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Water–energy nexus and the Arab Gulf countries case

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ABSTRACT

The Gulf cooperation countries (GCC) have severe water scarcity and abundant, but finite, energy supply. Population growth, urbanization, and economic development in GCC significantly increase water demand. Water demands in GCC are mainly supplied by the extensive energy processes of water desalination, groundwater abstraction, water conveyance from one location to another, and treating wastewater for reclamation. Huge amounts of energy are used to produce, extract, treat, convey, and distribute freshwater; and collect, treat and dispose wastewater. Therefore, water and energy are intimately dependent, which is known as water–energy nexus and is briefly presented here. This paper illustrates, in general, the use of water in prime energy production and processing and electric power generation. Then, it discusses the extensive uses of energy in water processes such as water desalination, wastewater treatment and water conveyance. In GCC arid area, the demands for water and energy are on the rise, and the energy resources are drained in unsustainable way to satisfy water demands. The energy and water status in the GCC is presented. Example of the extensive energy use in desalting and conveying freshwater to one of the main cities, Riyadh, is illustrated. While the water in GCC is very scarce, water consumptions are among the highest in the world, as well as the energy consumption.

Keywords: Water; Energy; Wastewater treatment; Desalination; Water conveyance; Consumed energy

1. Introduction

Freshwater and energy are essential for human's well-being and sustainable development. Water and energy are closely linked and interdependent. Water is needed to produce prime fossil fuel extraction, refining, and utilization, biofuel production and processing, and electric energy generation and its use. Energy is crucial for producing desalted seawater (DW); extracting groundwater (GW); conveying water to domestic, industrial and agriculture uses; and collecting and treating wastewater (WW) and its conveyance of treated WW for disposing or reuse. The Gulf cooperation countries (GCC), including Saudi Arabia (SA), United Arab Emirates (UAE), Kuwait, Oman, Qatar, and Bahrain are vulnerable due to limited access of water. Water availability is a key to achieve growth, public health, and food security. It is unfortunate that GW supplies are diminishing, worldwide, with an estimated 20% of world's aquifers being over-exploited, some critically as in the GCC. The GCC are among the poorest countries in natural water resources, but very rich in fossil fuel, oil, and natural gas (NG) resources.

In GCC, demands for freshwater and energy are significantly increasing to meet the growing population, rising standard of living, urbanization, and economic developments. Limited natural water resources are real challenges in the GCC because of the rapid economic growth. Worldwide water demands (in terms of water withdrawals) are expected to increase 55% by 2050, mainly because of growing demands from industry (400%), thermal electric power (EP) generation (140%), and domestic use (130%). As a result, freshwater availability is increasingly strained, and more than 40% of world population is projected to live in areas of severe water stress through 2050 [1].

World energy demand is expected to grow by more than one-third over the period to 2035, with China, India, and Middle East countries accounting for about 60% of the increase. Electricity demand is expected to grow by approximately 70% by 2035 [1].

An energy–water nexus is concerned with the energy requirements for supplying and treating water, and water requirements for prime and electric energy productions. The water–energy nexus is extensively discussed in the literature, e.g., Gleick [2], DOE [3], NETL [4], Marsh [5], Bauer et al. [6], Klein et al. [7], and Macknick et al. [8].

Electric energy is needed to power pumps that abstract (from GW and surface water sources), transport, distribute, and collect water. It is also needed to drive pumps of desalting plants (DPs) and other treatment plants. NG (or oil) is needed to operate cogeneration power-desalting plants (CPDP) producing both EP and DW. In GCC, GW is heavily exploited and quality deteriorated, no rivers, and rain is extremely limited. Therefore, desalination, salt removal from seawater or brackish water, is heavily used, and it is an energy-intensive and expensive process. Electricity is needed for industrial and municipal wastewater treatment plants (WWTP) to prepare this water for disposal or reclamation (reuse) in several applications. Energy is also needed at water end users, often in households, such as water heating and washing clothes. Energy demands for water are on the rise due to population growth and improved standards of living, more stringent standards for water treatment, and shift in irrigation practices from surface or flood (relying on gravity) to pumped methods, which are more water-efficient but require more operational energy. Water used in energy production can be contaminated and needs treatment [9]. In 2010, water withdrawals for energy production were estimated at 583 billion cubic meters (Bm^3), of which 66 were not returned to the water body [9]. Water withdrawal is predicted to increase 20% by 2035, with consumption increase of 85%. In EP generation, water provides cooling at thermal power plants, and other related processes such as boiler make-up water and others.

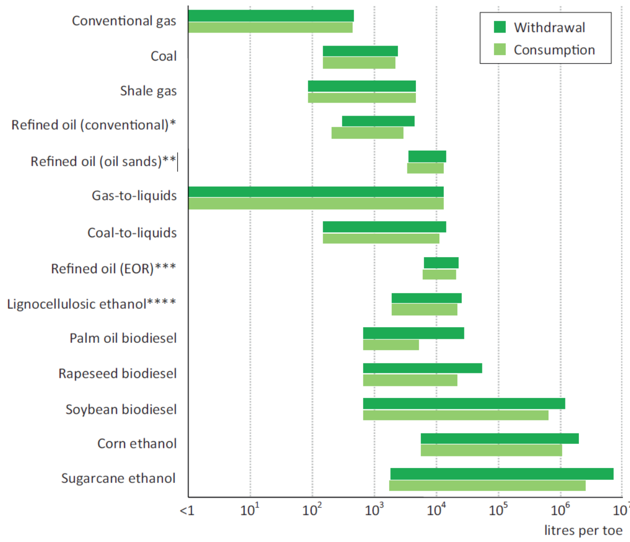

Fig. 1. Water use for primary energy production [9].
*The minimum is for primary recovery; the maximum is for secondary recovery.
**The minimum is for in situ production; the maximum is for surface mining.
***Includes CO_2 injection, steam injection and alkaline injection and in situ combustion.
****Excludes water use for crop residues allocated to food production.
Notes: Ranges shown are for "source-to-carrier" primary energy production, which includes withdrawals and consumption for extraction, processing and transport. Water use for biofuels production varies considerably because of differences in irrigation needs among regions and crops; the minimum for each crop represents non-irrigated crops whose only water requirements are for processing into fuels.

2. Water needs for energy

Water is extensively used in prime fuel production and in EP generation [10,11].

2.1. Water needed for prime fuel production

Waters are needed for prime energy extraction, refining, and transportation, as reported by Wu et al. [12], Mittal [13], and Mekonnen and Hoekstra [14].

Fig. 1 shows the specific minimum and maximum water requirements for different types of fuel production. The water needs for conventional NG drilling and processing (7 L/GJ) and primary oil extraction (5–7 L/GJ) are much less than that required for secondary crude oil extraction and processing. Secondary oil recovery by water flooding needs much more water (50–9,000 L/GJ) compared with those associated with primary recovery. Water consumed for different oil production techniques are given as 5–7 L/GJ for primary extraction, 245 L/GJ for secondary, and for tertiary treatment, 155 L/GJ for steam injection, 372 L/GJ for CO_2 injection, 111 L/GJ for caustic injection, and 55 L/GJ for forward combustion/air injection [15,16]. Oil refinery needs about 25–65 L/GJ. More waters are needed for liquefying NG to ease its transportation. Water used in fossil fuel extraction and processing becomes highly contaminated, and its treatment needs additional cost and consumed energy. Coal production needs water for mining activities such as coal cutting and dust suppression, and coal washing to increase the coal quality.

Oil production in SA uses mostly DW and brackish water for oil recovery at a range 40–131 L/GJ by using primarily water flooding (secondary recovery) [15].

Biofuels are an alternative to petroleum-based transportation fuels and are derived from renewable resources [17]. Irrigation water is used to produce biofuels and their processing. Most biofuels are derived from corn and soybeans, and need 9,000–100,000 L/GJ for corn irrigation and 50,000–270,000 L/GJ for soybeans irrigation. Corn fermentation used to produce ethanol needs about 47–50 L/GJ. Ethanol is the most commonly produced biofuel. While ethanol is primarily produced from corn grains, next generation of biofuels are cellulosic ethanol and algae-based fuels [17]. Refining crude oil to end-user products is more water (25–65 L/GJ) for cooling and processing.

Spang et al. [11] compiled data given in different sources, e.g., Cushion et al. [18], DOE [3], EIA [19], EIA [20], Gleick [2], IAEA [21], Meldrum [22], Mittal [13], WEC [23], WEC [24], and Wu [12] for several categories of fossil, nuclear, and biofuels and presented these data in Table 1. This table estimates the water consumption in m^3/GJ.

The above information indicate that the water demands in Qatar, as example, increase as more NG are liquefied for easy exporting, and most of oil fields extraction is moved from primary to secondary.

Table 1
Fuel production categories with water consumption factors [11]

Energy category	Subcategory	Water consumption factor (m^3 GJ^{-1})		
		Estimated	Minimum	Maximum
Fossil fuel	Coal	0.043	0.006	0.242
	Conventional oil	0.081	0.036	0.140
	Oil sands	0.114	0.072	0.132
	Oil refining	0.040	0.026	0.048
	Conventional gas	0.004	0.001	0.027
	Shale gas	0.017	0.003	0.221
Nuclear fuel	Uranium mining	0.033	0.000	0.252
	Milling	0.012	0.003	0.030
	Conversion	0.011	0.004	0.014
	Diffusion (enrichment)	0.037	0.034	0.039
	Centrifuge (enrichment)	0.004	0.003	0.006
	Fuel fabrication	0.001	0.001	0.003
	Biofuel processing	0.007	0.007	0.007
Biofuel processing	Ethanol	0.145	0.092	0.092
	Biodiesel	0.031	0.031	0.031
Biofuel cultivation	Sugarcane (ethanol)	24.550	0.000	156.000
	Maize (ethanol)	8.090	0.000	554.000
	Rapeseed (biodiesel)	19.740	0.000	270.000
	Soybean (biodiesel)	11.260	0.000	844.000

2.2. Water for electric generation

Water is consumed in conventional electric generating power plants using steam turbines (ST) Rankine cycle, simple combustion gas turbines (GT), or combined GT/ST cycle. Water consumed by thermoEP plants are studied by Barker [25], Macknick et al. [26], Fthenakis and Kim [27], Gleick [2], Mulder et al. [28], and Mielke et al. [15].

Simple GT cycles use almost no water for cooling. Water is mainly used in thermal power plants to condense the steam exhausted from ST in order to be returned to steam generator. The used cooling water can be totally consumed, i.e., would not be available for other uses once it is used, or return to source for other uses and partial consumption. Power plants are using several cooling systems such as once-through (OT) cooling water (Fig. 2(a)), wet cooling tower (CT) (Fig. 2(b)), and air cooling (Fig. 2(c)), or combination of air and water (Fig. 2(d)). Most power plants in the GCC use GT/ST combined cycle and OT cooling seawater. The scarcity of freshwater in GCC and the availability of seawater dictate this choice. The OT cooling uses more water but consume less compared with wet CT. Air cooling gives less power plants efficiency, and high capital cost, but consumes almost no water.

Wet CTs consume more water but do not require a reservoir for cooling. It is estimated that GT/ST combined cycle consumes about 400 L/MWh of electricity in OT cooling, while water withdraw about 51.5 m^3/MWh. On contrary wet CT consumes about 800 L/MWh, while withdraws 3.5 m^3/MWh [29].

The OT cooling systems draw water from a river, lake, or sea, Fig. 2(a) for CPDP, and return it back but at higher temperatures. It has high water withdrawals but low water consumption. Drawing vast volumes of cooling water through systems of pumps and pipes can also trap and kill fish, insect larvae, and other organisms. The recirculating or closed-loop systems wet cooling (Fig. 2(b)) withdraw only a fraction of the amount that OT systems do, but consume more water. The cost of installing the closed systems is about 40% more than for OT systems. Water required for dry cooling (Fig. 3) is negligible, compared with other systems, and better suited to dry climates, but it costs about 3–4 times as much as wet tower and is less effective at high temperatures. Sometimes dry cooling is installed in tandem with wet tower cooling to have a hybrid system (Fig. 2(d)) that offers flexibility to operate during warm and cool periods. The water use for electricity generation by several power plant types and cooling technology is shown in Fig. 3.

The scarcity of water in the GCC forces the use of power plants that consume the least amount of water such as GT plants and combined gas–steam cycle (GTCC) plants as shown in Fig. 3. Also, OT seawater cooling is extensively used, as its consumption is low while its withdrawal is high.

Spang et al. [11] compiled data given in different sources, e.g., EIA [20], Platts [32], NREL [33], Macknick et al. [26] and Meldrum et al. [22] for several categories of fossil, nuclear and biofuels and presented in Table 2. This table estimates the water consumption in m^3/GJ.

The water use for power plants using fossil fuel, nuclear, and renewable energy and several cooling technologies shown in Fig. 3 indicates that water withdrawals in L/MWh are higher for fossil and nuclear steam plants with OT cooling (75,000–450,000 L/MWh). This is between 20 and 80 times higher than if wet tower cooling were used, although such

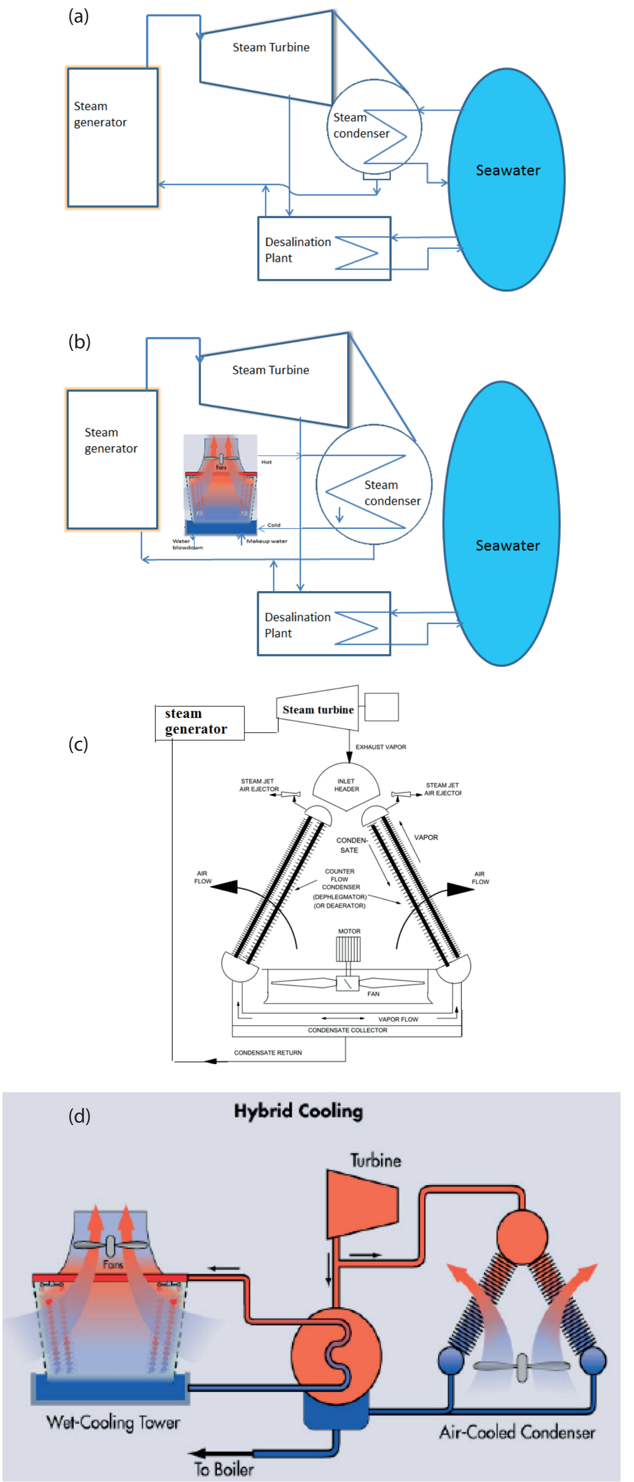

Fig. 2. (a) Diagram of once-through cooling system for CPDP; (b) diagram of closed-loop cooling with cooling towers for CPDP; (c) diagram of air-cooled system [30]; and (d) diagram of hybrid air-water cooled system [31].

systems increase water consumption. Combined-cycle gas turbines (CCGTs) have high thermal efficiency, and therefore require less cooling (570–1,100 L/MWh) water withdrawal using a wet CT. Renewable energy power plants of wind

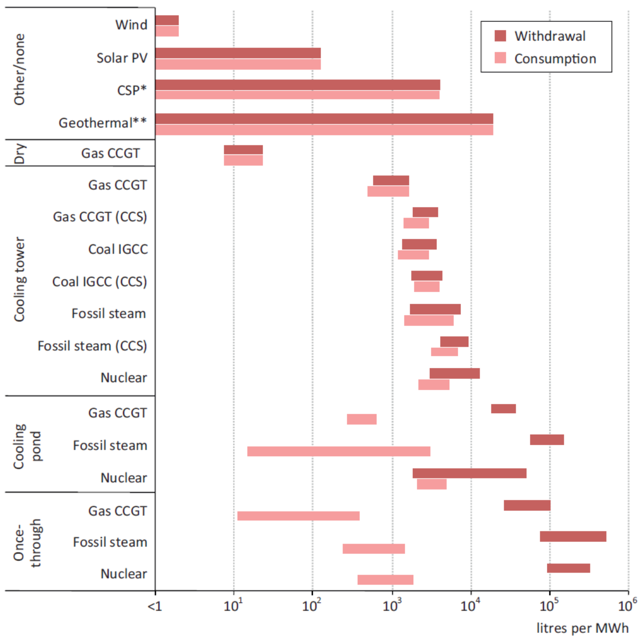

Fig. 3. Water use for electricity generation by cooling technology [2].
*Includes trough, tower and Fresnel technologies using tower, dry and hybrid cooling, and Stirling technology.
**Includes binary, flash and enhanced geothermal system technologies using tower, dry and hybrid cooling.
Note: Ranges shown are for the operational phase of electricity generation, which includes cleaning, cooling and other process-related needs; water used for the production of input fuels is excluded. Fossil steam includes coal-, gas- and oil-fired power plants operating on a steam cycle. Reported data from power plant operations are used for fossil-steam once-through cooling; other ranges are based on estimates summarized in the sources cited below.
Solar PV = solar photovoltaic; CSP = concentrating solar power; CCGT = combined-cycle gas turbine; IGCC = integrated gasification combined-cycle; and CCS = carbon capture and storage.

and solar photovoltaic (PV) use very low amounts of water, usually cleaning or panel washing.

The water needed to cool thermal plants is decreased with the increase of plant efficiency as heat rejected; heat is decreased with the efficiency increase (Fig. 4). The efficiency is defined as the electricity output to heat input.

3. Energy needs for water sectors

A review for the energy needed for water supply, water treatment, residential end use, WW treatment and agriculture end use was given by Plappally and Lienhard [35], Arani et al. [36], Pearce [37], and Abderrahman [38]. Natural water scarcity in GCC and increasing water demands force these countries to produce DW, distribute DW to inland locations, treating good share of municipal WW for reuse, and over-extraction of GW. Energy uses for some of these applications are outlined here.

Water from source (GW or surface water) is treated to meet proper quality requirements before being supplied to consumers such as potable water. The treatment and conveyance consume noticeable amounts of energy, as given in Table 3.

Table 2
Electricity generation categories with capacity factors, water consumption factors and data sources [11]

Electricity generation category[a]				Water consumption factor (m^3 GJ^{-1})		
Fuel	Technology[b]	Cooling	Capacity factor	Estimate	Minimum	Maximum
Coal	ST	CT	0.85	0.722	0.505	1.157
		OTF[c]	0.85	0.263	0.105	0.333
		CP[c]	0.85	0.573	0.315	0.736
		Air	0.85	0.027	0.027	0.027
Nuclear	ST	CT	0.9	0.757	0.610	0.936
		OTF	0.9	0.421	0.105	0.421
		CP	0.9	0.641	0.421	0.757
Gas/oil	ST	CT	0.85	0.768	0.589	1.157
		OTF	0.85	0.305	0.200	0.431
		CP	0.85	0.284	0.284	0.284
		Air	0.85	0.027	0.027	0.027
	CC	CT	0.85	0.221	0.049	0.315
		OTF	0.85	0.105	0.021	0.242
		CP	0.85	0.252	0.252	0.252
		Air	0.85	0.004	0.004	0.126
	GT	NA[d]	0.85	0.053	0.053	0.358
Biomass	ST	CT	0.68	0.581	0.505	1.015
		OTF	0.68	0.315	0.315	0.315
		Air	0.68	0.027	0.027	0.027
Waste heat	ST	CT	0.68	0.581	0.505	1.015
		OTF	0.68	0.315	0.315	0.315
		CP	0.68	0.641	0.421	0.757
		Air	0.68	0.027	0.027	0.027
Geothermal	ST	CT	0.84	0.736	0.736	0.736
		OTF	0.84	0.315	0.315	0.315
		CP	0.84	0.410	0.315	0.505
		Air	0.84	0.305	0.284	0.662
Solar	ST	CT	0.32	0.852	0.778	0.904
		Air	0.32	0.027	0.027	0.027
	PV	NA	0.2	0.006	0.001	0.027
Wind	NA	NA	0.39	0.000	0.000	0.001

[a]All data for global electricity production come from two sources: Platts [32] and EIA [20].
[b]Electricity generation technology types: ST – steam turbine; CC – combined cycle; GT – gas turbine and PV – photovoltaic.
[c]OTF – once through fresh-water and CP – cooling pond.
[d]NA = not applicable.

Table 3 also gives summary of typical energy requirements for treating WW to secondary and tertiary levels, generating DW by multi-stage flash (MSF) and multi-effect (ME) and reverse osmosis (RO) desalting methods, desalting brackish water and water distribution. The extensive energy is required for desalting seawater and thus high production cost, which are discussed in section 4.

DW is used extensively in GCC to satisfy municipal water needs (e.g., 99% in Qatar and 96% in Kuwait), and 57% of global installed desalting capacity exists in the GCC.

Beside DW source, treated wastewater (TWW) is another unconventional water resource. The WW has to be treated before it is safely disposed into the natural environment (e.g., land or sea). Energy is consumed during treatment to remove pollutants in WW. Such pollutants are usually classified as organic contaminants, pathogens, nutrients and synthetic chemicals, which can be harmful to environment. High concentration of organic waste (and ammonia) can reduce the oxygen available in water for species and can lead to devastating effects, such as an exponential increase in the mortality of certain fish. In WW treatment, these organic substances are converted to common gases like carbon dioxide and nitrogen when dissolved oxygen is present. Pathogens like bacteria or viruses cause diseases and should be avoided in discharge streams. Reuse of TWW became common practice in many countries especially for agriculture applications.

3.1. Energy needed for water conveyance

Water is usually transported by pumping through pipelines from where water is available to where it is needed. Example of large water conveyance pipeline is the Disi-Amman Water Conveyance Project used to pump 100 Mm^3/year to Oman, Jordan, from the Disi aquifer lies beneath the desert in southern Jordan and northwestern SA. The project would provide 40% of Jordan's annual water demand, but consume 4% Jordan's total electricity consumption [49,50]. The project moves water through 325 km of pipeline going through several water stations including Ma'an, Tafileh, Karak, Madaba and finally Amman. The project abstracts water from 55 water wells and uses 2 pumping stations to pump water through 120 km ductile pipeline and 345 km steel pipeline.

Other water conveyance projects in Australia were reported by Plappally and Lienhard [35], based on data collected by Stokes and Horvath [51], Scott et al. [52], COA [53] and GWA [54], and include the 116 km length line from southern seawater desalination plant at Perth, Australia, to Perth integrated water system, which consumes 0.21 kWh/m^3 EP; the 11 km length line from Perth desalination plant to Perth integrated supply system, which consumes 0.055 kWh/m^3; and Australia pipe lines of 450 km length, which consumes 3.3 kWh/m^3. Another pipeline was also reported in Spain from Tortosa to Aguadulce of 744 km length, which consumes 4 kWh/m^3.

In GCC, water is routinely transported from regions where DW is produced to inland where water is needed. Conveyance and distribution techniques are used such as

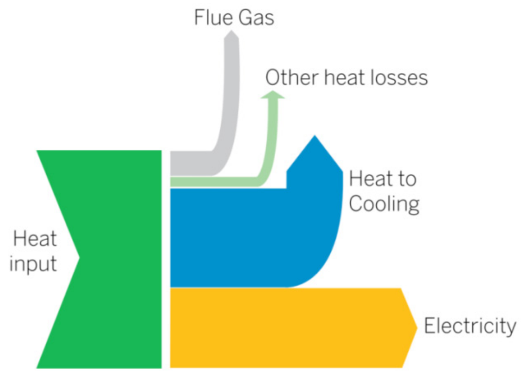

Fig. 4. Simplified visualization of heat balance of a fossil fuel [34].

Table 3
Energy requirements, GHG emissions and costs for various types of potable water [36]

Process	Thermal energy (MJ/m^3)	Electrical Energy[a] (kWh/m^3)	Total electric equivalent (kWh/m^3)	GHG emissions (kg CO_2/m^3 H_2O)	Costs ($\$/m^3$) (2009, dollars)	Product water recovery ratio (%)
Treated surface water	–	0.15–0.3 [37]	0.15–0.3 [37]	0.29[b]	Nd	N/a
Groundwater	–	0.4–0.8 [38]	0.4–0.8 [38]	0.77 [38]	$0.31–$1.68 [39]	N/a
Secondary treated wastewater	–	0.13–0.64 [40]	0.13–0.64 [40]	0.12–0.61[b]	$0.13–$0.63 [41]	N/a
Tertiary treated wastewater	Nd	0.8–1.0 [37]	0.8–1.0 [37]	0.77–0.96[b]	$1.19–$2.03 [42]	N/a
MSF: Seawater (cogeneration)	250–300	3.5–5.0 [43]	15–25 [43]	10–20 [11]	$0.60 [43,44,47]	10–14 [45]
MED: Seawater (cogeneration)	150–220	1.5–2.5 [43]	8–20.1 [7]	11.2–19.6[b] [43,47]	$0.5 [47]	12–15 [45]
RO[a]: Seawater (cogeneration)	0	5.0–9.0 [43]	5.0–9.0 [43]	8.6[b] [43,47]	$0.46 [47]	34 [45]
RO[a]: Brackish groundwater	0	0.98 [46]	0.98 [46]	0.94	$0.26 [43]	
Distribution (per km):						
Horizontal	Nd	Nd	0.00024 [48]	Nd	$0.001 [43]	N/a
Vertical	Nd	Nd	0.233 [48]	Nd	0.92 [43]	N/a

[a]Electrical energy inputs vary based on whether or not an energy recovery system is used.
[b]CO_2 emissions are estimated based on the assumption that 1 kWh of electricity production results in 0.96 kg of CO_2 emissions.
Note: GHG: greenhouse gases; Nd: no data; N/a: not applicable.

tanker trucks and pipelines. One of the largest water conveyance systems in the GCC and the world is the Jubail-Riyadh water system in SA.

Pumping energy depends on elevation change (including depth in the case of GW), distance, pipe diameter and friction. A major pumping system conveying DW from the Arabian Gulf shore to the city of Riyadh, shown in Fig. 5, is given here as example [55]. This system has three separate pipelines:

- Lines A + B, known as "Riyadh Water Transmission System"

  It is closed hydraulic system extending 466 km from the seawater DP in Jubail to Riyadh. It transports about 830,000 m^3/d of DW through twin 60-inch carbon steel pipelines by using 6 pumping stations of 430 MW power capacity, and has 52 bar operating pressure. This is real high consumed energy of 12.4 kWh/m^3 for only conveying DW (or 0.0266 kWh/m^3 km), which can cost \$1.24/m^3 if the price of kWh is \$0.1/kWh. The system went into operation back in 1983 and was one of the largest water conveyance systems in the world at that time.
- Line C is an independent system known as "Riyadh Water Transmission System"

  Line C transports 380,000 m^3/d over a slightly more direct northern route of line A + B to Riyadh. It starts at the desalination plant in Al Jubail and covering a distance of 390 km along the Dammam-Riyadh highway with the help of four pumping stations of 150 MW installed capacity. The system went into operation in 1995. The calculated specific consumed energy is 9.47 kWh/m^3 (or 0.0243 kWh/m^3 km).

  Lines A + B and line C has a cumulative capacity of 1.2 Mm^3/d, which is close to the desalting capacity built in Jubail before 2015 to supply Riyadh with DW.
- Line (D + E) from Ras Al Khair to Riyadh

  In anticipation of the new built Ras Al Kair desalination plant that has 9 MSF units producing of 0.728 Mm^3/d by 9 MSF units of 91,000 m^3/d each [56], and SWRO plant producing 0.309 Mm^3/d by 17 SWRO trains of 18,184 m^3/d each [57], another line D + E was built to carry almost 1 Mm^3/d of DW from Ras Al Khair to Riyadh.
- Line D + E

  It has 947,000 m^3/d pumping capacity through twin carbon steel pipes, 72 inches in diameter, which extended (374 + 92) 466 km and should have been finished in 2013. Three pumping stations are used with 270 MW total installed power capacity. The specific pumping energy consumption in this line is improved to be 6.84 kWh/m^3, or 0.024282 kWh/m^3 km compared with line A + B of 12.4 kWh/m^3, and line C of 9.47 kWh/m^3.

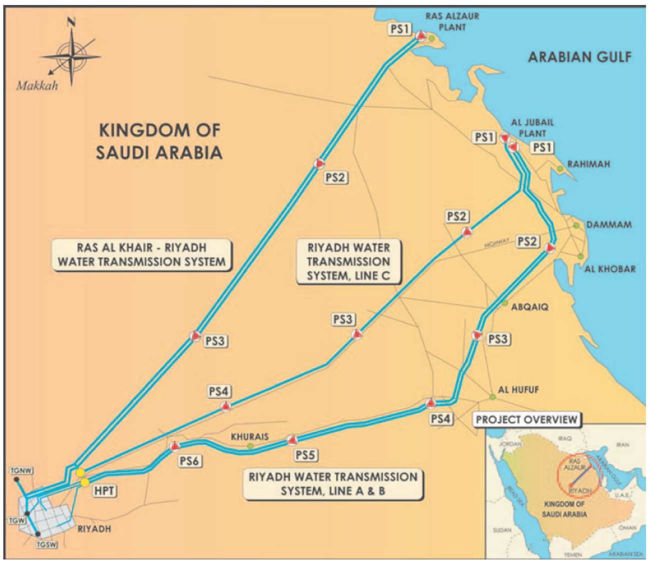

Fig. 5. Pipelines routes supplying desalted seawater from the Arabian Gulf to Ryiadh [55].

It is noticed here that the reported consumed energy per m^3 per km in the Riyadh projects are much higher than those reported for other large water conveyance systems, e.g., Perth seawater desalination plant in Australia through 11.2 km pipeline of 0.005 kWh/m^3 km [35].

The three lines' daily total capacity is 2.157 Mm^3/d, which consumes 20.3681 GWh (average 9.44 kWh/m^3) at cost of \$2.037 million per day (\$743.4 million per year) if the cost 1 kWh is \$0.1/kWh. If the energy consumed to produce 1 m^3 of water is 20 kWh/m^3, by thermal desalting systems, then the energy cost only to supply Riyadh with DW is \$2.32 billion per year. This covers only one city of SA.

In India, water is pumped and transported from the Indira Gandhi Canal to Jodhpur, more than 200 km away. As a result electricity costs are as high as 77% of the total operating cost [1].

3.2. Energy needed for wastewater (WW) treatment

Reclaimed treated WW is used for non-potable applications in the GCC (e.g., landscaping, irrigation, fire-fighting and cooling). However, reclaimed treated WW can directly or indirectly augmented with drinking water supplies in some countries, after being treated with RO and ultraviolet (UV) [58]. Table 4 gives the total water withdrawal, raw WW and TWW in the GCC in 2009.

WWTP use EP for moving and treating the WW. The cost of energy consumed in WWTP in USA is about 25%–30% of total plant operating and maintenance cost. However, several WWTP plants are becoming (or approaching) energy self-sufficient (net zero energy use) [60], e.g., the plants in Sheboygan, WI; East Bay MUD, CA; and several others in USA, and Strass WWTP in Austria [61]. The energy consumed in WWTP was addressed by several, but not many, authors, e.g., Plappally and Leinhard [35], Tassou [62], Yang et al. [63], Mizuta and Shimada [64], Andersson and Holmberg [65] and Electricity Use and Management [66].

Kuwait has the largest worldwide WW treatment and reclamation plan using microfiltration (MF), ultrafiltration (UF) and RO membranes to treat the WW to potable conditions in Sulaibiya (Fig. 6). The plant capacity increased from 375,000 to 600,000 m^3/d and produces effluent water of potable condition. In 2012, the plant received up to 480,000 m^3/d of WW, which represents about 13% increase in flow over its design capacity, and had 83% recovery ratio. The quality of its effluent water compared with potable condition standards is given in Table 5.

Other large WW treatment plants using RO are the 280,000 m^3/d Orange County Ground Water Replenishment (GWR) plant in the USA and the 228,000 m^3/d plant in Changi, Singapore. The most common process used for WW reclamation is the use of conventional activated sludge process, followed by UF or MF membrane filtration, RO desalination, and UV disinfection.

Municipal WW is usually treated in four stages: preliminary, primary, secondary and tertiary.

In preliminary step, the WW is collected, screened and chemically treated; grit is removed before sedimentation takes place in order to remove large solids from the stream to prevent damage of equipment further downstream. Raw sewage collection and pumping energy consumption is 0.04 kWh/m^3 in the USA [35]. In primary treatment, some organic nitrogen, organic phosphorus, and heavy metals associated with solids are removed. About 25%–50% of incoming biochemical oxygen demand (BOD_5), 50%–70% of total suspended solids (TSS), and 65% of oil and grease are removed during this primary treatment. Total energy consumed in the primary treatment in Australia is ranged from 0.01 to 0.37 [35,68].

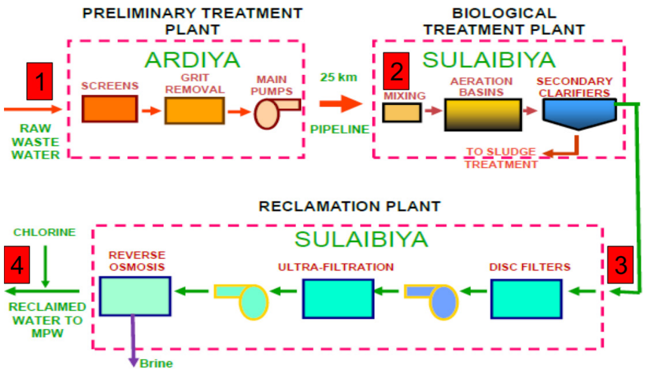

Fig. 6. Layout of the Sulaibiya wastewater treatment and reclamation plant in Kuwait [67].

Table 4
Total water withdrawal, raw wastewater and treated wastewater in the different Arab countries in 10^9 m^3/year [59]

Countries	Total water withdrawal (10^9 m^3/year)	Total wastewater produced (10^9 m^3/year)	Volume of treated wastewater (10^9 m^3/year)	Volume of treated water reused (10^9 m^3/year)
Saudi Arabia	23.67	0.73	0.652	0.166
Bahrain	0.3574	0.0449	0.076	0.0163
United Arab Emirates	3.998	0.5	0.454	0.248
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

Table 5
Effluent water quality criteria as compared with potable water quality criteria [69]

Parameter	Unit	Contract effluent quality from Sulaibiya	Actual effluent quality from Sulaibiya (2012)	WHO maximum allowable limit	Kuwait Standard for unbottled water (maximum)
pH	–	6–9	7.3	6.5–8.5	6.5–8.5
TDS	mg/L	>100	39	1,200	1,000
Total suspended solids (TSS)	mg/L	>1	0.024		
VSS[a]	mg/L	>1	0.019		
BOD	mg/L	>1	0.23		
Ammonia nitrogen as N	mg/L	>1	0.03	35	1.5
Nitrate nitrogen as N	mg/L	>1	0.7	10	
Total phosphate	mg/L	2	0.08		
Sulfide	mg/L	>0.1	1.3E-04	0.1	0.05
Fat oil and grease	mg/L	>0.05	0.015	0.01	
Total organic carbon	mg/L	>2	0.34		
Hardness as $CaCO_3$	mg/L	>10		500	500
Color	TCU	>1	Clear		15
Total coliform	MPN/100 mL	>2.2	1		Free

[a]VSS – volatile suspended solids.

The secondary treatment removes more of organics and suspended solids left in the primary effluent. It involves the removal of biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Aerobic biological treatment is performed in the presence of oxygen by aerobic microorganisms (principally bacteria) that metabolize the organic matter in the WW, thereby producing more microorganisms and inorganic end products (principally CO_2, NH_3 and H_2O). Microorganisms must be separated from treated WW by sedimentation to produce clarified secondary effluent. This biological treatment includes bacteria attached-growth and suspended-growth systems. The attached growth uses trickling filters (oxidizing beds) and rotating biological contactors, and the bacteria are located on a medium over which WW is passing through. In suspended growth, the bacteria are found in the WW flow as suspension and are one of the most common processes that use this type of activated sludge process. In the activated sludge process, dispersed-growth reactor is an aeration tank or basin containing a suspension of the WW and microorganisms, the mixed liquor.

Plappally and Lienhard [35] reported the intensity of energy in the secondary WW, as: 0.18–0.42 kWh/m^3 for trickling filter and 0.33–0.60 kWh/m^3 for activated sludge.

The aim of tertiary treatment can include disinfection to kill off pathogens by using chlorine, ozone or UV radiation; reducing the nitrogen (N) and phosphorous (P) content of the effluent and final solid removal. Most WWTP in Qatar have preliminary, primary, secondary, tertiary and advanced treatments. In tertiary most of the suspended solids are removed, usually though granular medium filtration, surface filtration and/or membranes, and typically include disinfection and nutrient removal. Finally, advanced treatments remove trace constituents, as required, for specific water reuse applications.

All the stages of municipal WW consume energy but with different intensity based on the strength and characteristics of the WW, plant size, and required quality of effluent. Energy (in the form of EP) is used mainly in aeration and pumping. An example of the consumed energy by 375,000 m^3/d capacity TWWP studied by Newell [70], and based on the WW strength defined as given in Table 6. In this plant, the WW influent is screened by the bar racks to remove large solids and remove grit in the aerated grit chambers. The primary clarifier partially removes the BOD and TSS. The aeration basins and secondary clarifiers then remove BOD, TSS, ammonia and phosphorous. Some of the TSS remaining is also removed in the dual media filters, and the effluent is disinfected with UV irradiation.

Table 7 shows that the specific consumed energy is 0.237, 0.238, and 0.496 kWh/m^3 for low, average and high WW strengths, respectively. The share of the secondary treatment is 0.145, 0.225 and 0.366 kWh/m^3 or 60%–73% of total consumed energy for low, average and high WW strengths, respectively.

The 2014 UN World Water Development Report [1] suggested that supply and management of WW in the state of California consume up to 20% of the total state consumed energy, and the energy can cost up to 40% of total operating cost in countries like Bangladesh and India.

In urban water supply and WW management systems, water conveyance and the use of advanced water treatment options are generally the most energy-intensive activities (Fig. 8). Water reuse may also require significant energy, depending on the technology used, but this is still less energy intensive than desalination or transporting water over extremely long distances as shown in the Jubail–Riyadh convergence water system, and by the UN report [1].

Fig. 7 shows that different levels of treatment are required for different uses. Drinking water typically requires extensive treatment, and once used, it needs to be treated again to reach a standard that is safe for return to the environment or to be reclaimed. Many of the used processes are energy intensive. Seawater desalination is at the high end of the energy intensity scale, with energy requirements being a function of water temperature and salinity (Fig. 7).

4. Energy and water in GCC

4.1. Energy and water status in GCC

While the GCC has severe natural water scarcity compared with other parts of the world (Fig. 8), they have

Table 6
Wastewater characteristics and effluent criteria [70]

Contaminant	Influent			Effluent
	Low strength	Average strength	High strength	
Influent flow, MGD	100	100	100	N/A[a]
TSS, mg/L	120	210	400	<30
Volatile portion of TSS, %	80	80	80	N/A
5 d biochemical oxygen demand, mg/L	110	190	350	<30
Total phosphorous, mg/L	4	7	12	<0.2
Total Kjeldahl nitrogen/ammonia, mg/L	20	40	70	<0.5
Total coliform, MPN/100 mL	10^6–10^8	10^7–10^9	10^7–10^{10}	<200
Peak flow factor for all liquid units but dual media filters, low pressure high output UV	1.5	1.5	1.5	N/A
Peak flow factor for dual media filters, low pressure high output UV, and medium pressure high output UV	1.9	1.9	1.9	N/A

[a]N/A - not applicable.

Table 7
Energy consumption per unit operation for a 100 MGD wastewater treatment plant treating different wastewater strengths [70]

	Component	kWh/MGal		
		Low strength	Average strength	High strength
Bar racks	Rakes	0.07	0.09	0.13
Grill chambers	Blowers	4.1	6.29	8.21
Primary classifiers	Sludge pumping	0.86	1.17	1.85
	Torque	0.46	0.47	0.53
	Total	1.32	1.64	2.37
Aeration basins	Blowers	336.2	631.3	1,081
	Chemical pumps	0.54	1.24	1.61
	Mixers	104.8	104.8	125.8
	Total	441.5	737.3	1,208.4
Secondary clarifiers	RAS	100.3	101.8	160.5
	Torque	0.7	0.8	0.8
	WAS	1	2	3.8
	Total	102	104.6	165.1
Dual media filters	Filter influent pump station (FIPS)	125.7	125.7	125.7
	Backwash pump energy	1.7	2.9	3.8
	Backwash blower energy	0.7	1.2	2
	Total	128.1	130.2	133.1
UV	MPHO[a] UV	184.3	201.6	254.4
Gravity thickness	Rake arm	0.12	0.25	0.37
	Overflow pumps	0.16	0.31	0.63
	Sludge pumps	0.22	0.34	0.58
	Total	0.5	0.9	1.58
DAFTS[a]	Recycle pumps	9.3	18.5	35.4
	Rake arms	2×10^{-2}	4×10^{-2}	7×10^{-2}
	Sludge pumps	0.2	0.3	0.7
	Air compression	8×10^{-2}	0.2	0.3
	Overflow pumps	0.7	1.3	2.5
	Total	10.2	20.1	39
Centrifuges	Feed acceleration	14.4	24.5	43.9
	Cake conveyance	1.7	3.3	5
	Total	16.1	27.8	48.9
	Total energy	888.3	1,230.80	1,861.1

[a]Note: MPHO – mean pressure high output and DAFTs – dissolved air filtration thickeners.

abundant fossil fuel production (23.3% of total world production) and among the highest energy consumption countries in the world (Fig. 9). Fossil fuel reserves are not endless.

In 2010, the GCC natural water resources per capita was 92 m^3/year Ca (or less than the minimum survival level of 100 m^3/year Ca) and is expected to decrease to 61 in 2030 (Table 8). Kuwait had the lowest in 2010 (7 m^3/year Ca) followed by UAE (20 m^3/year Ca), and Qatar (33 m^3/year Ca).

These are much far below the water poverty line stands at 1,000 m^3/year Ca. The situation is worsened by population increase, scarcity of rainwater and high per capita consumptions (Table 9 and Fig. 10). The natural resource is mainly GW, as the rainwater is almost negligible, and no surface water.

SA, Libya, Yemen and UAE have hit peaks in water production and are depleting their water supply (Table 10). There are two definitions of peak water developed by the Pacific Institute in USA [72]. The first is peak renewable water that applies where flow constraints limit total water availability over time. The second is peak non-renewable water that is observable in GW systems where production rates are much exceeding the natural recharge rates and where over-pumping or contamination leads to a peak of production followed by a decline, similar to more traditional peak-oil curves.

Water scarcities in the GCC pose severe challenges. The challenges are high costs of generating DW and treating WW, tapping non-renewable GW sources, depletion and pollution of GW, wasteful use of already developed water supplies by over-consumption, and degradation of soil in irrigated areas. This is further exacerbated by government subsidies of water and energy use. Qatari citizens consume water at 1,200 L/d Ca because they got free utilities (water and EP), while non-Qatari residents consume 150 L/d Ca because they pay about one-third of the water cost. Table 11 shows the water and electricity production cost, tariffs, and subsidy rates in select GCC countries.

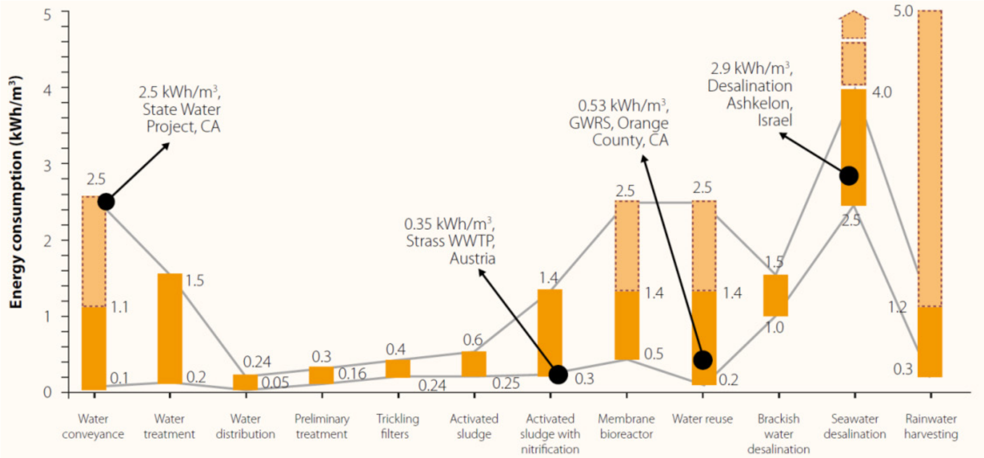

Fig. 7. Typical energy footprint of the major steps in water cycle management with examples from different treatment plants using specific technologies [1].
Note: GWRS, groundwater replenishment system; WWTP, wastewater treatment plant.

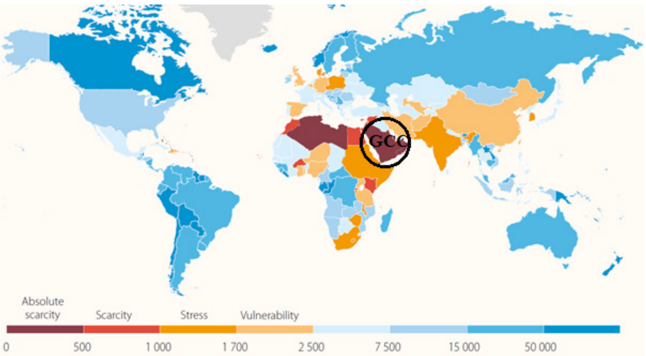

Fig. 8. Total renewable water resources, 2011 (m³/capita/year) [1].

Fig. 9. Energy consumption per capita by country, 2010 [1].

SA suffers the biggest gap between renewable GW supply and demand. It has only 2.4 km³/year of renewable water resources, yet extracts 23.67 km³/year, almost 10 times renewable water resources. Food production in SA has been based on fossil (non-renewable) GW of negligible replenishment rate, and bound to run out someday. SA has abandoned, its self-sufficient food production, based on fossil water, and is now importing virtually all of its food. The DW provides about half the country freshwater. The balance is supplied by GW (40%), surface water (9%) and reclaimed WW (1%).

Table 8
Renewable water resources and per capita share in the GCC and Yemen [73]

Country/ subregion	Natural water resources (Mm³)	Average share (m³/capita)		
		2010	2030	2050
Bahrain	116	92	70	64
Kuwait	20	7	5	4
Oman	1,400	503	389	374
Qatar	58	33	24	22
Saudi Arabia	2,400	87	62	53
United Arab Emirates	150	20	14	12
GCC	4,144	95	68	59
Yemen	2,100	87	51	34
GCC and Yemen	6,244	92	61	47

Meanwhile, the GCC are very rich in prime energy (oil and gas) reserves and productions. The GCC have 495.0 Bbbl of oil reserve (29.9% of total world reserve), and 42.4 trillion m³ (TCM) of NG reserve (20.3% of the total reserve). The NG reserves are concentrated in Qatar alone with more than 25 TCM, nearly half of total Arab reserves. Qatar's NG reserves are the currently third largest in the world, after Russia and Iran, and Qatar is the largest producer and exporter of liquefied natural gas. Significantly smaller gas deposits are found in SA (8.2 TCM), the UAE (6.1 TCM) and Algeria (4.5 TCM).

The GCC prime energy oil in barrels per day (b/d) and gas productions in Bm³ are given in Table 12(a), and total energy production in thousand barrels of oil per day equivalent (boe/d) is given in Table 12(b).

Similarly, the GCC prime energy oil and gas consumptions are given in Table 13(a), and total energy consumption is given in Table 13(b). Consumption rates are continuously increasing than production rates.

The oil and gas domestic consumption as a percentage of production for the GCC is given in Fig. 11. This figure shows that almost all GCC, except Qatar, have almost no income from exporting NG. The consumed prime energy is continuously on the rise (Fig. 12).

The government revenues in the GCC depend mainly (more than 80%) on the income of oil and gas exports, and are vulnerable to price volatility, and increase domestic consumptions. The revenues' high dependence on hydrocarbon exports is shown in Fig. 13(a).

The sensitivity of regional budgets to oil prices is expressed by the breakeven oil price for each country, i.e., the oil price at which a country's budget would be balanced. The Emirates National Bank of Dubai analysis suggests that Bahrain and Oman have the highest breakeven oil prices in the GCC, at \$125/bbl and \$121/bbl, respectively (based on 2014 expenditure and oil production estimates), and Kuwait has the lowest breakeven oil price at \$61/bbl, while

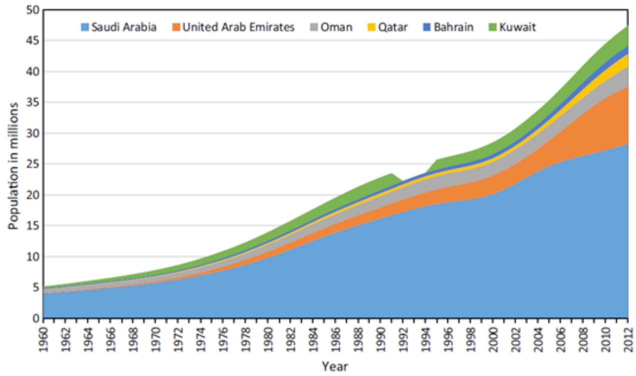

Fig. 10. The GCC population growth since 1960 [71].

Table 9
Data on GCC population, water runoff, rain water, annual evaporation and per capita consumption in GCC [74]

Country	Area (km^2)	Population (M)	Surface runoff (MCM)	Rainwater (Bm^3)	Annual evaporation (mm)	Consumption per capita (L/d)
SA	2,149,690	28.5	3,210	158.47	3,500–4,500	252
Kuwait	17,818	3	0.1	2.27	1,900–3,500	476
Bahrain	695	0.5514	0.2	0.4	1,650–2,050	455
Qatar	11,610	1.4	1.4	0.47	2,000–2,700	407
UAE	77,700	2.444	150	6.72	3,900–4,050	770
Oman	300,000	2.518	1,470	37.6	1,900–2,700	146
Total	2,557,513	38.4134	4,831.7	205.93 avg.	2,500–4,500 average	400

Table 10
Freshwater shortfall in GCC, Libya and Yemen [75]

Region and country	Total freshwater withdrawal (km^3/year)	Total freshwater supply (km^3/year)	Total freshwater shortfall (km^3/year)
Saudi Arabia	23.67	2.4	21.27
Libya	4.27	0.6	3.7
Yemen	6.63	4.1	2.5
United Arab Emirates	2.3	0.2	2.2
Kuwait	0.44	0.02	0.4
Oman	1.36	1	0.4
Qatar	0.29	0.1	0.2
Bahrain	0.3	0.1	0.2

Table 11
Water and electricity production cost, tariffs and subsidy rates in selected GCC countries [71]

Country	Product production cost (US \$)	Tariff (US \$)	Subsidization rate (%)
Bahrain	Electricity 0.07/kWh	0.01–0.04/kWh	43–86
	Water 1.92/m^3	0.80–1.06/m^3	45–58
Qatar	Electricity 0.07/kWh	0.02–0.04/kWh	42–67
	Water 2.74/m^3	1.21–1.92/m^3	30–56
UAE	Electricity 0.07–0.09/kWh	0.01–0.04/kWh	40–88
	Water 2.48/m^3	0.60/m^3	76–100

Table 12(a)
Prime energy (oil and gas) production in the GCC [76]

	Oil production ('000 b/d)	Share in world production (%)	Ratio of export to consumption	Gas production (Bm^3)	Share in world production (%)	Ratio of export to consumption
GCC states	19,505.1	23.3	5.8	350.3	10.7	–
Bahrain	47.4	0.1	5.0	13.0	0.4	–
Kuwait	2,681.9	3.2	7.7	13.0	0.4	–
Oman	888.9	1.1	6.7	26.5	0.8	0.7
Qatar	1,637.5	2.0	6.0	146.8	4.5	4.4
SA	11,153.0	13.3	3.8	99.2	3.0	–
UAE	3,096.3	3.7	5.3	51.7	1.6	0.3

Table 12(b)
Total energy production, thousand boe/d [65]

Year	2013	2012	2011	2010	2009
UAE	4,200.9	4,035.2	3,956.7	3,551.2	3,403.5
Bahrain	464.8	424.9	435	425.8	416.2
SA	12,759	12,869.3	12,195.7	10,902.1	10,682.2
Qatar	5,441.6	5,439.2	5,338.7	4,809.3	3,504.8
Kuwait	3,350.3	3,450.3	3,068.2	2,699.1	2,621.1
Oman	1,501.7	1,439.7	1,403.9	1,335	1,258.9
Total	27,718.3	27,658.6	26,398.2	23,722.5	21,886.7

Table 13(a)
Prime energy (oil and gas) consumptions in the GCC [64]

	Crude oil and petroleum products ('000 b/d)		Average annual increase (%)	Natural gas (Bm^3)		Average annual increase (%)
	2000	2010	2000–2010	2000	2010	2000–2010
GCC states	2,256	3,855	5.0	111.48	214.5	6.1
Bahrain	23	47	6.6	8.5	12.3	3.4
Kuwait	264	354	2.7	6.9	14.5	7
Oman	53	106	6.6	5.68	17.5	10.8
Qatar	48	152	11.0	9.16	21.8	8.2
Saudi Arabia	1,537	2,650	5.1	49.81	87.7	5.3
UAE	330	546	4.7	31.43	60.8	6.2

Table 13(b)
Total prime energy (oil and gas) consumption, thousand boe/d [77]

	2013	2012	2011	2010	2009
UAE	1,542.2	1,467.4	1,400.8	1,336.9	1,268.1
Bahrain	281.5	265.4	254.7	256.7	245.8
SA	3,937.6	3,890.3	3,652.6	3,474.9	3,197.5
Qatar	1,328.5	1,390.5	1,345.5	1,343.7	898.7
Kuwait	518.6	537.6	531.2	585.6	529.8
Oman	518.9	476.9	457.4	389.6	362.4
Total	8,127.3	8,028.1	7,642.2	7,387.4	6,502.3

SA breakeven oil price this year is about \$100/bbl [80]. Other breakeven estimate is given in Fig. 13(b).

4.2. Desalination in the GCC

The increase of freshwater demands due to fast economic growth in GCC cannot be satisfied by the main renewable water source, namely by GW. DW is used mainly to satisfy municipal water needs in the GCC. DW was originally produced by using land-based multi-effect desalting (MED) system (up to 1958), when the MSF system was introduced in Kuwait in 1959. The dependence of GCC on DW grew, especially after 1973, due to significant increase in oil prices.

DW generated in the GCC has high drinking water quality, is the main source for municipal water and is used directly or blended with low percentage of GW (e.g., 1% in Qatar and 4% in Kuwait). Desalting seawater was the only option in GCC to secure municipal water needs, although it is very expensive. In 2013, the GCC have 7,499 contracted and online DPs, and this represents 43% of the total global DP number. These DP (contracted and online) have 62.34 Mm^3/d and represent 70% of the total global capacity. Most recent figures of online and contracted plants and capacities of the GCC countries [82,83] are given in Table 14(a). Fig. 14 shows the cumulative installed desalination capacity in GCC countries since 1970 [29].

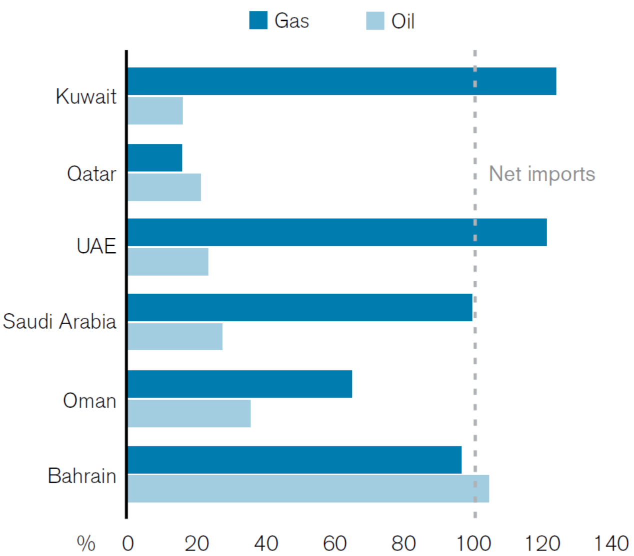

Fig. 11. GCC countries oil and gas consumption as a percentage of production [78].

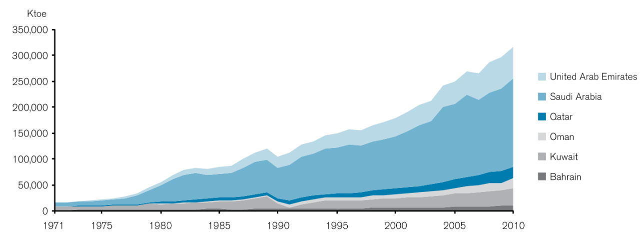

Fig. 12. GCC energy consumption, 1971–2010 (ktoe) [78].

An example of the significant growth of population and desalination capacity in the last decade is given for Qatar. Qatar's total population increased from 0.52 million (M) in 1960 to 1.447 M in 2008 to 2.2 M in 2013 (4,240% in the last 50 years). Desalination plants in Qatar (by the end of 2010) had cumulative capacity of 325 MIGD or almost 1.5 Mm^3/d, and DW production increased from 178 Mm^3/year in 2004 to 465 Mm^3/year in 2013.

Also, SA is the largest producer of DW in the world, with DW plant capacity close to 15 Mm^3/d, almost 14% of global capacity. SA is the largest oil-consuming nation in the Middle East. SA consumed 2.9 Mbbl/d of oil in 2013 out of about 11 Mbbl/d productions, almost double the consumption in

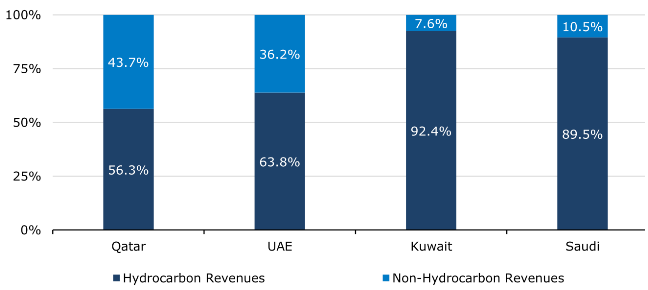

Fig. 13(a). Share of Hydrocarbon Revenues to Government Revenues [79].

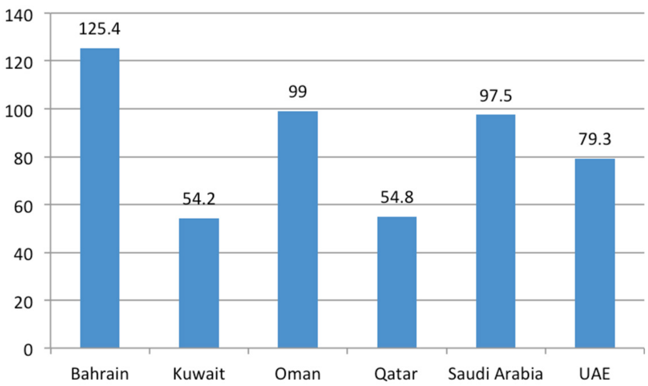

Fig. 13(b). Gulf state breakeven oil prices (US$/barrel) [81].

Table 14(a)
The GCC online and contracted desalting plants number and capacity in Mm^3/d [82].

	Online plants	Contracted plants	Online capacity (Mm^3/d)	Contracted capacity (Mm^3/d)	Population in millions
UAE	492	497	9.358	10.109	9.206
KSA	2,664	2,664	13.080	14.792	28.29
Qatar	139	139	1.833	1.997	2.035
Oman	184	184	1.095	1.351	3.87
Kuwait	88	88	3.023	3.478	3.251
Bahrain	165	165	1.113	1.113	1.318
Total	3,732	3,737	29.503	32.84	47.969

2000. Contributing to this growth is raising direct burn of crude oil for power generation producing both EP and DW, which has reached an average of 0.7 Mbbl/d from 2009 to 2013 during the months of June to September. The domestic oil demand is expected to reach more than 8 Mbbl/d of oil equivalent by 2030 if there were no improvements in energy efficiency.

The majority of the seawater DPs in GCC is thermally operated such as MSF, multi-effect-thermal vapor compression (ME-TVC) and seawater reverse osmosis (SWRO) DPs. The share of SWRO DPs is on the rise, and all brackish plants are using RO plants (Fig. 15). The DW is very costly, is energy intensive, is negatively affecting the environment and cannot be continued forever.

There is strong link between water and consumed energy in GCC because of the large share of DW in water withdrawal. The DW represents 99%, 93% and about 66% of municipal water in Qatar, Kuwait and SA, respectively. DW is also transported long distance from its production plants on shore to inland by pumping energy, e.g., about 466 km from the Gulf shores to Riyadh in SA as given before.

The GCC estimated production of DW in 2012 was about 26.937 Mm^3/d (17.245 Mm^3/d) by the thermally operated processes used in the GCC, namely MSF and ME-TVC, and 9.690 Mm^3/d by SWRO as shown in Table 14(b).

The MSF and ME-TVC are consuming both thermal energy, about 270 MJ/m^3, for plants having average gain ratio (distilled water to heating steam) about 8; and both consume pumping power, about 4 kWh/m^3 for MSF and 2 kWh/m^3 for ME-TVC systems. The total consumed equivalent mechanical energy is 20 kWh/m^3 for both systems, and this gives 200 MJ/m^3 consumed fuel energy for the MSF and ME-TVC systems [84]. The consumed pumping energy for SWRO is in the range of 5 kWh/m^3, or 50 MJ/m^3, for SWRO [72]. This is much higher cost than \$1/m^3, reported in literature, which is for SWRO of 4–6 kWh/m^3 specific energy consumption.

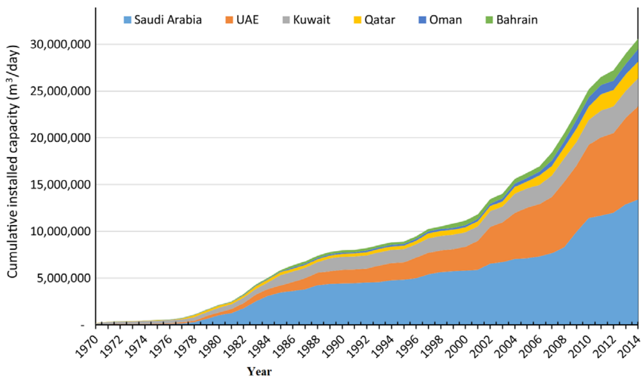

Fig. 14. Cumulative installed desalination capacity in GCC countries since 1970 [71].

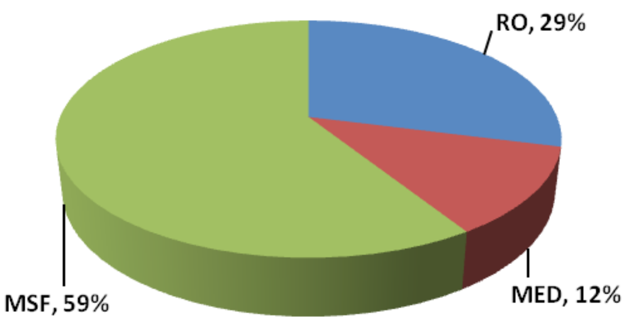

Fig. 15. Desalination capacity by technology in the GCC countries [82].

This shows the heavy economic burden of using DW. For example, in Qatar, the consumed DW in Qatar was 373 Mm^3/year in 2010 [85], and this was increasing at annual rate of 14% between 2004 and 2010, more than doubled in 6 years. Therefore, the cost of DW in Qatar was about \$1.275 billion in 2010 and can be \$2.55 billion before 2020.

There are several ways to reduce the cost of producing DW. First, the more energy-efficient SWRO desalting system should be used in place of the predominantly used MSF and ME-TVC systems. The use of relatively cheap NG fuel, compared with oil will also reduce the DW production cost. The DW quality is high, as well as its cost, and its use should be limited to cooking and drinking, while TWW should be used for application that do not need high water quality such as toilet flushing, gardening, etc.

An example from SA, where access to freshwater, is one of the most important challenges; the Saudi Ministry of Water and Electricity (MoWE) estimated that 25% of Saudi oil and gas production in 2009 was used domestically to generate electricity and produce water, with present demand rates suggesting that this figure will reach 50% by 2030 [36]. NG demands are consequently also anticipated to double from 2007 to 2030, from 7.1 to 14.5 BCF/d [36]. The MoWE has estimated that an investment of \$53 billion will be required for water desalination projects over the next 15 years, with an equivalent amount required for the sewage sector [36].

Domestic water demand increased at an annual growth rate of 6%, i.e., from 200 Mm^3/year in 1970 to 2,063 Mm^3/year in 2010 [86]. SA is currently relying on building costly desalination plants to satisfy around half of the water demand. In Riyadh, the capital city with a population about 5 million, water supplies come from local brackish GW (906,644 m^3/d or 48%) treated by RO for agriculture use. The balance comes from desalination plants on the Arabian Gulf through about 466 km conveyance line. The other part of water supply

Table 14(b)
The 2012 estimated daily desalted water production in the GCC [82]

Country	Thermal + SWRO + BW	Thermal processes	SWRO
SA	13,530,973	5,426,131	5,479,792
UAE	9,753,024	7,411,069	2,209,065
Kuwait	2,134,253	1,461,136	275,254
Qatar	1,944,195	1,771,638	155,160
Oman	1,626,149	417,990	988,888
Bahrain	1,398,064	756,967	582,667
Total	30,386,658	17,244,931	9,690,826

comes from three desalination plants MSF-I (starting year 1982, capacity of 118,447 m^3/d), MSF-II (starting year 1983, capacity of 815,185 m^3/d) and RO (starting year 2002, capacity of 78,182 m^3/d). A total desalinated seawater of little more than 1 Mm^3/d. The water supply system in the city is also characterized by large unaccounted for water, estimated to be 30% of the water supply. The residential per capita water consumption in the city is estimated in 2011 to be 308 L/d [6]. The projected water demand in 2030 is of 2.610 Mm^3/d, or 1.6 Mm^3/d; more DW is needed by 2030 [86]. Ras AlKhair of almost one Mm^3/d was built, but the other MSF plants in Jubail are near their end expected life.

5. Conclusion

The relation between water and energy was briefly introduced with water needed for prime energy extraction and/or processing, as well as EP generation. The water demands for oil extraction in GCC are on the rise as most GCC finished their primary extraction to the second, which consumes much more water. Also, liquefaction of NG in Qatar for easy transportation also increases the water demands. The water scarcity in GCC forces these countries to use GT and GTCC power cycles for their EP production. OT seawater cooling in power plants is extensively used with low water consumption but high water withdrawal.

The water and energy status in GCC is presented. It is clear that in GCC, water and energy consumptions are on the rise in unsustainable way, and water generated from seawater consumes too much energy due to the high demands and the use of inefficient desalting systems.

Huge amounts of energy are consumed in GCC to produce DW, used mainly for municipal water demands, and conveying DW from desalination plants on shores to inland cities like Riyadh in SA, and Dukhan in Qatar.

The thermal desalting processes such as MSF or ME-TVC consume about 260 MJ/m^3 thermal energy, and pumping energy of 4 kWh/m^3 for MSF and 2 kWh/m^3 for ME-TVC system. This gives specific consumed equivalent mechanical energy (SEC) about 15–20 kWh/m^3 when combined with power plants, and 35 kWh/m^3 when directly operated by boilers. The idea that thermal energy supplied to MSF or ME-TVC is waste heat rejected from power plants is false. The SEC is directly related to the fuel consumed to produce DW. Burning fuel is accompanied with CO_2 emission, which pollutes air environment. Marine environment is also polluted due to high seawater extraction (6–10 times the product D), and brine discharge with high salinity (70,000 ppm), at temperature higher than that of seawater when MSF desalination system is used for example. It is clear that in GCC the use of SWRO desalting system should be expanded as it consumes about 6 kWh/m^3 pumping energy. Most of DW plants are located on the Arabian Gulf, a semi-closed sea, with too much salinity and thermal energy disposing.

Conveying DW from far away DPs to large cities consumes more pumping energy. As example, the three lines' daily total capacity is 2.157 Mm^3/d, from Jubail to the city of Riyadh in SA, which consumes 20.3681 GWh/d (average 9.44 kWh/m^3). If EP cost is \$0.1/kWh, then the cost of energy only for 1 m^3 to reach Riyadh is about \$3/m^3, \$2/m^3 for energy by MSF desalting system and \$1/m^3 for its conveyance.

The energy consumed for WW treatment to potable condition is much lower (about one-fourth) than that consumed for desalting seawater, and this does not include its conveying to inland. Treated WW is a valuable water source that should be used to substitute DW production especially inland cities. Moreover, TWW does not need long way conveyance.

The GCC are mining their fossil water reserve, and thus, GW water resources have already been over-exploited; quality deteriorated.

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