, and for 189,250 (50 MGD), the SEC is 0.264 kW h/m^3. Different distributions of consumed energy for the WWT processes are reported in the literature. Fig. 14 shows that for a typical WWTP, pumping consume about 12%, while aeration process consumes about 60% of the overall energy demand. The percentage of aeration energy is high since it includes activated sludge aeration in addition to dissolved air flotation thickening processes.

Menendez [33] gave relative shares of the consumed EP by the processes as shown in Fig. 14. Table 10b shows consumed energy for several plants' capacity and different WWT processes. More advanced treatment plants use relatively less electricity share for pumping, but higher total consumed EP.

The energy consumed by the WWTP solids treatment processes has the second highest share (20–30%). Small plants, (less than 37,850 m^3/d), usually use aerobic digestion to treat solids since its capital cost is lower than those of anaerobic digestion. The use of anaerobic digestion, in plants of more than 10 MGD may be more economical to the aeration process (and thus its energy) is less plus recovered energy from the biogas produced with the anaerobic digestion process. The advanced treatment to potable conditions usually uses RO which consumes large amounts of energy (1.5–3.5 kW h/m^3) compared to other TWW quality levels.

Table 10a
Unit electricity consumption for wastewater treatment by size of plant [26]

Treatment plant size (cubic meters per day)	Unit electricity consumption (kW h/cubic meter) Trickling filter	Activated sludge	Advanced wastewater treatment	Advanced wastewater treatment nitrification
3,785	0.479	0.591	0.686	0.780
18,925	0.258	0.362	0.416	0.509
37,850	0.225	0.318	0.372	0.473
75,700	0.198	0.294	0.344	0.443
189,250	0.182	0.278	0.321	0.423
378,500	0.177	0.272	0.314	0.412

Table 10b
Typical consumed energy for several plants' capacity and different WWT processes [26]

Treatment plant description	Electric energy intensity kW h/MG, (kW h/m^3)
6 MGD sequencing batch reactor, dried biosolids sold for reuse, UV disinfection	2,250 (0.59)
20 MGD trickling filter with anaerobic digester	1,520 9 (0.40)
3 MGD membrane bioreactor for water reuse	4,910 (1.30)
85 MGD advanced wastewater plant using BNR	2,040 (0.54)

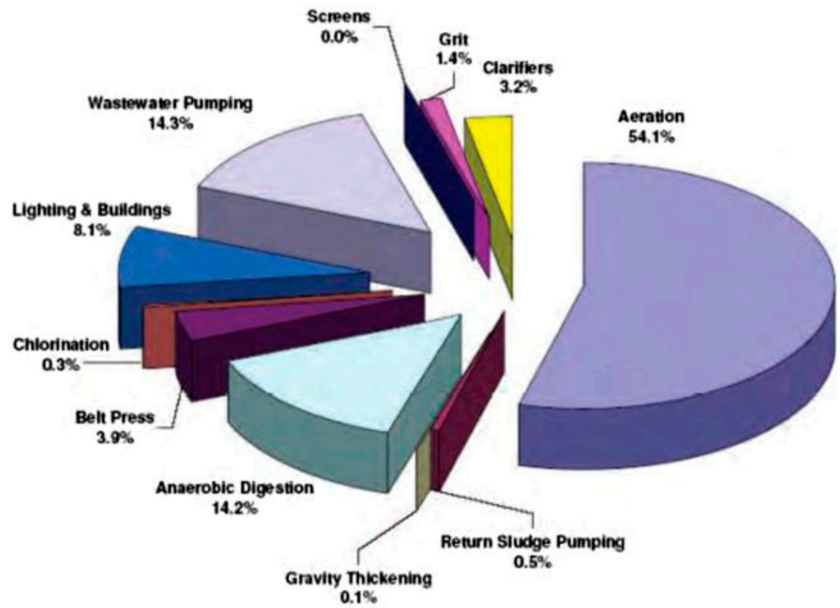


Fig. 14. Percentage breakdown of typical wastewater system energy consumption [26].

3.2. Energy consumed by MSF desalting system

The commonly used MSF system in Qatar and other GCC is an energy intensive process. Beside thermal energy, extensive pumping energy is used. A typical example of 7.2 MIGD (378.9 kg/s) MSF unit is used here as an example to show how to calculate its consumed energy. The unit consists of three major sections, the heat rejection section (HJS), heat recovery section (HRS), and heat input section (HIS). The unit has 110°C top brine temperature (TBT), 40°C last stage temperature, typically 28 stages, 3 for HJS, and 25 for HRS. For equal temperature difference ΔT of the recirculation stream, R, the $\Delta T = (100 - 40)/28 = 2.5$°C, has a 8.22 gain ratio (GR), (Gr is the mass of distillate D to steam supplied to the brine heater S or D/S). The recirculation stream R enters the first stage at TBT = T_o, = 100°C, leaves the stage n (28) at 40°C and at flow rate (R–D), or average flow rate (R–$D/2$) and its temperature drop is ($T_o - T_n$), and its heat loss generates D, or

$$(R - D/2)C(T_o - T_n) = DL, \text{ or}$$

$$R/D = 0.5 + \frac{L}{C(T_o - T_n)} = 0.5 + \frac{2335}{4(110-40)} = 8.84, \text{ or } R = 378.9 \times 8.84 = 3348.616 \text{ kg/s}$$

The stream R enters the condensers of stage 25 at $T_n = 40$°C, and its temperature is successively increased as it leaves the condenser of the first stage at $t_1 = 40 + 2.5 \times 25 = 102.5$°C, and enters the HIS to increase its temperature to TBT, $T_o = 110$°C by condensing the steam supply S, and this gives:

$$SLs = RC(T_o - t_1)$$

$S/D = (RC/DLs)(110 - t_1)$, this gives $D/S = 8.221$, and the specific heat supplied is:

$$qs = Qs/D = SLs/D = 2180/8.221 = 265.2 \text{ kJ/kg} = 265.2 \text{ MJ/m}^3$$

The specific pumping energy consumed by recirculation pump can be calculated as:

$$W\ (R \text{ pump})/D = (R/D)(\Delta P \text{ in kPa})/(\eta_p \eta_m) = 8.82 \times 750/(0.75 \times 0.9) = 9800 \text{ kJ/m}^3 = 2.722 \text{ kW h/m}^3$$

where 750 kPa is typical ΔP in kPa for the recirculation pump, 0.75 and 0.9 are the pump efficiency $_p$, and motor efficiency $_m$. The second high stream flow rate of the MSF unit is the cooling water Mc extracted from the sea, say at 30°C to the HJS to reject the heat added to the unit, and leave this section at temperature equal to T_n (40°C) in this case. The vapor generated from the flashing brine and accumulated distillate in the last three rejection stages (both has flow rate R) and is equal to $3yR$ is condensed on the condenser of the last three stages and gives its latent heat to Mc, then:

$$3y(R/D)L = (Mc/D)C(T_n - t_c)$$

where y is the flashing fraction, and is equal to

$$y = C\Delta T/L = 4 \times 2.5/2330 = 0.004283$$

This gives:

$$Mc/D = 3 \times 0.004283 \times 8.82/[4 \times (40 - 30)] = 6.6.$$

Part of Mc is used as a feed F, which is treated chemically and becomes part of R. The balance $(Mc–F)$ is rejected to the sea. The typical pressure across the cooling seawater pump is 250 kPa, and thus the specific pumping energy of this pump is:

$$\begin{aligned} W\ (Mc\ \text{pump})/D &= (Mc/D)\ (\Delta p\ \text{in kPa})/(\eta_p \eta_m) \\ &= 6.6 \times 250/(0.75 \times 0.9) \\ &= 2444\ \text{kJ/m}^3 = 0.68\ \text{kW h/m}^3 \end{aligned}$$

Similar calculations can be done for the distillate pump (flow rate = D, and typical Δp = 500 kPa) and steam condensate pump (flow rate = $D/8.24$, and typical Δp = 1,000 kPa). Adding this pumping energy gives 3.65 kW h/m^3, or almost 4 kW h/m^3.

For $D = 1\ m^3/s$, $R = 8.82\ m^3/s$, typical Δp = 750 kPa, the steam supply should steam temperature of T_S at 7–10˚C higher temperature than the TBT, say at 120˚C. However, this steam is extracted from the turbine at little higher temperature and is de-superheated before it enters to the desalination unit, say at 127˚C. For 7.2 MIGD (378.9 kg/s), then S = 46.09 kg/s and has about 2,180 kJ/kg of latent heat at 127°C. When this steam is supplied to Carnot cycle working at 127°C (400 K) high temperature and 37˚C (310 K), it can have Carnot efficiency equal to 0.225 and produces work equal to: 22,607 kJ/s, and the consumed mechanical work equivalent to thermal energy per unit distillate is 59.67 kJ/kg (16.7 kW h/m^3). The steam extracted to operate the steam ejectors of the MSF can raise the last mentioned number (14.8 kW h/m^3) to 16 kW h/m^3. The total unit pumping energy is in the range of 4 kW h/m^3 and is used to move the pumps of the MSF unit streams, say cooling water Mc to the HJS at rate of $7D$, the recirculation flow rate R at the rate of $9D$, and steam condensate at the rate of $D/9$, the brine rejection at a rate of $2D$, and the cooling water rejection at a rate of $4D$. This gives total mechanical energy consumption of 20 kW h/m^3.

For the estimated DW of 1.1353 Mm^3/d (414.382 Mm^3/y) in 2011, the consumed energy by desalting is 8,288 GW h/y. For the international cost of \$0.12/kW h, the desalination energy cost in Qatar amounts to \$M 995. Strangely this number can be reduced to 25% of its value if SWRO was used. The EP generated in 2011 was 28,242 GW h. If the DW consumed energy is considered as consumed EP, the equivalent total power in 2011 would be 36,530 GW (28,242 for EP + 8,288 DW), with 22.7% for desalination, and 71.7% for EP, and the fuel share for EP and DW should allocate according to these ratios. If the efficiency of the CPDP is considered equal to 0.36, the total consumed fuel energy by the CPDP in 2011 would be 36,530 × 3,600/0.36 = 365.3 million GJ (equivalent to 61 million barrel of oil), with the share of 82.88 million GJ for desalination to produce 282.242 for EP. For the generation of 414.382 Mm^3 of DW in 2011, the specific consumed DW energy is 200 MJ/m^3 of desalted water.

3.3. SWRO energy consumption

In SWRO desalting system, semipermeable membranes are used to separate freshwater from saline feed water. The seawater feed (F), say at the rate of $3D$, where D is the desalted water (called here permeate), is pumped after pre-treatment to the membranes at pressure higher than feed water osmotic pressure. The membranes allow water, but not salt, to pass through the membranes. For Qatar high salinity seawater, the applied pressure to the membrane would be in the range of 70 bar. Most of the energy consumed (about 80%) in the SWRO process is that of high pressure (HP) that supplied the feed to the membranes. For one m^3/s of permeate, the feed would be 3 m^3/s, and for 70 bar applied pressure, the consumed energy is:

$$\begin{aligned} W\,(\text{feed pump}) &= (F\,\text{in}\,\text{m}^3/s)\,(\Delta P\,\text{in kPa})/\eta\,(\text{pump and motors}) \\ &: 3 \times 7000/(0.8 \times 0.9) \\ &= 29{,}167\,\text{kJ/m}^3\,(8.102\,\text{kW h/m}^3) \end{aligned}$$

The 0.8 is the pump efficiency and 0.9 is the motor efficiency. The brine energy at a rate 2 m^3/s leaves the membrane at HP, little lower than the feed pressure (say at 67 bar). The brine energy is usually recovered and help the HP feed pump. The energy obtained from the brine can be calculated as:

W (turbine) = (B in m^3/s) (ΔP in kPa) $\times \eta$ (turbine)

$2 \times 6700 \times 0.9 = 12060$ kJ/s or (3.35 kW h/m^3), or

The net consumed energy is $(8.102 - 3.35 = 4.75185$ kW h/m^3.

By assuming the energy consumed by the HP as 80%, the total consumed energy is 5.94 kWh/m^3, say 6 kWh/m^3.

The consumed energy is a function of the feed water quality (salinity, turbidity, temperature, etc.), and efficiency of the pump, motor, and turbine used. The feed water salinity increase is raising the feed water HP to membranes and thus consumes more energy. High turbidity feed water can cause fouling where membrane pores are clogged with suspended solids, and thus the SWRO needs extensive feed water pretreatment, that bring the silt density index (SDI) of the feed water to less than 5 for spiral wound membranes.

3.4. EP water share

In 2011, the CPDPs in Qatar's generated EP was 28,242 GW h power, and 414.283 Mm^3 of DW with equivalent EP consumption equal to 20-kW h/m^3, or 8,286 GW h. Then, the equivalent total EP production is 36,530 GW h, with 22.7% for DW, and 72.3% for EP.

Other water EP consuming sector is the GW sector including GW extraction and conveyance. The GW water conveyance for all water will be estimated later. The estimated consumed EP per m^3 of GW extraction was given before as 0.36 kW h/m^3. In 2011, the estimated GW extraction in Qatar was estimated by 250 Mm^3/y, and thus the estimated consumed EP is: $250 \times 0.36 = 90$ GW h. This represents 0.32% of Qatar's total consumed EP in 2011 (28,242 GW h), Fig. 5c. The GW is supposed to be of high quality, that required no treatment, and thus no energy is needed more than its extraction energy. The EP consumed by the WW sector includes the WW collection, the WWT processes, and the TWW effluent conveyance. The former two items are considered first while the conveyance is to be dealt with later.

A typical consumed average energy of 150 kW h/MG (0.04 kW h/m^3) depending on topography, system size, and age, Water and Energy Nexus [24]. For total WW collection of 256.2 Mm^3/y (including Doha North) is 10.25 GW h. The reported tertiary treated WW in Qatar was 175,500 m^3/d (64.06 Mm^3/y) with dis-nitrification (N) and phosphorous (P) removal, 159,400 m^3/d (58.81 Mm^3/y) for just disinfection, and 2,000 m^3/d for secondary treatment.

Typical specific energy consumed in medium size plant for tertiary treatment is 0.44 kW h/m^3 in case no nitrogen (N) or phosphorous (P) removal, and 70% more when both N and P are removed or 0.74 kW h/m^3. These give 73 GW h. When the TWW capacity increases from the present capacity of 352,860 (m^3/d) to 701,860 m^3/d (256.2 Mm^3/y) after adding the Doha North WW plant soon, the consumed EP by WWTP would increase from 73 GW h to 153 GW t capacity after adding the Doha North WW plant soon. The conveyance of water total water withdrawal, including 414.382 Mm^3/y of DW, and 257.2 Mm^3/y of GW, and 256.2 of treated WW (after adding North Doha plant) are 928 Mm^3/d. The conveyance EP energy consumption can be very roughly estimated as equal to that of process water treatment (0.44 kW h/m^3), and this gives 408 GW h. So, the total EP consumed by the whole water sector is 8,947 GW h (408 for conveyance + 153 for WWT + 10.25 for WW collection + 8,286 for DW + 90 for GW extraction), and this represents 24.5% of the total equivalent EP consumption including DW.

4. Water and food security

Many think that food security is satisfied only for a country like Qatar if it is capable of being food self-sufficient. Other argue that it is not necessary for a country to grow its own food to have food security, but being financially capable of acquiring the needed food by importing its food needs, and this has been defined as self-reliance. Qatar's self-sufficiency is impossible in view the country's severe water scarcity, limited agricultural land, and continuously growing the population. Water used for agriculture in Qatar is abstracted non-renewable groundwater (GW).

In 2009, there were world food cost increases due to export restrictions by exporting food countries. The country has the financial ability from its export earnings to import food or to be self-reliant. The choice to satisfy food security should not be completely by being self-sufficiency or self-reliance, but by having an efficient growing food (agriculture) and determine its share in satisfying its food needs. This is the strategy adopted by the Qatar Food Security program.

Therefore, there is a distinction between self-sufficiency defined as the national production of all foodstuffs needed by a population, whereas food security is seen as access to affordable food.

4.1. Importing virtual water in Qatar

Another food security definition is [34,35]: food security exists when people at all times, have physical, social, and economic access to sufficient and nutritious food that meets their dietary needs for a healthy and active life. Based on this definition, the Global Food Security Index was developed. This index looks beyond hunger at the factors that influence the ability of consumers to access sufficient amounts of safe, high quality, and affordable food. It depends on three factors: affordability; availability; quality and safety. The affordability measures the ability of consumers (or the country) to purchase food and at costs under normal or occasional shock conditions. The availability examines how structural elements determine a country's capacity to produce and distribute food and explores aspects that might create bottlenecks or risks to sufficient availability. Countries lacking freshwater resources and arable land depend on international food supply chain. The problem of water scarcity to grow food is partly solved by importing virtual water in the form food products, and using non-conventional water resources.

Qatar's main types of food imports in 2011 and their virtual water values, and the percentage of country's self-sufficiency in these food types are given in Table 11 [36]. The cost of these imports was $1,325 M. Cereals are the most important source of total food consumption, as they provide 56% of the food calories worldwide. The table shows that the percentage of self-sufficiency is extremely low in cereal, potatoes, pulses, sugar, fats and oil, and sugar. In 2011, the population was 1.7 M, and the main virtual water export, according to Table 11, is 6,222 Mm^3/y, or the virtual water consumption per capita is 3,660 m^3/y Ca, the cost of import food per capita is $779/y Ca.

Although Kuwait and UAE have similar water scarcity like Qatar, they were ranked higher (28 and 30, respectively, among 109 countries) in food security. The score out of 100 was 72.2 for Kuwait, 70 for the UAE, and 69.6 for SA, although these countries depend mainly on food imports, and their scores were higher than those for Turkey (63.8), Tunisia (55.7), Morocco (50.1), Egypt (49.3), Algiers (47.5), Syria (40.3), and Yemen (35.2). It is noticed that high score was given to Kuwait and UAE due to lower food consumption cost as a share of household expenditure, and improving economic conditions. Still, many feel that food security in the GCC is threatened by mostly being dependent almost fully on food import. The practice of trade sanction against some countries in the region, due to political reasons, enforces this feeling of food security threatening. Also, export sanction by some exporting counties threaten food security, similar to what happened in Russia and Ukraine in 2010–2011 by banning wheat export due to low harvesting.

So, importing food has several disadvantages as it depends on factors that are beyond the control of the importing country such as, the international market and food production in food exporting countries, price increase, and possibly routing disruption. Qatar and other GCC can absorb the price increase risk. Other risks include the vulnerability of import routes such as the possibility of closing of the Suez Canal, and

Table 11
Qatar's main food imports in 2011, their specific virtual water, and self-sufficiency [36]

Item	*Q* in 1,000 ton	ton/kg	Virtual water (M m^3/kg)	% self sufficiency
Cereals (total)	468.97	0	0	0.37
Wheat and flour	150.28	1.6	240.448	0.02
Maize	13.7	0.71	9.727	7.62
Rice	134.18	3.4	456.212	0.00
Barley	127.76	1.91	244.0216	0.42
Potatoes	42.94	0.287	12.32378	0.05
Pulses (total)	14.95	1.754	26.2223	0.00
Vegetables (total)	113.22	0.2	22.644	22.89
Fruits (total)	136.3	0.5	68.15	13.67
Sugar(refined)	41.11	0.318	13.07298	0.00
Fats and oils(total)	55.81	3.83	213.7523	0.00
Meat (total)	133.42		0	10.77
Red meat	38.96	15.415	600.5684	8.68
Poultry meat	94.46	43.25	4,085.395	11.60
Eggs	20.31	4.9	99.519	16.59
Milk and dairy products	130.28	1.000	130.28	22.65
Fish	23.67			37.30

Bab El Mandab or Hormoz strait. About 81% of the GCC's food imports pass through the Suez Canal. It was reported that a shipment of 5.8 Million tons (Mt) of the wheat pass through Bab El Mndab to GCC (almost 39% of their total wheat import) annually coming through the Suez canal, and 5.2 Mt of wheat (35% of total wheat import), 2.5 Mt of rice (81% of total rice) pass through Hormoz straits. This problem can be partially resolved by building storage capacity for the strategic food such as wheat, flours, and rice [37].

Qatar's wealth is contributing significantly to food security to individuals, by subsidizing food commodities and promoting self-sufficiency. Food subsidies in 2010 were about $82 M. Qatar like other GCC is trying to produce food in some countries having sufficient water and agriculture land. The GCC can purchase land and provide the capital to bring resources and technology to increase food production. So, the host country can have more agriculture revenue and food for itself, and they could increase exports to the GCC. However, some of the suggested host countries have some opposition to this policy.

The GW should be recharged to balance the water deficit by injected clean water (such as DW, or TWW of potable quality, and harvested rainfall). These waters can also be used as strategic water storage. Groundwater aquifers can certainly provide natural strategic water storage. Recharging GW aquifers with reclaimed wastewater of potable quality is an approach to wastewater reuse that results in the planned augmentation of GW sources. The benefits of artificial recharge of groundwater utilizing wastewater include:

(1) Stopping the decline of GW levels due to excessive GW withdrawal;
(2) Protecting coastal aquifers against saltwater intrusion from the sea;
(3) Storing water for future use;
(4) Stopping the decline of GW levels due to excessive GW withdrawal;
(5) Protecting coastal aquifers against saltwater intrusion from the sea;
(6) Storing water for future use;
(7) Groundwater recharge also occurs incidentally/naturally in the process of municipal and industrial wastewater disposal via infiltration.

5. Conclusion

Qatar and the GCC region are facing acute water scarcity. The water problem in Qatar is more worsen by the very rapid increase in population, urban expansion, and consumed water. The increasing demand for food cannot be met by the scarce and dwindling conventional GW water resources. These conventional resources have already been over exploited by irrigation practices. The water problem should be solved by sustainable water management to cope with ever-increasing water demands. Securing DW by solar energy, aquifer recharge using recycled wastewater, and the use of recycled water of better than tertiary-TWW for irrigation and other purposes are some of the sustainable solutions. In conclusions:

(1) Qatar is mining its fossil water reserves. This should not only be stopped, but GW should be replenished by potable quality injected to aquifers to restore the GW resource, and use it as strategic water storage. DW and/or advanced TWW (both of potable quality) should be used for aquifer storage and recharge. The current storage capacity of DW to meet any emergency situation is limited to two days and will be extended to 9 d. So, strategic water storage in aquifers is needed for months.
(2) Qatar is using the most inefficient desalting systems, namely MSF and ME-TVC. Additional of these systems should be stopped. Any new installed DW system should use the most efficient SWRO desalting system.
(3) Qatar should fully utilize its wastewater. It should be treated beyond its tertiary water quality (designed for disposable purposes), unrestricted water usage, say to potable water quality. This should replace the usage of GW for agriculture, and usage DW for municipal water for non-drinking and cooking needs. The dual distribution system can be constructed: one for high quality system DW for drinking water and other high quality uses; and second, for reclaimed water for agricultural irrigation, landscaping, and fire protection.
(4) Water pricing should reflect the real value of water. The government should not end up by subsidizing the depletion of an essential natural resource. Under-pricing or zero-pricing lower the incentive to conserve water, and does not reflect the scarcity value of the water. Implementation of real cost, especially for water consumed beyond basic needs (that should be considered wasteful) is mean for demand and water wastage management. This should not be in conflict with the right of all individuals to the adequate, reliable, and affordable supply of potable water.

(5) Water efficiency in agriculture through water management and drainage and improved surface irrigation alongside drought-heat tolerant crop varieties (in parallel with improvements in plant breeding or genetic manipulation to reduce irrigation demand).

Abbreviations

AC	—	air conditioning
AGR	—	annual growth rate
Ashghal	—	public works authority
B	—	billion
bbl	—	barrel
BCF	—	billion cubic feet (BCF)
BCM	—	billion cubic meters
BPST	—	back pressure steam turbine
Btu	—	British thermal unit
Btu	—	British thermal units
Ca	—	capita or person
CC	—	combined cycle gas-steam turbine cycle
CPDP	—	cogeneration power desalting plant
D/S	—	distillate product/supplied steam
DP	—	desalting plant
DW	—	desalted seawater
ECST	—	extraction-condensing steam turbine
EP	—	electric power
GCC	—	Gulf co-operation countries
GDP	—	gross domestic product
GJ	—	Gigajoule
HRSG	—	heat recovery steam generator
IMF	—	international monetary fund
IPP	—	independent power project (IPP)
IWPP	—	independent water and power project
IWRM	—	integrated water resource management
KAHRAMAA	—	Qatar General Electricity and Water Corporation,
kWh	—	kilo watt hour
LEC	—	levelized energy cost (LEC)
LNG	—	liquefied natural gas
LP	—	low pressure
M	—	million
ME-TVC	—	multi effect-thermal vapor compression
MMBtu	—	million British thermal units
MSF	—	multi stage flash
Mt	—	million ton
NG	—	natural gas (NG)
PP	—	power plants
QEWC	—	Qatar electricity & water company (qewc), qp
QR	—	Qatari Riyal
RAF	—	Ras Abu Fontas power plant
RO	—	reverse osmosis
SA	—	Saudia Arabia
ST	—	steam turbines
SW	—	seawater (SW)
SWRO	—	seawater reverse osmosis
TCF	—	trillion cubic feet (TCF)
TCM	—	trillion cubic meters TCM)
Toe	—	ton of oil equivalent
TWW	—	treated wastewater

References

[1] www.qsa.gov.qa, accessed (Febraury 20, 2015).

[2] Qatar GDP. Available from: <http://www.tradingeconomics.com/qatar/gdp> accessed (Augsut 4, 2014).

[3] Qatar—2014 Article IV Consultation Concluding Statement of the International Monetary fund (IMF) Mission, February 19–20, 2014. Available from: <https://www.imf.org/external/np/ms/2014/030714.htm>, accessed (August 4, 2014).

[4] MoEI, Sustainability in the Qatar Energy and Industry Sector Report 2012, Ministry of Energy and Industry, 2013.

[5] OPEC Statistical Bulletin. Available from: <http://www.opec.org/library/Annual%20Statistical%20Bulletin/interactive/current/FileZ/Main.htm>, accessed (Augsut 4, 2014).

[6] Sustainable Development Indicators in the State of Qatar, April, 2012, The Statistics Authority and the Diplomatic Institute. Available from: <http://www.qsa.gov.qa/eng/publication/reports/2012/Sustainable%20Development%20Indicators-2011.pdf>, accessed (Augsut 4, 2014).

[7] International Energy Statistics, EIA. Available from: <http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=2&cid=CG8,&syid=2007&eyid=2011&unit=BKWH>, accessed (August 4, 2014).

[8] R. Gupta, Qatar seeks to cut down on electricity and water usage, Oct 20, 2013. Available from: <http://www.bqdoha.com/2013/10/qatar-seeks-cut-utilities-usage>, (accessed June 21, 2014).

[9] KAHRAMAA, Statistics Report 2013. Available from: <www.km.com.qa>.

[10] S. Zafar, The power of the sun: Qatar's solar energy ambitions, published 19 March 2015, The Edge, 2015.

[11] Water Governance in the Arab Region, Managing Scarcity and Securing the Future, 2013, the United Nations Development Programme, Regional Bureau for the Arab States (RBAS). Available from: <http://arabstates.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/Arab_Water_Gov_Report/Arab_Water_Gov_Report_Full_Final_Nov_27.pdf>, accessed on (June 25, 2014).

[12] MoEI, Sustainability in the Qatar Energy and Industry Sector Report 2013, Ministry of Energy and Industry, 2014

[13] M. Nagy, Structure and content of the Environment Statistics Report, 2013, Lessons learnt and data shortcomings, Environment Statistics Workshop, 2–3 December 2013. Available from: <http://www.qsa.gov.qa/eng/Activities/EnvironmentWorkshop2013/3_Report_Structure_MN.pdf>, (accessed August 4, 2014).

[14] A.-K. Sadik, Food Security and Agricultural Sustainability, in the Arab Environment 5, Survival Option: Ecological Footprint of Arab Countries, in: N. Saab, Report of the Arab Forum for Environment and

Development, 2012. Available from: <http://www.footprintnetwork.org/images/article_uploads/Survival_Options_Eng.pdf>.

[15] MoE, Studying and developing the natural and artificial recharge of ground water aquifer in the state of Qatar, final report, Department of Agriculture and Water Research (DAWR), Ministry of Environment (MoE), prepared by Schlumberger Water Service (SWS), 2009.

[16] Qatar National Vision 2030, Advancing sustainable development, Qatar's second human development report, Qatar National Vision 2030, General Secretariat for Development Planning, 2009

[17] C. Malek, Thousands of abandoned farms across UAE to be brought back to life, The National. Available from: <http://www.thenational.ae/news/uae-news/thousands-of-abandoned-farms-across-uae-to-be-brought-back-to-life>, (accessed May 22, 2013).

[18] Global desalination capacity (GDC) growing substantially, finds study, Water World, 2013. Available from: http://www.waterworld.com/articles/2013/10/global-desalination-capacity-tops-80-million-cubic-meters-per-day.html, accessed (Aug 3, 2014).

[19] A Water Sector Assessment Report on the Countries of the Cooperation Council of the Arab States of the Gulf, Report No: 32539-MNA, March 31, 2005.

[20] M.A. Darwish, R. Mohtar, Qatar water challenges, Desalin. Water Treat. 51(1–3) (2013), doi:10.1080/19443994.2012.693582. Available from: <www.deswater.com>; M.A. Darwish, H.K. Abdulrahim, Y. Mohieldeen, Qatar and GCC water security, Desalin. Water Treat. (2014).

[21] Desaldata, 2013. Available from: <www.desaldata.com>.

[22] Will Qatar Turn the Arabian tide to RO desalination?, Water world. Available from: <http://www.waterworld.com/articles/wwi/print/volume-27/issue-1/regional-spotlight/middle-east-africa/will-qatar-turn.html>.

[23] Wastewater Characterization & Treatment Wastewater Characterization & Treatment, Chapter 2. Available from: <http://iqtma.uva.es/instrat/Presentaciones_pdf/Chapter2-Wastewater%20Characterization%20_%20TreatmentR.pdf>.

[24] Qatar 38.—Global Water Intelligence. Available from: <http://www.globalwaterintel.com/client_media/uploaded/GWM_2011_sample_chapter.pdf>.

[25] Doha North Sewage Treatment Works (DNSTW), Qatar. Available from: <http://www.water-technology.net/projects/doha-north-sewage-treatment-works-dnstw-qatar/>.

[26] Water and Energy Nexus: A Literature Review, Water in the West, 2013. Available from: <http://waterinthewest.stanford.edu/sites/default/files/Water-Energy_Lit_Review.pdf>.

[27] R. Andersson, M. Holmberg, Energy conservation in wastewater treatment operation,- a case study at Himmerfjärden WWTP, A master thesis, Department of Industrial Electrical engineering and Automation, Lund University, 2006. Available from: <http://cenres.ctu.edu.vn/decuong/tai%20lieu%20nop/van%20hanh%20va%20quan%20ly%20cong%20trinh/energy%20conservation%20in%20wastewater%20treatment%20operation.pdf>.

[28] B. Kiepper (Oct. 2013), Understanding Laboratory Wastewater Tests: I. ORGANICS (BOD, COD, TOC, O&G) (C 992). Available from: <http://extension.uga.edu/publications/files/pdf/C%20992_3.PDF>, (accessed Augsut 3, 2014).

[29] Electricity Use and Management in the Municipal Water Supply and Wastewater Industries, Final Report, November 2013, Electric Power Research Institute (EPRI).

[30] Metcalf and Eddy, Inc. (Revised by G. Tchoganologous, F.L. Burton, H.D. Stensel, Wastewater Engineering—Treatment and Reuse, Tata McGraw-Hill, New Delhi, 2003.

[31] Water Reuse in the Arab World, From Principle to Practice, Voices from the Field, Current status of water in the Arab world, A Summary of Proceedings Expert Consultation, Wastewater Management in the Arab World, 22–24 May 2011, 2011. Available from: <http://water.worldbank.org/publications/water-reuse-arab-world-principle-practice>, accessed (Augsut 3, 2014).

[32] The United Nations World Water Development Report 2014: Water and Energy, WWAP (United Nations World Water Assessment Programme), UNESCO, Paris, 2014.

[33] M.R. Menendez, How we use energy at wastewater plants … and how we can use less. Available from: <http://www.ncsafewater.org/Pics/Training/AnnualConference/AC10TechnicalPapers/AC10_Wastewater/WW_T.AM_10.30_Menendez.pdf>, (accessed July 7, 2014).

[34] FAO, Trade reforms and food security, Conceptualizing the Linkages, Food and Agriculture Organization of the United Nations, Rome, 2003.

[35] The Global Food Security Index. Available from: <http://foodsecurityindex.eiu.com/>.

[36] A. Sedghi, How much water is needed to produce food and how much do we waste? (2013). Available from: <http://www.theguardian.com/news/datablog/2013/jan/10/how-much-water-food-production-waste>.

[37] R. Bailey, R. Willoughby, Edible Oil: Food Security in the Gulf, Energy, Environment and Resources, Chatham House, November 2013 | EER BP 2013/03.