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Desalination Project Cost Estimating and Management

Nikolay Voutchkov

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Preface

One of the key challenges associated with the wider implementation of seawater desalination is its relatively high cost. This book provides engineering guidelines for assessment of seawater desalination project construction, operation and maintenance (O&M) costs, and presents practical approaches for cost management using state-of-the-art technologies and equipment.

The book describes step-by-step desalination cost-estimating procedures and practices. It clearly explains key factors impacting desalination costs and available tools to manage such impacts. It also provides an overview of the main cost-saving features incorporated in some of the best-in-class seawater desalination plants worldwide and shares lessons learned from the implementation of recent low- and high-cost desalination projects. This book contains example construction, O&M and water production cost estimates for a typical desalination project.

At present, membrane reverse osmosis (RO) desalination is the fastest growing technology for the production of fresh water from saline water sources. Desalination plants use less energy to produce the same volume of fresh water than thermal desalination facilities. Therefore, this book focuses exclusively on the cost estimating of reverse osmosis desalination projects.

Preparation of cost estimates for the construction, funding, and operation of desalination plants is more complex and demanding than that for conventional water treatment facilities in terms of professional skills, knowledge, and understanding of treatment processes, technologies, and equipment employed in the desalination processes. As the advances in desalination technology make desalination more competitive to other alternative sources of water supply, preparation of accurate cost estimates for the construction and operation of desalination projects becomes of critical importance for identifying the size and role of desalination in the mix of alternatives that provide sustainable and reliable water supply portfolio for municipal coastal centers around the world.

This book provides detailed information on how to determine the costs associated with the implementation of seawater RO desalination plants. The book's content covers practically all aspects of cost estimating: from fundamentals, to factors impacting project costs; type and accuracy of cost estimates; overview of existing cost models and their practical use; and detailed guidance for calculation of capital costs, operation and maintenance (O&M) expenditures, and fresh water production costs of desalination projects. The book also has capital and O&M cost curves for key desalination facilities as well as examples for the preparation of cost estimates.

This book consists of eight chapters, which follow the process of determining all desalination project cost components of capital, O&M and water production costs. Each chapter includes essential knowledge, numerous practical tips, and rules-of-thumb for the preparation of budgetary cost estimates. Moreover, this book contains easy-to-use curves, which helps in preparing budgetary construction and O&M cost estimates as a function of the desalination project size and the type of applied technology and equipment – from open intakes to clarification and filtration pretreatment systems; reverse osmosis facilities, membranes, and equipment; and post-treatment facilities.

Chapter 1 (Project Cost Overview) contains background information on desalination project cost-related definitions and fundamentals needed to understand the procedures and calculations of key desalination project costs, as well as to learn about the parameters used for cost comparison of desalination facilities and equipment.

Chapter 2 (Project Cost Factors) presents the key factors that have a significant impact on the capital, O&M and desalinated water production costs of desalination plants and provides indexes that quantify and compare the impact of these factors on the expenditures for seawater reverse osmosis (SWRO) desalination projects with different fresh water production capacity, source and product water qualities, design availability, method of funding and delivery, concentrate disposal alternatives, project risk profile, power supply source and tariff structure, and project risk profile. This chapter addresses both cost factors that are within the control of the project owner and can be adjusted to control costs, as well as factors that the owner cannot influence directly, but have to consider and reflect into the project cost estimates.

Chapter 3 (Cost Estimates – Type and Accuracy) describes what key project information is needed to prepare accurate conceptual, preliminary, budgetary, and detailed cost estimates of desalination projects. This chapter also discusses the accuracy of the various types of cost estimates and the purposes for which such estimates are used when planning and implementing desalination projects. Chapter 3 also contains an overview of existing cost models widely used by desalination project planners and practitioners worldwide.

Chapter 4 (Capital Costs) provides an overview of key components of capital expenditures typically incorporated in desalination project cost estimates. The capital costs are divided into two main groups of expenditures – direct (construction) costs and indirect (soft) costs. The construction cost components addressed in this chapter are: plant site-related costs; intake and pretreatment costs; RO system expenditures; post-treatment costs; concentrate disposal and waste and solids handling costs; expenditures related to the installation of the electrical and instrumentation system; building costs; and plant startup, commissioning, and acceptance testing costs. The chapter also has guidance for the calculation of all indirect capital costs, including: costs of project engineering services; project development costs, expenditures associated with project funding and contingency provisions. Chapter 4 also contains cost curves for all main plant facility and equipment components such as: intake structures and piping and pump station; band, drum, and wedgewire screens; microscreens (strainers); cartridge filtration systems; lamella settlers and dissolved air flotation (DAF) clarifiers; granular media and membrane pretreatment filters; single and two-pass SWRO systems; and lime and calcite post-treatment systems. This chapter also illustrates the use of the cost curves for the preparation of a budgetary construction cost estimate for a 100,000 m^3/day SWRO desalination plant.

Chapter 5 (Operation and Maintenance Costs) defines the key components of plant O&M costs and presents practical information of how to estimate such costs. This chapter incorporates detailed information on cost estimating and control of the following main direct O&M cost components: power; chemicals; labor; maintenance and repairs; membrane and cartridge filter replacement; desalination plant waste stream management; and environmental and performance monitoring of plant operations. The chapter also features estimating of indirect O&M costs, such as staff training, plant administration, laboratory services, contingencies, and insurance. Chapter 5 also contains annual O&M cost curves for the same equipment and facilities for which construction costs are provided in Chapter 4. In addition, this chapter illustrates an estimate of the annual O&M costs for a 100,000 m^3/day SWRO desalination plant.

Chapter 6 (Water Production Cost) presents methodology for determining the cost of production of desalinated water from seawater applying SWRO membrane separation. The chapter discusses the calculation of the fixed and variable components of the water production cost and explains how this cost varies with plant capacity and availability factor. The chapter contains an example for the calculation of the cost of water produced by a 100,000 m^3/day SWRO desalination plant.

Chapter 7 (Project Implementation and Costs) is dedicated to cost impacts of the commonly used methods for project delivery such as design-bid-build (DBB); design-build-operate (DBO); and build-own-operate-transfer (BOOT). The chapter emphasizes the key contractual structure provisions, advantages and disadvantages of the alternative project delivery methods in terms of construction costs, annual O&M expenditures, and water production costs and provides lessons learned from the implementation of seawater desalination projects worldwide. The chapter gives practical guidance of what project delivery and implementation features have been incorporated in recent SWRO desalination projects that have yielded the lowest costs of water production as well as what key project implementation factors have resulted in high costs in plant construction and operation. Chapter 7 also discusses the impact of the project delivery schedule on the plant construction costs and elaborates on the typical causes for project delays and construction cost overruns.

Chapter 8 (Cost Management) presents an overview of the latest design approaches, technologies and desalination process configurations widely used in practice for management of the construction, and O&M and water production costs for seawater reverse osmosis desalination projects. This chapter discusses cost and energy use factors and trends, and describes specific technologies, equipment, and membranes which have proven to be effective tools for desalination project cost management such as: collocation of desalination and power plants; use of lower salinity source water; higher productivity RO membrane elements; large-diameter membranes; hybrid and split-permeate RO membrane configurations; and the use of pumps and energy recovery devices of high energy efficiency. In addition, the chapter contains information on future desalination technology advances and research directions, which have the potential to yield significant further reduction of the costs for producing fresh water from saline water resources.

This book is intended for desalination project planners, engineers, and designers; water utility professionals involved in the development of water resource management plans; equipment and membrane developers; operation and troubleshooting specialists; as well as for students and teachers in the desalination field. The book contains need-to-know desalination project cost-estimating practices and information, which would benefit practitioners, decision-makers, and scholars alike.

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Mr. Voutchkov is a registered professional engineer and a board certified environmental engineer (BCEE) by the American Academy of Environmental Engineers. He has over 25 years of experience in planning, environmental review, permitting and implementation of large seawater desalination, water treatment, and water reclamation projects in the United States and abroad.

Mr. Voutchkov has extensive expertise with all phases of seawater desalination project delivery: from conceptual scoping, pilot testing, and feasibility analysis; to front end and detailed project design; environmental review and permitting; contractor procurement; project construction and operations oversight/asset management.

Mr. Voutchkov is President of Water Globe Consultants, LLC – a private company specialized in providing expert advisory services in the field of seawater desalination and reuse. For over 11 years prior to establishing his project advisory firm, Mr. Voutchkov was a Chief Technology Officer and Corporate Technical Director for Poseidon Resources, a private company involved in the development of the largest seawater desalination projects in the United States.

In recognition of his outstanding efforts and contribution to the field of seawater desalination, Mr. Voutchkov has received a number of prestigious awards from the International Desalination Association, the International Water Association, the WateReuse Association and the American Academy of Environmental Engineers.

He is one of the principal authors of the American Water Works Association's Manual of Water Supply Practices on Reverse Osmosis and Nanofiltration and of the World Health Organization's Guidance for the Health and Environmental Aspects Applicable to Desalination. Mr. Voutchkov has authored over 10 books and 40 technical articles in the field of water and wastewater treatment and reuse.

Units

Bar – unit for pressure, 1 bar = 14.5 psi
cm – centimeter
˚C – degrees Celsius – unit of temperature
d – day
GW – gigawatt – 1 GW = 1 million kW
ha – hectare
hr – hour
Hp – horsepower (unit of power)
kg – kilogram
km – kilometer
kW – kilowatt (unit of power)
kWh – kilowatt-hour (unit of energy)
kWh/m^3 – kilowatt hours per cubic meter (measure of energy used to produce or convey one cubic meter of fresh (desalinated) water
l or L – liter
Lmh – liter per square meter per hour
m – meter
m^2 – square meter
m^3 – cubic meter
mm – millimeter
mg/L – milligrams per liter
m^3/day – cubic meters per day
MW – megawatt – unit for power – 1 MW = 1,000 kW
µ – µm or micrometer (one-millionth of a meter)
µg/L – microgram per liter
µS/cm – micro-Siemens per centimeter – unit of specific conductivity of water
psu – practical salinity units (1 psu = 1,000 mg/L)
ppb – parts per billion (1 ppb = 1 µg/L)
ppm – parts per million (1 ppm = 1 mg/L)
ppt – parts per thousand (1 ppt = 1,000 mg/L)
psi – Unit of pressure – pounds per square inch
s – second
yr – year

Abbreviations

AfDB	African Development Bank
ADC	Affordable Desalination Collaboration
ASTM	American Society of Testing and Materials
AWWA	American Water Works Association
BOOT	Build-own-operate-transfer
BTA	Best Technology Available
BWRO	Brackish water reverse osmosis
Ca	Calcium
CCI	Construction cost index
CDI	Capacitive deionization
CEB	Chemically enhanced backwash
CEDI	Continuous Deionization
CDI	Capacitive Deionization
CIF	Climate Investment Funds
CIP	Clean-in-place
CO_2	Carbon dioxide
CPI	Consumer Price Index
CMR	Construction Manager at Risk
CNT	Carbon nanotubes
CRF	Capital recovery factor
CWA	Clean Water Act
DBB	Design-bid-build
DBO	Design-build-operate
DEEP	Desalination Economic Evaluation Program
DO	Dissolved oxygen
EBRD	European Bank for Reconstruction and Development
ED	Electrodialysis
EDR	Electrodialysis Reversal
ENR	Engineering News Record
EP	Equator Principles
EPC	Engineering, Procurement and Construction
EPFI	Equator Principle Financial Institutions
ERT	Energy Recovery Technology
FO	Forward Osmosis
GHG	Greenhouse Gas
GMP	Guaranteed Price Maximum
GRP	Glass Reinforced Plastic
GWI	Global Water Intelligence
H_2SO_4	Sulfuric Acid
HDD	Horizontal Directionally Drilled
HDPE	High-Density Polyethylene
IAEA	International Atomic Energy Agency

IRENA	International Renewable Energy Agency
IRR	Internal Return on Investment
ISD	Internally Staged Design
IWPP	Independent Water and Power Project
IX	Ion Exchange
FRP	Fiberglass Reinforced Plastic
KSA	Kingdom of Saudi Arabia
LIBOR	London Inter-Bank Offered Rate
LSI	Langlier Saturation Index
MD	Membrane Distillation
MED	Multi-effect Distillation
MED-TVC	Multi-effect Distillation with Thermal Vapor Compression
MENA	Middle East and North Africa
MF	Microfiltration
MSDT	Multistage Dual Turbocharger
MSF	Multistage Flash Distillation
Mg	Magnesium
MGD	Million Gallons per Day
MLD	Mega Liters per Day: 1 MLD = 1,000 m^3/day
MM	Million
MTBE	Methyl Tertiary Butyl Ether (gasoline additive)
Na	Sodium
NaOH	Sodium Hydroxide
NGO	Non-Government Organization
NDMA	N-nitrosodimethylamine
NST	Nanostructured
NTU	Nephelometric Turbidity Unit
NUS	National University of Singapore
OEM	Original Membrane Manufacturer
O&M	Operation and Maintenance
ORP	Oxidation-Reduction Potential of Water
PAC	Powdered Activated Carbon
PP	Polypropylene
PPA	Power Purchase Agreement
PPP	Public-Private Partnership
PV	Photovoltaic
PVC	Polyvinyl Chloride
RFQ	Request for Qualifications
RO	Reverse Osmosis
SAR	Sodium Absorption Ratio
SDI	Silt Density Index
SOQ	Statement of Qualifications
SP	Salt Passage
SPC	Special Project Company
SWCC	Saline Water Conversion Corporation of Saudi Arabia
SWIM-SM	Sustainable Water Integrated Management – Support Mechanism

SWRCB	State Water Resource Control Board – California
TAK	Toray Advanced Materials Korea
TDS	Total Dissolved Solids
TFN	Thin-Film Nano-composite
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UF	Ultrafiltration
UAE	United Arab Emirates
US, USA	United States of America
USBR	US Bureau of Reclamation
USEPA	United States of America's Environmental Protection Agency
VC	Vacuum Compression
WaTER	Water Treatment Estimation Routine
WDR	Water Desalination Report
WHO	World Health Organization
WPA	Water Purchase Agreement
WRA	Water Reuse Associates
WRRF	Water Reuse Research Foundation
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant
Y	Plant Recovery, %

1 Project Cost Overview

1.1 INTRODUCTORY REMARKS

Desalination is gaining popularity as an alternative water supply resource as many municipalities and utilities worldwide are facing increasing population growth pressures, shortage of suitable local water resources, and more stringent water quality regulations. Until recently, use of seawater desalination was limited to desert-climate dominated regions. Recent technological advances and associated decreases in water production costs and energy demand have expanded use of desalination in coastal areas traditionally supplied with fresh water resources (Bazargan, 2018; Gude, 2018).

At present, more than 19,000 desalination plants worldwide produce a total of 99.8 million cubic meters per day (m^3/day) of fresh water from seawater and brackish water (GWI, 2017) and provide approximately 1% of the world's drinking water supply. The number and size of desalination projects worldwide have been growing at a rate of 5%–6% per year since 2010, which corresponds to an addition of 3.0–4.0 million m^3/day of newly installed desalination plant fresh water production capacity every year.

This growth is due to a number of long-term global trends including: (1) steadily increasing population growth and associated demand for fresh drinking water in urbanized coastal areas; (2) prolonged drought in the arid and semi-arid coastal areas of the world; and (3) limited availability of untapped traditional low-cost fresh water resources in these areas. Arid and semi-arid coastal zones of the world are inhabited by over 70% of the world's population and are usually the fastest growing and most urbanized areas.

In total, 18% of the existing desalination plants are large size (i.e., have fresh water production capacity of over 100,000 m^3/day) and 36% are medium size (i.e., have a production capacity of 10,000–100,000 m^3/day). Medium and large size plants contribute approximately 90% (86 million m^3/day) of the existing total installed desalination plant capacity worldwide.

A clear recent trend in seawater desalination is the construction of larger capacity plants, which deliver an increasingly greater portion of the fresh water supply of coastal cities around the globe. While most of the large desalination plants built between 2000 and 2010 were typically designed to supply only 5%–10% of the drinking water of large coastal urban centers, today most regional or national desalination project programs in countries such as Spain, Australia, Israel, Algeria, and Singapore aim to secure 25%–30% of their long-term drinking water needs with desalinated seawater.

In the next 5 years, the largest investments in new desalination projects are projected to occur in the Middle East and North Africa (US$28.2 billion), East Asia and the Pacific (US$9.6 billion), North America (US$5.1 billion), Latin America/Caribbean (US$4.9 billion), and Western Europe (US$2.9 billion) (GWI, 2017).

Since 2010, reverse osmosis (RO) desalination has been the main technology of choice for production of fresh water from saline water worldwide (Figure 1.1).

The prevalence of this desalination technology is due to the fact that for most saline sources and applications worldwide, it yields fresh water at overall energy use and costs lower than those of thermal desalination technologies such as multi-effect distillation (MED) and multi-stage flash distillation (MSF) – see Table 1.1.

At present, over 50% of the existing desalination plants are located in the Middle East and North Africa (MENA) region. The majority of the plants built in this region over the past 5 years employ seawater RO (SWRO) membrane desalination (Figure 1.2) for production of fresh water. The steady trend of increasing use of SWRO membrane desalination in the MENA region is mainly attributed to the lower energy use, high efficiency, and lower fresh water production costs associated

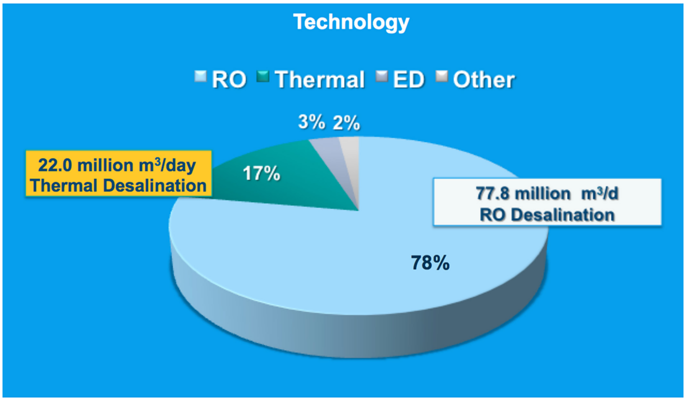

FIGURE 1.1 Breakdown of installed desalination plants worldwide by technology (2017).

TABLE 1.1

Energy and Water Production Costs for Alternative Desalination Technologies

Process/Energy Type	MED	MSF	VC	BWRO	SWRO
Steam pressure (ata)	0.2–0.4	2.5–3.5	Not needed	Not needed	Not needed
Electric energy equivalent (kWh/m³)	4.5–6.0	9.5–11.0	NA	NA	NA
Electricity consumption (kWh/m³)	1.2–1.8	3.2–4.0	8.0–12.0	0.3–2.8	2.5–4.0
Total energy use (kWh/m³)	5.7–7.8	12.7–15.0	8.0–12.0	0.3–2.8	2.5–4.0
Water production costs (US$/m³)	0.7–3.5	0.9–4.0	1.0–3.5	0.2–1.8	0.5–3.0

Note: NA – Not applicable.

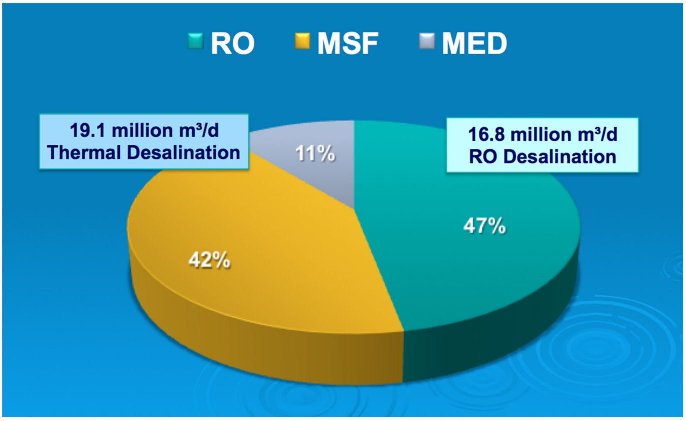

FIGURE 1.2 Breakdown of installed desalination plants in MENA by technology (2017).

with this technology as compared to thermal desalination (Ghaffour et al., 2013; Loutatidou et al., 2014).

The decline of thermal desalination is reflected in the recent decision of Saudi Arabia's government not to build any MSF plants in the future, after the construction of the largest hybrid (MSF and SWRO) desalination plant in the world in Ras Al-Khair (WDR, 2017). This facility incorporates a 727,000 m^3/day MSF plant and 310,000 m^3/day SWRO plant. A similar trend toward preferential use of SWRO desalination technology for future projects is observed in other Middle Eastern countries such as Oman, Qatar, and the United Arab Emirates as well as in most countries in North Africa (Caldera and Breyer, 2017; Shazhad et al., 2017).

Source water salinity is one of the most important factors determining desalination project design and costs (AWWA, 2007; Papapetrou et al., 2017). Based on the salinity of the source water they process, desalination plants can be divided into three broad categories: low-salinity and high-salinity brackish water desalination plants, and seawater desalination plants.

Low-salinity brackish water (BW) desalination plants often have a relatively simple single-stage RO system configuration and are typically designed to treat water of total dissolved solids (TDS) concentration between 500 and 2,500 mg/L. For such plants, it is common that 5%–30% of the source water flow is bypassed and blended with permeate produced by the RO system. Therefore, such facilities are relatively less costly to build and operate.

Depending on the target water quality and method of concentrate disposal, low-salinity BWRO plants may employ more than one RO stage in order to reduce concentrate volume and costs. For example, the majority of the BWRO plants in Florida and Texas are low-salinity groundwater desalination plants. It should be pointed out that the low-salinity surface water BWRO plants usually produce desalinated water at 10%–20% higher cost, usually because of the more costly and complex pretreatment.

High-salinity BWRO plants are configured to process brackish source waters with TDS content in a range of 2,500–10,000 mg/L, usually treat the entire source water flow, and as a minimum incorporate a two-stage RO system. Typically, fresh water production costs of high-salinity desalination plants are 15%–35% higher than those of low-salinity desalination projects. The main cost differences originate from the higher energy use associated with the elevated source water salinity, the more complex RO system configuration, and the lower fresh water recovery at which such plants typically operate.

Seawater desalination projects are designed to process source water of salinity between 15,000 and 46,000 mg/L. Usually such plants are configured as multi-pass, multi-stage RO systems, which operate at significantly lower recoveries and have higher energy use than brackish water desalination plants. In addition, SWRO membrane elements and vessels are more costly because they are designed to withstand higher pressures. As a result, the costs for desalinating seawater are usually measurably higher than those for producing the same quality of fresh water by brackish water desalination.

Depending on the target product water quality and site-specific conditions such as energy costs and concentration of other source water constituents besides sodium and chloride, saline waters of TDS concentration between 10,000 and 15,000 mg/L could be processed by both seawater and brackish water desalination systems.

While brackish water desalination plants are less costly to build and operate, often brackish water sources are not readily available and usually are fairly limited in volume and extraction rate. Seawater reverse osmosis desalination is the most widely used membrane salt separation technology at present, because it allows tapping into the largest natural source of water on the planet – the seawater contained in the oceans and seas.

Approximately 75% (1.6 million m^3/day) of the new globally installed desalination plant capacity for the period of June 2016 to July 2017 (2.14 million m^3/day) was for seawater desalination and only 15% (0.32 million m^3/day) was for brackish water desalination (GWI, 2017). The remaining 10% (0.32 million m^3/day) of the desalination plants have applied other water treatment technologies such as electrodialysis reversal (EDR), ion exchange (IX), forward osmosis (FO), and capacitive deionization (CDI).

This trend is expected to continue in the future with an overall slowdown of the construction of new brackish water desalination plants, because most of the known brackish water aquifers near large urbanized centers worldwide are already tapped in, and brackish water in general is of limited availability. Only 1.1% of the worldwide water resources are located in brackish water aquifers while 97.5% of the planet's water is in the oceans and seas. Therefore, this book focuses mainly on cost estimating of seawater reverse osmosis projects.

1.2 PROJECT COST DEFINITIONS

The key economic parameters of seawater reverse osmosis desalination projects are:

- Capital costs;
- Operation and maintenance costs;
- Cost of water production.

1.2.1 CAPITAL COSTS

Capital costs include all expenditures associated with desalination project implementation: from the time of conceptual development, through design, permitting, financing, construction, commissioning, and acceptance testing for continuous operation. Construction costs encompass all direct expenditures needed to build plant source water intake and concentrate discharge systems and all project-related structures; procure and install all facility equipment; install and connect plant piping and service utilities; and deliver desalinated water to final user(s). Because of their direct association with the construction of physical facilities, construction costs are also referred to as "direct" or "hard" capital costs. Construction costs of seawater desalination plants are typically 50%–85% of the total capital costs.

The remaining 15%–50% of capital costs are often referred to as "indirect" or "soft" costs. These costs are associated with all engineering, administrative, permitting, and funding efforts necessary to bring the project to fruition. In addition, indirect capital costs incorporate expenditures needed to procure contractors for design, construction, and operation of the desalination project.

Total project capital costs are typically presented in monetary units (e.g., US$) and are estimated either for the year when project construction is initiated or are referenced to the middle of the construction period. Depending on the type, length, and term of project funding, capital costs are often converted to monetary units per year and referred to as amortized or annualized costs (US$/yr). In addition, both capital and construction costs are sometimes presented as expenditures per unit of desalination project fresh water production capacity (e.g., US$/m^3/day or US$/1,000 gallons).

1.2.2 OPERATION AND MAINTENANCE COSTS

Operation and maintenance costs are all expenditures associated with desalination plant operations (power, chemicals, labor, and replacement of consumables, such as membranes and cartridge filters); with maintenance of plant equipment, buildings, grounds and utilities; and with compliance with all plant operation and environmental permits, and other pertinent regulatory requirements. The operation and maintenance costs associated with a given project are typically expressed as the all-inclusive operational expenditures for a period of one year (e.g., US$/yr) or as operational costs for the production of unit volume of desalinated water (e.g., US$/m^3).

Operation and maintenance (O&M) costs may be divided into two main categories: fixed and variable. Fixed O&M costs are annual expenditures that are not a function of the actual amount of fresh water produced by the desalination plant. Such O&M expenditures include labor costs (staff wages and fringe benefits), costs for routine preventive equipment maintenance, environmental and performance monitoring, operational insurance, administrative costs, and other miscellaneous overhead expenses.

Variable O&M costs are typically proportional to the actual volume of desalinated water produced by the desalination plant and include expenditures for power; chemicals; replacement of RO membranes, pretreatment membranes (if membrane pretreatment is used), and cartridge filters; as well as expenditures for disposal of waste (screenings, spent membrane cleaning chemicals, spent backwash water, disposal of dewatered residuals if pretreatment backwash is treated before, and pumping costs for conveyance and disposal of plant concentrate and other liquid discharges). Typically variable costs are 50%–85% of the total annual O&M costs of SWRO desalination plants, while the fixed costs are 15%–50% of these expenditures.

1.2.3 COST OF WATER PRODUCTION

Cost of water is an economic parameter that incorporates all project capital and annual O&M expenditures associated with water production. Typically this cost parameter is expressed in monetary units per unit volume of desalinated water (e.g., US\$/m³). The total cost of fresh water production (cost of water) is calculated by dividing the sum of the amortized (annualized) capital costs (e.g., US\$/yr) and the annual O&M costs (e.g., US\$/yr) by the total actual or projected annual volume of fresh water produced by the desalination plant, expressed in m³/yr. For a typical SWRO plant, the amortized capital costs and the O&M costs are usually in a range of 40%–60% of the total cost of water, each.

1.2.3.1 Water Production Costs of BWRO Desalination Plants

Table 1.2 provides a summary of the costs of fresh water production of low-salinity and high-salinity brackish water desalination plants. The cost summary presented in this table is based on comparative analysis of over 40 brackish water desalination plants worldwide. The actual costs of the individual projects used to generate Table 1.2 were adjusted for time scale, scope, and location to provide a common base for comparison.

Review of Table 1.2 indicates that at present (i.e., year 2018) the industry-wide average cost for production of fresh water by low-salinity and high-salinity BWRO plants is US\$0.7/m^3 and US\$0.9/m^3, respectively. As anticipated, use of low-salinity brackish water yields lower fresh water production costs. However, it is interesting to note that the cost difference is not proportional to salinity.

Often, low-salinity sources may contain additional contaminants such as silica, cyanide, iron, manganese, or large quantities of organics and dissolved gases that have a profound impact on plant construction costs because their removal usually

TABLE 1.2
Water Production Costs of Medium and Large Size BWRO Desalination Plants

	Cost of Water (US\$/m³)	
Classification	**Low-Salinity BWRO Plants**	**High-Salinity BWRO Plants**
Low-end bracket	0.2–0.4	0.3–0.6
Medium range	0.5–0.8	0.7–1.0
High-end bracket	1.0–1.5	1.3–1.8
Average	**0.7**	**0.9**

requires additional treatment steps and expenditures. In addition, typically both low-salinity and high-salinity brackish water plants use the same type of RO membrane elements, vessels, and pumps, which have the same unit costs per processed capacity (i.e., their costs are mainly determined by plant production flow and recovery, and are not as significantly impacted by source water salinity as they are by production flow).

Figures 1.3 and 1.4 show a breakdown of the water production costs of low-salinity and high-salinity BWRO plants by main components: direct (construction) and indirect capital costs; and power and other O&M costs. For low-salinity desalination plants, construction costs (i.e., direct capital costs) are typically the largest component of the water production costs. The wide range of these costs is mainly attributed to the economy of scale, and differences in intake and concentrate disposal cost components.

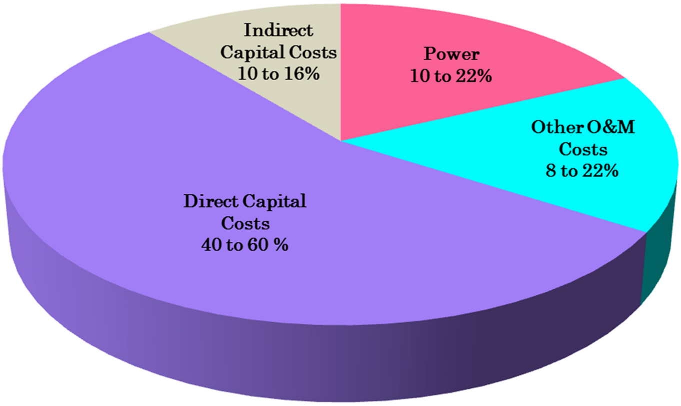

FIGURE 1.3 Typical cost of water breakdown for low-salinity BWRO plants.

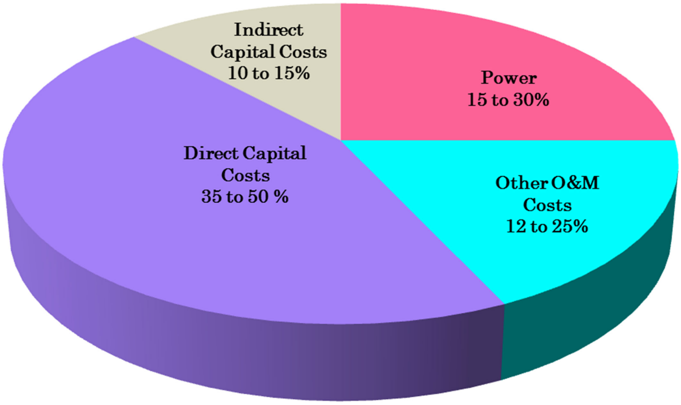

FIGURE 1.4 Typical cost of water breakdown for high-salinity BWRO plants.

Comparative analysis of Figures 1.3 and 1.4 indicates that in high-salinity BWRO plants power expenditures are a slightly larger portion of the total water production costs (typically because of the higher source water salinity). However, the energy cost component is not directly proportional to the salinity because high-salinity BWRO plants often apply energy recovery devices, which typically are not cost attractive for low-salinity BWRO plants, and also operate at lower recoveries, which results in elevated construction costs and lower energy use.

1.2.3.2 Cost of Water Produced by SWRO Desalination Plants

Table 1.3 presents the range of water production costs of medium and large size seawater reverse osmosis desalination projects. Information for this table is compiled based on comparative review of over 50 desalination projects in the United States, Australia, Europe, the Middle East, the Caribbean, and other parts of the world. As seen in Table 1.3, at present (in 2018 US$) the average industry-wide cost of production of desalinated water by reverse osmosis is approximately US$1.1/m^3.

Comparison of Tables 1.2 and 1.3 reveals that on average seawater desalination production costs are 1.2–1.6 times higher than those for producing fresh water by high-salinity and low-salinity brackish water desalination, respectively. When comparing some individual projects however, this difference could be significantly higher.

For example, the cost of water production of a low-salinity BWRO project in the low-end cost bracket (i.e., US$0.2–0.4 m^3/day) could be over 10 times higher than the water production cost of a SWRO desalination project in the high-end cost bracket (US$1.6–3.0/m^3). While factually accurate, such comparisons are misleading if they are taken out of context of the site-specific project conditions, which may differ very significantly from one project to another.

Figure 1.5 depicts a typical breakdown of the fresh water production costs of medium and large size seawater reverse osmosis desalination projects. Although the ratio between the key cost components varies from project to project, the largest pieces of the "cost pie" are usually the plant construction expenditures (i.e., the direct capital costs), power, and the other O&M costs (i.e., maintenance, chemicals, membranes, etc.). The indirect capital costs, which mainly include expenditures for project engineering, development, and finance, are also a measurable portion (typically 10%–20%) of the water production costs.

TABLE 1.3

Water Production Costs of Medium and Large Size SWRO Desalination Plants

Classification	Cost of Water (US$/m^3)
Low-end bracket	0.5–0.8
Medium range	0.9–1.5
High-end bracket	1.6–3.0
Average	**1.1**

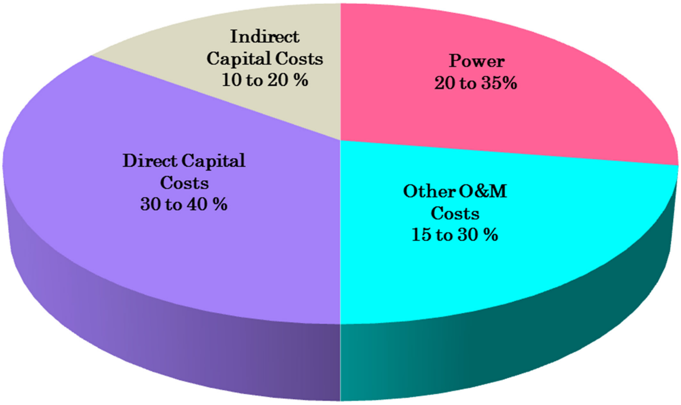

FIGURE 1.5 Seawater reverse osmosis plant – cost of water breakdown.

Comparison of Figures 1.3 through 1.5 indicates that capital costs for BWRO facilities are usually a higher portion of the total water production expenditures than those for SWRO plants (45%–76% vs. 40%–60%). In BWRO projects, energy contributes 10%–30% of the total costs, as compared to SWRO projects where the energy contribution is usually in a range of 20%–35%, and in extreme conditions for remote plant locations with high unit energy costs, energy expenditures for SWRO desalination could exceed 50% of the total costs of water production.

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2 Project Cost Factors

2.1 INTRODUCTORY REMARKS

Project capital, operation and maintenance (O&M), and overall water production costs depend on a number of factors, most of which are site specific to desalination project location, size, and technical and socioeconomic circumstances. In general, there are two types of factors that strongly influence desalination project costs: (1) factors controlled by the decisions of the facility owner; and (2) subjective factors beyond the control of the facility owner, including those which result from regulatory requirements and market forces of a free economy. Factors impacting desalination project costs have been an object of a number of studies over the last 10 years (Karagiannis and Soldatos, 2008; Wittholz et al., 2008; Loutatidou et al., 2014; Papapetrou et al., 2017). This chapter discusses key factors influencing cost of water production based on practical experience with project development and implementation.

2.2 COST FACTORS WITHIN THE CONTROL OF THE PLANT OWNER

The key cost factors that are within the control of the project owner are discussed below.

2.2.1 Project Size

Project size has a significant influence on the overall production cost of desalinated water. As illustrated in Figure 2.1, the cost of water production by seawater desalination can be reduced significantly by building a fewer large-scale desalination plants rather than a large number of small facilities.

For example, analysis of Figure 2.1 indicates that the specific water production costs can be reduced by approximately 2 times when plant capacity is increased from 5,000–200,000 m^3/day. Economy-of-scale savings are mainly driven by the size of the individual treatment and pumping units, especially the reverse osmosis (RO) trains. Currently, the largest size seawater RO (SWRO) train that can be built using off-the-shelf standard equipment (high-pressure pumps, pressure exchangers for energy recovery, and 8-inch RO membranes) has production capacity of 25,000 m^3/day. Construction of larger individual trains is possible, but usually is not as cost-effective because it would require the use of custom-made RO system equipment, which is significantly more costly than the off-the-shelf standard equipment units and, as a result, some of the economy-of-scale savings are negated by the additional equipment costs.

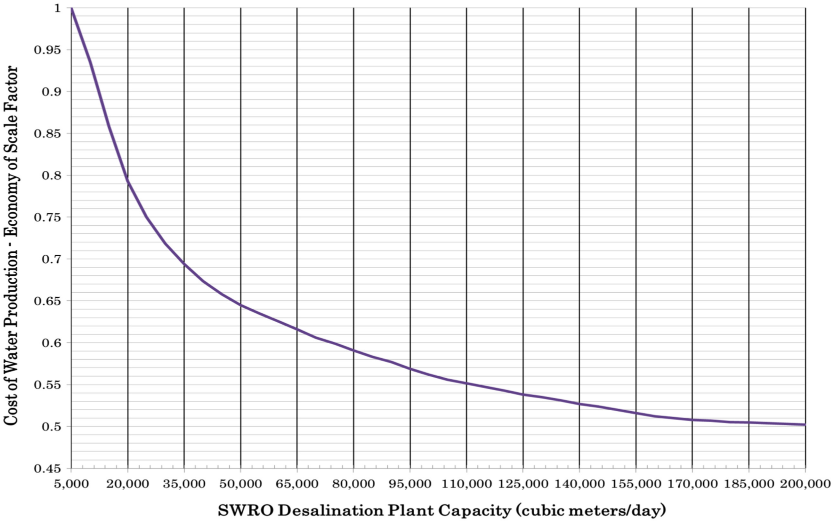

FIGURE 2.1 Effect of desalination plant size on water production cost.

Figure 2.2 depicts the relationship between the unit construction cost of SWRO desalination plants, expressed in million (MM) US$ per 1,000 m^3/day (MLD) of plant fresh water production capacity (US$ MM/MLD), as a function of the plant size. This figure was derived based on the costs of actual projects built in the most competitive market in the world (the Middle East and North Africa [MENA]) between the years 2012 and 2017.

Review of this figure indicates that constructing SWRO plants with a size of between 150,000 and 200,000 m^3/day would yield the lowest unit construction cost of US$1.1–1.4 million/1,000 m^3/day of installed fresh water production capacity.

For plants larger than 200,000 m^3/day (e.g., mega-size plants), the economy-of-scale benefits are very limited mainly because of the added complexity of flow distribution, treatment, and operations. In fact, at present most plants with capacity larger than 200,000 m^3/day are built as multiple 100,000–150,000 m^3/day-trains of identical parallel desalination systems, which share common intake and outfall. As seen in Figure 2.2, construction of larger SWRO desalination plants would result in slight dis-economy of scale because of the duplicative equipment and piping needed to evenly distribute flow among the multiple treatment trains of which the mega-sized plant would consist.

Figure 2.3 presents construction costs of large and mega-size SWRO desalination plants built in Saudi Arabia over the past 10 years. This figure illustrates the dis-economy of scale observed for mega-size SWRO projects with capacity over 100 MLD.

Dis-economy of scale for plant capacities beyond 150,000 m^3/day is observed in the construction costs of SWRO desalination projects built over the past 7 years in Oman, Qatar, and the United Arab Emirates (see Figure 2.4).

Similar to Figure 2.3, the cost graph shown in Figure 2.4 also indicates that in terms of construction costs, the optimum size SWRO plant for the Middle Eastern region at present is between 100,000 and 150,000 m^3/day. A study reviewing costs of

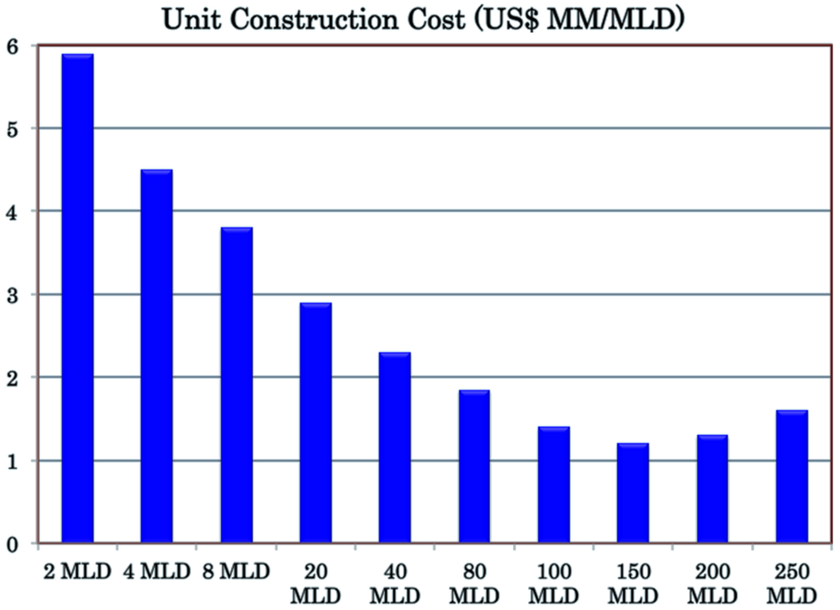

FIGURE 2.2 Effect of desalination plant size on construction cost.

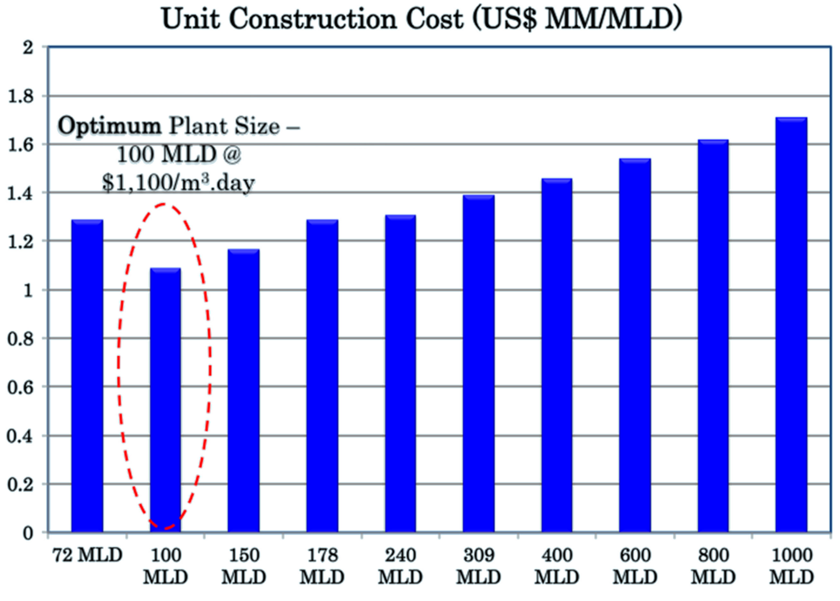

FIGURE 2.3 Construction cost of large SWRO plants built in Saudi Arabia over the past 10 years.

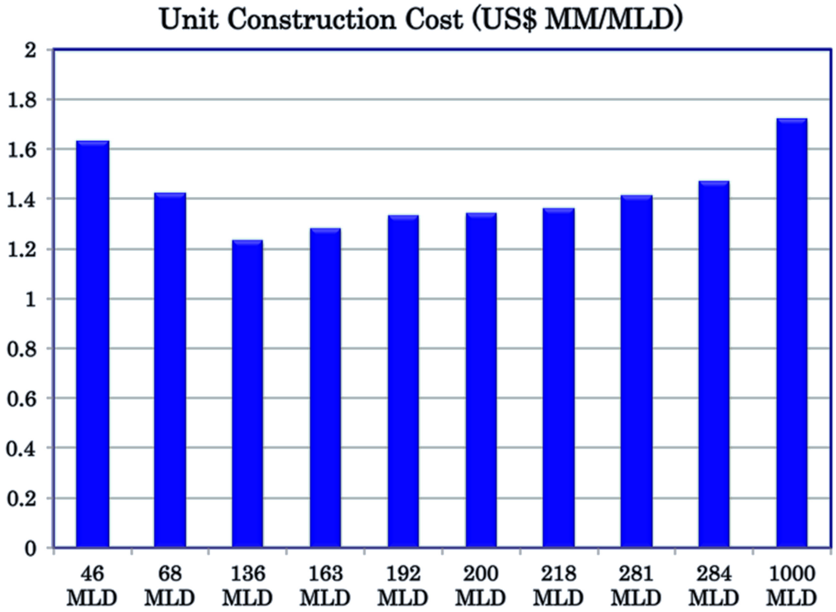

FIGURE 2.4 Construction cost of SWRO plants recently built in Oman, United Arab Emirates, and Qatar.

seven of the largest desalination plants in Spain of size between 65,000 and 240,000 m^3/day (Lapuente, 2012), identified the 210,000 m^3/day Aguilas SWRO desalination project as the plant with the lowest unit construction cost of US$1,232 m^3/day. The unit construction cost for the slightly larger (240,000 m^3/day) Torrevieja desalination project was reported at US$1,472 m^3/day.

As described in a white paper on desalination costs in the MENA region prepared by Water Globe Consultants for the World Bank (World Bank, 2016), SWRO desalination projects yield economies of scale beyond 200 MLD, in terms of operation and maintenance costs – see Figures 2.5 and 2.6. If extrapolated, the threshold for economies of scale for SWRO plants built on the Red Sea and the Arabian Gulf would be 600 MLD and 800 MLD, respectively. Since O&M costs and construction costs for SWRO plants contribute approximately 50% to the cost of water, and taking into consideration the threshold for economies of scale of construction cost of 200 MLD, the overall cost of water economy-of-scale threshold for SWRO facilities in the MENA region would be between 400 and 600 MLD and would depend on the seawater source.

As the maximum unit size of commercially available desalination plant equipment (pumps, membranes, pressure vessels, energy recovery systems, etc.) increases in the future, it is likely that the breakpoint plant capacity at which economy of scale would not yield measurable savings would shift to 800,000 m^3/day (800 MLD) or higher. A step in this direction is the introduction of SWRO desalination elements of diameter of 16 inches and larger in 2005, and the increase in productivity of newer models of SWRO elements, which are released by the key RO membrane manufacturers every 2–3 years (for more details see Chapter 8).

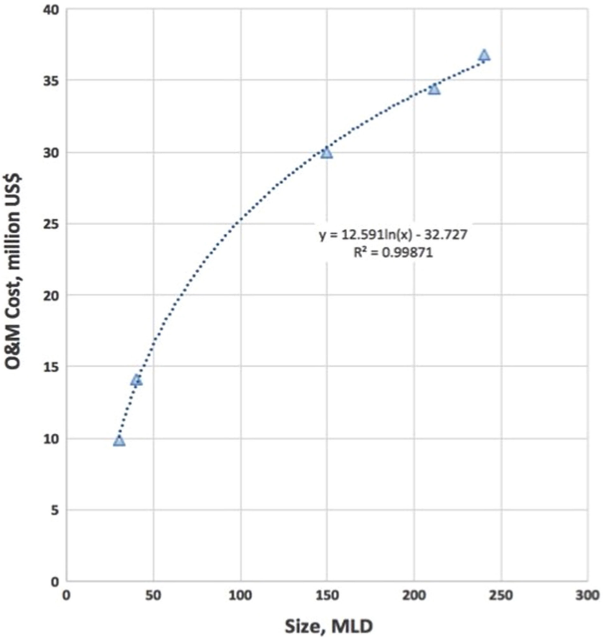

FIGURE 2.5 O&M cost of SWRO plants recently built on Red Sea.

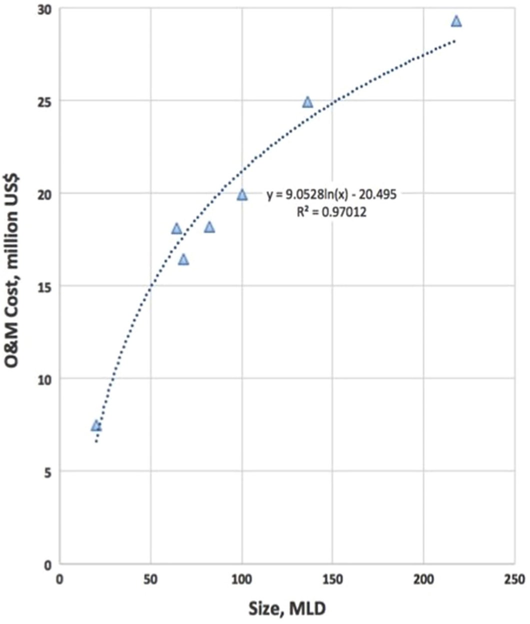

FIGURE 2.6 O&M cost of SWRO plants recently built on the Arabian Gulf.

It should be pointed out that the economy-of-scale threshold varies for key SWRO desalination plant components (see Table 2.1). Technologies used for pretreatment and SWRO separation have the lowest thresholds of economy of scale, which are mainly determined by the maximum size and productivity of the commercially available filtration equipment and membranes.

For comparison to SWRO plants, the largest individual multi-stage flash distillation (MSF) units presently available on the market have fresh water production capacity of 96,000 m^3/day, which explains the competitive advantage of MSF thermal desalination technology for mega-size projects (i.e., projects with production capacity above 200,000 m^3/day) especially for production of fresh water from high-salinity seawater in regions of the world where the unit cost of electricity is less than US$0.05/kWh, such as the Middle East. Similarly, the largest commercially available MED units at present have capacity of 76,000 m^3/day, which extends the economy-of-scale threshold for this technology to 1,200,000 m^3/day.

The higher economy-of-scale threshold for thermal desalination plants as compared to SWRO facilities explains the competitiveness of thermal technologies applied in recent mega-size projects in the Middle East. Figures 2.7 and 2.8

TABLE 2.1

Thresholds of Economy of Scale for Key SWRO Desalination Plant Components

SWRO Desalination Plant Component	Economy-of-Scale Threshold (MLD)	Key Factor for Limiting the Economy of Scale
Intake		Pretreatment costs
• Onshore open intake	10	Aquifer permeability
• Wells	20–50	Maximum number & size of intake piping and screens
• Offshore (wedgewire screens/intake towers)	400–600	
Pretreatment		Max size & number of filter units
• Granular media filters (pressure/gravity)	100/270	Max size & number of membrane modules and trains
• Membrane filters (vacuum/pressure)	100/160	
SWRO System	300	Pump efficiency, availability, CIP cleaning complexity & time
Post-treatment (lime/limestone)	200/500	Unit capacity & number
Discharge (onshore/offshore)	200–500/1200	Environmental impacts
O&M costs	400–600	Energy use/membrane cleaning length, complexity
Capital costs	200 (100–150 optimum)	Maximum size of commercially available plant components

Note: 1 MLD – 1,000 m^3/day.

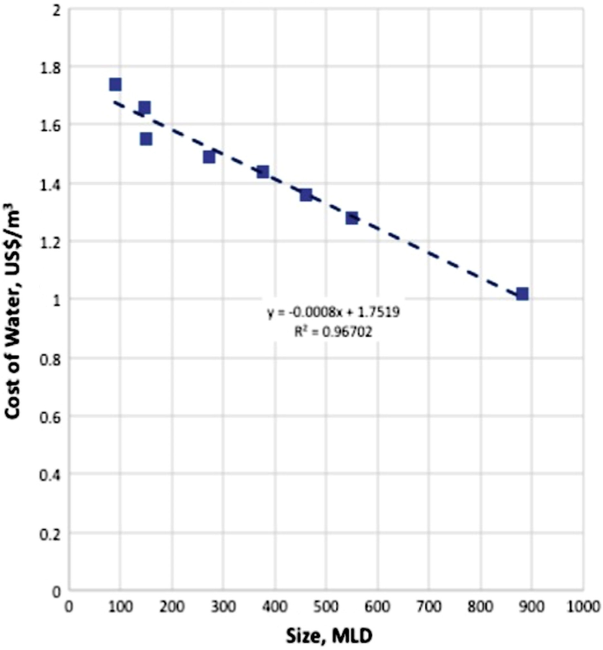

FIGURE 2.7 Cost of water for MSF desalination plants recently built in MENA.

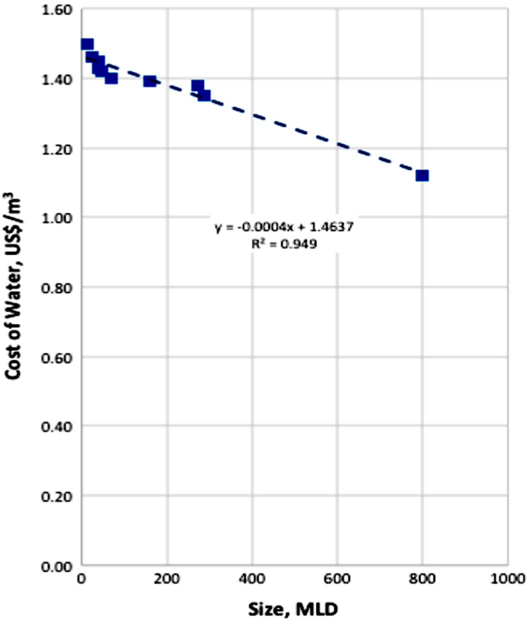

FIGURE 2.8 Cost of water for MED-TVC desalination plants recently built in MENA.

(World Bank, 2016) present graphs of the total cost of water production for projects built over the last 15 years using Red Sea and Arabian Gulf water for thermal desalination by MSF and multi-effect distillation (MED) with thermal vapor compression (MED-TVC).

Review of the cost curves contained in these graphs allows one to conclude that mega-sized thermal desalination facilities in the Middle Eastern region with size of 400 MLD or more could produce desalinated water at a cost comparable to that of SWRO plants of similar capacity and are likely to be less costly for plants sized beyond the economy-of-scale threshold size of 600 MLD for SWRO plants in the region.

Another conclusion that stems from the graphs is the lack of significant economy of scale for thermal desalination technologies for the entire range of existing projects. This observation could be explained by the fact that the thermal desalination technology market is very mature and offers a very large variety of MSF and MED equipment unit sizes that allow one to closely fit plant design to the actual target plant capacity over a wide range of 50–1,000 MLD. For comparison, the same range of plant capacities is typically delivered by only one size (8-inch) of SWRO membrane elements, except for less than a dozen membrane desalination plants worldwide using large size (16-inch) membranes.

Comparison of Figures 2.7 and 2.8 also reveals the fact that MED-TVC thermal desalination plants are very competitive to MSF facilities for plant sizes of up to 600 MLD. Beyond this size, MSF plants built to date tend to yield a slightly lower cost of water production. The largest MED-TVC thermal desalination plant is the 486-MLD Az Zour North Phase 1 facility in Kuwait, while the largest MSF plant in the world has a capacity of 726 MLD and is part of the largest existing desalination plant in the world – the 1,036-MLD Ras Al-Khair facility in Saudi Arabia.

It should be pointed out that the cost data presented in Figures 2.2 through 2.8 are representative for seawater desalination projects constructed since 2000 in the well-developed, highly competitive, and mature desalination markets of MENA and Spain. Such costs will vary in other parts of the world and would change from year to year. For example, the global average unit construction cost in 2014 was US$1,824 m^3/day and in 2015 it increased to US$3,581 m^3/day (Caldera and Breyer, 2017). Such desalination market differences and variations should be accounted for when estimating the conceptual capital costs of projects located outside of the MENA region and Spain.

2.2.2 CAPACITY AVAILABILITY FACTOR

The capacity availability factor is defined as the percentage of time per year during which the seawater desalination plant is producing fresh water flow equal to or higher than the plant's designed-for capacity (i.e., the average annual fresh water production flow rate). For example, if the desalination plant design capacity is 40,000 m^3/day and the plant capacity availability factor is 100%, then the total average annual fresh water flow that the plant can produce is 40,000 m^3/day × 365 days/yr = 14,600,000 m^3/yr.

If the actual fresh water flow produced by the same plant over the period of one year was only 13,140,000 m^3/yr, then the plant capacity availability factor for that year was 90% (13,1400,000 m^3/yr divided by 14,600,000 m^3/yr = 90%). At present, most well-designed and -operated SWRO desalination plants have capacity availability factor of 96%–98%, which means that these plants experience complete or partial downtime for only 7–15 days per year [$(1-0.98)\times 365$ days = 7.3 days and $(1-0.96)\times 365$ days = 14.6 days].

Desalination plant design and operation both have a significant impact on the overall plant availability. From a design point of view the SWRO desalination plant capacity availability factor is mainly impacted by the type of the selected technologies for key process components (e.g., intake, pretreatment, SWRO system, and post-treatment) as well as by the conservativeness of the selected key process and equipment design criteria; the number of standby units; and the quality of the equipment and materials.

For example, SWRO plants with vertical beach well intakes that have 20% or more of additional standby intake wells have significantly higher availability than plants with 10% or less of standby intake wells (>98% vs. <94%). Plants with open intakes that incorporate three or more intake towers usually have much better availability (more than 99%) than plants with single intake tower and seawater conveyance pipeline (availability of 95% or less) even if their capacity is oversized by 25%–30%.

Practical experience to date shows that membrane pretreatment for SWRO desalination plants has significantly lower availability factor (85%–95%) than that of conventional gravity granular media filtration systems (98%–99%). Use of membrane pretreatment could reduce the availability of the entire SWRO desalination plant below 80%, if the design flux of the pretreatment membranes exceeds 55 liters per square meter per hour (lmh) for source seawaters with high fouling potential such as those in the Arabian Gulf.

The track record of existing SWRO plants in the Middle East also indicates that, contrary to popular belief, use of dissolved air flotation (DAF) clarifiers upstream of granular media or membrane pretreatment systems does not result in a measurable increase in SWRO desalination plant capacity factor and does not effectively protect the downstream SWRO membranes from biofouling during moderate and heavy algal blooms for reasons described in detail elsewhere (Voutchkov, 2017).

At present, two SWRO train design practices are commonly adopted worldwide to achieve plant availability factor of 95% or more: (1) addition of one standby RO train and (2) installation of 10%–20% of additional production capacity to each of the duty RO trains without the provision of a separate standby train. It should be noted that the installation of additional standby SWRO desalination train usually yields higher plant availability (>98% vs. ≤96%) than using oversized individual SWRO trains. If both design features (e.g., standby train and additional capacity of the individual trains) are combined, RO plant availability could be increased to 99% or more.

It is a common practice to select the size of the individual RO trains to be 10%–20% of the overall plant capacity in order to provide operational flexibility and increase the plant capacity availability factor. This design approach is based on the fact that during routine membrane cleaning of one RO train, the production capacity of the rest of the RO trains in operation can be increased 10%–20% for a short period of time, in order to compensate for the production of the train taken out of service for cleaning.

This design approach typically allows achieving an average annual production capacity availability of 90%–95%, because often in years of unusual source seawater quality (i.e., prolonged rains, red tide events, or dredging of the intake area), frequently two or more RO trains may need to be taken out of service at the same time in order to maintain effective operations, which ultimately lowers the plant availability factor.

Usually, capacity availability factor of 90%–95% is acceptable for seawater desalination plants that provide only a relatively small portion (<25%) of the flow for a given fresh water user (municipality, community, or industry). If a desalination plant is projected to supply the majority or all of the fresh water used by a given water customer (e.g., municipality, industry), then this plant has to be designed for a capacity availability factor of 96% or higher.

At present, many of the existing large municipal SWRO plants worldwide are designed to supplement existing conventional water supply sources rather than to be the primary or the only source of water supply for a given area. Therefore, the operation of these plants does not need to have the flexibility to follow the actual diurnal and monthly product water demand fluctuations and most of the plants are designed to operate at constant production capacity and availability factor of 90%–96%.

As seawater desalination gains wider application in the future, SWRO plants are likely to become a prime rather than a supplemental source of water supply for many coastal communities with limited traditional local sources of fresh water supply (i.e., groundwater, river, or lake water). Desalination plants servicing such areas have to be designed with built-in operational flexibility to match fresh water production with potable water demand patterns of the water users and to have capacity availability factor of 96% or higher.

Shift of the SWRO plant operational paradigm from constant to variable production flow requires a change of the typical SWRO configuration from one that is most suitable for constant production output to one that is most cost-effective for delivery of varying fresh water production flow. A response to such shift of the desalination plant operational paradigm is the three-center RO system configuration implemented for the first time for the 330,000 m^3/day Ashkelon seawater desalination plant in Israel (see Figure 2.9).

Under this configuration, the RO membrane vessels, the high-pressure pumps, and the energy recovery equipment are no longer separated in individual RO trains, but rather are combined in three functional centers – a high-pressure RO feed pumping center, a membrane center, and an energy recovery center (Figure 2.10) (Liberman, 2002). The three functional centers are interconnected via service piping.

The RO feed pumping center includes only a few large-capacity high-pressure pumps that deliver seawater to the RO membrane center. The main benefit of using a small number of large-capacity high-pressure pumps rather than a large number of small-capacity units is the gain in overall pumping efficiency.

Typically, the smaller the ratio between the pressure and the flow delivered by a given pump, the better the pump efficiency and the “flatter” the pump curve (i.e., the pump efficiency is less dependent on the variation of the delivered flow). Therefore,

FIGURE 2.9 330-MLD Ashkelon SWRO desalination plant – aerial view.

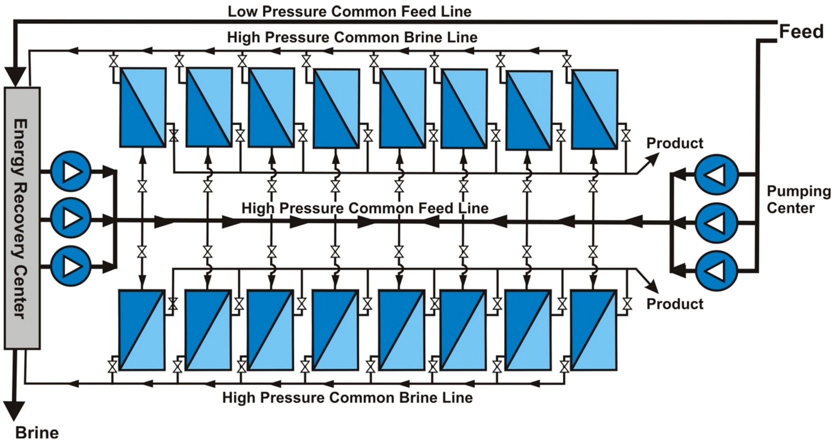

FIGURE 2.10 Three-center SWRO system configuration.

pump efficiency can be improved by either reducing the pressure delivered by the pump or by increasing pump flow. Since the pump operating pressure decrease is limited by the RO system target salt separation performance and the associated osmotic pressure, the main approach to improve pump efficiency is to increase unit pump flow.

While a conventional size, high-pressure RO feed pump of small capacity would typically have maximum total energy use efficiency of 80%–85%, the use of a 10 times larger size pump may allow an increase of pump efficiency to 88%–90%, especially for large SWRO plants. This beneficial feature of the three-center design is very valuable in the case of systems delivering varying flow.

While in a conventional RO train design configuration membrane vessels are typically grouped in 100–200 units per train and in 2–20 RO trains, the membrane center configuration contains a 2 to 4 times larger number of RO vessel groups (banks) and a smaller number of membrane vessels per bank. Under this configuration the individual vessel banks are directly connected to the high-pressure pump feed lines and can be taken out of service one at a time for membrane replacement and cleaning. Although the feed water distribution piping for such membrane center configuration is more elaborate and costly than that used for individual RO trains that contain 2 to 3 times more vessels per train, what is lost in capital expenditure is gained in overall system performance reliability and availability.

A reliability analysis completed for a 95,000 m^3/day SWRO plant (Liberman, 2002) indicates that the optimum number of vessels per bank for this scenario is 54 and number of RO banks per plant is 20. A typical RO train–based configuration would include 2 to 4 times more (108–216) vessels per RO train and 2 to 4 times fewer (5–10) RO trains. According to this life-cycle cost analysis, using a three-center instead of conventional RO-train configuration allows an increase in RO system availability from 92% to 98%, which is a significant benefit in terms of additional amount of water delivered to customers and improvement in water supply reliability.

The centralized energy recovery system included in the three-center configuration (Figure 2.10) uses high-efficiency pressure exchanger based energy recovery technology. This configuration allows improvement in the overall energy efficiency of the RO system and reduces system power, equipment, and construction costs. Because of the high efficiency of the pressure exchangers, the energy penalty for operation at lower recovery is small. This allows operating the SWRO plant cost-effectively in a wide range of plant recovery while delivering variable product water flow.

For example, if SWRO plant output has to be reduced by 30% to accommodate low diurnal demand, a SWRO system with RO train–based configuration has to shut down 30% of its trains and, if this low demand persists, it has to flush these trains in order to prepare them for the next startup. Frequent RO train starts and stops result in increased membrane cleaning costs, in shorter membrane useful life, and in higher labor expenditures. An RO system with three-center configuration would only need to lower its overall recovery in order to achieve the same reduction in diurnal water production.

Although temporary operation at lower recovery would result in elevated costs for pumping and pretreatment of larger volumes of source water, these additional operational expenditures are typically compensated by the lower osmotic pressure needed to operate the SWRO system at lower recovery and by the increased energy use efficiency of the RO system when operated at lower recovery as a result of the use of piston-type energy recovery system (pressure exchangers).

The main reason why the overall energy use efficiency of SWRO system equipped with pressure exchangers increases with decrease in RO system recovery is because as the recovery is lowered more of the feed water is pumped into the SWRO system using the higher efficiency pressure exchangers than the lower efficiency high pressure feed pumps. While the pressure exchangers are piston-type pumps with efficiency of 92%–96%, the high-pressure centrifugal-type pump efficiency typically is only 83%–88% (see Figure 2.11).

As indicated previously, designing the SWRO plant around a higher capacity availability factor (98% vs. 90%) results in increased plant construction costs because of the additional production capacity and process configuration flexibility needed to secure uninterrupted production of fresh water at or above design capacity. The incremental cost of water increase to improve capacity availability from 90% to 95% is typically in a range of 3%–5%. Increasing plant capacity availability factor from 95% to 98% usually is more costly, and would result in a 5%–10% increase in water production costs. However, in many cases, the incremental water production costs associated with improved reliability can be compensated for by the increased plant production capacity. If assume that the cost of production of 1 m^3 of fresh water by a 100,00 m^3/day plant with capacity availability factor of 90% is US\$0.80/m^3. The annual water sales revenue that this plant would generate at this availability factor is: 90% × US\$0.80/m^3 × 100,000 m^3/day × 365 days = US\$26,280,000/yr.

Let's now assume that this plant design is modified to improve plant capacity availability factor from 90% to 95%, at a cost of water production increment of 3%, i.e., the new cost of water is 1.03 × US\$0.80/m^3 = US\$0.824/m^3. The additional annual cost of water production that the utility will incur is {95% × (US\$0.824/m^3 – US\$0.800/m^3) × 100,000 m^3/day × 365 days} = US\$832,200/yr.

However, the additional annual revenue the water utility will gain (5% in this example), even if the fresh water produced by the desalination plant is sold at the same

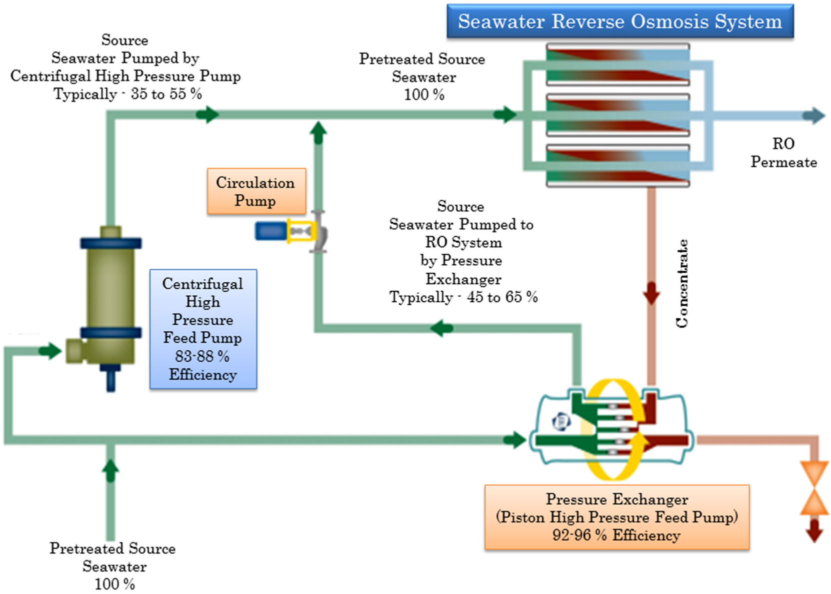

FIGURE 2.11 SWRO system with pressure exchanger type energy recovery system.

price (i.e., US\$0.80/m³), is: 95% × 0.05 × US\$0.800/m³ × 100,000 m³/day × 365 days = US\$1,387,000/yr. Thus, in this hypothetical example, the utility will increase its annual revenue from drinking water sales by US\$554,800/yr (US\$1,387,000/yr – US\$832,200 = US\$554,800/yr), which is a 2.1% increment over the utility's baseline revenue of US\$26,280,000/yr.

This example, although hypothetical, illustrates a very real actual desalination industry trend, which is that in most cases in the long run it pays to build facilities of higher capacity availability factor than lower cost/lower reliability plants, especially when there is high and continuous demand for the desalinated water in the plant service area.

Another very important factor that impacts plant availability is the operation and maintenance of the plant – more specifically the skills and experience of the O&M team, and the maintenance approach the team applies. Usually, employing operators with limited experience in running desalination plants of similar size and complexity could cause a significant decrease in the plant capacity availability factor. Similarly, if plant maintenance staff mainly does reactive rather than preventive maintenance of key equipment, instrumentation, and controls, and does not have adequate skills to closely track the plant performance and clean in place the SWRO membranes, then plant downtime is likely to increase significantly within 12–18 months after plant commissioning.

Plant availability has a significant impact on cost of water production. According to a review of some of the largest SWRO desalination plants in Spain (Lapuente, 2012), the cost of water for these plants increases significantly with the decrease of their availability (see Figure 2.12). The average availability of the seven SWRO desalination plants included in this study was 94.8%. These plants have capacity of

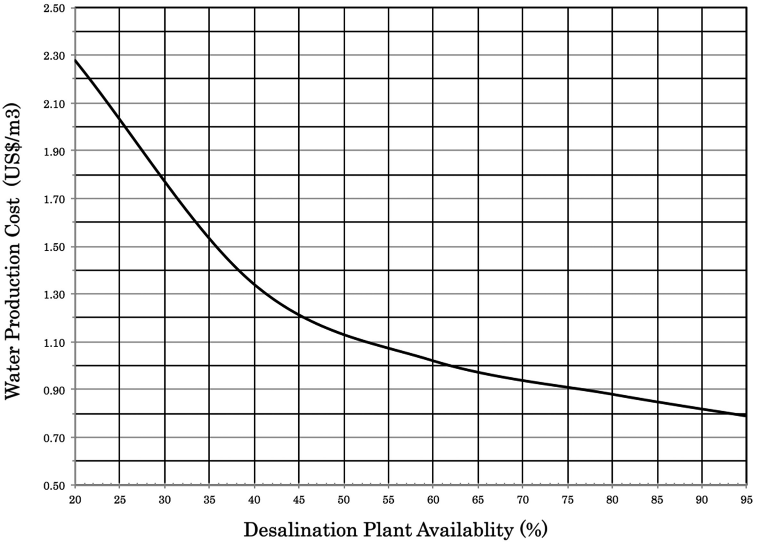

FIGURE 2.12 Water production cost and availability (Spanish SWRO plant experience).

between 65,000 and 240,000 m^3/day and use source water from the Mediterranean Sea. As seen from this figure, a decrease of plant availability from 94.8% to 80% would result in an increase in plant production cost from US$0.78 to 0.90/m^3.

2.2.3 Source Water Quality

The key source water quality parameters that impact desalination system design, operations, and cost of water production are total dissolved solids (TDS), temperature, turbidity, silt density index (SDI), organic content, nutrients, algae, bacteria, boron, silica, barium, calcium, and magnesium. Of these parameters, seawater TDS and temperature are the two key source water quality parameters that have the most significant influence on costs of water production by seawater desalination. Table 2.2 presents typical TDS concentration and temperature of various seawater sources.

In general, desalination plant construction and O&M costs rise with the increase in source seawater's TDS concentration and with the decrease in water temperature. Source seawater TDS concentration is directly related to the SWRO system design and operating feed pressures, as well as the overall plant design recovery and configuration. Therefore, the use of lower salinity source seawater (such as bay water or a mix of ocean and brackish water or fresh groundwater exiting the ocean bottom) typically allows a reduction of the costs associated with construction and operation of the SWRO system and an increase in plant recovery.

However, it is important to note that the consistency of the source water TDS concentration is almost as equally important for a successful low-cost SWRO design, as is the level of TDS of the source water. In addition, usually fresh surface water sources that may enter the desalination plant intake, such as river or lake water, may carry turbidity, organics, nutrients, and other man-made pollutants which are in an order of magnitude higher levels than those of open ocean water. As a result, the removal of contaminants contributed by introduction of surface fresh water into the SWRO plant feed water may require a more elaborate pretreatment, which may cost more than the savings associated with lower source water TDS concentration.

TABLE 2.2

Salinity and Temperature of Various Seawater Sources

Seawater Source	Total Dissolved Solids Concentration (ppt)	Temperature (°C)
Pacific and Atlantic Oceans	33–36 (avg. 35)	14–30 (avg. 18)
Caribbean	35–38 (avg. 36)	16 to 35 (avg. 26)
Mediterranean	38–41 (40)	16 to 28 (avg. 24)
Gulf of Oman/Indian Ocean	39–42 (40)	22 to 35 (avg. 30)
Red Sea	40–42 (41)	24 to 33 (avg. 28)
Arabian Gulf	42–46 (44)	22 to 35 (avg. 26)

Note: Seawater TDS and temperature may be outside the table ranges for a site-specific location.

Table 2.3 presents a comparison between the cost of construction, operation, and water production of Pacific/Atlantic ocean water (assigned a unit value of 1) and other water sources indicated in Table 2.2. The cost multiplier ranges in Table 2.3 account mainly for the differences in source water TDS concentration and temperature, and are normalized for all other key factors that influence costs, such as product water quality, cost of capital, power cost, concentrate disposal costs, membrane useful life and costs, etc.

The multipliers in Table 2.3 apply for medium and large seawater desalination projects of capacity between 40,000 and 200,000 m³/day. The actual costs of individual projects may vary because of site-specific project differences and conditions. A detailed analysis of the effect of source water quality on the costs for seawater desalination is provided elsewhere (Moch, 2002).

Plant source seawater temperature has a measurable effect on the SWRO system design feed pressure and membrane performance. The required SWRO feed pressure typically is reduced by 5%–8% on a linear scale for every 10°C source water temperature increment in a temperature range of 12°C–40°C (AWWA, 2007). Based on tests completed at the Carlsbad seawater desalination pilot plant on cold Pacific Ocean water in the winter, when the source water temperature drops below 12°C, the temperature effect is even more dramatic – the SWRO feed pressure increases with 5%–10% for every 2°C of temperature drop on an exponential scale until the source water temperature reaches 4°C, below which the source water would begin to freeze and seawater desalination is dramatically hindered (see Figure 2.13).

The illustrative example presented in Figure 2.13 is developed for single-pass SWRO system desalinating Pacific Ocean water. The actual energy use for other water sources will differ but the relative effect of temperature on unit energy use will remain approximately the same.

The accelerated exponential increase in operational SWRO system feed pressure for source water temperatures below 12°C is explained by similar curvilinear increase in source water density in the temperature range of 4°C–12°C combined with changes in membrane material behavior. This curvilinear effect of very low temperature on energy use could be a challenge particularly for desalination plants with deep open ocean intakes or subsurface intake wells, which in some locations

TABLE 2.3

Effect of Source Water on Desalination Costs

Water Source	Construction Costs	O&M Costs	Cost of Water
Pacific/Atlantic Ocean	1.00	1.00	1.00
Caribbean	1.05–1.35	1.02–1.10	1.04–1.20
Mediterranean	1.10–1.40	1.05–1.15	1.07–1.25
Gulf of Oman/Indian Ocean	1.15–1.45	1.10–1.25	1.12–1.35
Red Sea	1.20–1.55	1.12–1.30	1.15–1.45
Arabian Gulf	1.25–1.60	1.15–1.35	1.20–1.48

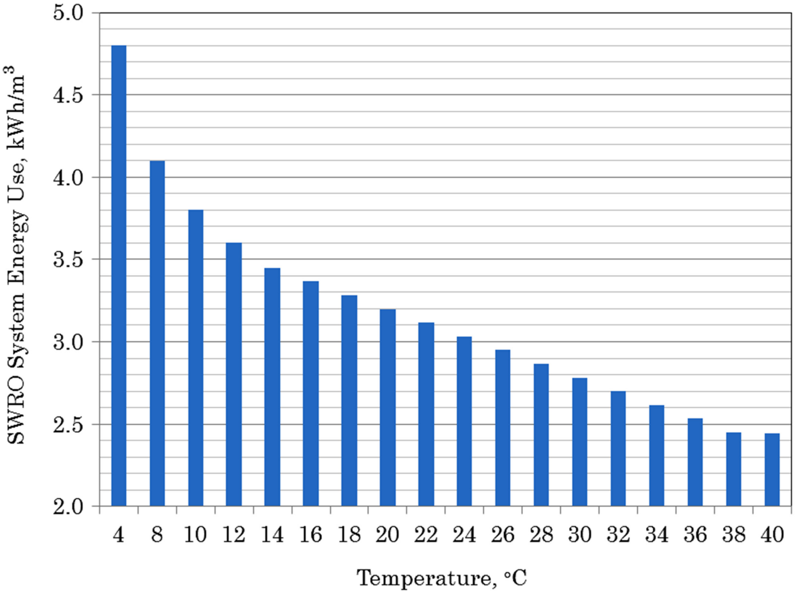

FIGURE 2.13 Effect of temperature on SWRO system energy use.

(e.g., northern coastal waters of California, Chile, Japan, Korea, and China) may see seasonal seawater temperature drops below 10°C.

Increase in source seawater temperature may have three potential impacts on membrane performance that may negate the positive effect on membrane pressure: (1) increased concentration of TDS and other minerals in the desalinated water (see Figure 2.14); (2) change in membrane material behavior (membrane compaction), especially for temperatures above 40°C, which could result in shorter membrane useful life; and (3) accelerated membrane biofouling due to the effect of the temperature on bacterial growth.

Operation at high source water temperatures (typically 30°C or more) may compromise meeting product water quality goals in terms of TDS, chlorides, boron, sodium, and other product water quality requirements and may require the installation of an additional treatment step – partial or full second pass – to address the negative effect of temperature on product water quality.

SWRO system construction cost increase associated with the installation of partial or full second RO pass is typically in a range of 10%–25% of the cost of the first-pass SWRO system. The additional O&M costs associated with the operation of a two-pass SWRO system vary between 3% and 10% of the costs for operation of a single SWRO pass system of the same permeate production flow rate.

Chapter 4 (Capital Costs) contains construction cost curves for SWRO systems with single-pass, full two-pass, and partial second-pass configurations. Similarly, Chapter 5 (Operation and Maintenance Costs) has direct non-energy annual O&M cost curves for the same three types of reverse osmosis system configurations.

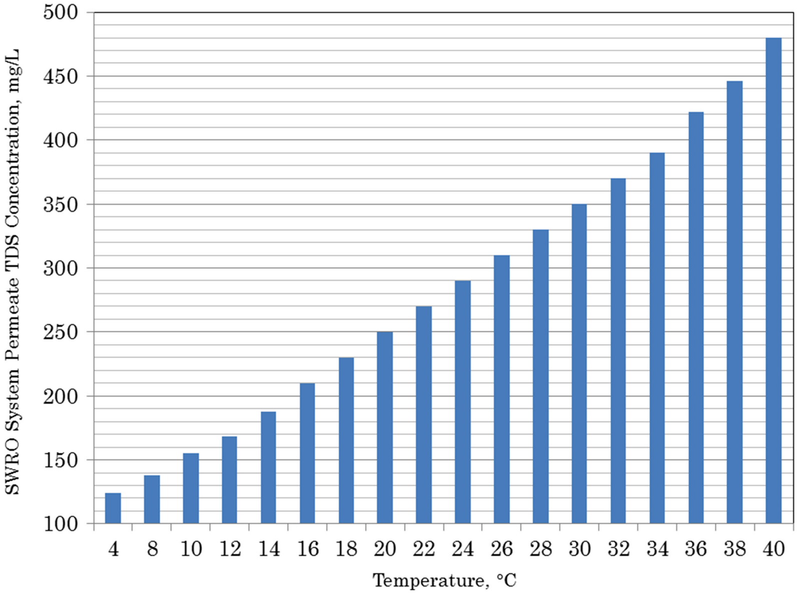

FIGURE 2.14 Effect of source water temperature on SWRO permeate TDS concentration.

In general, the seawater of the Arabian Gulf has higher content of salinity and boron and significantly more elevated RO membrane biofouling potential than the seawater from most other seawaters worldwide. In addition, the Arabian Gulf is very shallow near the shoreline and as a result obtaining source water quality adequate for SWRO desalination requires the construction of 1- to 2-mile-long costly offshore intakes as compared to the Mediterranean Sea for example, where often good quality water can be obtained in only 0.3–0.6 miles from the shore.

In addition, because of the high fouling potential of the source seawater, the SWRO plants will have to be designed at lower plant recovery (typically 38%–40% vs. 45%–50%) and at lower membrane loading rate (flux) as compared to desalination plants in the Mediterranean, which ultimately results in the need to install larger size intake, pretreatment system, and more RO membranes. Such source water quality factors have a direct impact on plant costs.

Frequent and prolonged algal blooms in the Arabian Gulf result in heavy biofouling of the SWRO membranes, which requires SWRO desalination plants to be constructed with robust and costly pretreatment facilities and increases the frequency and chemical costs for membrane cleaning. The record high-intensity algal blooms that occurred in 2008–2009 in the Arabian Gulf have resulted in the shutdown of most the SWRO desalination plants located in the gulf for a period of one to three months.

Such performance challenges have prompted the need for the construction of multi-step pretreatment processes including dissolved air flotation (DAF) followed by granular media or membrane filtration in order to remove algae and organics from the source seawater prior to RO separation. As a result of these less favorable conditions for SWRO desalination in the Arabian Gulf as compared to other water sources (e.g., the Mediterranean Sea), the overall cost of water production by SWRO is typically 20%–40% higher.

2.2.4 TARGET PRODUCT WATER QUALITY

Product water quality has a measurable impact on SWRO plant configuration, design, and costs. Typically, the higher the required product water quality the higher the desalinated water costs. Potable use of desalinated seawater is closely related to the levels of TDS, chlorides, boron, and bromides in this water. Drinking water regulations worldwide usually establish levels of TDS and chlorides in the product water below 500 and 250 mg/L, respectively.

However, when using desalinated seawater, the importance of these parameters is often overshadowed by the health and irrigation related water quality requirements in terms of boron, and disinfection related water quality targets in terms of bromides. The main reason why boron and bromides are of specific importance for the overall desalinated water quality is the fact that their concentration in seawater is usually an order of magnitude higher than that of typical freshwater sources (rivers, lakes, groundwater, etc.).

For example, typical river water has boron concentration of 0.05–0.20 mg/L, while source seawater boron levels are usually between 4.00 and 6.00 mg/L and the boron content of desalinated water treated by a single-pass SWRO system is usually between 0.60 and 1.40 mg/L. Similarly, bromide levels in fresh water sources are usually between 0.05 and 0.30 mg/L, while source seawater typically has bromide concentration of 55–85 mg/L and the content of bromide in permeate produced by a single-pass SWRO system is typically between 0.60 and 0.90 mg/L. While SWRO membranes remove over 80% of the boron and over 99% of the bromides in the source seawater, the remaining levels of these compounds are still several times higher than that in fresh surface water sources.

Boron level in the desalinated water is often required to be reduced to less than 1 mg/L to achieve public health goals and to less than 0.75 mg/L (sometimes even less than 0.5 mg/L) in order to alleviate problems associated with the use of desalinated water for irrigation of sensitive crops (e.g., citrus trees, avocados, strawberries) or ornamental plants. In order to achieve these water quality goals, often the desalinated water TDS and chloride levels have to be reduced below 100 and 50 mg/L, respectively.

Bromide concentration of desalinated seawater may also have a significant effect on the target TDS removal rate, especially if this water is disinfected using chloramines rather than chlorine, or if it is ozonated. Disinfection of desalinated water with chlorine only (in the form of chlorine gas or sodium and calcium hypochlorite) creates very stable chlorine residual that shows minimum decay over long periods of time (60 days or more).

However, applying a combination of chlorine and ammonia to desalinated water in order to create chloramines (a practice widely used in the United States, for example) may yield unstable total chlorine residual that decays rapidly (within several hours) to unacceptably low levels. This de-stabilizing effect of bromides on chloramine residual is very pronounced for desalinated water, with bromide content of 0.4 mg/L or higher.

Although the destabilizing chloramine residual impact of desalinated water with high bromide concentration could be mitigated by supper-chlorination (i.e., applying initial chlorine at dosages of 4.0 mg/L or more) or by two-pass SWRO treatment, this effect has to be accounted for in the chemical costs for seawater desalination.

Ozonation of desalinated water with bromide concentration of 0.4 mg/L or more may result in formation of unacceptably high content of bromate in the finished water. Most drinking water regulations worldwide (Cotruvo et al., 2010) contain a maximum bromate limit of 10 μg/L. This limit could be exceeded if the desalinated water has a high bromide level.

In addition to the potable uses discussed above, desalinated water of even higher quality may be required for some industrial applications, especially these where ultrapure water quality is needed (e.g., production of semiconductors and pharmaceuticals). Such applications may necessitate the removal of silica, specific ions, oxygen, and other water quality constituents which would require permeate treatment through one or more additional water quality polishing processes such as ion exchange, activated carbon adsorption, and so on. Such water quality polishing steps could sometimes double desalinated water costs as compared to expenditures associated with producing drinking water.

Producing higher quality desalinated water is associated with a measurable cost increment. Table 2.4 provides information on the relationship between the target product water quality and the associated costs for plant construction and operation

TABLE 2.4

Effect of Target Product Water Quality on Water Costs

Target Product Water Quality (mg/L)	Construction Costs	O&M Costs	Cost of Water
TDS = 500 Chloride = 250 Boron = 1 Bromide = 0.8	1.00	1.00	1.00
TDS = 250 Chloride = 100 Boron = 0.75 Bromide = 0.5	1.15–1.25	1.05–1.10	1.10–1.20
TDS = 100 Chloride = 50 Boron = 0.5 Bromide = 0.2	1.25–1.40	1.15–1.25	1.20–1.30
TDS = 30 Chloride = 10 Boron = 0.3 Bromide = 0.1	1.40–1.60	1.30–1.40	1.35–1.50

and for overall water production. The costs for product water with TDS concentration of 500 mg/L, chloride level of 250 mg/L, boron of 1.0 mg/L, and bromides of 0.8 mg/L are used as a base for comparison and are assigned a value of 1. Incremental expenditures needed to achieve more stringent product water quality goals are assigned multiplier values.

The use of single- vs. two-pass RO systems is very dependent on the target product water quality. For example, all SWRO desalination plants in the MENA region before 2010 were built as two-pass RO systems because of the very stringent limit for content of boron in the drinking water of 0.5 mg/L established by the World Health Organization (WHO) and adopted by the regulatory bodies of all MENA countries.

In 2011, the WHO issued new Guidelines for Drinking Water Quality (WHO, 2011), which increased the boron limit to 2.4 mg/L. These new guidelines were adopted in the drinking water regulations of all MENA countries except for Israel. As a result, some of the new SWRO desalination plants built after 2011 do not have second-pass SWRO systems or if a second-pass RO system was installed it usually is not operated.

Pretreatment of seawater with high RO membrane biofouling potential often involves construction of multiple clarification and filtration facilities in series, which increases the plant capital and O&M costs. The biofouling potential of the source seawater is proportional to its content of easily biodegradable organic substances, which usually increases measurably and often impacts plant performance. Shallow coastal areas of the Arabian Gulf and the Red Sea are significantly more prone to frequent occurrence of heavy algal blooms and therefore usually require more sophisticated and costly pretreatment than the SWRO desalination plants located along the Mediterranean Sea.

2.2.5 Concentrate Disposal Method

Depending on the site-specific conditions of a given project, concentrate disposal expenditures may have a measurable contribution to the total plant construction and O&M costs and to the overall cost of water. Use of existing outfall for concentrate disposal and more specifically co-disposal with power plant cooling water or wastewater treatment plant effluent usually yields the lowest concentrate disposal costs.

For small seawater desalination plants with low-cost access to an existing wastewater collection system, concentrate disposal may be very cost attractive as well. On the other hand, construction of long new discharge outfalls or series of deep groundwater injection wells, although widely practiced for small desalination plants, is often costly and site-prohibitive for large projects.

2.2.6 Power Supply and Unit Power Cost

Salt separation from seawater requires a significant amount of energy to overcome the naturally occurring osmotic pressure exerted on the reverse osmosis membranes. Seawater reverse osmosis (SWRO) desalination is several times more energy intensive than conventional treatment of fresh water resources. Table 2.5 presents the energy use associated with various water supply alternatives.

TABLE 2.5
Energy Use for Alternative Fresh Water Production Methods

Water Supply Alternative	Energy Use (kWh/m^3)
Conventional treatment of surface water	0.2–0.4
Water reclamation	0.5–1.0
Indirect potable reuse	1.5–2.0
Brackish water desalination	1.0–1.5
Desalination of Pacific Ocean Water	2.5–4.0

Analysis of this table indicates that the energy needed for seawater desalination is approximately 8–10 times higher than that for production of fresh water from conventional sources such as rivers, lakes, and fresh water aquifers. It should be pointed out, however, that such resources are limited to less than 2.5% of the water available on the planet, and that in large urbanized centers of most developed countries worldwide traditional fresh water resources are near depletion, while new sources are not readily available to sustain long-term population growth, industrial development, and quality of life.

Review of Table 2.5 reveals that energy use for water reclamation is significantly lower than that for seawater desalination. However, compared to desalination, water reclamation does not create new fresh drinking water – it merely provides a more efficient use of the already available fresh water resources. Therefore, in most coastal urban areas worldwide both seawater desalination and water reclamation are implemented in parallel and are viewed as integral parts of a well-balanced and environmentally sustainable long-term water supply portfolio.

As indicated on Figure 1.5 (Chapter 1) the cost of power for SWRO desalination is typically 20%–35% of the total cost of production of desalinated water. Therefore, both unit power cost and desalination plant power use have a profound effect on project water production costs.

At present, most desalination plants worldwide are supplied by power generated from fossil fuel. However, a number of recent SWRO desalination plants in Australia have implemented wind-driven power generation projects, which produce as much power as that used by the desalination plants. In recent years, a number of MENA countries have taken the initiative to develop a robust portfolio of renewable power generation plants to provide electricity for seawater desalination. The present deployment of renewable-based desalination is less than 1% of the installed desalination capacity in the MENA region. Ever increasing reliance on desalinated water in MENA, combined with the relatively high power and water production costs and significant carbon footprint of desalinated water, make fossil fuel–driven desalination in the MENA region unsustainable in the long run.

A recent World Bank report entitled Renewable Energy Desalination: An Emerging Solution to Close the Water Gap in the Middle East and North Africa (World Bank, 2012) provides a detailed discussion of the potential for renewable energy–based desalination in the MENA region and the challenges associated with the technology, costs, and environmental implications of fossil-fueled desalination.

Solar power is the most abundant renewable energy source in MENA. Therefore, it is the prime choice of energy supply for many ongoing pilot and full-scale desalination projects in the region, which are specifically planned and designed to run on renewable power. Some renewable energy–based desalination projects under development in the MENA region consider wind and geothermal power as potentially viable and cost-competitive to solar power. Viability and advantages and disadvantages of alternative renewable power supply sources for the various countries of the region is presented in detail elsewhere (World Bank, 2012; GWI, 2015).

Key advantages of solar power desalination–based projects for MENA as compared to wind power–based desalination plants are the high intensity and reliability of the power source (e.g., solar irradiation), and their relatively lower construction and O&M costs. However, as with wind farms, a key challenge of solar power supply facilities is the need for a large amount of land for installation of the renewable energy equipment to supply power to SWRO desalination plants.

As a rule of thumb, the land area needed for construction of a solar power field for 1000 m^3/day (1 MLD) SWRO plant is 10 ha and for construction of a wind farm for the same size SWRO plant is 20 ha. This amount of land is approximately 50 times and 100 times higher, respectively than the land needed to construct the SWRO desalination plant. The total capital cost for construction of a solar power plant to supply the entire amount of electricity needed is typically 60%–80% of the capital cost of the desalination plant itself. More detailed discussion on the feasibility of linking renewable power and desalination projects is provided elsewhere (World Bank, 2012).

While for small desalination facilities such high land requirements are not a major challenge, in densely populated urban centers where land cost usually comes at a premium, the construction of medium or large size solar and wind-driven desalination plants often is practically impossible due to lack of available land and in many cases it is cost prohibitive.

The construction of solar power fields and wind farms for powering of brackish water reverse osmosis (BWRO) desalination plants requires approximately 10–20 times less land and lower costs than that for SWRO desalination plants. However, in most countries, the existing brackish water aquifers are already used and often over-pumped, and the remaining untapped brackish water resources can only supply a very limited portion of the new water demand planned over the next 10 years (e.g., the construction of large-scale BWRO plants of capacity adequate to solve drinking water demand challenges in the MENA region is practically not possible) (GWI, 2015).

Solar power–driven desalination projects under development at present encompass indirect or direct coupling of conventional SWRO, MSF, or MED desalination plants with either concentrated solar power generation technologies (CSPs) or photovoltaic cells (PVs) (Blanco et al., 2011; Palanzuela et al., 2011; Quteishat and Abu-Arbi, 2012). The most promising combinations of solar power and desalination technologies are: PVs with reverse osmosis (RO) and electrodialysis (ED) systems;

and CSPs with MSF or MED systems (Al-Karaghouli et al., 2009; Moser et al., 2013; Shatat et al., 2013; Pinto and Marques, 2017).

Currently, PV-based SWRO solar desalination is the main focal point of research and full-scale desalination project implementation because of the measurable decrease in solar panel costs over the last 5 years. The largest desalination plant with solar power supply under construction in the MENA region at present is the 60-MLD SWRO plant in Al Khavji, Saudi Arabia. This project is planned to be in operation by the end of 2018. The Al Khavji project will incorporate the construction of a 15 MW of PV solar power generation plant that will deliver electricity to the energy grid of total daily amount equal or higher than the daily desalination plant power demand. The SWRO desalination plant will receive electrical energy from the grid.

At present, conventional SWRO desalination plants powered through the electrical grid still remain economically more competitive than PV-powered RO or CSP-powered MED configurations as well as other combinations of desalination technologies and alternative power sources (Fiorenza et al., 2003; IRENA, 2012; Moser et al., 2013) (see Figure 2.15).

The water production costs presented in Figure 2.15 include both the capital and operation and maintenance expenditures for the desalination plant as well as those for the renewable power generation system (wind, solar, geothermal, etc.). These costs are for an autonomous, directly coupled desalination plant and renewable energy source and do not include the use of electricity from the grid. Costs for desalination plants de-coupled from the renewable power generation system could be lower and would depend on the site-specific project conditions (World Bank, 2016; Al-Karaghouli and Kazmerski, 2013).

Selecting the most suitable renewable energy–driven desalination technology depends on several factors, such as the size of the plant, salinity of the source water and product water, availability of access to the electric power grid, and the type of renewable power technology (Ghaffour et al., 2015).

Desalination based on the use of renewable energy sources can provide sustainable long-term production of fresh water and is expected to become economically

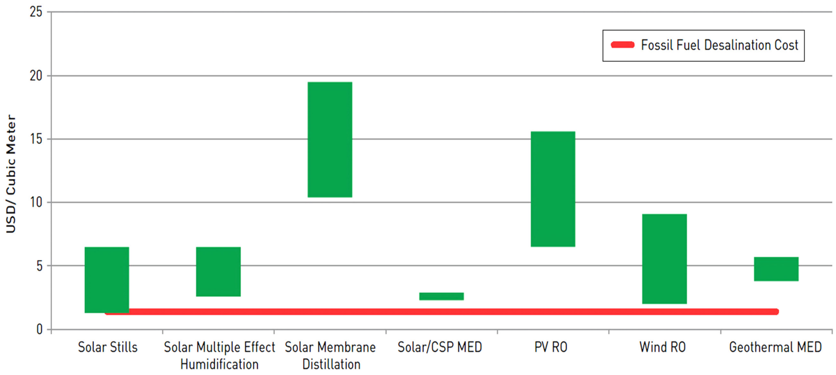

FIGURE 2.15 Costs of water produced by renewable vs. fossil fuel–driven desalination.

attractive in the near future as the costs of renewable energy production technologies continue to decline and the costs of fossil fuel continue to raise over time. In addition, environmental externalities associated with fossil-fuel based electricity generation (e.g., the need to offset desalination plants' carbon footprint) may offset the difference in energy and water production costs (Karagiannis and Soldatos, 2008; Gude, 2016).

Recent international agreements to minimize greenhouse gas (GHG) emissions and counter the effects of global warming are likely to increase the cost of fossil fuel–driven desalination and to contribute to closing the price gap associated with the use of renewable power sources for production of desalinated water. For example, the cost of water increase to mitigate the carbon footprint of the 200,000-m^3/day Carlsbad SWRO desalination project in the United States, which is the first project in the world that was required to implement carbon footprint mitigation measures, is approximately 8% (US\$0.14/m^3) of the baseline cost for production of desalinated water (US\$1.67/m^3). Such measures, however, do not include the use of renewable power and mainly rely on incorporating state-of-the-art desalination technology and purchase of carbon credits at relatively low unit costs (US\$5/ton CO_2).

As cost of carbon credits in California may increase in the future to reach current international levels of US\$50 to US\$80/ton CO_2, such carbon footprint mitigation approach could carry a significant potential for increase of desalinated water costs over time. Based on recent experience with the use of wind power for some of the largest state-of-the-art SWRO desalination projects in Australia (e.g., the 144-MLD Perth plant and 250-MLD Sydney plant) has resulted in 20%–30% increase in the baseline cost of desalinated water as compared to the use of fossil-fuel generated power.

The impact of the use of renewable power on the total desalination costs is very site specific. In large urbanized centers where fossil-fuel based electricity production costs are relatively low (US\$3–5 cents/kWh), renewable power is not likely to be cost-competitive. However, even at present, the use of locally available renewable energy resources for desalination in remote regions with low population density and lack of existing power and water infrastructure is often more cost-effective than existing conventional means of water supply because most remote municipalities in the MENA region are served by trucks which typically deliver water at cost of US\$4.0–US\$6.0/m^3.

Potential environmental benefits associated with the use of renewable energy are catalyzing ongoing efforts to identify cost-effective configurations that couple solar energy sources with desalination technologies (Al-Karaghouli et al., 2013; Fiorenza et al., 2003; Thompson, 2003).

Renewable energy development in the MENA region continues to attract investment and financial support from global institutions. In November 2015, the European Bank for Reconstruction and Development (EBRD) and other financial institutions have announced the launch of a funding framework for private sector renewable energy development in four countries across the MENA region, with private sector developers in Morocco, Egypt, Tunisia, and Jordan set to benefit from this framework. Thanks to the recent reforms in the four countries, which have started to allow private power producers to sell electricity directly to consumers, the EBRD program will support a number of new business models, from direct agreements between large developers and corporate consumers to small-scale generation in communities. In Tunisia, given the early stage development of the sector, direct sales to the Tunisian Electricity and Gas Company, the state-owned single buyer, are also eligible for financing.

The EBRD, along with the Climate Investment Funds' Clean Technology Fund, and Global Environment Facility (GEF), plans to provide $250 million through debt and equity funding. The first project to receive funding under this framework is the 120 MW Khalladi wind farm near Tangiers in Morocco, which is being developed by a special purpose company jointly owned by ACWA Power, Argan Infrastructure Fund, and UPC Renewables North Africa, that also received funding worth $124 million from Moroccan commercial bank BMCE Bank.

In February 2016, Morocco launched the first phase of the largest concentrated solar power (CSP) plant in the world. This project scope includes the construction of the three-plant Noor-Ouarzazate CSP complex, which is designed to produce over 500 megawatts (MW) and to supply power to 1.1 million Moroccans by 2018. It is estimated that the plant will reduce the country's energy dependence by about 2.5 million tons of oil per year, while also lowering carbon emissions by 760,000 tons per year. The Moroccan Agency for Solar Energy, responsible for project implementation secured over $3 billion needed for the Noor-Ouarzazate complex from the World Bank, the African Development Bank (AfDB), the Climate Investment Funds (CIF), and European financing institutions.

Egypt has emerged as a highly promising renewable energy market, project developers from around the world announcing plans to set up large-scale renewable energy projects in the country. Scatec Solar recently signed an agreement to set up 250 MW solar power projects, while ACWA Power, in partnership with the Masdar Group, plans to set up 2 GW of solar and wind energy projects.

At present, Masdar in the United Arab Emirates is developing a comprehensive program for incorporating renewable power into all new desalination projects with the ultimate goal that 100% of these projects will run on such power by year 2030. Masdar is owned by the Abu Dhabi government through the Mubabdala Development Company and is currently working with four firms – Abengoa, Sidem, Suez, and Trevi Systems – to develop pilot plants and complete comprehensive research of the best combination of desalination and renewable power technologies with an ultimate goal to reliably produce desalinated water at cost comparable to existing conventional desalination technologies powered by fossil fuels. By 2020, Masdar is planning to construct a full-scale desalination plant with fresh water production capacity of 100 MLD in a joint venture with one of the four companies listed above, which have proven to develop the most cost-competitive renewable desalination project.

2.2.7 PROJECT RISK PROFILE

As indicated previously, indirect capital costs, including expenditures associated with project financing, development, and permitting are a significant portion (10%–20%) of the overall water production costs. These costs are closely related to the risks associated with project permitting, construction, and operation.

Typically, financial institutions establish the interest rates of the funds they lend to the project and the acceptable project financial structure, based on a thorough evaluation of the project risk profile. In order to provide low interest rate funding for a given desalination project, financial institutions demand strong assurances that the project will be permitted and built in a timely and cost-effective manner; the power supply contract and tariff for the project will be commensurate with market conditions for industrial uses; the operation and maintenance of the desalination plant will be conducted by operations staff that has successful prior experience in seawater desalination; and that the regulatory and permitting (licensing) risks of the project are to be minimal and manageable at reasonable costs.

In the case of build-own-operate-and-transfer (BOOT) projects, financial institutions lending funds to a given project would require the final user of the desalinated water (public agency or private industrial end user of the water) and the BOOT contractor to execute a water purchase agreement (WPA) that is fair and balanced and that apportions risks equitably between the two parties.

The entity providing funding for a given project may vary from project to project and could be a combination of private sector commercial lenders, banks and multilateral agencies, and international financial institutions. Increasingly, funding for desalination projects is obtained from the capital markets and from project bonds. Lenders differ in their approach to project risk. Public sector bond underwriters/lenders and private sector lenders and equity investors often have different approaches and requirements for evaluation and mitigation of project risks.

As a general rule, desalination project lenders would only be willing and able to take risks that are quantifiable and manageable at reasonable costs. Typically, lenders are not involved with the construction, operation, or insurance activities related to project implementation. Therefore, they would not take risks associated with these activities and especially risks they are not familiar with or that can be more appropriately borne by other parties involved in the project.

In order to mitigate risks at early stages, lenders may be involved in the key milestones of project development and implementation, including negotiation of project contracts, review of key project design and construction activities, as well as review and approval of certification of project completion and project acceptance testing for continuous commercial operation. Lenders would generally exercise their review rights over the project implementation with the assistance of an independent engineer often referred to as the lender's or bank's engineer.

The key project risks considered by the lending institutions when determining their interest and conditions (i.e., the cost of money) for funding desalination projects are:

- Permitting (licensing) risks;
- Entitlement risks;
- Power supply risks;
- Construction risks;
- Source water risks;
- Technology risks;
- Regulatory risks;

- Operational risks;
- Desalinated water demand risks;
- Financial risks.

2.2.7.1 Permitting (Licensing) Risks

Permitting (licensing) risks are risks associated with obtaining and maintaining permits (licenses) legally required for all phases of project implementation including environmental permits (such as the concentrate discharge permit and drinking water production permit), construction permits, and operations permits. Because desalination projects are relatively new to many permitting agencies, and due to lack of precedents and experience in permitting of this type of project, the time and efforts required for permitting of desalination projects are usually more extensive than those for obtaining permits for construction and operation of conventional water and wastewater treatment projects.

Often permitting of large desalination projects requires long and costly environmental and engineering studies and is influenced by environmental opposition, which in some cases may pose significant political and legal pressures to delay and ultimately to derail the project. As a result, permitting risk is considered by lending institutions and public agencies alike to be one of the most significant and costliest risk exposures associated with desalination project implementation in countries such as the United States, Australia, and Spain.

For example, difficulty encountered with permitting of the Tampa Bay seawater desalination project was one of the key reasons why the public utility that initiated this project (Tampa Bay Water) decided to proceed with project implementation under a BOOT method of delivery, which allows this risk and the associated permitting costs to be transferred to the private BOOT contractor. The permitting process for the largest SWRO project in the United States at present – the 200,000 m^3/day Carlsbad desalination plant – has continued over a period of 10 years and permitting-related expenditures for this project exceeded US$20 million. The development of this project began in 2001 and project construction was completed in December 2016.

2.2.7.2 Entitlement Risks

Entitlement risks are mainly risks associated with control and costs of use of the site and infrastructure on which the desalination plant and associated facilities will be located as well as with the installation and operation of infrastructure for collection of source seawater, discharge of the plant waste streams, and delivery of the product water to the final users (e.g., rights of way for using or crossing public and private lands, roads, and other infrastructure).

In the case where the desalination plant would share existing intake and discharge infrastructure with other facilities, such as power generation plants or wastewater treatment plants (WWTPs), entitlement risks are associated with potential changes of the technology and capacity of the existing host facilities in the future that may require the desalination plant to build its own intake and discharge facilities or to significantly modify plant structures in order to accommodate the necessary changes implemented by the host facility.

For example, if a desalination plant uses existing WWTP outfall, and the WWTP owner decides to expand its capacity and, therefore, to decrease the allowable volume of concentrate discharge through its outfall, when this occurs the desalination plant may face the need and expenditures to build its own outfall, unless it is contractually entitled to use a predetermined portion of the discharge capacity of the existing outfall throughout the useful life of the desalination plant.

In this example, if the desalination plant does not have a contractual entitlement to use the wastewater plant outfall over the period for which a given lending institution would fund the project, the project lenders would consider this condition an entitlement risk and would penalize the project financing costs in order to provide adequate protection of lender investment against this risk. The size of the interest rate penalty of the borrowed funds will be commensurate with the additional expenditures needed to address this risk, if loss of entitlement occurs in the future.

2.2.7.3 Power Supply Risks

Power supply risks are risks associated with the availability of power and the magnitude of the unit power cost change over the useful life of the desalination project. Since cost of power is usually 20%–35% the total water production cost (see Figure 1.5), the financial institution funding the project would require the plant operation costs to be secured with a long-term power supply contract (e.g., Power Purchase Agreement – PPA) that would allow predictable power tariff/costs over the lending period. Financial institutions would typically expect the power tariff adjustments allotted in the PPA to be reflected in and matched with the water tariff adjustments in the water purchase agreement.

2.2.7.4 Construction Risks

Construction risks are risks associated with potential increase in the construction costs during the project implementation period due to the following: unusual site subsurface conditions; delay of delivery and installation of key equipment; construction cost overruns; designer and construction contractor errors and omissions; and performance and reliability risks related to plant startup, commissioning, and acceptance testing.

Well-recognized construction companies with a proven track record of successful construction of seawater desalination projects in similar settings and of similar size and technology would greatly increase the confidence level of the lenders involved with the project funding. Usually, construction companies that are newcomers to the desalination industry will be considered to increase the construction-related project risks and would typically be expected to pay higher project-related insurance premiums and to incorporate higher contingency in their construction cost estimates. Such requirements would ultimately result in increased cost of project funding, and ultimately cost of water production. Project lenders would consider construction companies with significant cost and schedule overruns and/or ongoing litigation on previous projects of similar size and complexity less favorably and sometimes may not accept such constructors as eligible and acceptable for participation in the project.

Typically, project lenders favor turnkey fixed-price/fixed-schedule contracts, which allow the owner to hold key contractors fiscally accountable for their performance obligations. Construction contract completion guarantees with clauses that require performance and payment bonds of size of 10%–30% of the turnkey construction price to be available to the lenders to rectify construction problems are preferred by the financial community as a proven mechanism to mitigate construction risks. Usually, the size of the performance and payment bond is commensurate with the probability of the contractor's default, which in turn is related to the previous track record of the contractor with similar projects and contractor experience with key technologies and equipment proposed to be used for the desalination project.

2.2.7.5 Source Water Risks

Source water related risks are associated with the potential impacts of the project source seawater quality on desalination plant operation and performance, and with the effect of potential changes in source water quality over the useful life of the desalination project on the water production cost. For example, increase in source water turbidity, organics, or other compounds that may result in accelerated fouling of the membrane elements or in the need for more elaborate pretreatment are typically of concern of the financial community. These water quality related risks can be addressed by avoiding the location of the desalination plant intake in the vicinity of existing WWTP discharges, industrial outfalls, or in large industrial or commercial ports and shipping channels.

In BOOT projects the source water quality related risks are contractually addressed by including a source water quality specification in the water purchase agreement with the public or private entities purchasing the water, and in the agreements for turnkey engineering, construction, and procurement (EPC) and O&M services. These agreements should also contain provisions for cost of water adjustments when the actual source water quality is outside of the contractual specifications and when unpredictable deviations from the source water quality specifications (e.g., heavy algal blooms) have material impacts on plant performance, availability, and costs.

2.2.7.6 Technology Risks

Technology risks are related to the potential downsides of using new and unproven technologies with limited or no track record on large-scale desalination plants. Although the use of new technologies typically has performance benefits such as reduction of project construction costs, power, and/or chemical consumption and expenditures, the potential downsides are inability to meet contractual product water quantity and/or quality obligations, and increased plant downtime due to process under-performance, equipment failure, or malfunction of key system components.

While project engineers typically tend to focus on the cost and performance advantages, project lenders always take under consideration both potential upsides and downsides on a life-cycle cost basis when evaluating the risks and benefits associated with using new technology for a given project. If potential project downsides outweigh cost savings or have a measurable negative impact on the plant capacity availability factor over the useful life of the project or the lending period, then the technology is considered higher risk and financing terms would typically penalize rather than reward the use of new technology for the project for which it is considered.

For example, if the use of a new energy recovery technology (ERT) under average conditions allows reducing power consumption by 10% as compared to a conventional ERT with well-proven track record, but the downtime of the new ERT is 10% higher than that of the conventional ERT, then the overall life-cycle cost-effect of the use of the new ERT may be negative and therefore it may be considered unfavorably by the financing community.

For the specific conditions of a given project, let's assume that (1) the plant capacity is 100,000 m^3/day; (2) the savings from using new energy recovery technology are 0.5 kWh/m^3, (3) the unit cost of power is US$0.06/kWh, (4) the new energy recovery technology has 8% higher downtime than the older technology it is compared with, and it reduces the plant capacity availability factor from 98% to 90%, and (5) the cost of desalinated water sold to the customer is US$0.80/$m^3$. For these conditions, the annual benefit of using the new energy recovery system is: US$0.06/kWh × 0.5 kWh/$m^3$ × 100,000 m^3/day × 365 da ys × 90% plant availability = US$ 985,500/yr. However, the loss of water sales during the 8% of additional downtime of the plant caused by the downtime of the new energy recovery system is: US$0.80/$m^3$ × 100,000 m^3/day × 365 days × 8% of downtime = US$2,336,000/yr. As illustrated by this hypothetical example, the penalty for lower reliability associated with the implementation of the new energy recovery technology is significantly higher than the benefit of higher energy savings this technology yields. As a result, the use of new ERT for this project is not warranted and represents a risk of US$2,336,000 – US$985,500 = US$1,350,500/yr.

Usually, the project lender would turn this risk into a cost overrun amortized over the term of lender investment and then into an incremental increase in the interest rate of the funds that the lender commits to the project. For example, let's assume that the fair and favorable market interest rate for lending money to a low-risk project with conventional ERT is 5.0%; the term for repayment of the investment is 20 years; and the total capital cost of the project is US$171.5 million (MM). The capital cost recovery (amortization) factor for this project is 11.752 estimated at interest rate of 5.7% and 20-year loan term (see Chapter 6 for calculation of the amortization factor). Therefore, the project annual amortized cost would be: US$171.5 MM/11.752 = US$14.6 MM/yr.

Because of the potential O&M cost overrun of US$1,350,500/yr due to the use of the new ERT, the annual amortized project cost would increase from US$14,600,000/yr to US$15,950,500/yr (US$14,600,000/yr + US$1,350,500/yr = US$15,950,000/yr). As a result, the actual amortization factor would decrease from 11.752 to 10.752 (US$171,500,000/US$15,950,500/yr = 10.752). For a 20-year loan term, the interest rate corresponding to this amortization factor is 6.8%.

In effect, because of the risk associated with the use of the new ERT in this illustrative example, the project lenders may raise the interest rate of the invested capital from 5.7% to 6.8% to cover potential risk of repayment of investment and loss associated with the use of the new ERT. In this case, the cost of water production may be penalized twice: once because of the increased interest rate of the borrowed funds to build the desalination plant, and a second time because the owner would receive less revenue from water sales due to the increased project downtime.

This example illustrates the fact that the use of new technology, although attractive from an engineering point of view, may not always be beneficial for reduction of the overall project costs, and in reality it may penalize the cost of water production through the increased cost of financing. Although simplified, this example illustrates the monetary value of technology risk through the point of view of project investors and the importance of using equipment with a proven track record.

In general, if a new technology is introduced and the technology lacks full-scale track record of actual availability (downtime), assumption of 5% to 10% of downtime of the new equipment is commonly used by the financial community to evaluate technology risks. This corresponds to the fact that new technology used for the first time on a given project usually goes through two to three generations of improvements until it reaches a typical reliability of well-proven and mature technology (i.e., technology with downtime of less than 1% and full-scale track record of 5 years).

The example above also underlines the fact that use of new technology is more attractive and warranted for projects where the potential for life-cycle monetary benefits is significantly higher than the penalties associated with equipment downtime and lost revenue from water sales. If, for the example above, the unit cost of power was US$0.15/kWh rather than US$0.06/kWh and/or the cost of water was lower, then the use of the new energy recovery equipment would be still warranted and the project financing would not be penalized.

This observation for example explains the fact why the pressure exchanger (isobaric-chamber) based energy recovery systems have first found full-scale application on small projects in the Caribbean where despite the higher downtime of the first prototype generation of pressure exchangers, the unit power costs are so high (typically between US$0.10/kWh and US$0.25/kWh) that the overall benefits of their use as compared to the older generation Pelton wheels clearly outweigh the potential downsides.

2.2.7.7 Regulatory Risks

Regulatory risks are risks associated with the effect that change in environmental, engineering, construction, or other government regulations pertinent to a given project may have on desalination plant construction and/or O&M costs. Regulatory changes may occur during the period of desalination plant construction (for example, changes in electrical or building codes) and/or during the period of plant operations (e.g., new product water quality regulatory requirements, or more stringent concentrate and waste stream disposal regulations). The financial community typically looks for flexibility features in desalination plant design that would allow accommodating future regulation-driven technology changes, and for contractual provisions that permit regulatory risks to be mitigated through cost-of-water tariff adjustments.

2.2.7.8 Operational Risks

Operational risks are risks associated with desalination plant operation and maintenance over the useful life of the facility/term of lender investment. Consistent and reliable plant operation and maintenance is the key to generating an adequate and steady revenue stream required to meet financial obligations associated with project financing and to comply with the water supply contract, which usually contains penalty provisions for nonperformance and regulatory noncompliance.

Because contracting of the desalination plant O&M services to an experienced and well established specialized private contractor with proven experience typically results in lower financing costs (usually due to shortages of local O&M labor), many plant owners are willing to outsource O&M services to third parties. As the seawater desalination market matures, O&M challenges such as risks associated with shortages of local skilled labor would likely be resolved over time, and the importance of this risk would diminish.

2.2.7.9 Desalinated Water Demand Risk

Desalinated water demand risk is closely related to the need for high-quality water in the service area of the desalination plant and to the affordability of this water as compared to that of available existing water supply sources. Typically, in a public-private partnership, the project lender would look for a “take-or-pay” provision in the BOOT contract, which ascertains that a predetermined minimum volume of desalinated water is purchased by the final user(s) under all circumstances or alternatively the final user(s) pay for this minimum amount of desalinated water independently of its use.

The lending community considers the water demand risk of desalination projects relatively high for conditions where the costs of alternative fresh water supplies (i.e., groundwater and surface water) are significantly lower than those of the cost of desalinated water, and where the need for water is driven by temporary drought or seasonal shortage of fresh water. Financing community concerns associated with desalinated water demand may be mitigated by putting in place a water cost structure that provides a temporary subsidy for the use of desalinated water; this subsidy is of size equal to the difference between the cost of desalinated water and the cost of water of other existing sources.

Examples of such subsidies are the US\$0.32/m³ (US\$1.20/1,000 gallons) credit given to the Tampa Bay Water by the South West Municipal Water District for the potable water produced at the Tampa Bay Water seawater desalination plant, and the US\$0.20/m³ (US\$250/acre-foot) credit given the Municipal Water District of Southern California that the United States has committed to provide to its customers for the use of desalinated seawater.

Similar direct or indirect mechanisms of reducing the water demand risk are used at state or local government levels throughout the world for almost all existing seawater desalination projects today. In many countries, the desalination cost subsidy is implicitly provided at governmental level, often by the state or local government taking upon a number of the risks presented above by providing payment guarantees, and thereby indirectly subsidizing desalinated water costs.

2.2.7.10 Financial Risks

These risks are directly related to the financial strength (credit) of the entity which will be the final user or the desalinated water, and which will be responsible for all payment obligations associated with the project financing as well as of the parties involved in the project construction and operation. Project lenders would favor financial agreements with entities that have proven track record in servicing and repayment of debt and equity obligations on similar projects and that do not carry excessive amount of previous fiscal obligations.

Other financial risks are the risks associated with the political stability of the country in which the desalination project is planned to be constructed and the country's currency stability (currency risk). Many of the financial risks associated with a given desalination project may be addressed cost-effectively by involving the private sector in project financing.

Before financial institutions commit to fund a given project they carefully quantify the risks described above and typically address the outstanding risks that are not already adequately mitigated by contractual and technical means, through the incremental increase in the interest rate of the funds they lend.

The majority of the countries in MENA have stable currencies pegged to the US$ or the euro, which in practical terms mitigates the impact of currency volatility on the desalination project costs. In addition, except for a few countries such as Libya and Yemen, the MENA region has relatively stable government and legal structures, which provide safe grounds for local and foreign investment. Such is not the case, however, in other regions of the world with volatile currencies and governance, such as Central and South Asia, sub-Saharan Africa, or Latin America. Because 55%–65% of the desalination project equipment and specialty services have to be purchased in US$ or euros, local currency fluctuations and political instability could result in significant price differences.

Usually, contractors try to mitigate currency and legal certainty risks by transferring them to the water offtaker or by incorporating contingency in their prices, which ultimately results in an overall increase in the cost of desalinated water. An example is the 100-MLD SWRO desalination project in Chennai, India – Nemmeli; its construction cost was US$97 million but the capital cost was US$160 million. A measurable portion of the difference is due to the fact that the Indian currency is of high volatility and therefore the project is prone to high currency risk, which ultimately results in higher cost of water.

Project delivery and financing method has a significant effect on the cost of desalinated water. Although desalination projects worldwide have been delivered under a number of different methods and financial arrangements, the most cost-of-water reduction breakthroughs to date have been achieved under a BOOT method of project delivery. A more detailed discussion of the alternative methods of project delivery and their effect on project costs is presented in Chapter 7 – Project Implementation and Costs.

2.2.8 Project Geographic Location

The geographic location of the project has a measurable impact on the desalination project costs (Papapetrou et al., 2017). Statistical analysis of desalination project cost data from 950 RO plants (Loutatidou et al., 2014) has shown that the region where the plant is installed is one of the four most important factors affecting costs (the other three factors are plant capacity, the year of construction, and the feed water salinity).

In general, 55%–65% of desalination project construction costs and 15%–25% of the O&M costs are associated with equipment and consumables manufactured by international companies, which offer such goods at approximately the same prices and conditions for all projects worldwide – therefore, these project costs are similar in all regions of the world. However, the remaining (35%–45% of construction and 75%–85% of O&M) costs are very specific to the region, country, market, and often site where the desalination project is located.

Because of the measurable differences in the value of these remaining costs in various regions/countries (e.g., United States/North America, Australia, Europe, China/Central Asia, Southern Asia, Mexico and Central America, South America, the Caribbean) accurate estimates of desalination project costs in each of these regions can only be developed by reflecting the site-specific market conditions in the geographic location of the project.

Therefore, the information provided in this book has to be extrapolated with caution and with thorough understanding of the conditions of the actual project location not only in terms of desalination technology, source of seawater and plant size, but also in terms of local labor, consumables, and service markets; contractor perception for local desalination project market importance and risks; influence of social and environmental safeguard regulations on project location, scope, and size; currency risks; funding sources; and other site-specific factors that may dramatically impact costs of desalination projects in various parts of the world.

In general, the MENA desalination market is the most mature and competitive of all regional world markets and has yielded some of the lowest cost desalination projects over the last 20 years. Often, because of their divergence from the conditions in MENA, desalination projects in other parts of the world with the same fresh water production capacity and using the same treatment technology may have several times higher costs or may have similar costs but under the influence of different factors, and the similarity of costs could be purely coincidental.

2.2.9 Other Project Cost Factors

Other factors that have a measurable impact on project costs are listed below:

- Intake type and design configuration:
  - Open ocean vs. subsurface intakes;
  - Collocation of intake and discharge with existing power plant;
  - Collocation of discharge with WWTP discharge;
- Pretreatment system type and design;
- SWRO system configuration:
  - Number and size of individual RO trains;
  - Redundant installed capacity;
  - Number of vessels per RO train;
  - Number of SWRO membrane elements per vessel;
  - Number and location of points of permeate collection from the individual vessels;
- Architectural design;

- Structural design:
    - Buoyancy control;
    - Structural reinforcement for wind and earthquake forces;
    - Foundations (piles, slab footings, etc.);
- Electrical design:
    - Power source (electrical grid; self-generation; direct connection to existing power generation units);
    - Site power supply system configuration – location and size of power substations and connecting conduits;
- Selection of key materials (piping, equipment and structures);
- Site work including:
    - Plant layout;
    - Lighting;
    - Roadways;
    - Site drainage and storm water management;
- Corrosion control:
    - Protective coatings of structures, equipment, and piping;
    - Cathodic protection.

2.3 COST FACTORS BEYOND THE CONTROL OF PLANT OWNER

The main site-specific cost factors that are usually outside of the control of the desalination plant owner but can have a very significant impact on the overall water production costs typically include the following issues:

- environmental regulations;
- regulatory design standards, building and fire codes;
- schedules mandated by third parties (regulatory agencies, emergency response needs, etc.);
- Conventions of prudent engineering practices;
- Construction, equipment, and consumable supplier market conditions;
- Local labor and material costs;
- Construction time constraints driven by local noise and traffic-related ordinances, and limitations of hours of operation of construction equipment;
- Use and condition of existing facilities;
- General economic environment;
- Climate conditions;
- Seasonal water demand and power tariff variations;
- Land costs and site subsurface conditions (i.e., soil and groundwater contamination; soil load bearing capacity and liquefaction potential; and subsurface obstacles).

The factors listed above are very site and project specific. The costs that account for these factors can contribute to over 100% variation of the baseline project costs and therefore have to be taken into account, especially when preparing budgetary and detailed cost estimates, and when comparing costs of two projects of similar capacity, source and product water quality, intake and discharge conditions, and treatment facilities (Alspatch and Watson, 2011).

2.3.1 ENVIRONMENTAL REGULATIONS

Environmental regulations may have very significant impact on desalination plant costs, especially in countries such as the United States, Australia, and Spain, where such regulations are very complex, robust, and demanding.

The main direct environmental impacts associated with desalination plant construction and fresh water production are related to the destruction of marine organisms by their intake facilities and by the environmental stress on marine life caused by the elevated content of salinity and residual treatment chemicals in their discharge. An indirect impact of plant operations is the relatively high carbon footprint associated with the production of desalinated water, where electrical energy from conventional fossil fuel–driven power generation plants is used for fresh water production.

2.3.1.1 Intake-Related Environmental Regulations and Their Potential Impacts on Costs

As with any other natural surface water source currently used for fresh water supply around the globe, seawater contains aquatic organisms (algae, plankton, fish, bacteria, etc.). Impingement occurs when organisms that are sufficiently large to avoid going through the intake screens are trapped against these screens by the force of the flowing source water. For example, algae, plankton, and bacteria are not exposed to impingement. On the other hand, entrainment occurs when marine organisms enter the desalination plant intake, are drawn into the intake system, and pass through to the treatment facilities.

Impingement typically involves adult aquatic organisms (fish, crabs, etc.) that are large enough to actually be retained by the intake screens, while entrainment mainly affects aquatic species small enough to pass through the particular size and shape of intake screen mesh. Impingement and entrainment of aquatic organisms are not unique to open intakes of seawater desalination plants only. Conventional open freshwater intakes from surface water sources (i.e., rivers, lakes, estuaries) may also cause measurable impingement and entrainment.

A third term, entrapment, is used when describing impacts associated with offshore intake structures connected to an onshore intake screen and pump station via a long conveyance pipeline or tunnel. Organisms that enter the offshore intake and cannot swim back out of it are often referred to as entrapped. Such marine organisms could either be impinged on the intake screens or entrained if they pass through the screens and enter the downstream facilities of the desalination plant.

It should be noted that, intake impacts are not unique to desalination plants only, they occur at all conventional drinking water treatment plants collecting source water for treatment by open intakes. Some environmental activists, however, tend to over-emphasize the environmental impacts of desalination plant intakes as compared to these of conventional fresh water intakes from rivers or lakes, because these plants collect approximately 2–2.5 times higher volume of source water than conventional water treatment plants to produce the same volume of fresh water.

The magnitude of environmental impacts on marine organisms caused by impingement and entrainment of open seawater intakes is site specific and varies significantly from one project to another. Open ocean intakes of desalination plants are equipped with coarse bar screens (Figure 2.16), which typically have openings between the bars of 20–150 mm followed by smaller-size (“fine”) screens with openings of 1 mm to 10 mm (Figure 2.17), which preclude the majority of the adult and juvenile marine organisms (fish, crabs, etc.) from entering the desalination plants. While coarse screens are always stationary, fine screens could be two types – stationary (passive) and periodically moving (i.e., rotating) screens. Figure 2.17 depicts a 3-mm rotating fine screen very commonly used in onshore open intakes.

Most marine organisms collected with the source seawater used for production of desalinated water are removed by screening and downstream filtration before this seawater enters the desalination system for salt separation. The marine organisms retained on the screens are disposed of to a landfill or returned to the ocean – and therefore are considered environmental losses. Similarly, the marine organisms in planktonic state that enter the desalination plant with the source seawater are destroyed by the plant’s treatment facilities.

Most countries worldwide do not have regulatory requirements specifically pertaining to the operation of seawater intakes for desalination plants and minimization of their environmental impacts (WRRF, 2016). Countries with advanced environmental legislation such as the United States, Australia, and many European states have policies and regulations that aim to minimize environmental impacts of intakes from power generation facilities where seawater is used for cooling. Such regulations, however, typically do not apply to desalination projects, because as compared to power plants, which can minimize intake impacts by using alternative means of

FIGURE 2.16 Coarse intake bar screen.

FIGURE 2.17 Fine intake screen.

cooling for power generation besides seawater, seawater desalination plants must collect seawater in order to produce fresh drinking water.

Over the past 10 years, environmental groups and political lobbies in Australia and California in the United States have exerted pressure on local regulatory agencies to apply to desalination projects the same stringent intake regulations as those pertinent to power generation plants. Such political pressures resulted in the implementation of lengthy (1- to 2-year) intake impingement and entrainment environmental impact studies worth between US$3 million and US$5 million per desalination project, which did not result in any substantive changes of the intake types and designs of the projects in Australia and California but have delayed project implementation, and have increased water production costs.

From a practical point of view, such studies have been found to have limited actual benefits to the environment because well-designed desalination plant intakes are already configured such that they minimize impingement and entrainment of marine organisms in order to reduce the negative impacts that these organisms have on plant operations, and to reduce the long-term plant O&M expenditures (chemicals, maintenance costs) and ultimately water production costs.

While environmental regulators and lobbies in Australia have accepted the original intake design for the desalination projects without modifications or penalties for environmental impacts, one of the ten regulatory agencies involved in permitting of desalination projects in California, the California Coastal Commission, has mandated the largest desalination project in California, the 200-MLD Carlsbad SWRO plant, to implement an intake impingement and entrainment mitigation program. This program requires the owner of the plant to build 26 hectares of coastal wetlands that aim to produce marine life of comparable type and amount as the marine life that could potentially be destroyed by the plant intake operations at maximum plant fresh water production. The expenditures for this intake impact mitigation project increased the total project capital costs by 5.3% (US$28 million) and the annual O&M costs by 4.5% (US$2.5 million/year). At present, this is the only desalination project worldwide that is required to implement such a program.

In May 2015, the State of California introduced the first-in-the-world regulations specifically pertaining to environmental impacts of seawater desalination plant intakes and outfalls (SWRCB, 2015). These regulations incorporate very stringent environmental requirements and mitigation measures, which aim to promote the use of subsurface intakes (wells) instead of open seawater intakes and to significantly increase the environmental mitigation requirements for desalination plant operations. Such stringent regulations are projected to increase the cost of production of desalinated water in California by 20%–25% and since their introduction such regulations have put on hold the implementation of new full-scale desalination projects in California.

It should be pointed out that for small desalination plants and suitable coastal geological conditions, subsurface intakes (e.g., beach wells) offer environmental and cost advantages, and have been already adopted by the desalination industry. However, at present over 95% of the SWRO desalination plants worldwide use open intakes instead of wells because in most existing locations desirable for construction of desalination plants, geological conditions have been found not to favor installation of subsurface intakes (WRA, 2011a,b).

Desalination plant-specific intake and outfall related regulations have not been adopted by any other state in the United States or any other country worldwide so far. The approach taken by most other countries worldwide, including these in MENA, Europe, and Asia, on the environmental regulation of desalination plant intakes has been to incorporate in new projects the best practices and lessons learned from over 50 years of worldwide experience in the desalination field, and for regulators to request incorporation of such best practices through the environmental project review process, rather than to mandate such practices by legislation or to require specific mitigation measures that result in direct increase of the production costs of desalinated water.

Instead of introducing environmental mitigation penalties to new desalination projects, most countries in the MENA region, Europe, and Asia have adopted an approach of development, funding, and implementation of statewide environmental restoration programs that aim to focus and prioritize funds where such funds will result in most significant environmental benefits for the country as a whole, rather than specifically to the environment in the immediate vicinity of the desalination plants' intakes and outfalls.

Despite claims of potential environmental impacts of intakes on the marine environment, practical experience worldwide to date does not show significant irreversible long-term damages of intake operations on the aquatic environment in the vicinity of desalination plant intakes. While environmental losses do occur, the compensatory processes that naturally exist in the sea in most desalination plant intake locations allow for the marine species in the intake areas to recover and sustain their population.

In addition, as indicated previously, most plants built worldwide in the past 15 years have adopted open intake configurations, which successfully minimize impingement of marine organisms by designing the entrance velocity into the intakes below 0.15 m/s (0.50 ft/s), which is consistent with US Environmental Protection Agency (EPA) best practices for reduction of impingement of aquatic organisms. In addition, many of the newest offshore intakes for SWRO desalination plants built over the past 10 years have adopted the use of special intake technology – wedgewire screens – which is intended to minimize impingement and entrainment and is considered the best technology available (BTA) by the EPA.

Driving forces behind the introduction and adoption of more stringent regulatory review and requirements of desalination projects in developing countries have been project financing institutions that have subscribed to the Equator Principles. The Equator Principles (EPs) is a risk management framework (EP Association, 2013), adopted by a large number of financial institutions, for determining, assessing, and managing environmental and social risk in projects and is primarily intended to provide a minimum standard for due diligence to support responsible risk decision-making. The EPs apply globally to all industry sectors and to four financial products: (1) project finance advisory services, (2) project finance, (3) project-related corporate loans, and (4) bridge loans.

The Equator Principles, formally launched in Washington, DC, on 4 June 2003, were based on existing environmental and social policy frameworks established by the International Finance Corporation. Currently 84 Equator Principles Financial Institutions (EPFIs) in 36 countries have officially adopted the EPs, covering over 70% of international project finance debt in developing countries. All EPFIs have committed to implement the EP in their internal environmental and social policies, procedures and standards for financing projects and will not provide project finance or project-related corporate loans to projects where the client will not, or is unable to, comply with the EPs.

While the EPs are not intended to be applied retroactively, EPFIs apply them to the expansion or upgrade of an existing project where changes in scale or scope may create significant environmental and social risks and impacts, or significantly change the nature or degree of an existing impact.

The EPs have greatly increased the attention and focus on social/community standards and responsibility, including robust labor standards, and consultation with locally affected communities within the project finance markets. They have also promoted convergence around common environmental and social standards. Multilateral development banks, including the European Bank for Reconstruction and Development, and export credit agencies involved in financing projects in developing countries are increasingly drawing on the same standards as the EPs.

In summary, most of the desalination plants built worldwide over the past 15 years have adopted intake designs, configurations, and technologies that minimize the environmental impacts of plant intake operations on the marine environment in the proximity of the intake. At present, environmental regulations outside of the United States do not require implementation of desalination plant intake impingement and entrainment mitigation measures for individual desalination projects. Instead, centralized statewide environmental restoration programs are implemented. If other countries decide to adopt desalination project environmental impact regulations similar to these promulgated in California in 2015 and introduce requirements for mitigation of the environmental impacts of intake operations of individual desalination projects, the desalination plant capital and O&M costs could increase significantly.

It should be pointed out that because thermal desalination plants use 30%–50% more source seawater to produce the same volume of drinking water per day compared to SWRO desalination plants, they will have proportionally higher environmental impact of their intake operations for the same plant location. Therefore, if more stringent intake regulatory requirements are introduced in the future, thermal desalination projects will be impacted at a greater extent and will be considered less favorable from this point of view.

2.3.1.2 Discharge-Related Environmental Regulations and Their Potential Impacts on Costs

Depending on the site-specific conditions of a given project, concentrate disposal expenditures may have a measurable contribution to the total plant construction and O&M costs and to the overall cost of water. Use of existing outfall for concentrate disposal and more specifically co-disposal with power plant cooling water or wastewater treatment plant effluent usually yields the lowest concentrate disposal costs.

Environmental regulations are one of the main policy tools for controlling the environmental impacts of desalination plant discharges. All developed countries worldwide have waste stream discharge regulations, which require the salinity of the desalination plant discharge to be reduced down to less than 10% of ambient salinity within 300 meters from the point of discharge. Such a goal is achievable and in most desalination projects built worldwide over the past 20 years the salinity reduction target is reached within 50 to 100 meters from the point of plant discharge release into the sea.

Discharge regulations vary from one location to another. For the majority of medium and large SWRO desalination projects in the MENA region the plant discharge configuration is similar – onshore open ocean outfall, which relies on near-shore mixing and dissipation of the concentrate discharge by naturally occurring tidal forces and near-shore currents. For comparison, discharge regulations in many other countries such as South Africa, the United States, Australia, India, and Singapore are measurably different from these in the MENA region and require construction of offshore outfall with diffusers, which is significantly more costly than near-shore discharges.

Many of the SWRO desalination plants worldwide constructed in the past 10 years have solids handling facilities specifically designed to treat the spent filter backwash water from the plant pretreatment system in order to prevent the discharge to the sea of the particulates contained in the source seawater and the chemical coagulant used for their removal. Such solids handling systems typically include lamella sedimentation and mechanical dewatering facilities for removal of the solids generated by the pretreatment system and for their disposal to a sanitary landfill as sludge.

It is important to point out that the installation of solids handling facilities in SWRO desalination plants is becoming a common requirement for new projects in a number of countries in the Gulf Cooperation Council (GCC) region (Qatar, Bahrain, Oman, Kuwait, United Arab Emirates) and in Israel as well as in other parts of the world. Such requirements are already included in discharge regulations in the United States, Europe, and Australia. The construction and operation of such facilities typically contributes 8%–15% of additional costs as compared to the most commonly used method for desalination plant waste – stream management – where the backwash water from the pretreatment system is disposed by blending with the desalination plant concentrate without treatment and the blend is discharged into the sea.

While most countries have a well-developed environmental regulatory framework that aims to minimize the impact of plant discharge on the marine environment, monitoring and ensuring compliance involves costs, and in many instances is difficult to administer, particularly in developing countries, which in most cases lack funds and staff for monitoring of desalination plant compliance with the regulatory requirements, and for imposing penalties for noncompliant parties.

An overview of existing desalination projects worldwide indicates that the recently introduced stringent regulatory requirements in some countries such as Australia, and US states such as California, have yielded desalination projects with the highest costs of water in the 50-year history of desalination of US\$2–US\$5/m^3. Such costs are several times higher than those in the MENA region for example. While complex environmental and renewable energy and carbon footprint mitigation policies are not the only key factors that have caused such dramatic cost differences between desalination projects in MENA and other parts of the world, these policies have a measurable contribution to the overall cost increases.

Actual experience to date shows that the more stringent regulatory requirements in some countries with desalination project and renewable energy-specific regulations such as Australia did not result in the use of desalination and environmental protection technologies different from those already adopted in MENA and never yielded projects where desalination plants were directly coupled with renewable energy generation technologies.

For example, the 218-MLD SWRO desalination project in Al Dur, Bahrain, uses the same state-of-the-art intake, discharge, and desalination technologies as that of the 444-MLD Melbourne desalination plant and it is designed, built, and operated by the same experienced international contractor. However, the cost of water of the Al Dur SWRO plant is several times lower than that of the Melbourne plant. Besides labor market and funding source differences, the main factors contributing to the disparate costs are overly stringent environmental regulations and renewable power use related requirements in Australia.

The main lesson learned from the recent desalination project experience in Australia and California is that as new environmental policies are currently being created focusing specifically on desalination, such new policies and regulations have to be well balanced with the actual benefits to the environment from enforcement of more stringent regulatory requirements and the true costs the society has to pay for such benefits.

2.3.2 Contractor Market Experience and Perception

Over 70% of the medium, large, and mega-size desalination projects worldwide are completed by a dozen international companies that have different experience and perception for the risks and importance of the desalination markets in various regions of the world. Contractor fees for design, construction, and operation of desalination plants in various regional desalination markets are almost always reflective of their past experience and perception for market importance and profit margins.

Market importance is determined by the ability of contractors to complete multiple high-profit margin projects and by their perception for the overall long-term revenue and profit margins a given regional market can yield. In addition, contractor perception of a given market is driven by the potential risks and overhead costs associated with the implementation of projects in this market.

Contractor experience and perception of market importance may have two opposite impacts on the costs of desalination projects – e.g., they may result in a decrease or significant increase of their price as compared to market conditions. In some cases, when a contractor decides to enter into a new market that they consider of great potential for completion of multiple similar projects and high long-term profit margins, the contractor often offers turnkey price for their first project which is significantly below the typical market costs in the region in order to gain a substantial market share.

An opposite trend, where the contractor offers a price that is measurably above market conditions, is when the contractor enters a new market with which they are unfamiliar and they perceive to be a high risk due to lack of successful experience in the region. An example of such a project is the Carlsbad desalination plant in the United States where the main contractor responsible for turnkey project completion was a newcomer to the desalination market and has decided to incorporate a significant safety margin into their price.

This factor along with high labor prices, stringent environmental regulations, and non-government organization (NGO) intervention related cost penalties, resulted in the highest cost desalination project ever built in the Americas. It is interesting to note that the same contractor has offered a project price much closer to the average conditions typical for the local desalination market on their second desalination project in Santa Barbara, California, after they had the opportunity to gain experience with desalination project-related risks and challenges on the Carlsbad project. In both cases of the California projects, however, the profit margin of this market is much higher than the mature desalination market in MENA – large desalination projects are new for California and are therefore considered higher risk and higher reward projects by international contractors as compared to projects in most MENA countries – especially those in GCC.

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3 Cost Estimates – Types and Accuracy

3.1 INTRODUCTORY REMARKS

Four types of desalination project cost estimates (conceptual, preliminary, budgetary, and detailed) are commonly used in engineering practice at present depending on their purpose and the associated level of advancement of project development (see Table 3.1). Because of the specificity of the project conditions, the various levels of accuracy of cost estimates of reported desalination project costs, and the influence of the various cost factors discussed in Chapter 2, the actual costs for desalination projects of the same production capacity could vary widely (Pinto and Marques, 2017). Therefore, understanding the types and accuracy of various cost estimates is of critical importance when comparing the desalination project costs.

3.2 CONCEPTUAL COST ESTIMATE

A conceptual cost estimate is developed during the initial planning/scoping phase of the desalination project and its purpose is to determine an order-of-magnitude value of the project's capital, operation and maintenance (O&M), and water production costs. This type of estimate is typically used for preliminary screening of water supply alternatives; for general cost-of-water comparisons with other existing or planned alternative water supply sources (such as surface water, reclaimed water, brackish or groundwater, etc.); for desalination plant site screening; and for preparation of initial fatal-flaw analysis for a given desalination project.

The conceptual cost estimate is usually prepared without detailed engineering data or comprehensive knowledge of the final project scope and is based on cost-capacity curves available in the literature (Moch, 2002; Watson et al., 2003; MEDRC, 2013; World Bank, 2016) and in Chapters 4 and 5 of this book, or on scale-up or scale-down empirical factors using cost information from existing projects of similar scope, source and product water quality, location, and size.

Often, the conceptual cost estimate is referred to as "incremental budgeting" (Farrell and Cimino, 2003), because this type of estimate for a new desalination project is derived from the cost of existing similar project or projects used as benchmark(s) to which incremental "plus" or "minus" cost factors are applied. A key factor of critical importance in the preparation of an accurate conceptual cost estimate based on "benchmark" project costs is to have a detailed understanding of the scope of the benchmark project(s) and the cost items incorporated in the benchmark project costs.

Because seawater reverse osmosis (SWRO) technology advances at a high rate while conceptual cost budgeting is based on past data, including on projects applying older technology, the use of this cost-estimation technique often leads to conservative

TABLE 3.1
Type and Accuracy of Project Cost Estimates

Estimate Type	Cost Basis	Purpose	Expected Accuracy (Percent of Actual Costs)
Conceptual (incremental budgeting)	• Initial project scope and conceptual design; • Costs of similar projects; • Scale factors; • Cost – plant capacity curves and tables.	• Conceptual planning; • Fatal-flaw analysis; • Project scope definition.	−50 to +100%
Preliminary	• Preliminary project design; • Cost models; • Cost graphs, formulas, and tables for individual treatment processes and equipment.	• Process, technology, and equipment selection; • General evaluations; • Guidance for future investigations.	−30 to +50%
Budgetary	• Advanced project development and design; • Budgetary vendor quotes for key equipment, piping, and facilities; • Cost estimates based on sizing and quantification of construction materials and labor.	• Facility owner budget; • Project authorization.	−15 to +30%
Detailed (zero base budgeting)	• Detailed project design; • Equipment and material specifications and quantification; • Firm vendor quotes/ purchase orders; • Guaranteed subcontractor prices for various activities.	• Preparation of project tender (Bid) price; • Control of project implementation.	−5 to +10%

results and therefore is unsuitable for preparation of competitive or budgetary cost estimates and formal project bid offers.

A very important factor that has to be taken into consideration when preparing conceptual cost estimates based on benchmark projects is to account for the differences associated with the time the two projects are implemented and the currency in which the cost of water, and construction and O&M costs, are presented. The time-related cost differences are mainly due to general inflation and fluctuations in cost of key construction materials (such as steel, lumber, and fuel), labor, equipment, and consumables. Therefore, if old cost curves or benchmark project costs are used to develop conceptual costs for a new project, the time of construction difference of the two projects has to be reflected in the conceptual cost estimate (Bazargan, 2018).

In the United States, inflation and change in construction material costs over time can be reflected in the construction cost estimate for a given project using the Engineering News Record (ENR) construction cost index (CCI). The ENR contains tabular information that allows comparing costs of construction of the same type of projects in various countries, which in turn could be used to further refine the conceptual cost estimate for a new project based on cost information for an overseas benchmark project. The ENR also contains detailed information on cost of key construction materials (i.e., cement, steel, lumber) which allows one to identify mayor cost trends and to forecast potential construction cost changes over the period of project implementation.

There are two types of CCI indexes – one is a nationwide cumulative index and the other type is a regional index provided for 20 individual large US cities and the regions around them. While the nationwide ENR CCI index is suitable for comparing costs of projects in the United States to those in other parts of the world, the city-specific CCI indexes allow one to account for the region-specific impacts on costs such as costs of labor, chemicals, and construction materials in the United States.

Another important factor that has to be taken into consideration when comparing projects is the currency differences and conversion ratios. Many countries experience fluctuations in the currency conversion ratio against the euro, the US$, or the yen. Such currency conversion ratio fluctuations have to be reflected in the preparation of conceptual cost estimates based on benchmark projects.

Usually, desalination project conceptual cost estimates are based mainly on a comparative cost analysis of plants with similar fresh water production capacity and source water salinity only, and therefore are very rudimentary. The level of accuracy of this type of estimate is fairly low (typically between –50% and +100% of the actual costs).

3.3 PRELIMINARY COST ESTIMATE

A preliminary cost estimate is typically used for initial site-specific project cost assessment; for evaluation of alternative treatment processes and equipment; and to define baseline for further investigations. This cost estimate is prepared during the planning stage of the project after the project scope has been clearly defined; the overall treatment approach and key processes, and technologies, have been selected; and the conceptual design of the main plant treatment facilities (i.e., intake, outfall, pretreatment, SWRO system, post-treatment, and product water delivery system) have been completed.

As a minimum, the following project-related information has to be available in order to develop an accurate preliminary cost estimate:

- Average annual, daily average, minimum and maximum SWRO plant production capacities;
- Design plant capacity availability factor;
- Source water quality specification;

- Product water quality specification;
- Plant intake and discharge type, size, and configuration;
- Selection and size of key facilities, equipment, and piping for:
  - Source water pretreatment;
  - SWRO desalination and energy recovery;
  - Product water post-treatment;
  - Concentrate disposal;
  - Solids and liquid waste handling.
- Process flow diagram;
- Preliminary facility layout;
- RO system performance projections;
- Solids mass balance.

A combination of comparative cost analysis with other similar projects, specific treatment processes and equipment, combined with equipment quotes from key vendors and the use of cost models/software are most commonly used to prepare preliminary project cost estimates.

Typically, preliminary cost estimates carry a significant contingency (30% or more) to address a number of site-specific unknown factors such as site soil conditions under the main project structures; plant hydraulics; site-specific costs of construction services, labor, materials; and other site-related costs. Because the preliminary cost estimate is based on actual information for the given project rather than extrapolation of costs from other projects, the accuracy of this estimate is higher than that of the conceptual cost estimate: –30% to +50% of the actual costs.

3.4 BUDGETARY COST ESTIMATE

A budgetary cost estimate is mainly used for authorization of project implementation and for project inclusion into the owner's fiscal planning and budgeting process. In addition to the project information required for preparation of a preliminary cost estimate, the budgetary cost estimate, at a minimum, involves refinement of the project design and cost based on:

- Preliminary geotechnical and hydro-geological investigations;
- Preliminary design of:
  - Key project structures and foundations;
  - Electrical supply system;
  - Instrumentation and control system;
  - Architectural façades and appearance of key buildings;
- Plant hydraulic profile;
- Basic specifications of key equipment and piping, equipment data sheets, and budgetary quotes from vendors;
- Project implementation plan and schedule.

The budgetary cost estimate typically accounts for all key site-specific factors that have measurable (over 10%) influence on project costs. This type of cost estimate usually incorporates 20%–25% of contingency. The accuracy of the budgetary cost estimate is usually within −15% and +30% of the actual project costs.

3.5 DETAILED COST ESTIMATE

This type of cost estimate is prepared during the contractor procurement phase of the project and is often used by both contractors and owners to determine the project tender (bid) contract price, and the most probable project construction, O&M, and water production costs. The preparation of a detailed cost estimate is often referred to as "zero base budgeting" because all key project costs are estimated based on genuine, site-specific estimates rather than on cost comparisons derived from other similar projects or from empirical experience.

Detailed cost estimates are based on:

- Advanced level of project design (30%–50% of design completion);
- Detailed construction survey;
- Detailed geotechnical investigation and soil analysis;
- Comprehensive project implementation schedule;
- Detailed quantification and cost estimates of key construction activities;
- Binding vendor price quotes for all equipment and prefabricated facilities of unit value in excess of US$10,000 including:
  - Source water intake, screening, and pretreatment equipment;
  - RO and pretreatment membranes and cartridge filters;
  - Large pumps;
  - Energy recovery equipment;
  - Stainless steel and large size piping;
  - Construction materials and labor for equipment and facility installation, startup, and commissioning;
  - Automation and control systems;
  - Chemical feed systems;
  - Electrical substations and conduits;
  - Consumables (such as chemicals and power).

The detailed cost estimate typically includes contingency equal to 5%–10% of the total project capital cost. The size of project contingency of this type of cost estimate is usually commensurate with the contractor profit margin, which is based on the fact that the contractor cannot put at risk more than its potential profit from project implementation. Typically, the upper end of the contingency range is used for establishing the not-to-exceed contractor binding project cost offer. The accuracy of this type of cost estimate is between −5% and +10% of the actual costs.

3.6 OVERVIEW OF EXISTING COST MODELS

Currently, there are several models and cost reference tools that can be used for the preparation of preliminary cost estimates for membrane seawater desalination projects. A recent cost estimation program, WTCost©, was developed by the US Bureau of Reclamation (USBR) in April of 2002 (Moch, 2002). This computer model uses Visual Basic and is based on cost curves developed by the US Environmental Protection Agency (USEPA) in 1979 and updated in 2001 as well as an upgraded Excel spread sheet – Water Treatment Estimation Routine (WaTER) developed by the USBR in 1999.

The WTCost model allows one to choose the type of the selected pretreatment system (conventional gravity filters vs. microfiltration [MF] or ultrafiltration [UF] membranes); pretreatment chemicals (coagulants, lime, caustic soda, antiscalant, and powdered activated carbon [PAC]); and the type of the selected salt separation process (RO, ion exchange, or electrodialysis) and can be used for estimating construction, capital, and O&M costs for both seawater and brackish water desalination plants. This cost estimating software program allows users to take into account the selected type of desalination plant intake and discharge, post-treatment technology, and the quality of the source water and the product water.

All input data needed to run the WTCost model – such as source water quality information, power and chemical use and prices, labor costs and rates, construction indexes, and cost of capital – have default values that can be modified by the user. The cost model is membrane supplier neutral and allows one either to use membranes included in the model database or to incorporate a different membrane model and costs. This program was last updated in 2008 (Moch et al., 2008).

Because the unit cost assumptions in the software are relatively old, these assumptions have to be confirmed based on recent projects and updated cost quotes for chemicals, membranes, and other consumables for the region where the desalination project is located.

Another software package that is available for the preparation of preliminary cost estimates is the Desalination Economic Evaluation Program (DEEP), developed by the International Atomic Energy Agency (IAEA). This cost estimating software is available for free download at the IAEA's website (www.iaea.org/NuclearPower/NEA_Desalination/index.html). The DEEP desalination project cost estimating tool can be used for performance and cost evaluation of various power and seawater desalination co-generation configurations.

The first version of the DEEP software was introduced in 1989 (IAEA, 2000) and has been continuously updated since. The latest version of this software, DEEP 5.1, which was released in late 2014, added new features that enhance the financial economic analysis of nuclear desalination plants and introduced a new user-friendly interface. The latest DEEP 5.1 software version provides the following features, which makes it easier to use:

- Detailed cash flow analysis of dual-purpose desalination plants. This analysis is appropriate for use in "bankable" feasibility studies.
- Scenario manager screen, for comparing scenarios and importing/exporting to files.
- All features introduced in previous versions, such as sensitivity analysis and case comparison, have been reworked and optimized for faster and easier access. The default parameters have also been updated to reflect generic cases according to the latest developments.

DEEP is suitable for comparative analysis of different types of power generation plants (steam, gas, combined cycle, and heat-only plants), different fuels (nuclear, oil, coal), and various desalination options including multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO), and hybrid options. It allows users to model alternative turbine configurations, backup heat, intermediate loop, water transport costs, and carbon tax.

A recent study (Al-Bazedi et al., 2016) provides comparative review of the WTCost and DEEP desalination cost models. The study concludes that the two models yield comparable assessment of capital, O&M, and water production costs for SWRO desalination plants with capacity of 100,000 m^3/day or more. For medium size SWRO desalination plants (i.e., plants with capacity between 10,000 and 50,000 m^3/day), the WTCost provides more accurate assessment of the actual project costs. However, the results of the models deviate significantly for small plants (i.e., plants with fresh water production capacity of 1,000 m^3/day or less), where the WTCost software typically produces more conservative cost estimates.

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4 Capital Costs

4.1 INTRODUCTORY REMARKS

Project capital costs can be divided into two broad categories: (1) construction costs (also referred to as "direct capital costs" or "hard project costs") and (2) other project-related capital costs (engineering, development, financing, and contingencies), which are also known as "indirect capital costs" or "soft project costs". A typical breakdown of the direct and indirect capital costs of seawater reverse osmosis (SWRO) desalination projects is presented in Tables 4.1 and 4.2, respectively.

Both tables contain cost ranges for low-complexity and high-complexity projects. Project complexity is determined based on desalination plant size (i.e., fresh water production capacity); source water quality and its variability; type of plant intake; method of disposal of concentrate and other plant waste streams; complexity of permitting regulations governing project implementation; project funding sources and structure. Usually low-complexity projects are:

- Relatively small plants (i.e., projects of production capacity of 20,000 m³/day or less) located in non-environmentally sensitive areas with project-friendly local community;
- Plants with good source water quality: turbidity (measured in nephelometric turbidity units (NTU) and silt density index (SDI) of less than 1; trace levels of organics and bacterial contamination; and very low content of fouling and scaling constituents.
- Plants with subsurface or open intakes, which collect saline source water that is not under the influence of contaminated surface fresh water sources, groundwater aquifers, or waste discharges.
- Plants with simple, low-cost concentrate disposal methods, such as direct sewer or near-shore ocean discharge with suitable environmental conditions that do not require waste stream treatment prior to discharge and construction of complex discharge structures such as long outfalls equipped with diffusers.
- Regulatory environment where the key regulating agencies involved in the project permitting process have experience with similar type and size desalination projects and adequate expertise to complete project environmental review in an expeditious and timely manner.
- Projects that have simple and well-developed funding method and tariff structure where project costs and revenues, and risks and rewards, are well balanced and where the cost of desalinated water is competitive to that of other available water sources.

The construction portion of the capital costs varies with the size and complexity of the individual projects, and typically ranges between 50% and 85% of the total

TABLE 4.1
Breakdown of Direct Capital Costs of SWRO Desalination Projects

Cost Item	Percentage of Total Capital Cost (%) Low-Complexity Project	Percentage of Total Capital Cost (%) High-Complexity Project
Direct Capital (Construction) Costs		
1. Site Preparation, roads, and parking	1.5–2.0	0.5–2.0
2. Intake	4.5–6.0	5.0–6.5
3. Pretreatment	8.5–9.5	7.0–10.0
4. RO system equipment	38.0–40.0	27.5–30.0
5. Post-treatment	1.5–2.5	1.0–2.5
6. Concentrate disposal	2.5–3.5	1.5–2.5
7. Waste and solids handling	1.5–2.5	1.0–2.0
8. Electrical & instrumentation systems	3.5–8.5	2.5–7.0
9. Auxiliary and service equipment and utilities	2.5–3.0	1.0–2.0
10. Buildings	4.5–5.5	2.0–3.5
11. Startup, commissioning, and acceptance testing	1.5–2.5	1.0–2.0
Subtotal-Direct (Construction) Cost (% of Total Capital Cost)	*70.0–85.0*	*50.0–70.0*

capital costs. The indirect (non-construction) portion of the capital cost is usually within 15%–50% of these costs. The cost breakdown brackets presented in Tables 4.1 and 4.2 are based on data from actual seawater desalination projects completed to date, and encompass the most frequently encountered conditions associated with project implementation.

It should be pointed out that brackish water desalination plants have different breakdown of the same capital cost components. Tables 4.3 and 4.4 provide such breakdown for low- and high-salinity brackish water reverse osmosis (BWRO) desalination projects. As indicated in Chapter 1, low- and high-salinity brackish water desalination plants are typically designed to treat water of total dissolved solids (TDS) concentration between 500 and 2,500 mg/L, and between 2,500 and 10,000 mg/L, respectively.

If the site-specific conditions of a given individual project differ significantly from those encountered in desalination projects completed worldwide over the past 10 years, the actual cost breakdown for this project may be outside the cost brackets presented in Tables 4.1 through 4.4. These tables should be used for preparation of conceptual cost estimates only and are intended to reflect current market conditions for the individual cost items. With the advancement of membrane technology and maturing of the markets involved in funding and serving the development, construction, and operation of desalination projects, the ratios between the individual cost items are expected to change over time. Gradual changes are expected every 2–5 years. A more dramatic change is likely within a 10-year time frame.

TABLE 4.2
Breakdown of Indirect and Total Capital Costs of SWRO Desalination Projects

	Percentage of Total Capital Cost (%)	
Cost Item	**Low-Complexity Project**	**High-Complexity Project**
Project Engineering Services		
12. Preliminary engineering	0.5–1.0	1.0–2.0
13. Pilot testing	0.0–0.5	0.5–1.5
14. Detailed design	3.5–4.5	5.0–7.0
15. Construction management and oversight	1.0–2.0	2.5–4.5
Subtotal-Engineering Services	*5.0–8.0*	*9.0–15.0*
Project Development		
16. Administration, contracting and management	1.0–1.5	2.0–3.0
17. Environmental permitting (licensing)	0.5–3.5	3.5–5.0
18. Legal services	0.5–1.0	1.0–2.0
Subtotal-Project Development	*2.0–6.0*	*6.5–10.0*
Project Financing Costs		
19. Interest during construction	0.5–2.5	3.0–4.5
20. Debt service reserve	2.0–5.5	4.5–6.5
21. Other financing costs	0.5–1.0	2.0–4.0
Subtotal-Project Financing	*3.0–9.0*	*9.5–15.0*
22. Contingency	5.0–7.0	5.0–10.0
Subtotal-Indirect Capital Cost (% of Total Capital Cost)	*15.0–30.0*	*30.0–50.0*
Total Capital Cost	100	100

4.2 CONSTRUCTION COSTS

4.2.1 Site Preparation, Roads, and Parking-Related Construction Costs

Site-related construction costs include expenditures for land acquisition and for site preparation for construction (clearing, grubbing, fill, grading, and fencing), as well as costs for construction of access roads to the desalination plant and to all buildings, facilities, and equipment within the desalination plant. The cost of land, the expenditures for site clearing, soil contamination mitigation, and dewatering, as well as the cost and length of access roads, are very site specific and could vary significantly from one location to another.

The land requirements for a typical desalination plant are summarized in Table 4.5. The plant site size information in this table is based on actual information from 70 SWRO plants constructed over the past 15 years. This table can be used for initial planning of both brackish and seawater desalination projects. However,

TABLE 4.3
Breakdown of Direct Capital Costs of BWRO Desalination Projects

Cost Item	Percentage of Total Capital Cost (%) Low-Salinity BWRO Project	Percentage of Total Capital Cost (%) High-Salinity BWRO Project
Direct Capital (Construction) Costs		
1. Site preparation, roads, and parking	0.5–1.5	0.5–1.0
2. Intake	16.0–25.0	8.0–14.0
3. Pretreatment	0.7–2.0	0.5–1.5
4. RO system equipment	30.0–35.0	34.0–40.0
5. Post-treatment	0.5–2.0	1.0–1.5
6. Concentrate disposal	0.2–1.0	0.2–2.7
7. Waste and solids handling	0.1–0.5	0.3–0.8
8. Electrical & instrumentation systems	5.0–8.5	6.5–10.5
9. Auxiliary equipment and utilities	1.5–2.5	1.0–2.0
10. Buildings	4.5–5.5	2.0–4.0
11. Startup, commissioning, and acceptance testing	1.0–1.5	1.0–2.0
Subtotal-Direct (Construction) Cost (% of Total Capital Cost)	*60.0–85.0*	*55.0–80.0*

it should be pointed out that, in general, brackish desalination plants would require 10%–15% less land than seawater desalination plants of the same fresh water production capacity, mainly because of their simplified pretreatment facilities and smaller size of the RO trains. On the other hand, many BWRO plants have post-treatment facilities for hydrogen sulfite gas removal, which typically are not needed for SWRO desalination.

In general the plant site preparation, roads, and parking-related construction costs are in a range of US\$10–US\$30/m³/day of plant production capacity. It should be noted that the information presented in Table 4.5 is developed based on information from actual projects reflective of typical configurations and layouts of the treatment facilities.

If the selected plant site has size constraints, the plant design and configuration could be optimized for more compact layout, which could be 30%–50% smaller than the typical plant size requirements presented in Table 4.5. For example, the 200,000 m^3/day Carlsbad SWRO desalination plant has a total plant site size of 25,600 m^2 (see Figure 4.1), while the typical plant site requirement for such size SWRO plant based on information in Table 4.5 is 36,400–48,600 m^2.

4.2.2 INTAKE CONSTRUCTION COSTS

The intake construction costs include expenditures for plant saline water intake structures (intake towers, wells, onshore forebays, etc.) and pipeline, intake pump station, and associated coarse and fine screening facilities. These costs vary depending on the

TABLE 4.4
Breakdown of Indirect and Total Capital Costs of BWRO Desalination Projects

Cost Item	Percentage of Total Capital Cost (%) Low-Salinity BWRO Project	Percentage of Total Capital Cost (%) High-Salinity BWRO Project
Project Engineering Services		
12. Preliminary engineering	0.5–1.5	0.5–2.0
13. Pilot testing	0.0–1.0	0.0–1.5
14. Detailed design	2.0–6.0	4.5–8.0
15. Construction management and oversight	1.5–2.5	2.0–3.5
Subtotal-Engineering Services	*4.0–11.0*	*7.0–15.0*
Project Development		
16. Administration, contracting, and management	1.0–2.0	1.0–2.5
17. Environmental permitting (licensing)	0.5–5.5	1.0–4.0
18. Legal services	0.5–3.5	0.5–3.5
Subtotal-Project Development	*2.0–11.0*	*2.5–10.0*
Project Financing Costs		
19. Interest during construction	1.0–3.0	1.5–3.0
20. Debt service reserve	1.5–6.0	2.5–5.0
21. Other financing costs	0.5–1.0	0.5–1.0
Subtotal-Project Financing	*4.0–10.0*	*4.5–10.0*
22. Contingency	5.0–8.0	6.0–10.0
Subtotal-Indirect Capital Cost (% of Total Capital Cost)	*15.0–40.0*	*20.0–45.0*
Total Capital Cost	100	100

type of source seawater intake – open (onshore or offshore) or subsurface (vertical beach wells, horizontal directionally drilled [HDD] wells or Raney-type wells).

4.2.2.1 Construction Costs of Open Onshore Intakes

Figure 4.2 provides a budgetary estimate for the construction costs of onshore intakes as a function of the desalination plant's intake flow. Because of the significant impact of the site-specific condition of the actual intake costs, such costs may vary within 30% above or below the values indicated in Figure 4.2.

4.2.2.2 Construction Costs of Open Offshore Intakes

The construction costs graphed in Figure 4.3 are for intake systems with offshore inlet structures (intake towers) and high-density polyethylene (HDPE) pipelines and for intake towers with concrete tunnels. These costs are presented as a function of the plant intake flow and are expressed in dollars per meter of intake conduit.

Similar to the construction costs of onshore intakes, these costs will vary from one location to another; based on site-specific conditions such as water depth, geology, and currents, they could be within a 30% envelope of the values

TABLE 4.5
Seawater Desalination Plant Land Requirements

	Typical Plant Site Land Requirements	
Plant Capacity (m³/day)	**m²**	**Acres**
1,000	800–1,600	0.2–0.4
5,000	2,000–3,200	0.6–0.8
10,000	4,500–6,100	1.1–1.5
20,000	10,100–14,200	2.5–3.5
40,000	18,200–24,300	4.5–6.0
80,000	22,200–30,500	5.5–7.5
100,000	26,300–34,400	6.5–8.5
150,000	33,000–42,000	8.0–10.0
200,000	36,400–48,600	9.0–12.0
300,000	58,700–83,000	14.5–20.5
400,000	81,000–100,000	20.0–25.0

Note: Land requirements based on conventional plant layout. Compact plants may require less surface area.

FIGURE 4.1 Aerial view of the 200-MLD Carlsbad SWRO desalination plant.

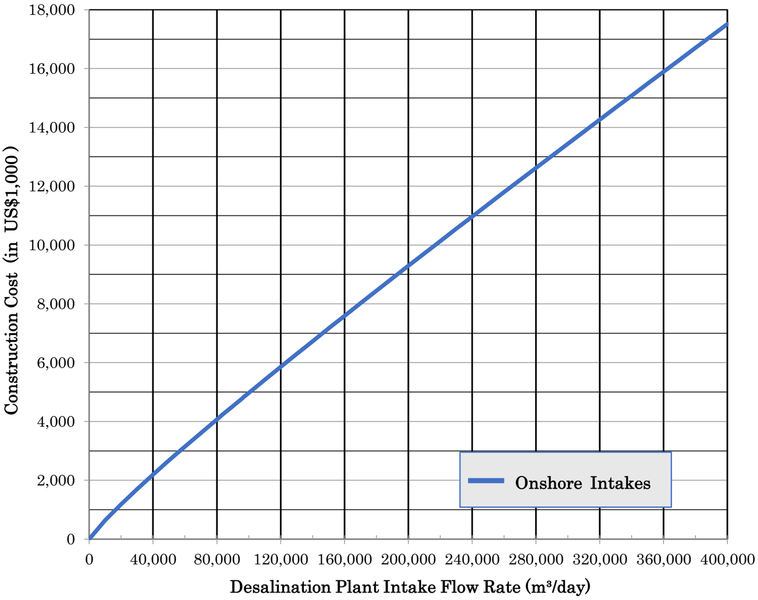

FIGURE 4.2 Construction cost for open onshore intakes.

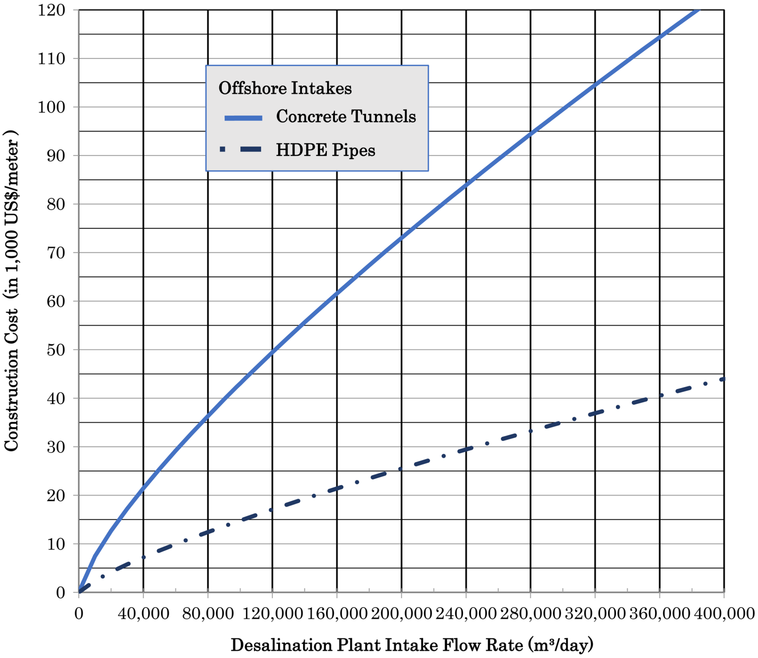

FIGURE 4.3 Construction cost for open offshore intakes.

indicated in Figure 4.3. Analysis of this figure indicates that the construction of desalination plant intakes with deep tunnels is typically several times costlier than the installation of one or more HDPE pipelines on the bottom of the source water body.

4.2.2.3 Construction Costs of Subsurface Intakes

Table 4.6 summarizes the typical productivity and construction costs of alternative types of subsurface intakes that have found implementation for desalination projects. As seen from this table, the construction costs for HDD wells and Ranney wells are typically 20%–30% higher than these of vertical wells for the same capacity, while infiltration galleries are usually the most costly type of subsurface intakes.

The vertical intake wells are usually less costly than the horizontal wells but their yield is relatively small (0.1–3.5 MLD) and, therefore, vertical wells are typically used for supplying relatively small quantities of water (usually less than 20,000 m^3/day). Table 4.7 provides construction costs for vertical intake wells as a function of their depth and intake plant flow for diameters ranging between 100 and 400 mm (4 and 16 inches).

TABLE 4.6

Costs of Alternative Subsurface Intakes

Well Type	Typical Production Capacity (Yield) of Individual Well (MLD)	Cost of Individual Well (US$ million)
Vertical wells	0.1–3.5	0.2–1.5
Horizontal radial collector wells	0.5–20.0	1.3–6.0
Slant wells	0.5–10.0	0.8–2.8
HDD wells (e.g., neodren)	0.1–5.0	0.4–2.0
Infiltration galleries	0.1–50.0	0.5–27.0

MLD, 1,000 m^3/day.

TABLE 4.7

Construction Costs of Vertical Intake Wells

Intake Well Production Capacity (m^3/day)	Construction Costs as a Function of Well Intake Flow, Q (m^3/day) and Well Depth, H (m)
1,000–2,000	$42\,Q + 730\,H + 26{,}000$
2,000–4,500	$52\,Q + 900\,H + 52{,}000$
4,500–6,500	$68\,Q + 1{,}150\,H + 80{,}000$
6,500–10,000	$80\,Q + 2{,}100\,H + 155{,}000$
10,000–15,000	$88\,Q + 2{,}200\,H + 200{,}000$
15,000–30,000	$94\,Q + 3{,}400\,H + 270{,}000$

The costs listed in Table 4.7 do not include expenditures associated with the construction of ground water monitoring wells for the well field, and piping for delivery of the source water to the desalination plant. However, these costs incorporate the capital expenditures for the intake well pumps and auxiliary equipment associated with pump operations (i.e., electrical and instrumentation, civil works, etc.).

The predominant type of subsurface intakes used for both brackish water and SWRO desalination plants are the shallow vertical wells. Typically, the lowest cost open seawater desalination plant intake is that collocated with the discharge of an existing coastal power plant, which uses seawater for cooling. The collocated desalination plant taps into the power plant discharge to collect source seawater. This collocation approach allows avoiding construction of new desalination plant intake structure, pipeline, and screens, which reduces approximately 60%–80% of the total intake construction expenditures. Other advantages of collocation are discussed elsewhere (Voutchkov, 2011).

Vertical beach wells are often very cost-competitive intake facilities as compared to open ocean intakes. However their cost advantages and practical applicability are usually limited to small and medium size SWRO plants (Voutchkov, 2004a,b). The installation of HDD wells for large size facilities may prove beneficial for favorable coastal aquifer soil conditions (e.g., limestone) where the HDD wells can collect high-quality seawater at a rate that can be sustained over the useful life of the project. The main challenge with using intake wells is maintaining their production capacity and water quality over time. Practical experience shows that often intake wells have useful life of 10–15 years only, while the useful life of open ocean intakes typically extends to 50 years or more.

4.2.2.4 Construction Costs of Intake Pump Stations

A cost graph for intake pump stations with wet-well and dry-well configurations is presented in Figure 4.4. Construction costs are depicted as a function of the desalination plant intake flow. The cost estimate does not include the expenditures for intake screens, intake structure, or piping interconnecting the pump station and the downstream pretreatment facilities.

Additional information on comparisons of alternative source water intakes and screening facilities is provided in other sources (Watson et al., 2003; Mackey et al., 2011; Voutchkov, 2013). Usually, the total intake construction costs for SWRO desalination plants are in a range of between US$90 and US$120/m^3/day.

4.2.3 PRETREATMENT CONSTRUCTION COSTS

Pretreatment construction costs include expenditures for removal of particulate, colloidal, scaling, and organic contaminants in the seawater that may impact normal operation of the RO membrane separation process and cause accelerated membrane fouling and/or premature replacement. The magnitude of these costs depends mostly on the content of solids (turbidity/total suspended solids); biodegradable organics and non-organic membrane fouling compounds in the source water; and the selected type of pretreatment technologies and equipment needed for their effective removal.

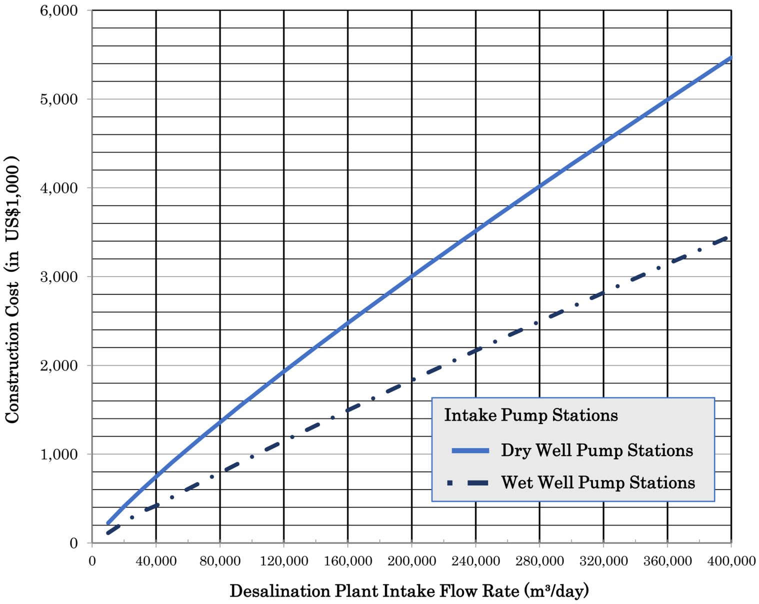

FIGURE 4.4 Construction cost for intake pump stations.

The pretreatment process may involve physical removal of contaminants by coarse and fine screening and microscreening; grit separation; sedimentation; dissolved air flotation; granular media or membrane filtration, as well as chemical conditioning of the source water to prevent non-organic scale formation (addition of antiscalants); membrane biofouling (biocides and UV irradiation); enhanced boron removal (by pH adjustment); and for improved solids removal by source seawater conditioning with coagulants, acid, and flocculants.

Because of the significant difference in the quality of the saline source water from one project location to another and in the variety of available pretreatment technologies and equipment for solids and organics removal, and chemical conditioning, the costs associated with source water pretreatment may vary significantly. Typically, the construction costs for pretreatment of seawater for RO desalination vary in a range of US$150–US$230/m³/day. Detailed discussion of the areas of application, performance, and cost differences of alternative pretreatment systems is presented elsewhere (Voutchkov, 2017).

4.2.3.1 Construction Costs of Band and Drum Screens

The graph presented in Figure 4.5 provides budgetary cost estimates for band and drum screens as a function of the desalination plant's feed water flow. As shown in this figure, band screens are generally less costly than drum screens for projects of the same size.

While drum and band screens are pretreatment facilities for removal of particulate solids from the source water, they are located upstream of the intake pumps and, therefore, in cost estimates the equipment and installation costs of these facilities are incorporated into the construction cost of the intake pump station.

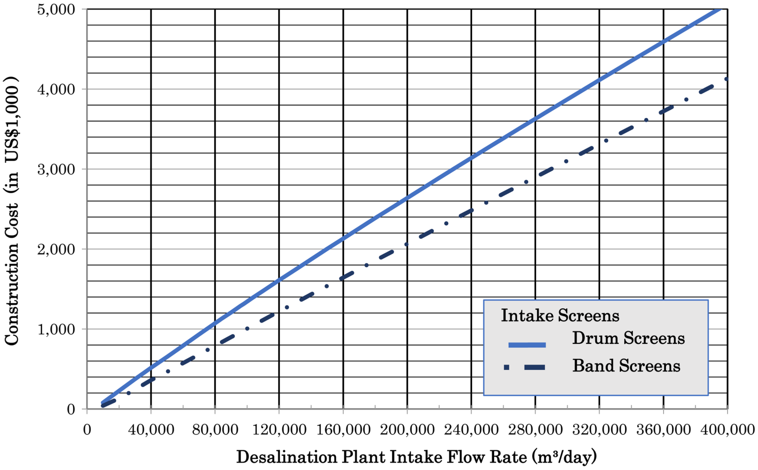

FIGURE 4.5 Construction cost for drum and band intake screens.

4.2.3.2 Construction Costs of Wedge Wire Screens

Figure 4.6 presents a graph of the costs of wedge wire screens as a function of the plant's source water flow. This type of screening technology has been receiving wider acceptance and use in the past 10 years because of its relatively lower construction cost as compared to other commonly used screening equipment such as band and drum screens. The construction of offshore intake with wedge wire screens instead of intake towers eliminates the need for additional screening of the source water upstream of the intake pumps, which simplifies the design of the intake pump station and reduces its construction and operation and maintenance (O&M) costs.

While wedge wire screens serve pretreatment function (i.e., screening of coarse and fine residue in the source water), their construction cost is typically incorporated into the cost of the intake system, rather than the pretreatment system.

4.2.3.3 Construction Costs of Microscreens

Figure 4.7 shows a budgetary construction cost graph for microscreening systems as a function of the intake flow they are designed to process. Microscreens (e.g., self-cleaning strainers and disk filters) are typically installed downstream of the desalination plant intake facilities and are widely used in SWRO desalination plants if membrane pretreatment is selected to protect the ultrafiltration (UF) or microfiltration (MF) membranes selected for pretreatment from loss of integrity due to punctures caused by fine sharp objects in the water (e.g., shell particles). Strainers are also used in BWRO desalination plants to remove sand from the source water.

Typically, in construction cost estimates the expenditures for the microscreening system are incorporated into the pretreatment cost of the membrane filtration system or accounted for separately. In SWRO desalination plants, microscreens are used exclusively as pretreatment equipment upstream of the UF or MF membrane filtration system. Performance and integrity of granular media filtration systems are not

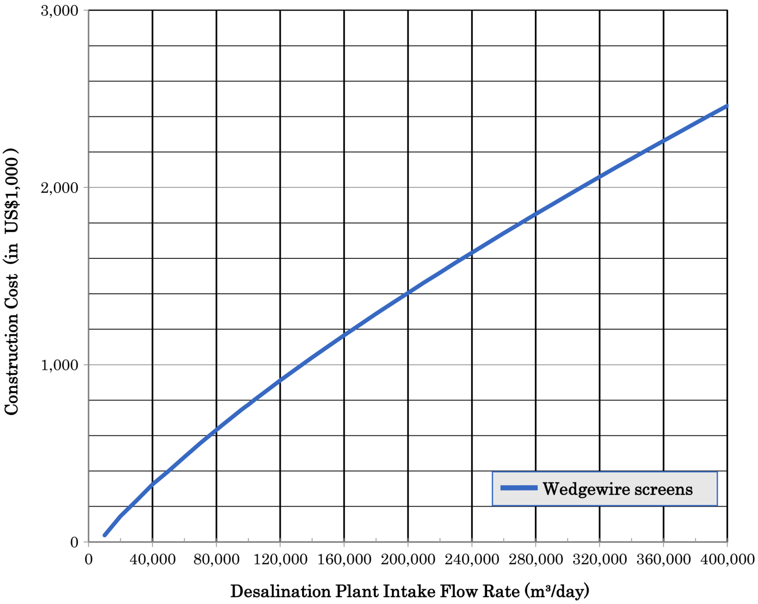

FIGURE 4.6 Construction cost for wedge wire intake screens.

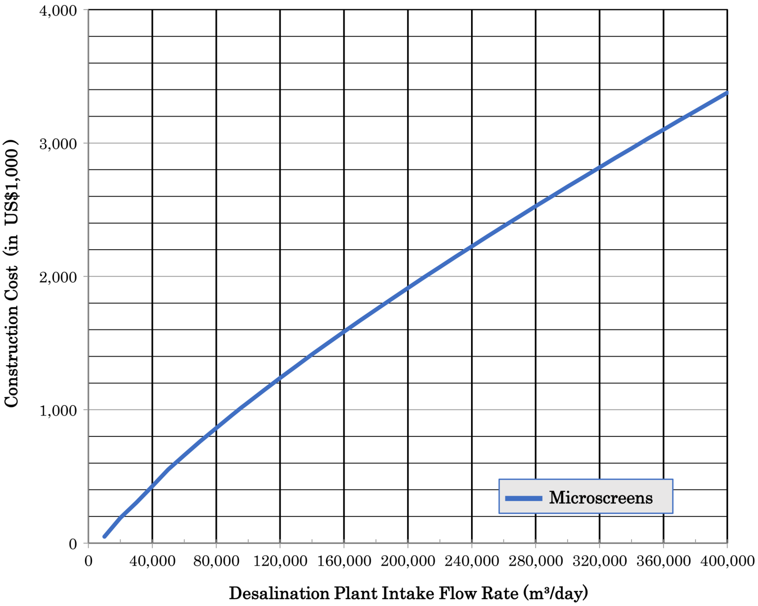

FIGURE 4.7 Construction cost of microscreening system.

sensitive to the content of sharp objects in the source water and, therefore, microscreens are not needed if this type of filter is used for pretreatment.

4.2.3.4 Construction Costs of Lamella Settlers and DAF Clarifiers

Lamella settlers are usually used upstream of granular media filters and membrane filters when the saline source water has daily average turbidity higher than 30 NTU or experiences turbidity spikes of 50 NTU or more that continue for a period of at least several hours. If sedimentation basins are not provided, large turbidity spikes may cause the downstream pretreatment filters to exceed their solids holding capacity which in turn would reduce the duration of the filter runs and the ability of the pretreatment system to provide adequate volume of filtered water to the RO system and ultimately would result in reduction of desalination plant fresh water production capacity.

Dissolved air flotation (DAF) technology is typically used when the saline source water contains large amount (usually over 5 NTU) of floating particulate foulants such as algal cells; over 0.01 mg/L of oil or grease; or more than 0.02 mg/L of total hydrocarbons or other contaminants that cannot be effectively removed by sedimentation or filtration. If well selected and designed, DAF systems can produce effluent turbidity of <0.5 NTU and prevent downstream pretreatment and RO systems from heavy fouling.

DAF process uses very small-size air bubbles to float light particles and organic substances (oil, grease) contained in the source water. The floated solids are collected at the top of the DAF tank and skimmed off for disposal, while the low-turbidity source water is collected near the bottom of the tank.

Figure 4.8 depicts the construction costs of lamella settlers and DAF clarifiers as a function of the plant intake flow. As indicated on this figure, lamella settlers are less costly than DAF clarifiers for the same volume of pretreated source water. The DAF clarifiers can remove both suspended solids and floatable objects but they are not very efficient if the solids have limited floatability.

4.2.3.5 Construction Costs of Granular Media Pretreatment Filters

Figure 4.9 presents the construction costs for granular media gravity and pressure filters as a function of the desalination plant intake flow they process. As seen from this figure, pressure filters have a lower cost than gravity filters for the same daily volume of pretreated saline source water. However, pressure filters are not suitable to handle source water turbidity of 10 NTU or higher, and during algal blooms cause significant algal cell breakage, release of organics from the broken cells, and accelerated fouling of the downstream SWRO membrane systems. Therefore, while more costly to build, gravity granular media filers are often preferred over pressure filters for pretreatment of seawater collected from shallow open intake, if the intake is exposed to prolonged algal bloom events, heavy rains, or agricultural runoff.

4.2.3.6 Construction Costs of Membrane Pretreatment Filters

The construction costs for membrane pretreatment are difficult to determine based on existing projects because of the relatively limited track record of this type of pretreatment as compared to granular media filtration, and also because of the

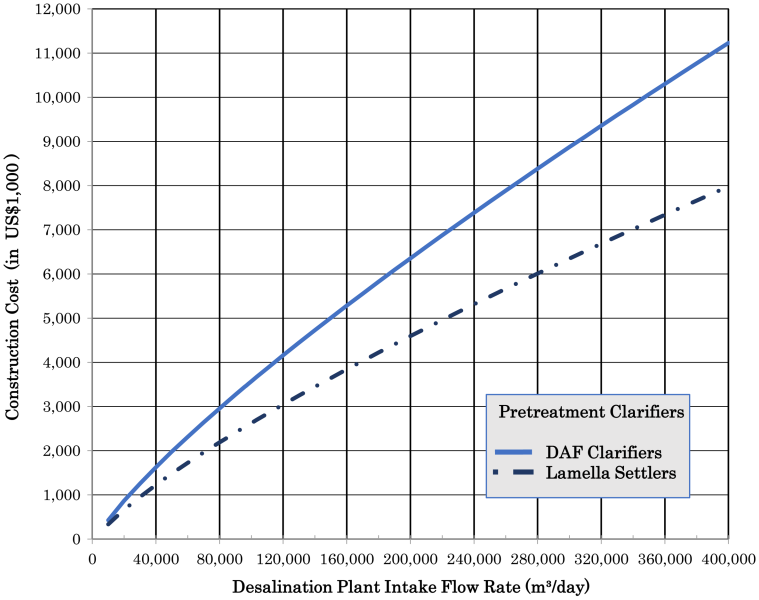

FIGURE 4.8 Construction cost for DAF clarifiers and lamella settlers.

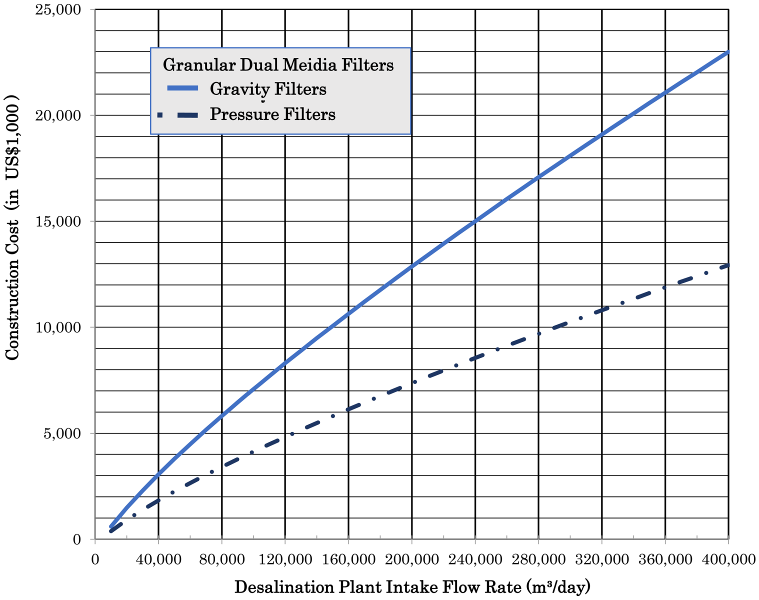

FIGURE 4.9 Construction cost for granular dual media filters.

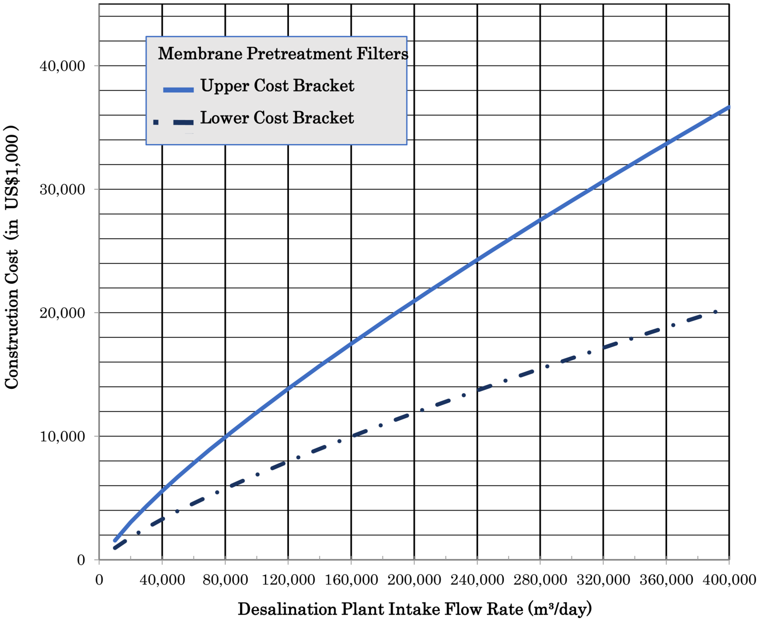

FIGURE 4.10 Construction cost for membrane pretreatment filters.

diversity of membrane products and configurations presently available on the market. Therefore, rather than a single cost curve, Figure 4.10 presents a range of construction costs for membrane pretreatment for desalination plants as a function of the plant intake flow rate.

4.2.3.7 Construction Costs of Cartridge Filter System

A budgetary construction cost graph of a cartridge filtration system is presented in Figure 4.11. Cartridge filters are usually installed downstream of granular media filters and upstream of the SWRO desalination trains to capture fine particulate solids that could accidentally be released from the filters and protect the RO membranes from accelerated fouling.

Many of the membrane pretreatment systems installed over the past 10 years do not have cartridge filters downstream of the pretreatment membranes because it is assumed that these membranes will capture all fine particulate solids in the source water. Practical experience shows that such assumption is not always commensurate with reality, especially if the fibers of the pretreatment membranes selected by the project designer are made of weak material and the membrane fibers break easily and frequently.

4.2.4 RO SYSTEM EQUIPMENT COSTS

This cost item includes the expenditures associated with the procurement, purchase, installation, and construction of the following facilities and equipment:

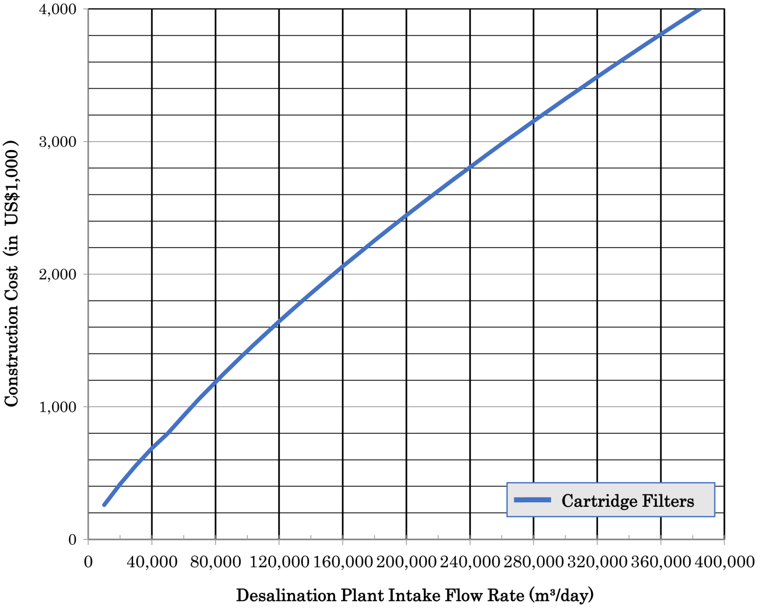

FIGURE 4.11 Construction cost of cartridge filtration systems.

- Cartridge filters;
- High-pressure pumps and motors to feed the RO system;
- Energy recovery system;
- RO pressure membrane vessels and racks;
- SWRO membrane elements;
- Membrane cleaning system;
- Membrane flush system;
- Interconnecting piping.

The costs of key membrane SWRO system components are summarized in Table 4.8.

Approximately 10%–20% has to be added to the costs shown in Table 4.8 for shipping, handling, installation oversight, and insurance. The cost of the membrane RO modules (trains) is proportional to the design capacity and flux of the SWRO system. Typically, one SWRO module contains 50–200 membrane vessels with 7 elements per vessel and has capacity between 100 to 25,000 m³/day.

While there is limited economy of scale in terms of the costs of the RO membranes and vessels, the costs of the other RO system components (high-pressure pumps, energy recovery devices, stainless steel piping, and valves) can benefit significantly from the use of larger size units. For example, the high-pressure feed pump efficiency and cost improves with the increase of pump size, and the economy of scale between two sizes of stainless steel pipe is usually 10%–15%. Therefore, as the RO membrane module size increases, the relative cost of the SWRO system per unit volume of produced permeate decreases.

TABLE 4.8
Construction Cost of Key Membrane SWRO System Components

Item	Construction Cost (US$/Item or as Indicated)
8-inch SWRO membrane elements	US$400–US$600/element
16-inch SWRO membrane elements	US$2,900–US$3,400/element
8-inch brackish RO membrane elements	US$300–US$400/element
SWRO pressure vessels for 8-inch elements	US$1,400–US$1,800/vessel
SWRO pressure vessels for 16-inch elements	US$3,700–US$5,200/vessel
Brackish RO pressure vessels for 8-inch elements	US$1,100–US$1,400/vessel
RO train piping	US$260,000–US$620,000/RO train
RO train support frame	US$160,000–US$360,000/RO train
RO train instrumentation and controls	US$32,000–US$110,000/RO train
High-pressure pumps	US$160,000–US$2,500,000/RO train

Note: All costs in year 2018 US$.

There are two limitations of the maximum size of the membrane train (module) – system reliability and the available off-the-shelf equipment and RO membranes that can be used to build a very large module. The main limiting factor for using large size RO membrane trains is the loss of production capacity when one or more RO trains are shut down for membrane cleaning or replacement, or for equipment and piping repairs. The larger the individual RO train, the greater the potential loss of plant fresh water production capacity, and therefore the lower the plant capacity availability factor. Since the availability factor is directly related to the cost of water, a SWRO system with lower availability factor yields higher cost of water.

Another factor that limits the benefits of constructing very large SWRO trains is the need to use custom-made rather than off-the-shelf equipment (mainly high-pressure pumps, motors, and energy recovery devices). Although the manufacturing of this equipment is possible, the one-time custom design and production of such equipment is significantly more costly than the use of standard off-the-shelf equipment with well-known production costs, performance parameters, and proven track record. Therefore, in such applications, often the gain of the economy of scale due to the use of large custom-made equipment and trains is negated by the additional expenditures for equipment production and risks associated with the lack of long-term track record of equipment performance.

The introduction of large-diameter (16–19 inch) RO membranes and pressure vessels in 2006 has increased the envelope of the maximum size RO trains that can be used for seawater desalination.

The SWRO system is the most complex portion of the desalination plant and usually contributes 40%–60% of the total plant construction costs. The design and construction costs of this system are mainly influenced by the source water salinity and temperature, and by the target product water quality the system is designed to yield. The construction cost of the SWRO system is predominantly determined by the cost of the membrane vessels and racks, high-pressure pumps, and piping;

cost of the energy recovery system; and the price of the SWRO membrane elements. Typically, the SWRO system construction cost varies between US$450 and US$520/m³/day.

The most common SWRO systems used in municipal membrane desalination plants at present have one of the following: single-pass RO; full two-pass RO; or split-partial two-pass RO configuration. A brief description and construction cost curve for each of these SWRO system configurations are presented below.

It should be pointed out that the cost graphs are developed for source seawater of two different salinities (35,000 and 46,000 mg/L) in order to reflect the entire potential cost range of SWRO systems with such configurations. The construction cost of the SWRO system with feed water TDS concentration of 35,000 mg/L is determined for design recovery of 50% and membrane flux of 13–14 Lmh. The SWRO system with feed seawater salinity of 46,000 mg/L has design recovery of 45% and membrane flux of 10–12 Lmh. The full and the split-partial second pass of the two-pass RO membrane systems is designed for 90% recovery and membrane flux of 25 Lmh and has two stages. Both stages of the second pass are equipped with the same model of high-rejection BWRO membranes. The design criteria for the three SWRO system configurations were selected to reflect those most commonly used in practice at present.

4.2.4.1 Construction Costs for Single-Pass SWRO Systems

Single-stage SWRO systems are designed to produce desalinated seawater (permeate) in one step using only a single set of RO trains operating in parallel. Under a typical single-stage SWRO system configuration, each RO train has a dedicated system of transfer pump for pretreated seawater followed by a high-pressure RO feed pump. The high-pressure feed pump motor/operation is coupled with that of energy recovery equipment (see Figure 4.12).

Single-stage SWRO systems are widely used for production of desalinated water. However, these systems have product water quality limitations. Even if using the highest-rejection RO membrane elements commercially available today (nominal minimum rejection of 99.85%), the single-stage SWRO desalination systems typically cannot consistently yield permeate with TDS concentration lower than 200 mg/L, chloride level of less than 100 mg/L, and boron concentration lower than 0.5 mg/L, especially when source water temperatures exceed 18–20°C. If enhanced

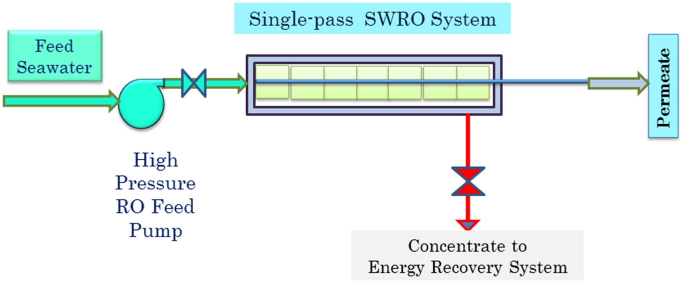

FIGURE 4.12 Schematic of single-pass SWRO system.

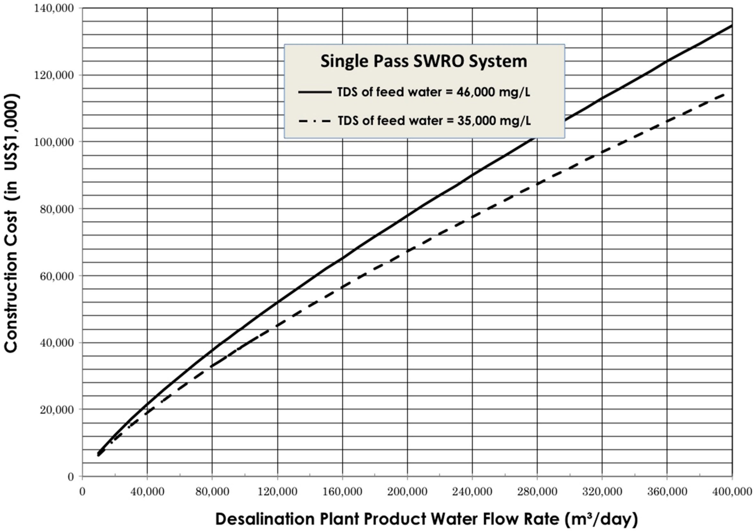

FIGURE 4.13 Construction cost for single-pass SWRO system.

boron removal is needed in such systems, high boron rejection membranes are used, and/or sodium hydroxide and antiscalant is added to the RO system feed water to increase pH to 8.8 or more, which in turn improves boron rejection. Figure 4.13 presents the construction cost curves for single-pass SWRO systems designed for source water salinities of 35,000 and 46,000 mg/L, respectively.

4.2.4.2 Construction Costs for Full Two-Pass SWRO Systems

Two-pass SWRO systems are typically used when either the source seawater salinity is relatively high (e.g., exceeds 35,000 mg/L) and/or the product water quality requirements are very stringent. For example, if high-salinity/high-temperature source water (such as Red Sea and Arabian Gulf seawater) is used in combination with standard-rejection (99.6%–99.8%) SWRO membranes, then single-stage SWRO systems may not be able to produce permeate suitable for drinking water use. In this case, two-pass SWRO systems are applied for potable water production. RO systems with two or more passes are also widely used for production of high-purity industrial water.

The two-pass SWRO systems typically consist of a combination of a single-pass SWRO system and a single or multiple-stage brackish water RO (BWRO) system connected in series. Permeate from the SWRO system (i.e., first pass) is directed for further treatment to the BWRO system (i.e., second pass) to produce a high-quality TDS permeate. The concentrate from the second-pass BWRO system is returned to the feed of the first-pass SWRO system to maximize the overall desalination system production capacity and efficiency. Two-pass SWRO systems are classified in two main groups: full two-pass systems and split-partial two-pass systems.

In full two-pass SWRO membrane systems (see Figure 4.14), the source seawater is first treated by a set SWRO membrane trains (referred to as first RO pass) and then

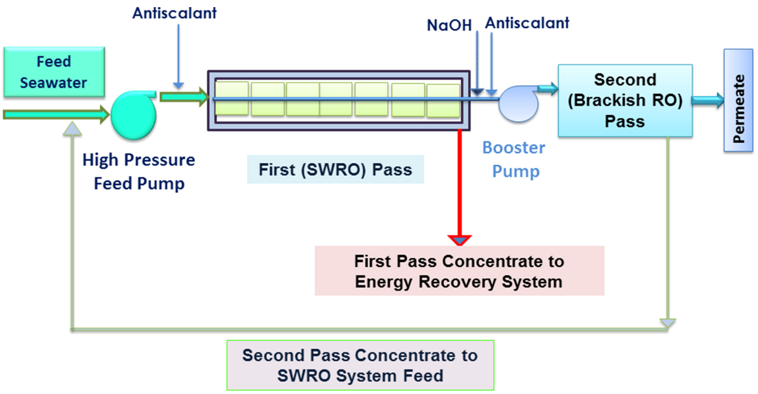

FIGURE 4.14 Schematic of full two-pass SWRO system.

the entire volume of desalinated water from the first pass is processed through a second set of brackish water desalination membrane trains. If enhanced boron removal is needed, sodium hydroxide and antiscalant are added to the feed permeate of the second RO pass to increase pH and improve boron rejection. Full two-pass desalination systems can employ either the same elements throughout the entire vessel or internally staged membrane configuration within the vessels.

Figure 4.15 depicts the construction cost for full two-pass SWRO system determined at two source water salinities – 35,000 and 46,000 mg/L. The cost estimate includes the equipment and construction expenditures for the sodium hydroxide and antiscalant systems shown in Figure 4.14.

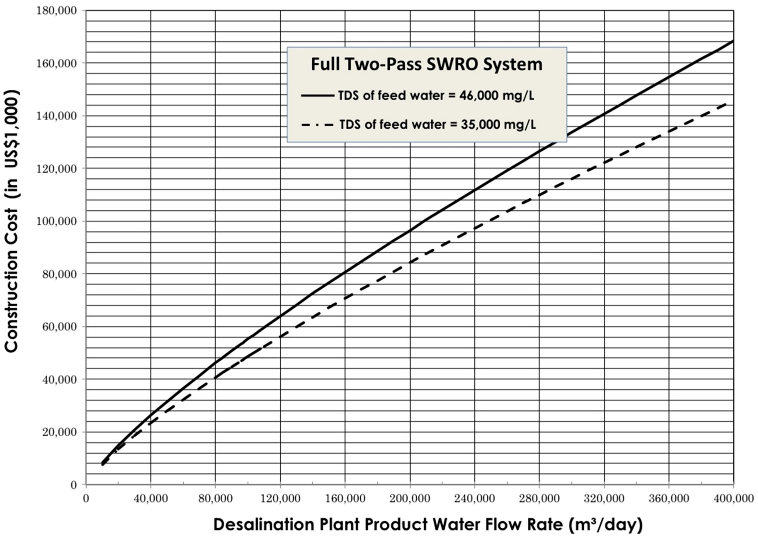

FIGURE 4.15 Construction cost for full two-pass SWRO system.

4.2.4.3 Construction Costs for Split-Partial Two-Pass SWRO Systems

In split-partial two-pass systems the second RO pass typically processes only a portion (50%–75%) of the permeate generated by the first pass. The rest of the low-salinity permeate is produced by the front (feed) SWRO elements of the first pass. This low-salinity permeate is collected and without additional desalination it is directly blended with permeate produced by the second RO pass (see Figure 4.16).

As depicted in Figure 4.16, the second-pass concentrate is returned to the feed of the first RO system pass. When the desalination system is designed for enhanced boron removal, this concentrate will have pH of 9.5 to 11 and potentially could cause precipitation of calcium carbonate on the membranes. In order to avoid this challenge, typically antiscalant is added to the feed of the partial second-pass (brackish RO) system.

While the recycling of the second-pass concentrate returns a small portion of the source water salinity and, therefore, it slightly increases the salinity of the seawater fed to the first RO pass, the energy use associated with this incremental salinity increase is significantly smaller than the energy savings from processing only a portion (25%–50%) of the volume of the first-pass permeate through the second pass.

Under the split-partial two-pass configuration the volume of permeate pumped to the second RO pass and the size of this pass are typically 20%–50% smaller than the volume pumped to the second RO pass under conventional once-through operation. Since pumping energy is directly proportional to flow, the energy costs for the second-pass feed pumps are reduced proportionally, i.e., with 20%–50%.

For an SWRO system operating at 45% recovery, such savings will amount to 14%–22% of the energy of the first-pass RO pump. The concentrate returned from the second pass carries only 1%–2% of additional salinity to the first-pass RO feed,

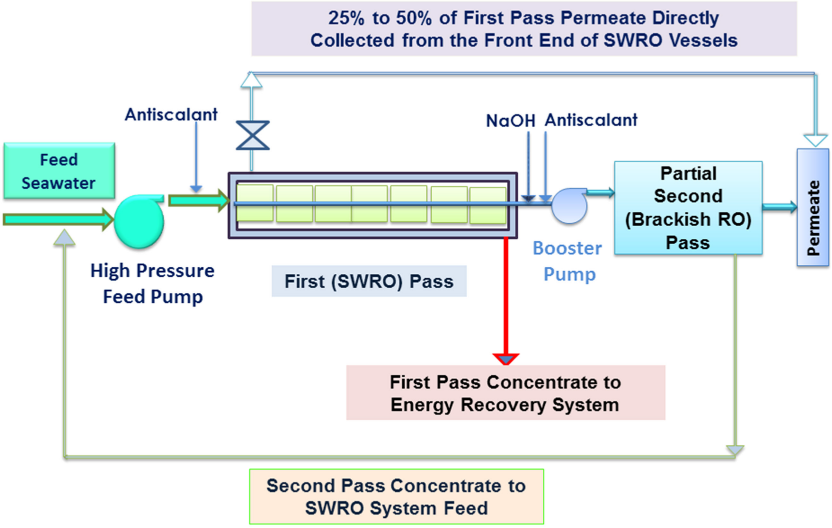

FIGURE 4.16 Schematic of split-partial two-pass SWRO system.

which reduces the energy benefit from such recovery proportionally – i.e., by 1%–2% only. As a result, the overall energy savings of the use of split-partial two-pass RO system as compared to conventional two-pass RO system are between 12% and 20%. Practical experience with large SWRO desalination plants indicates that the average total RO system life-cycle cost savings associated with applying such SWRO system configuration are typically between 10% and 15%.

At present, most new SWRO desalination systems are designed with split-partial two-pass configuration because this configuration allows reducing the size of the second-pass RO system and the overall fresh-water production costs. The first pass of this two-pass system usually employs hybrid membrane configuration with the first two or three SWRO elements being high-rejection/low productivity and the remaining elements being low-rejection/high-productivity SWRO membranes. Figure 4.17 presents the construction cost for split-partial two-pass SWRO system.

4.2.5 POST-TREATMENT CONSTRUCTION COSTS

Post-treatment costs incorporate the costs for construction of:

- Chemical conditioning system for permeate stabilization;
- Disinfection system;
- Facilities for product water quality polishing.

The post-treatment costs are mainly driven by the target product water quality and the final use of the desalinated water. Typically, the costs for construction of

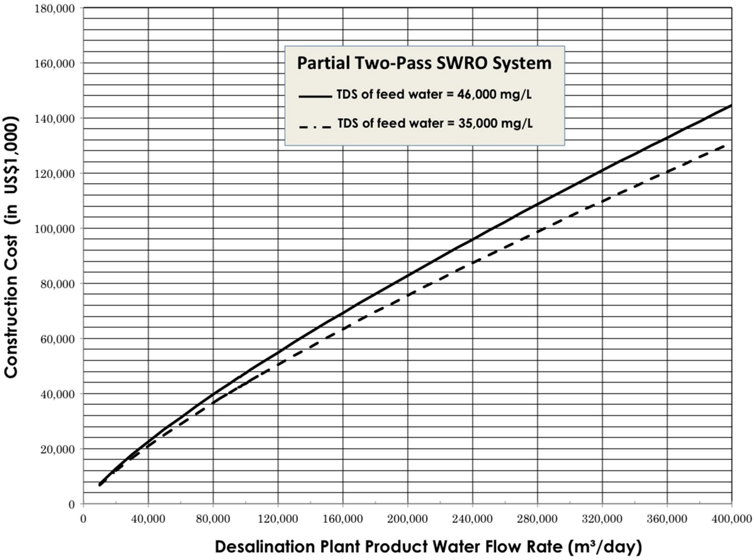

FIGURE 4.17 Construction cost for split-partial two-pass SWRO system.

post-treatment facilities for permeate stabilization and disinfection are in a range of between US\$30 and US\$75/m³/day. However, if the permeate has to be polished to achieve high levels of boron removal and/or removal of other specific constituents (i.e., silica, dissolved gases), then these costs may increase beyond the range indicated above.

The two most common systems for permeate stabilization use (1) a combination of lime and carbon dioxide, and (2) calcite (limestone) and carbon dioxide. The cost curves for these two post-treatment technologies are presented in Figure 4.18.

Review of Figure 4.18 reveals that the capital costs for product water conditioning using lime and carbon dioxide feed systems are significantly higher than for those that use the calcite filtration-based systems. Such difference is due not only to the higher complexity of the lime feed systems but also because of the fact that calcite contractors for most desalination plants built over the last 10 years are designed to process only 25%–30% of the entire RO permeate flow, to saturate this flow with calcium carbonate using acid, and then to blend it with the rest of the permeate.

Figure 4.19 depicts the cost curves for construction and installation of the feed and storage facilities of the two most widely used chemicals for disinfection of desalinated water – bulk sodium hypochlorite and chlorine dioxide. Bulk sodium hypochlorite is usually delivered at the desalination plant site as a 12.5%–15% liquid solution while chlorine dioxide is generated on site. Bulk sodium hypochlorite is the most commonly used disinfectant in desalination plants at present. Chlorine dioxide is most widely used in Middle Eastern and North African (MENA) countries because of its advantages in terms of chemical handling and costs, and the more stable and longer lasting chlorine residual it creates in conditions of high ambient temperature.

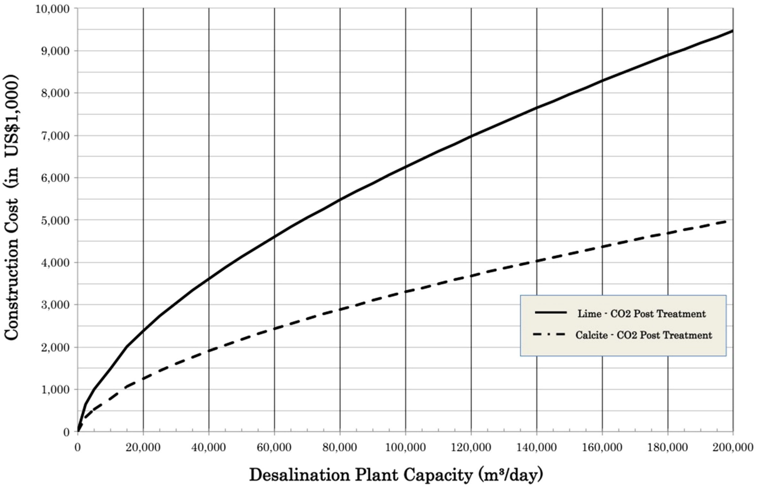

FIGURE 4.18 Construction cost for lime and calcite post-treatment systems.

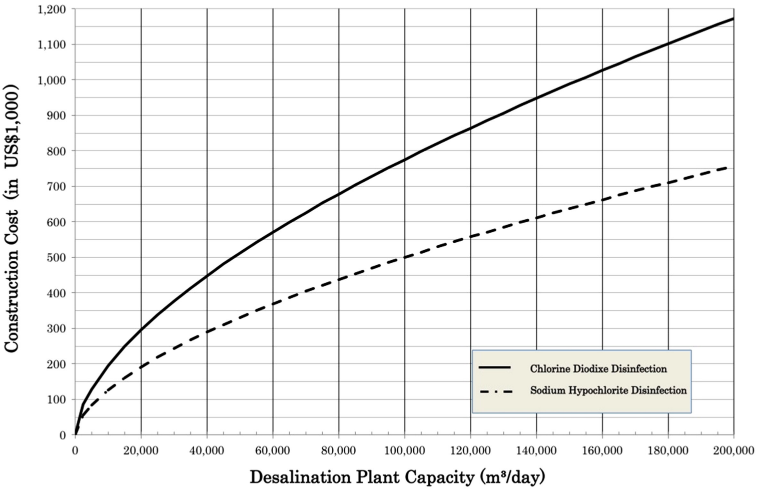

FIGURE 4.19 Construction cost for chlorine dioxide and sodium hypochlorite disinfection systems.

4.2.6 CONCENTRATE DISPOSAL SYSTEM–RELATED CONSTRUCTION COSTS

Concentrate disposal costs encompass expenditure for the conveyance and disposal of the concentrate and other waste streams generated at the desalination plant (see Figure 4.20). These costs can vary significantly depending on the concentrate disposal method.

Table 4.9 presents a typical construction cost range for concentrate disposal alternatives most commonly used in seawater desalination plants. Review of this table indicates that the sanitary sewer and surface water discharge are the two most cost-effective methods for concentrate disposal. Depending on the site-specific conditions, deep well injection, evaporation ponds, and spray irrigation could be competitive concentrate disposal alternatives, especially for disposal of concentrate from brackish water desalination plants, where the volume of generated concentrate is several times smaller and less saline than that generated by SWRO desalination plants of the same fresh water production capacity.

Zero liquid discharge systems typically have the highest construction and operation costs – for brackish desalination plants these costs are often comparable to the plant costs. However, under specific circumstances (such as cold climate, low evaporation and soil uptake rates, lack of suitable aquifers for concentrate disposal, high land costs, and low power costs) the zero liquid discharge systems could be cost-competitive to evaporation pond and spray irrigation disposal alternatives.

The most common concentrate management method for SWRO plants is co-disposal with cooling water from nearby power plant or effluent from wastewater treatment plant (WWTP); onshore discharge; and offshore disposal using outfall equipped with diffusers.

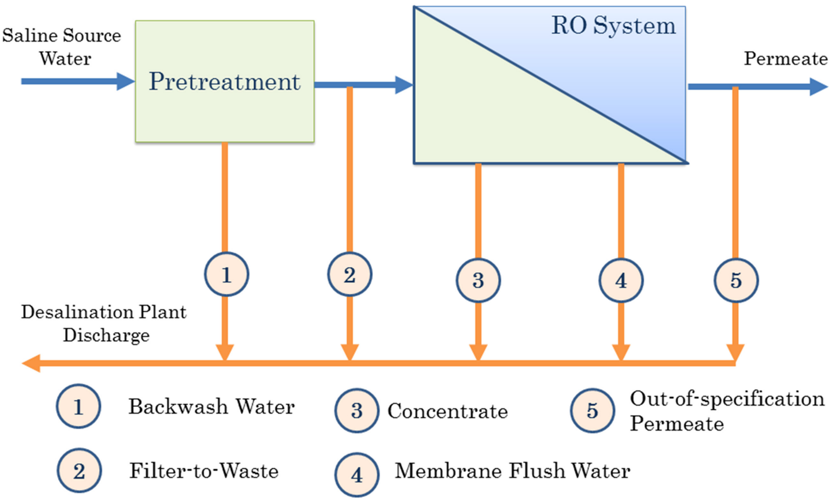

FIGURE 4.20 Desalination plant discharge streams.

TABLE 4.9
Construction Costs for Common Concentrate Disposal Alternatives

Concentrate Disposal Method	Disposal Construction Cost (US$/m³/day)
New surface water discharge (new outfall with diffusers)	40–800
Collocation of desalination plant and power plant discharge	20–40
Co-disposal with wastewater treatment plant discharge	30–160
Sanitary sewer discharge	10–120
Deep/beach well injection	210–650
Evaporation ponds	320–4,650
Spray irrigation	210–1,110
Zero liquid discharge	1,600–5,200

Note: All costs in year 2018 US$.

The costs for concentrate conveyance are typically closely related to concentrate volume and the distance between the desalination plant and the discharge outfall. The outfall construction costs are very site specific and in addition to the outfall size and diffuser system configuration (which is driven by the concentrate volume and salinity) these costs are dependent on the outfall configuration, and pipeline length and material, which in turn are determined by the site-specific hydrodynamics and environmental conditions of the receiving water body – usually ocean or bay.

Construction cost of sanitary sewer discharge is very site-specific and the key cost components for this disposal method are the cost of concentrate conveyance (pump station and pipeline) and the expenditures and fees for connecting to the sanitary sewer and for treatment/disposal of the concentrate. In some instances when the WWTP discharge volume is comparable to the volume of the desalination plant discharge, and the wastewater discharge outfall has limited mixing capacity, the co-disposal of concentrate and WWTP discharge may require equalization of the concentrate to match the diurnal variability of the WWTP effluent flow.

The key factors that influence deep well injection construction costs are well depth and diameter of well tubing and casting rings. Well diameter seems to have a very limited influence on the costs. Several other key cost factors are: (1) the need for concentrate pretreatment prior to disposal; (2) concentrate feed pump size and pressure, which vary depending on the type of the desalination plant energy recovery system, the geological conditions, and the depth of the injection zone; (3) environmental monitoring well system size and configuration; and (4) site preparation, mobilization, and demobilization.

The construction costs for concentrate evaporation ponds are mainly driven by the evaporation rate (local climate); the concentrate volume; the land and earthwork costs; the liner costs; and the salinity of the concentrate. The main cost variable is the evaporation area. Typically, evaporation rates are lower than soil uptake rates and, therefore, disposal of the same volume of concentrate using evaporation ponds requires more land than disposal by spray irrigation.

Usually, spray irrigation is cost-effective only if the concentrate is blended with a fresh water source to reduce its salinity to a level acceptable for crops/vegetation irrigation and its feasibility depends on the type of the crops/vegetation and on the soil uptake rates. The key cost factors of this disposal method are the costs of land, the storage and distribution system costs, and the irrigation system installation costs. Most of these costs are driven by concentrate volume and salinity.

Achieving zero liquid discharge is usually the most costly method for concentrate disposal, because it requires the use of elaborate mechanical equipment for evaporation, crystallization, and concentration (dewatering) of the salts in the concentrate as well as a source of waste heat. Although this method has found practical application in industrial water reuse facilities, it has not yet been used for disposal of concentrate from large seawater desalination plants.

4.2.7 Waste and Solids Handling–Related Construction Costs

These costs include expenditures for construction of facilities for collection, conveyance, and disposal of solid waste (spent membranes and cartridge filters) from the plant site as well as for the construction of solids handling system for treatment and disposal of residuals generated during the pretreatment process (screenings; residuals settled in the sedimentation tanks or DAF clarifiers; solids from the spent filter backwash water). In addition, these costs also encompass expenditures for equipment and storage tanks for collection, conveyance, and treatment (if necessary) of the waste membrane cleaning chemicals and flush water to their final disposal site (typically the sewer system or the desalination plant discharge after pretreatment by neutralization). Usually, the system for collection and disposal of waste membrane cleaning chemicals consists of an equalization storage tank, and pumps and piping to convey the spent cleaning chemicals to the storage tank and from the tank to the nearby sewer system or plant discharge.

SWRO systems, which have open ocean intakes, would generate a large quantity of solids, which are removed from the source water by the plant pretreatment system. If regulatory constraints limit the disposal of these solids back to the ocean, the filter backwash solids will have to be settled, dewatered, and disposed to a landfill. The expenditures for construction of a solids handling facility for backwash water residuals are typically in a range of US\$20–\$40/m³/day.

4.2.8 Construction Costs of Electrical and Instrumentation Systems

These costs include all expenditures for the desalination plant's electrical supply system (electrical substation; equipment and conduits connecting the desalination plant to the electrical grid or to a power generation facility); the equipment transformers and motor control centers; and all electrical conduits and other equipment to convey electricity to the individual plant equipment and instruments. The electrical system construction costs incorporate the expenditures for emergency power generation equipment as well.

These expenditures also encompass all equipment, software, programming, and installation costs for the plant's online monitoring instruments and computerized control system. The plant electrical and instrumentation costs are usually 5%–10% of the construction costs and range between US\$40 and US\$110/m³/day.

4.2.9 Construction Costs of Auxiliary and Service Equipment and Utilities

The facilities in this category are the plant chemical storage and feed systems; process air and water supply facilities; the plant fire protection system; sanitary wastewater collection system; storm water management system; and all utilities needed for the normal plant operation (potable and utility water; telephone; gas, etc.). These costs also incorporate the expenditures for an initial set of spare parts for the desalination plant facilities. The expenditures for construction of auxiliary and service equipment and utilities are usually between US\$15 and US\$35/m³/day.

4.2.10 Building Construction Costs

Typically, the desalination plant has one or more buildings that house the following: plant administration and management; laboratory; operator locker and shower facilities; maintenance shop; equipment and chemical storage area; and the key equipment of the SWRO system (high-pressure pumps; membrane vessels and racks; energy recovery system, etc.). Depending on the complexity and size of the desalination plant, as well as its location, appearance, and ambient environment, the construction costs for the desalination plant buildings may vary from US\$10–\$20/m² of the building footprint and range between US\$40 and US\$80/m³/day.

4.2.11 Startup, Commissioning, and Acceptance Testing Costs

Such costs include all expenditures for labor, consumables (electricity, chemicals, etc.), and equipment used during the plant commissioning, startup, and acceptance testing process. These expenditures typically also incorporate the costs for construction-related permitting and insurance; for preparation of plant operation and maintenance manuals; for initial training of the permanent desalination plant O&M staff; and for equipment and other items that are required for normal plant operations (tools for the workshop; service vehicles for plant operations staff and management; furnishings and equipment for the plant laboratory and administration building; etc.).

The startup, commissioning, and acceptance testing construction costs also incorporate all expenditures associated with the use of outside services, such as lab analysis of all source and product water quality parameters that cannot be completed in-house. Depending on the complexity of the project, the non-energy component of these costs can vary in a range between US$10 and US$30/m^3/day. If the plant acceptance testing would need to be repeated, such costs may exceed US$50/m^3/day.

4.3 COSTS OF PROJECT ENGINEERING SERVICES

4.3.1 Preliminary Engineering Costs

Preliminary engineering costs encompass all expenditures associated with initial assessment of project feasibility, definition of project scope and size, as well as studies required to determine the project location; the type of project intake and discharge, and the configuration of key project facilities and equipment: i.e., intake, pretreatment, RO separation, concentrate disposal, permeate post-treatment, and product water conveyance and delivery. The preliminary engineering costs are very dependent on the project size and complexity. These costs range from US$15–US$35/m^3/day of project's product water capacity.

4.3.2 Pilot Testing Costs

Pilot testing is highly recommended for large desalination projects (i.e., projects of production capacity of 40,000 m^3/day or higher, especially when the source water is an open ocean intake or a series of large beach wells, such as horizontal directionally drilled (HDD) or Ranney-type wells. Typically, the main purpose of pilot testing is to:

- Assess feasibility of seawater desalination plant intake and concentrate discharge technologies and configuration;
- Generate technical data required for project permitting (licensing), such as the characteristics of the plant waste streams (concentrate, filter backwash, spent chemical cleaning solutions, solids residuals, etc.);
- Compare alternative pretreatment technologies and energy recovery systems for the site-specific project configuration and conditions and determine the most viable technologies for the site-specific conditions of the project;

- Provide source water quality and process performance information needed for detailed project design and implementation and for optimum operation of the desalination plant;
- Create opportunities for public outreach and education regarding the benefits of seawater desalination, and advantages of desalinated seawater as compared to existing water supply sources.

Although pilot testing costs are relatively high – US\$5/m³/day to US\$15/m³/day – they usually are a good investment toward the successful implementation of large desalination projects. In addition to the costs for constructing a pilot plant, it is recommended to budget US\$10,000–\$20,000 per month of expenditures for pilot operations and maintenance.

In order to be truly beneficial for a given project, pilot testing has to be completed for a period of at least 6–12 months and has to encompass conditions of challenging source water quality such as high-intensity winds, rain events, and algal blooms; seasonal currents; large waste discharges in the plant intake area; dredging within a 1-km radius of the intake; and periods of intense boat traffic.

Project testing during periods of elevated source seawater temperature is very beneficial to determine the impact of high temperature on membrane fouling rate, membrane cleaning frequency, and permeate water quality as well as to identify the most suitable approach for boron removal from the source seawater.

4.3.3 Detailed Design Costs

Development of detailed project drawings and specifications typically encompasses expenditure in a range of US\$80 and US\$100/m³/day. Detailed project design also includes the development of as-built drawings and specifications that document the actual project implementation and deviations from the original design during construction.

4.3.4 Construction Management and Oversight Costs

Construction management and oversight include all engineering activities associated with project construction as well as with the management of construction contractors and all equipment and material suppliers involved in project implementation. The construction management and oversight costs range between US\$30 and US\$60/m³/day.

4.4 PROJECT DEVELOPMENT COSTS

Project development costs comprise all desalination plant owner expenditures associated with project implementation – from its inception and conceptual development to initial planning; administrative review and budgeting; environmental permitting; procurement of contractors for project construction and implementation; project funding; and staffing of desalination plant operations.

4.4.1 PROJECT ADMINISTRATION, CONTRACTING, AND MANAGEMENT

Project administration, contracting, and management are owner responsibilities that usually involve in-house expenditures for owner staff and overhead associated with project implementation as well as costs for contracting of outside engineering consultants and other advisers to provide specialized support services to project owner as needed (Ziolkowska, 2015). Expenditures associated with these efforts depend on the owner in-house capabilities and experience with the implementation of seawater desalination projects and may vary between US$20 and US$60/m^3/day.

4.4.2 ENVIRONMENTAL PERMITTING

Expenditures associated with environmental permitting (licensing) include two key components: (1) costs for preparation of environmental studies and engineering analysis needed to obtain environmental permits (licenses), and (2) fees associated with environmental permit filing and processing. Environmental permitting efforts and related costs depend on the size and complexity of the desalination project, on the methods planned to be used for disposal of the desalination plant concentrate, and on the site-specific environmental conditions of the area of plant intake and discharge.

Extensive waste discharge modeling studies are often necessary to ascertain the environmental viability of large ocean outfalls and deep injection wells. Usually, the completion of these studies is a multi-year effort and involves significant cost expenditures, expert reviews, and a multi-step evaluation process.

Environmental permitting costs and efforts also depend on the experience of the regulatory agencies with permitting similar desalination projects and the advancement of the regulatory law addressing concentrate discharge permitting and monitoring. For example, in many countries in the Middle East that have over 50 years of experience with permitting and environmental monitoring of desalination projects (e.g., Saudi Arabia, Oman, Qatar, United Arab Emirates, Bahrain, Kuwait), the regulatory review of new desalination projects is well streamlined and usually takes 6–12 months. In contrast, the permitting process for the first large SWRO desalination plant in California (the 200-MLD Carlsbad plant) took over 10 years. Because of the significant differences in desalination plant discharge permitting experience in various countries, the cost of environmental permitting may vary within an order of magnitude from project to project and from country to country (see Chapter 3). Overall, the costs associated with project permitting are in a range from US$30–$65/m^3/day.

4.4.3 LEGAL SERVICES

Costs for legal services include expenditures associated with legal review and processing of environmental permits, and with the preparation and negotiation of contracts for water supply, engineering, construction, and O&M services. In addition, these expenditures encompass costs for review and processing of contractual agreements for acquisition of land for the desalination plant site; obtaining easements for source water and product water pipelines and electrical supply lines to and from the site; for negotiation of power supply contract(s); and for preparation of other contracts for services, equipment, and goods needed for construction and operation of the desalination plant. The cost of legal services is directly related to the complexity of the project and usually varies between US$15 and US$35/m³/day.

4.5 PROJECT FINANCING COSTS

Project financing costs include expenditures for obtaining all funds and insurance needed for project implementation, from its conception and development through construction, startup, and commissioning. The most common methods of financing desalination projects are:

- *Government financing*: Where the public sector or the local or state government directly lends funds or provides grants, subsidies, or guarantees for repayment of the funds required to build the desalination plant.
- *Conventional (bond or construction loan) financing*: Where long-term funds are raised by issuing bonds or by providing a long-term construction loan by a private lender to public agency, private utility, or business enterprise against an independent credit risk rating and/or ongoing revenues from water sales or other assets.
- *Private project financing*: Where private lenders fund the desalination project via a special project company, and rely only on future cash flow from the project for repayment of their investment with no recourse to the project owner/developer and/or product water purchaser (non-recourse financing).

4.5.1 Government Financing

Government financing of an entire seawater desalination project is not very common at present and it is usually available for construction of small projects and under emergency conditions. However, in many countries, such as the United States, Australia, Israel, Spain, and some Caribbean and Middle Eastern states, the government directly or indirectly subsidies costs associated with seawater desalination in order to close the gap between the cost of water of the traditionally available surface and/or groundwater sources and the cost of desalinated water.

Often, the state government provides sovereign guarantees for payment for water supply services under a build-own-operate-transfer (BOOT) contract with a private company, especially in circumstances where the direct purchaser of desalinated water is a public agency under the fiscal and administrative control of the state government. Sovereign government guarantee is critical for privately financed projects when the contracting public agency does not have fiscal autonomy and/or is not credit risk–rated.

4.5.2 Conventional (Bond or Construction Loan) Financing

This type of financing is based on issuing long-term debt in the form of general obligation or revenue bonds or a commercial bank loan for a given project. General obligation bonds are used for financing of publicly owned projects and are secured by the full faith and credit of the issuing entity. In order to issue this type of bonds the entity seeking funding (government, public utility, municipality, etc.) has to have taxing powers to support payments of debt obligations. The key advantage of the general obligation bonds is that they are backed by the full taxing capacity of the governmental entity/public agency and consequently they are considered to have the strongest security pledge available to a lender, and therefore come at the lowest available net interest rate. In addition, issuance of general obligation bonds is usually simpler and frequently less costly than raising other types of debt.

However, the use of general obligation bonds for funding of desalination projects has a number of constraints. In order to issue such bonds, the legislation of most countries requires prior legislative or voter approval of the bond issue and limits the amount of tax-supported debt that can be issued by a legal administrative entity (utility, municipality, authority, etc.). As a result, financing large seawater desalination projects with general obligation bonds may reduce a government agency's ability to issue debt for future projects and may have a negative impact on the agency's credit rating. This type of bond cannot be issued by private entities/businesses. The interest rates for general obligation bonds typically vary from 2.5%–4.0%.

The second option for conventional project financing is the use of public or private activity revenue bonds. The interest and principal of the long-term debt raised through revenue bonds are payable solely through the revenue generated from the specific utility and/or the project owner. Revenue bonds are generally tax-exempt and are typically issued at interest rates lower than these of taxable debt/bonds and construction loans but higher than general obligation bonds. Typically, tax-exempt revenue bonds have interest rates of 3.5%–6.0%. Taxable debt/bonds usually have interest rate of 4.5%–8.0%.

Since debt service on revenue bonds and commercial loans is typically secured by the revenue stream generated by a particular project a reduction or discontinuance of this revenue could result in a default on these bonds or loans. In order to protect against default, lenders issuing revenue bonds or commercial construction loans require the establishment of several reserve funds that provide security to the investors that an adequate amount of funds is available for repayment of the debt, as well as for normal plant operations and for ongoing capital improvements. The typical reserve funds required to be included in project capital costs when revenue bonds or commercial construction loans are issued are:

- *Interest during construction*: This fund is established for payment of debt service obligations during the period of construction. Usually, during the construction phase of the project the owner pays interest only on the money that is used for construction rather than on the entire principal of the bond issue/loan. Therefore, this interest is often referred to as interest during construction. Since the project does not generate revenue during the construction period, the money required to pay interest and the construction-related portion of the principal on the loan/bond during construction usually have to be borrowed as well, and therefore they become a part of the project capital costs.

- *Debt service reserve fund*: This reserve account is intended to protect project lenders against project owner's inability to repay debt where the project revenue is insufficient during the operations period. Similar to the interest during construction, this reserve fund has to be borrowed as part of the loan/bond issue and is considered a capital cost item as well.
- *Working capital (operating fund)*: The size of this fund is typically 15%–20% of the annual O&M costs. This fund provides routine working capital during project construction, startup, and commissioning, as well as during normal plant operations. The working capital fund is usually included as a portion of the bond value (i.e., capitalized) when new seawater desalination projects are constructed.
- *Insurance reserve*: Funds reserved for self-insurance or for supplementing existing insurance coverage for items not covered by traditional insurance policies of the owner or of the contractors involved in desalination project implementation.

All reserve funds described above are typically included in the commercial construction loan/bond proceeds and, therefore, have to be accounted for in the plant capital costs. As a result, the reserve fund requirements can cause the loan/bond size to increase by 5%–10% or more.

Bonds are typically used to finance medium and large size projects (i.e., projects of 20,000 m^3/day or higher). Smaller projects are often funded by construction loans issued by commercial banks/lenders specialized in such financing. Fixed-rate commercial loans are widely used for this purpose and these loans have constant interest rate and payment for the full term of the loan.

The term of such loans depends on the project size and risk profile, and typically is between 5 and 20 years. The interest rate for commercial loans is usually set at a spread ranging from 150–275 points (i.e., 1.50%–2.75%) over internationally accepted and established inter-bank interest rates such as the London inter-bank offered rate (LIBOR). LIBOR is a rate that most creditworthy international banks charge each other for large loans.

4.5.3 PRIVATE PROJECT FINANCING

This type of financing is widely used for implementation of large BOOT seawater desalination projects. Under this method of financing the source of funds are private lenders – most often the BOOT project developer, private banks, and institutional investors, such as pension and insurance funds. Private project financing is usually a non-recourse financing. In this type of financing, the purchaser and consumer of desalinated water (the public or private water supply entity and its customers) does not have any direct liability for repayment of the funds used for project development and construction and, therefore, does not need to pledge any of its assets for fulfillment of the project funding related obligations.

The desalinated water user (public or private entity purchasing the water from the private developer) only pays for water services and does not carry project payment obligations on their balance sheet. The sole source of repayment of the funds invested in the project is the revenue generated from the sales of desalinated water. Responsibility for repayment of funds for the development and implementation of the privately financed project lies within the special project company established by the private BOOT contractor, the assets of which are owned by the project investors providing equity for the project.

Privately financed projects are usually funded by a combination of debt and equity. In some cases, funding can be obtained from Multilateral Lending Agencies (e.g., the European Investment Bank, the World Bank, the Asian Development Bank, the European Bank for Reconstruction and Development) or national export-promoting agencies. Debt may be in the form of bonds, commercial construction loans, and/or other financial instruments with a long-term or short-term repayment periods. The equity portion of the project funds is typically provided at the request and in accordance with the conditions of the financial institution issuing the project debt, and is usually in a range of 10%–50% of the total project capital costs.

Commercial banks, financial corporations, and project finance funds are typical sources of debt for seawater desalination projects. Equity for a given desalination project is usually provided by the BOOT contractor and/or outside equity fund (e.g., private equity fund, insurance or pension fund). If the BOOT project is properly structured and priced, the BOOT contractor equity contribution could be either a direct cash payment and/or indirect contribution of the funds the BOOT contractor actually expends for project development (“sweat equity”).

For example, if the capital cost for a given project is US$20 million and the BOOT contractor’s gross profit in the project is 5%, or US$1.0 million, this 5% can be “invested” as a portion of the equity contribution required for the project. If the lender of debt to the project requires a minimum of 10% of equity contribution from other sources and is willing to lend debt for 90% of the project capital cost, then the BOOT contractor can use its 5% of “sweat equity” against the 10% equity requirement and, therefore, has to raise only the remaining 5% of the required equity from outside investors.

Revenue-based (non-recourse) project financing typically is more complicated and costly to structure than an asset-based debt. Transaction costs normally include financial advisory fees, bank fees, legal fees, and independent bank engineer fees. As a result, private non-recourse financing may not be practical or cost-competitive for relatively small desalination projects (projects with capital costs of less than US$10 million), unless the transaction costs can be streamlined or multiple projects can be combined into one financial package.

When the project is operational, the revenue generated from the desalinated water sales is used to: (1) pay for the plant’s O&M expenditures; (2) repay debt obligations; and (3) pay for return on equity investment. The payment seniority usually follows the sequence described above. Because project equity investors get paid last, after all other project-related payment obligations are met, and because plant revenue is the only source of repayment for all project fiscal obligations, the equity investors are exposed to the highest risk of not achieving their return-of-investment goals.

Typically, project debt investors are protected by a “take-or-pay” clause of the water sales agreement between the BOOT contractor and the entity purchasing the desalinated water. However, project equity investors usually do not have such protection of their investment and, therefore, their return-on-investment expectations are higher than those of the debt lenders. In general, equity investors have expectations of returns commensurate with the returns yielded by financial stock markets trading securities of comparable risk profile. However, these investors also take the highest project performance related risk.

Annual interest at a preset rate is charged for the use of the funds, which lenders provide under any of the forms of project financing described above. For a given public utility, the cost of funds required to finance a desalination project would depend mainly on the credit rating of this utility and on the restrictions that apply to the public utility in relation to assuming new debt obligations. Public utilities with relatively low credit rating and/or limited capacity to borrow adequate amount of funds/issue bonds may often be able to obtain a more favorable financing terms by using private sources of financing.

In addition to lowering the overall cost of project funding and the project risk profile, involvement of the private sector in the project financing also has the benefits of keeping such financing off the balance sheet of the public utility which is embarking on a desalination project and of sharing project implementation, and performance risks, and costs with the private sector. Many public utilities who are newcomers to the desalination market prefer to minimize their project-related risks and fiscal exposure by opting to transfer key project risks and funding responsibilities to private companies and lending institutions specialized in delivering desalination projects. Therefore, many of the recent large seawater desalination projects worldwide are funded applying a BOOT project delivery structure and non-recourse private project financing.

The structure of desalination project funding is very project and country specific. Typically, DB and DBO projects are funded by long-term syndicated bank loans provided by a group of local and international banks, while independent water and power project (IWPP), build-own-operate (BOO) and BOOT projects are financed using a combination of equity and debt.

Table 4.10 provides the summary of the typical discount rates, loan repayment periods, and internal rate of return of desalination projects in the MENA region (World Bank, 2016). For projects funded by debt and equity, the debt-to-equity ratio usually varies between 70%/30% to 90%/10%.

Analysis of the project funding related information shown in Table 4.10 indicates that Red Sea and Arabian Gulf SWRO desalination projects have the highest cost of capital in terms of both debt and equity, which could be explained by the elevated risks associated with the construction and operation of these projects, and the involvement of large international corporations, private investors, and banks with relatively higher investment return expectations.

It is interesting to point out that SWRO projects that use membrane pretreatment are usually penalized by the investment community because of their worse performance track record as compared to projects with conventional granular media pretreatment. Over 10 years of experience with the use of membrane pretreatment for SWRO desalination projects in the Gulf Cooperation Council (GCC) countries and Cyprus has shown that SWRO desalination projects with membrane pretreatment usually have a lower plant capacity availability than plants with conventional

TABLE 4.10
Key Funding Parameters for Desalination Projects in the MENA Region

	Discount Rate (%)		Loan Repayment Period (Years)		Internal Rate of Return (IRR)	
Desalination Plant Type	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
MSF	2.0–6.5	4.8	15–25	20	5.6–13.3	9.8
MED-TVC	4.8–8.0	5.7	10–20	15	6.8–12.0	11.2
SWRO Mediterranean Sea	5.4–7.6	6.4	15–20	18	7.8–16.8	14.9
SWRO Arabian Gulf	5.6–8.4	7.6	10–15	12	8.9–18.5	16.8
SWRO Red Sea	6.0–9.1	8.4	10–20	18	9.4–17.2	17.2
Hybrid – MSF/MED & SWRO	5.6–8.4	6.1	10–25	20	8.4–15.3	13.8

MED-TVC, multi-effect distillation – thermal vapor compression; *MSF*, multi-stage flash distillation; *MENA*, Middle East and North Africa.

granular media filtration during algal bloom events, which in the Arabian Gulf could last 3 to 4 months and occur every year.

Multi-stage flash distillation (MSF) and multi-effect distillation–thermal vapor compression (MED-TVC) desalination projects have the lowest cost of investment return expectations, mainly because these thermal technologies are fairly mature and risks associated with construction and operation of this type of project is well understood by the investment community. In addition, many of the thermal desalination projects attract local funding that is very competitive to international funding sources.

Most turnkey BOOT and BOO/IWWP projects funded with the participation of international banks have a two-tranche based financial structure: (1) a local tranche denominated in the currency in which the project is located; and (2) an overseas tranche based on the terms issued by the international bank to the local government. Both tranches typically are equal in rights on a pari-passu basis.

Usually the special project company (SPC) formed for the implementation of the desalination projects secures a financing structure based on a senior debt, which equals 80% to 90% of the total project costs. The remaining 10% to 20% of the total project costs are financed by equity provided by the SPC shareholders during the construction period, pro-rata to the senior debt facility.

The turnkey (BOOT/BOO/IWPP) agreement typically allows for financing in local currency, euro, and US$, and provides a mechanism to hedge against changes in the exchange rates, relevant inflations, and base interest rates applicable to these currencies. This allows the SPC to optimize its sources of financing. The senior debt typically comprises:

- *Local currency tranche*: Typically 40%–50% of the debt – consists of short-term nominal financing in local currency during construction, to be replaced with long-term local currency consumer price index (CPI) linked financing by the same group of local lenders at a predetermined date, which usually occurs during the last quarter of the second year of operation. This long-term financing is repaid during the operation period.

- *International bank tranche*: The remaining 50%–60% of the debt is long-term international currency (US$, euro, yen) based financing, drawn during construction and repaid during the operation period.

This structure allows the SPC to take advantage of the low short-term interest rates and reduce the financing costs during the first period of the concession and until such time as the short-term loans are replaced by the long-term CPI linked local currency loans. This also applies to the international bank tranche, with the shifting of international (e.g., LIBOR or EURIBOR) floating rate to fixed (swap) rate at the same time as the local currency loans are converted from short to long term.

In addition, typically the SPC structures have an Equity Bridge Facility, Standby Facility, and a Working Capital Facility. The Equity Bridge Facility is used to finance the equity contribution required for the project during construction, alongside the senior debt facilities. The Standby Facility is designed to fund cost overruns not absorbed by the turnkey BOOT/BOO/IWPP contractor. The Working Capital Facility is a loan facility to fund working capital requirements.

It should be noted that the project funding parameters presented in Table 4.10 vary significantly from one region of the world to another and their values would not be applicable to derive the cost of financing of desalination projects outside of MENA. Typically, debt and equity return rates for desalination projects in a number of regions outside of MENA (sub-Saharan Africa, Central and South Asia, Australia, and Latin America) are higher than those for MENA projects because the desalination market in MENA is the most matured market in the world, where major project financing and technology risks are well known and can be predicted more easily, and local currencies are stable and usually pegged to the US dollar. Chapter 2 provides additional clarifications on some of the key differences, which cause the dissimilar project funding costs.

4.5.4 INTEREST DURING CONSTRUCTION

Debt/bond obligations are typically repaid using revenue from the sale of the desalinated water to the consumers of this water. However, during the period of time when the project is under construction no revenue is available to repay debt obligations. Therefore, typically the owner of the project borrows additional funds to pay the interest on the money used for construction.

Typically, interest during construction is calculated by multiplying the construction cost of the project by the annual interest rate of the loan and by 50% of the length of the construction period in years. This estimate assumes that 50% of the loan on average will be outstanding. Depending on the type of financing used for funding of the desalination project, interest during construction is usually between 1.5% and 4.5% of the total capital costs.

4.5.5 Debt Service Reserve

As indicated previously, the debt service reserve is intended to protect project lenders against inability of the owner to repay debt because the revenue generated by the project is insufficient. Depending on the type of financing, the complexity of the project, and the revenues of the water sales as compared to the debt obligations, the debt service reserve is typically set as one of the following three values: (1) maximum annual debt service; (2) 125% of the average debt service; or (3) 10% of the principal. The debt service reserve typically ranges between 2.0% and 8.5% of the project capital costs.

4.5.6 Other Financing Costs

Other project financing costs include expenditures associated with the funding of other reserve funds in addition to the debt service reserve fund, if needed to satisfy lender requirements; of administrative and legal costs related to issuing project bonds or arranging project loans and administering payments; and of costs associated with arranging project equity, if equity contributions are used for project financing.

Other financing costs also include expenditures associated with purchasing insurance and obtaining performance and payment bonds to protect the owner and contractors against construction failures and problems, and for payment of various taxes associated with project implementation as well as for covering shipping costs for delivering plant components to the site. These costs range between 0.5% and 4.0% of the total capital costs.

4.6 CONTINGENCY

Contingency provisions in the project cost estimate reflect the fact that even when a detailed cost estimate is completed, there are a number of unknown factors that may influence the actual expenditures associated with project implementation. As indicated previously, the size of contingency funds included in a given cost estimate depends on the level of accuracy of this estimate as well as on project complexity, size, funding structure, contractor experience with similar projects, and other project-related risks described in Chapter 2.

The various levels of accuracy of the project cost estimate and the associated contingencies are discussed in detail in Chapter 3. A detailed cost estimate usually carries contingency factor of 5%–10% depending on the complexity and size of the project. Higher contingency levels are used in lower accuracy cost estimates.

4.7 EXAMPLE OF DESALINATION PROJECT CAPITAL COST ESTIMATE

This section presents a budgetary cost estimate for a 100,000 m^3/day seawater desalination project. All costs included in this example are in year 2018 US$ and are based on actual data from similar size projects supplemented with cost information form budgetary vendor quotes and cost estimates for all key equipment, piping, materials, and buildings.

This cost estimate is provided for illustrative purposes only. As indicated in the previous chapters of this book, many factors and site-specific differences for a given project may cause other projects of similar capacity, source, and product water quality to yield costs significantly different from those presented in this illustrative example.

4.7.1 PROJECT DESCRIPTION

4.7.1.1 Plant Capacity and Availability

The example project is a hypothetical seawater desalination plant with an average annual plant production capacity of 100,000 m³/day, and maximum installed production capacity of 110,000 m³/day when operated at 50% recovery. The plant is designed to have an availability factor of 96%, i.e., to produce 100,000 m³/day or more for 96% of the time (350 days per year) and to operate in a recovery range of 45%–50%. The plant's minimum daily fresh water production capacity is 80,000 m³/day.

4.7.1.2 Plant Location, Intake, and Discharge

The plant is located on a 30,000-square-meter site in a commercially zoned area and is approximately 800 m from the shore. The plant site is an abandoned commercial property, which has an elevation of 10 m above the mean ocean tide level. The plant has an open ocean intake that extends 200 meters beyond the shoreline. The plant discharge is a 950-m pipeline of which 150 m extends into the ocean. The last 50 m of the outfall are equipped with diffusers for concentrate dissipation.

4.7.1.3 Intake Water Quality

Key plant intake water quality parameters are summarized in Table 4.11. The source seawater is typical Pacific Ocean water that is not influenced significantly by algal

TABLE 4.11

Key Intake Seawater Design Characteristics

Parameter	Design Minimum Value	Design Maximum Value	Design Average Value
Intake flow (m³/day)	176,000	240,000	220,000
Salinity (TDS) (mg/L)	32,500	36,500	35,000
Chloride (mg/L)	16,900	21,800	19,000
Bromide (mg/L)	52	79	73
Boron (mg/L)	3.6	5.0	4.5
Temperature (°C)	10	26	18
Turbidity (NTU)	0.2	20	2
Total suspended solids (mg/L)	0.5	30	4
pH	7.3	8.1	7.8

Note: All design characteristics are daily average values.

blooms, hydrocarbon contamination, and other potential sources of pollution that may exist in other circumstances. Review of Table 4.11 indicates that the source seawater for the hypothetical desalination project has relatively low fouling potential and consistent water quality.

4.7.1.4 Product Water Quality

The desalination plant will supply product water of quality that is in compliance with the key parameters specified in Table 4.12. Product water quality in this table is very typical for drinking water applications in the United States. Level of boron in Table 4.12 is driven by drinking water quality standards in the US state of California. Boron level requirements sometimes are more stringent if the water will be used for agricultural and horticultural irrigation.

The boron level requirement listed in Table 4.12 would allow the SWRO desalination plant to be designed with a two-pass RO membrane system. During the summer, the source seawater pH will need to be elevated to approximately 8.8 in order to achieve the desired boron water quality goal. Such pH adjustment will be accomplished using sodium hydroxide at a dosage of 15 mg/L.

Allowed bromide levels in Table 4.12 are acceptable for desalinated water that will be disinfected by chlorination. If the desalinated water is disinfected using chloramines, this water will need to be chlorinated at relatively high dosages (2–4 mg/L) in the summer when bromide level in the SWRO permeate exceeds 0.5 mg/L in order to prevent the negative impact of the relatively high bromide levels on the stability of the chloramine residual.

4.7.1.5 Key Plant Treatment Facilities

The seawater desalination plant will have the following key treatment facilities:

- Two offshore intake towers and pipelines made of HDPE;
- Four coarse bar rack intake screens with 80 mm openings;
- Four fine band intake screens – 10 mm openings;

TABLE 4.12

Key Product Water Quality Specifications

		Sampling			Concentration Limits	
Quality Parameter	**Analytical Method**	**Sample Period**	**Sample Method**	**Units**	**Central Tendency**	**Extreme**
Total Dissolved Solids	2540 C	One year	Weekly grab	mg/L	150	200
Chloride	4110 B	One year	Weekly grab	mg/L	100	150
Bromide	4110 B	One year	Weekly grab	mg/L	0.4	0.7
Boron	3120 B	One year	Weekly grab	mg/L	No limit	1
Turbidity	2130 B	One month	Continuous	NTU	0.3	0.5

- Intake pump station equipped with four duty and one standby vertical turbine pumps;
- Pretreatment facility combining coagulation and flocculation chambers and dual media (sand and anthracite) gravity filters with 12 duty and 2 standby filtration cells;
- Ten full two-pass duty and one standby (10 + 1) RO trains of 10,000 m^3/day production capacity each designed to operate at average recovery range of up to 50%. Each RO train includes filter effluent transfer pump, cartridge filter, high-pressure pump, pressure exchanger type energy recovery device, and an RO rack with membrane vessels and associated piping and equipment;
- Post-treatment system with limestone filtration and sodium hypochlorite disinfection;
- Concentrate disposal via new outfall pipeline with diffusers that is designed to handle the volume of plant concentrate and liquid waste streams;
- Chemical feed and storage systems;
- Solids handling system, which consists of lamella clarifiers for settling of the spent pretreatment filter backwash, and belt filter presses for dewatering of clarifier residuals;
- Administration, RO system, and chemical storage buildings;
- Electrical substation;
- Auxiliary facilities.

Plant construction schedule is 28 months. The project will be implemented under a BOOT method of delivery. The debt financing for the project will be secured using commercial construction loan of 5.25% interest rate and 20-year term. The project will be financed with 10% of equity and 90% of debt. Project equity return on investment is 10%. The overall interest rate of the amortized investment is 5.73%.

This is a high-complexity project, which will require a two-year permitting process, a detailed hydrodynamic modeling of the plant discharge area, and extensive source water sample collection and analysis. The project is likely to face legal challenges from local environmental groups.

4.7.1.6 Plant Operations

The desalination plant will be highly automated and will be operated by a staff comprised of 25 employees. The unit cost of power is US$0.06/kWh while the total power plant energy demand is 3.40 kWh/m^3. Dewatered sludge from the spent filter backwash will be disposed to a sanitary landfill in the vicinity of the plant. The spent cleaning solution from the reverse osmosis membrane cleaning will be discharged to a sanitary sewer.

Plant effluent discharge water quality will be measured at the point of exit from the desalination plant and the effect of this discharge on the marine environment will be monitored by collection and analysis of water quality samples at 16 monitoring stations located in the vicinity of the plant discharge.

4.7.2 Capital Cost Estimate

The capital costs for construction, startup, and commissioning of the 100,000-m^3/day seawater desalination plant are presented in Table 4.13. The total capital costs for this desalination plant are estimated at US$171,500,000 (US$1,715/m^3/day).

TABLE 4.13
Project Capital Cost Breakdown

	Capital Cost	
Cost Item	**(US$)**	**(% of Total Capital Cost)**
Direct Capital (Construction) Costs		
1. Site preparation, roads and parking	2,000,000	1.2
2. Intake	9,700,000	5.6
3. Pretreatment	16,600,000	9.7
4. RO system equipment	48,600,000	28.3
5. Post-treatment	3,800,000	2.2
6. Concentrate disposal	4,000,000	2.3
7. Waste and solids handling	3,000,000	1.8
8. Electrical & instrumentation systems	7,500,000	4.4
9. Auxiliary and service equipment & utilities	2,500,000	1.5
10. Buildings	6,000,000	3.5
11. Startup, commissioning, & acceptance testing	3,300,000	1.9
Subtotal-Direct (Construction) Cost (% of Total Capital Cost)	*US$107,000*	*62.4%*
Project Engineering Services		
12. Preliminary engineering	2,000,000	1.1
13. Pilot testing	1,200,000	0.7
14. Detailed design	9,000,000	5.3
15. Construction management and oversight	4,500,000	2.6
Subtotal-Project Engineering Services	*16,700,000*	*9.7*
Project Development Costs		
16. Administration, contracting and management	3,500,000	2.3
17. Environmental permitting	6,500,000	3.8
18. Legal services	2,000,000	1.2
Subtotal-Project Development	*12,500,000*	*7.3*
Project Financing Costs		
19. Interest during construction	5,150,000	3.0
20. Debt service reserve fund	9,100,000	5.3
21. Other financing costs	3,900,000	2.3
Subtotal-Project Financing	*18,150,000*	*10.6*
22. Contingency	17,150,000	10.0
Subtotal-Indirect Capital Cost (% of Total Capital Cost)	*US$64,500,000*	*37.6%*
Total Capital Cost	US$171,500,000	100%

The following paragraphs describe the methodology used to determine the cost items listed in Table 4.13:

Item 1: “Side Preparation, Roads, and Parking” construction cost of US$2.0 million is determined based on the middle value (US$20/m^3/day) of cost range shown in Section 4.2.1 – US$10 to US$30/m^3/day. For plant average production flow of 100,000 m^3/day and unit cost of US$20/m^3/day, this cost is US$2 million.

Item 2: “Intake” construction cost of US$9.7 million is calculated using cost information from Figures 4.2 through 4.4 for an average plant intake flow of 220,000 m^3/day (US$5.5 million + US$2.0 million + US$2.2 million). For the average plant intake flow rate, the unit cost of HDPE pipe on Figure 4.2 is US$27,500/meter. At 200 meters of total pipeline length, the total intake cost is US$5.5 million (200 m × US$27,500/m = US$5.5 million). Using Figure 4.3, the construction cost for intake pump station with wet well designed for an intake flow of 220,000 m^3/day = US$2.0 million. For the same intake flow rate and band screens the cost of the screening facilities is determined to be US$2.2 million based on reading from Figure 4.4.

Item 3: “Pretreatment” construction cost is determined for plant intake flow of 220,000 m^3/day, using Figure 4.8 (US$14.0 million for Gravity Filters) and Figure 4.10 (US$2.2 million for Cartridge Filtration System) for a total of US$16.6 million.

Item 4: “RO System Equipment” – the construction cost for this item is determined using Figure 4.15 (Construction Cost of Full Two-Pass RO System) based on a reading for the plant product water capacity of 100,000 m^3/day of US$48.6 million. Full-two pass system is selected for this project to address the stringent product water quality requirements of the project.

Item 5: “Post-Treatment” construction cost of US$3.8 million is calculated as a sum of the cost for Calcite-CO_2 system of US$3.3 million (Figure 4.18) and of the cost for Sodium Hypochlorite Feed System (Figure 4.19) of US$0.5 million.

Item 6: “Concentrate Disposal” of US$4.0 million is selected based on the low end of the unit cost range (US$40/m^3/day) in Table 4.9 for “New Surface Water Discharge (New Outfall with Diffusers)” which is designed for the volume of the concentrate only, and for the plant production capacity. The low end of the cost range was selected because the outfall length in the ocean is relatively short as indicated in plant description.

Item 7: “Waste and Solids Handling” construction cost of US$3.0 million is determined based on the middle value (US$30/m^3/day) of rule-of-thumb range of US$20 to US$40/m^3/day indicated in Section 4.2.7 “Waste and Solids Handling–Related Construction Costs.”

Item 8: “Electrical and Instrumentation Systems” construction cost of US$7.5 million is calculated for the average value of US$75/m^3/day of the cost range of US$40 to US$100/m^3/day presented in Section 4.2.8 “Costs of Electrical and Instrumentation Systems.”

Item 9: "Auxiliary and Service Equipment & Utilities" – construction cost of US$2.5 million is estimated for the average value (US$25/m^3/day) of the range (US$15 to US$35/m^3/day) of the unit costs presented in Section 4.2.9 "Construction Costs of Auxiliary and Service Equipment and Utilities."

Item 10: "Buildings" – expenditures for construction of plant buildings of US$6.0 million is estimated for the average value (US$60/m^3/day) of the range (US$40 to US$80/m^3/day) of the unit costs presented in Section 4.2.10."

Item 11: "Startup, Commissioning, and Acceptance Testing" – the construction expenditures of this item (US$3.3 million) are calculated as a sum of the non-energy costs of US$2.0 million (based on the average value of the range of such costs in Section 4.2.11 of US$20/m^3/day) and the cost of energy for 2 months of commissioning and acceptance testing activities of US$1.3 million. The energy costs are determined for plant demand of 3.4 kWh/m^3, average plant production flow of 100,000 m^3/day and two months (62 days) of commissioning and acceptance testing – 3.4 kWh/m^3 × 100,000 m^3/day × 62 days × US$0.06/kWh = US$1.265 million – rounded up to US$1.3 million.

The total construction cost (direct capital cost) is calculated as a sum of items 1–11 described above and for this example is estimated at US$107.0 million. This cost is 62.4% of the total capital cost of the project (US$171.50 million) – see Table 14.13. The calculations of indirect capital costs associated with project implementation are presented below.

Item 12: "Preliminary Engineering" – the cost for this item (US$2.0 million) is calculated for US$20/m^3/day, which is the middle of the range for this cost item shown in Section 4.3.1 – US$15 to US$35/m^3/day.

Item 13: "Pilot Testing" – the cost for this item (US$1.2 million) is estimated for a period of one year of testing at US$10/m^3/day (US$1.0 million) and additional O&M costs for 12 months at US$15,000/month = US$0.18 million (rounded to US$0.2 million) – see Section 4.3.2 for further details.

Items 14 and 15: Item 14 "Detailed Design" (US$9.0 million) and Item 15 "Construction Management and Oversight" (US$4.5 million) are determined for the average unit cost value of the ranges for these two expenditures, which are US$80 to US$100/m^3/day and US$30 to US$60/m^3/day, respectively – see Sections 4.3.3 and 4.3.4. The average unit cost values (US$90/m^3/day and US$45/m^3/day) are multiplied by the plant fresh water production capacity of 100,000 m^3/day.

Items 16–18: All "Project Development Costs" (i.e., Item 16 – "Administration, Contracting, and Management" [US$4.0 million]; Item 17 – "Environmental Permitting" [US$6.5 million]; and Item 18 – "Legal Services" [US$2.0 million]) are calculated for the average values of the rule-of-thumb ranges for these cost items presented in Sections 4.4.1 through 4.4.3.

Items 19–21: All "Project Financing Costs" (i.e., Item 19 – "Interest During Construction" [US$5.3 million]; Item 20 – "Debt Service Reserve Fund" [US$9.0 million]; and Item 21 – "Other Financing Costs" [US$3.85 million]) are estimated using the typical cost ranges in Sections 4.5.4 through 4.5.6 expressed as percentage of the total capital costs. For this example capital cost estimate, the actual values of the Items 19 through 21 are selected to be in the middle of the ranges in the sections above. In actual projects the project financing costs will be determined based on the information provided from the project lenders and a financial model developed specifically for the project.

Item 22: Contingency (US$17.15 million) is calculated as 10% of the total capital cost. As indicated in Section 4.6, the amount of the actual contingency factor used in the total capital cost will depend on the level of accuracy of the project cost estimate and in this example it is selected at its maximum recommended value.

The indirect capital cost of US$64.5 million for this project is determined as a sum of cost items 12 to 22. The total capital cost of US$171.5 million for the hypothetical 100,000 m^3/day SWRO project treating Pacific Ocean seawater is presented in Table 4.13 and is calculated as the sum of the direct (US$107.0 million) and indirect (US$64.5 million) capital costs.

The unit capital cost pro-rated for the plant capacity is US$1,715/$m^3$/day. This estimate is more conservative than the lowest unit costs of US$1,100/$m^3$/day, which actual similar size SWRO desalination projects have yielded in the Middle East despite the fact that the source seawater used for desalination is of lower TDS content (see Figure 2.3). Such cost difference is to be expected when comparing conceptual and detailed cost estimates for the same project.

In addition, other factors as lower construction labor cost and cost of project financing; more streamlined environmental review process and less stringent regulatory requirements; as well as lower project engineering and development costs are some of the key reasons that explain the significant cost difference of the conceptual capital cost estimate presented in this chapter and the lowest capital cost the desalination market can yield for the same size project.

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5 Operation and Maintenance Costs

5.1 INTRODUCTORY REMARKS

As indicated in Chapter 1, desalination plant operation and maintenance (O&M) costs incorporate all expenditures associated with operating the desalination plant to produce a target fresh water quality and quantity, and to maintain its equipment, facilities, and systems. Usually O&M costs are assessed over a period of one year and are referred to as annual O&M costs (expressed in US$ or other currency per year). The key O&M cost components are energy (power), maintenance, chemicals, labor, and membrane replacement. In total these costs typically encompass over 80% of the annual O&M expenditures for seawater reverse osmosis desalination plants.

Sometimes, the total annual desalination plant O&M costs are apportioned to the key desalination plant components with which they are associated. In this case the O&M costs are usually divided into direct non-energy related costs for key plant facilities (e.g., plant intake, pretreatment, reverse osmosis, and post-treatment); total plant energy costs; indirect O&M costs; and other O&M costs. Curves for the direct non-energy O&M costs of key seawater reverse osmosis (SWRO) plant facilities are included in Section 5.10 of this chapter. Plant annual energy costs are calculated based on the projected total energy use of the plant and its annual design fresh water production capacity. Plant indirect costs are usually estimated as a percentage of the total annual O&M costs.

Most commonly in practice, desalination plant O&M costs are divided into two categories depending on their relation to the actual production of desalinated water – variable (function of the fresh water flow produced by the plant) and fixed (costs not related to the produced flow). Table 5.1 presents key annual O&M cost components. Similar to the capital cost breakdown provided in Chapter 4, the plant annual O&M cost breakdown in this table is presented for two types of desalination projects – low and high complexity.

Low-complexity projects are considered desalination plants with a relatively good source of seawater quality, simple pretreatment system, low level of automation and controls, and regulatory requirements that are easy to comply with and do not require elaborate discharge water quality and product water quality monitoring. High-complexity projects typically have source water with a high membrane fouling potential which requires elaborate pretreatment and process monitoring and have fully automated plant operations, which requires a very skilled staff and compliance with very stringent environmental regulations and/or product water quality requirements.

TABLE 5.1
Breakdown of Annual O&M Costs

Cost Item	Percentage of Total O&M Cost (%) Low-Complexity Project	Percentage of Total O&M Cost (%) High-Complexity Project
Variable O&M Costs		
1. Power	35.0–55.0	37.5–60.0
2. Chemicals	3.0–7.5	5.5–10.0
3. Replacement of membranes and cartridge filters	5.0–8.0	4.5–10.0
4. Waste stream disposal	2.0–4.5	3.0–5.0
Subtotal - variable O&M costs	45.0–75.0	50.0–85.0
Fixed O&M Costs		
5. Labor	10.0–15.0	4.0–10.0
6. Maintenance	9.5–22.0	3.5–15.0
7. Environmental and performance monitoring	0.5–3.0	1.0–5.0
8. Indirect O&M costs	5.0–15.0	7.0–20.0
Subtotal - fixed O&M costs	25.0–55.0	15.0–50.0
Total O&M costs	100%	100%

5.2 POWER COSTS

Annual desalination plant power costs are dependent on two key parameters: (1) the power tariff (and associated unit cost of power, usually expressed in monetary units per kWh); and (2) the amount of power used to produce desalinated water, typically presented in kWh per m³ or 1,000 gallons of fresh product water.

5.2.1 Power Costs Associated with Desalination Plant Energy Use

The SWRO system typically uses over 70% of the power required to operate the desalination plant. The rest of the power is consumed mainly by plant intake and pretreatment systems, and by the product water delivery pumps. An example of the power use of various facilities in a 200,000 m³/day seawater desalination plant treating source seawater with a total dissolved solids (TDS) concentration of 33,500 mg/L and average annual temperature of 23°C is presented in Figure 5.1. This example includes the use of pressure exchangers for energy recovery.

As discussed in Chapter 2, power costs are directly related to the source water salinity and temperature, and to the associated osmotic pressure that has to be overcome in order to produce fresh water (see Tables 2.2 and 2.3, and Figure 2.5). Source seawater of lower salinity and higher temperature yields lower power use for production of the same volume of fresh water mainly due to the reduction of reverse osmosis (RO) feed water osmotic pressure.

Another key factor associated with overall energy use is the efficiency of the applied SWRO energy recovery system. A large portion of the energy applied for

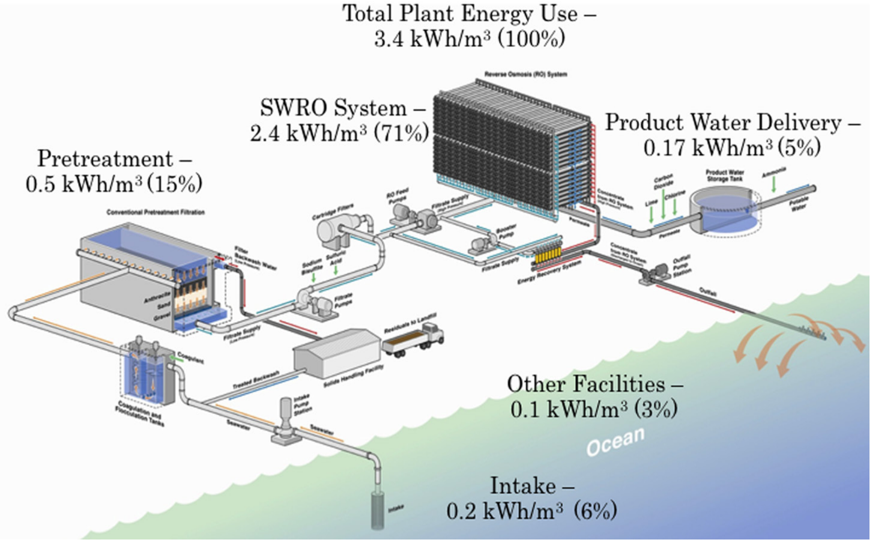

FIGURE 5.1 Breakdown of energy use of typical desalination plant.

desalination is contained in the high-salinity product of desalination (i.e., the concentrate). Over 96% of this energy can be reused in the desalination process by installing recovery equipment that transfers it from the concentrate to new seawater fed to the SWRO system. The efficiency of energy transfer from concentrate to source seawater varies with the type of energy recovery technology (pressure exchanger, Pelton wheel, turbocharger, or reverse running pump) and with the overall water recovery and configuration of the SWRO system.

Table 5.2 provides typical ranges for energy use of reverse osmosis membrane systems of medium and large seawater desalination plants (i.e., plants with fresh water production capacity of 40,000 m³/day or more). This table is based on actual data from over 30 SWRO plants constructed between 2010 and 2017. As seen from Table 5.3, SWRO systems of best-in-class desalination plants use between 2.4 and 2.8 kWh of electricity in order to produce one cubic meter of fresh water, while the

TABLE 5.2

Typical Energy Use for Medium and Large Size SWRO Systems

Classification	SWRO System Energy Use (kWh/m³)
Low-end bracket	2.4–2.8
Medium range	2.9–3.2
High-end bracket	3.3–4.0
Average	**3.1**

TABLE 5.3
Unit Chemical Costs

Chemical	Unit Cost (US$/kg)
Chlorine gas	0.6–1.1
Sodium hypochlorite	2.2–3.5
Ferric sulfate and ferric chloride	0.4–1.2
Sulfuric acid (93% H_2SO_4)	0.06–0.1
Citric acid	1.6–2.5
Biocide	3.0–5.5
Sodium hydroxide (50% NaOH)	0.65–0.85
Sodium bisulfite	0.35–0.55
Antiscalant (scale inhibitor)	1.6–4.0
Ammonium hydroxide	0.6–1.1
Hydrated lime	0.3–0.4
Calcite	0.05–0.08
Carbon dioxide	0.08–0.12
Sodium tripolyphosphate (corrosion inhibitor)	1.6–3.2
Other cleaning chemicals (US$/m³ of permeate)	0.005–0.008

Note: All costs in 2018 US$.

industry average energy use is approximately 3.1 kWh/m³. It should be pointed out that the energy use presented in Table 5.2 only encompasses SWRO system operations, rather than the energy consumption of the entire seawater desalination plant. Usually, SWRO systems contribute between 65% and 80% of total desalination plant energy demand.

The lowest theoretical energy consumption for the desalination of 35,000 mg/L of seawater at a temperature of 25°C (i.e., typical Pacific Ocean water) is 0.76 kWh/m³. This energy use corresponds to a condition of complete conversion of seawater into fresh water (100% recovery), which cannot be achieved in practical terms. For a more realistic 50% recovery, this minimum theoretical energy use would be 1.06 kWh/m³ (Elemelech, 2012). However, this energy consumption assessment assumes that all desalination plant equipment has 100% energy efficiency and all energy contained in the desalination plant concentrate is recovered and reused in the desalination process. Therefore, this energy threshold is the ideal theoretical minimum for seawater desalination.

Based on the systematic long-term testing of a full-scale state-of-the-art desalination system by the Affordable Desalination Collaboration (ADC) in the United States, the lowest energy use that could be achieved with actual state-of-the-art highly efficient commercially available desalination equipment and RO membranes at the time of testing (years 2006–2007) was determined to be 1.58 kWh/m³ (MacHarg et al., 2008). Such energy use was measured at RO system recovery of 42% and average SWRO membrane flux of 10.2 liters/m².hr (Lmh).

The ADC testing was completed using Pacific Ocean seawater collected by an open ocean intake and pretreated by granular media pressure filters (Seacord et al., 2006). The ADC study concluded, however, that SWRO system operation at such low recovery and flux does not yield the lowest overall cost of water production at unit cost of energy of US$0.10/kWh used for life-cycle cost assessment.

Based on a detailed cost-benefit analysis, ADC researchers have determined that for the tested seawater quality (e.g., typical Pacific Ocean seawater) the "Most Affordable Point" of SWRO system design is at plant recovery of 48% and flux of 15.3 Lmh. At this operational condition the minimum energy use of the SWRO system was determined to be 2.0 kWh/m^3. It should be pointed out that the "Most Affordable Point" design would vary with unit cost of energy and the project-and-location specific construction and engineering costs and source water quality. A detailed description of the ADC study scope, assumptions, test conditions, and results is presented elsewhere (MacHarg et al., 2008).

5.2.2 Power Costs Associated with Unit Price of Electricity

When electricity is purchased from an independent power generation supplier, the unit cost-of-power tariff is typically outside of the control of the desalination plant owner. In this case, the desalination plant could be designed to take advantage of the cost reduction associated with the off-peak power tariff rate, which is usually lower than this rate during the peak hours of power consumption.

Usually, the peak power rate timeframe coincides with the periods of peak water demand, during which the desalination plant often has to operate at maximum rather than minimum capacity. Therefore, provision of adequate amounts of product water storage would be essential to take advantage of the benefits of maximum off-peak power tariff operation of the desalination plant. Construction of additional plant product water storage capacity to accommodate off-peak power tariff benefits would increase plant construction costs and therefore, its viability has to be accessed on a life-cycle cost basis.

Some power generation utilities provide additional power tariff incentives if the desalination plant owner is willing to significantly curtail or completely discontinue plant operations during periods of the year when the power generation utility can sell this power at very high prices to other users. Power curtailment conditions, if offered by the electrical company, would vary from one power supplier to another, but in general such conditions would include a requirement for reduction of over 90% of the desalination plant power use for a period of 6 to 12 hours up to two times per month. Such conditions would have to be established for the site-specific circumstances of a given project. In order to accommodate the power plant company's curtailment schedule, the desalination plant design, operations, and water supply delivery commitments have to have built-in flexibility and extra product water storage capacity, which usually come with an increased capital expense.

Another potential alternative for reduction of the unit power rate is to collocate the desalination plant with an existing power plant and to connect the desalination plant's electrical system directly to the power plant generation units thereby completely avoiding the use of the power grid for electrical supply. Often, the power tariff consists of two components – a power generation and a power grid distribution charge component. Depending on the regulations governing power generation, supply, and distribution, the direct connection to the power plant's generation units may allow avoiding the payment of the power grid distribution component of the tariff. Since this component may be as large as half of the total power rate, the collocation approach could allow a substantial reduction of the unit power cost and therefore, of the total energy cost for desalination.

Another alternative to avoid power grid associated charges and to reduce the unit cost of power is to self-generate electricity at the desalination plant site. This approach is usually viable for very large plants (an example is the Ashkelon seawater desalination facility) because the generation of small quantities of electricity is typically not as cost-effective as power generation on a large commercial scale by an experienced power generation company.

Power self-generation may be cost-effective for small-size desalination plants in cases when there is no easy access to a nearby electrical power grid and/or when the commercially available power rate is very high and self-generation of electricity is cost-competitive. Another important issue associated with power self-generation is the risk the desalination plant owner and investors take with the increase in the unit cost of fuel (usually natural gas) used for power generation over time and the sustained availability of a particular type of fuel over the useful life of the desalination project. Taking these risks is usually prudent only if they can be shared with the water consumer, mitigated by the government, or taken by a major supplier of this fuel product via a long-term fuel supply contract that expands over the useful life of the project.

Cost of power is a variable annual expenditure and usually ranges between US\$0.15/m^3 and US\$0.25/m^3. The cost variation may be wider for site-specific conditions where power supply is difficult or power self-generation is applied. Alternative approaches for reducing desalination plant power expenditures are further discussed in Chapter 8.

5.3 CHEMICALS

Chemical costs are highly variable from one location to another and are mainly dependent on the source water quality, the selected pretreatment processes, and the target product water quality. Table 5.3 presents unit costs for various chemicals frequently used in seawater desalination plants. The actual chemical cost values for a given project have to be established based on quotes from local suppliers of the site-specific chemicals.

Cost of chemicals is a variable expenditure and typically is in a range of US\$0.030/m^3 to US\$0.060/m^3 of product water.

5.4 LABOR

Plant operation labor costs are closely related to plant size; complexity and number of treatment processes and equipment; and to overall level of plant automation.

Typically, medium and large size desalination plants are highly automated and reliable facilities, which use limited amount of specialized staff for overall plant performance monitoring and control, equipment maintenance, preparation of chemical batches for various treatment processes and collection and analysis of water quality samples.

Usually, every desalination plant is staffed with plant manager, shift supervisors, operators, one or more mechanics and electricians, and laboratory and administrative employees. Often several smaller facilities (i.e., package desalination plants with production capacity of 500 m^3/day or less) are supervised by one regional plant manager and serviced by a central laboratory, and instrumentation and control group.

Table 5.4 summarizes the typical plant staffing requirements for a seawater desalination plant as a function of the level of plant automation, treatment process complexity, and labor skills. As seen in this table, the number of plant staff varies with plant capacity and is strongly influenced by economy of scale.

Usually, desalination plant staff is organized in one to three shifts and in some smaller and fully automated plants plant operations are unmanned at night. Most large plants are staffed 24 hours per day, 365 days per year, with at least two operators on duty at all times. The labor costs are fixed for a given plant and are usually in a range of US\$0.015/m^3 to US\$0.045/m^3 of desalinated water.

5.5 MAINTENANCE AND REPAIRS

Maintenance costs are one of the larger cost components of the annual O&M expenditures. These costs include all expenditures associated with routine operation and preventive and emergency maintenance of plant equipment, structures, buildings, and piping. Typically, the useful life of most of the key desalination plant equipment is between 25 and 50 years. Therefore, the average annual maintenance expenditure

TABLE 5.4
Seawater Desalination Plant Staffing Requirements

	Plant Automation, Complexity, and Labor Skill Level	
Plant Capacity (m^3/day)	**High**	**Low**
1,000	2–3	4–6
5,000	4–6	8–10
10,000	7–10	12–14
20,000	9–12	16–18
40,000	12–16	18–20
100,000	14–18	20–25
200,000	18–28	30–40
300,000	35–50	60–80

is approximately 2% (100%/50 years) to 4% (100%/25 years) of the cost of the installed equipment.

Usually, annual costs for maintaining structures and piping are 1% to 2% of their construction costs. Maintenance costs vary from year to year because the key high-cost desalination equipment such as high-pressure pumps, energy recovery system, and other large-capacity pumps undergo routine rebuilding of key internal components every 5 to 10 years in order to maintain their high efficiency and consistent performance.

Since most of the plant equipment is maintained routinely on a preset schedule independent of the actual water production, some (typically 50% to 70%) of the routine equipment maintenance costs are often considered fixed O&M costs. The remaining portion of the maintenance costs is accounted for as a variable component and is related to the actual equipment run time. Plant total maintenance costs are typically in a range of US\$0.025/m³ to US\$0.070/m³ of desalinated water cost.

5.6 MEMBRANE AND CARTRIDGE FILTER REPLACEMENT

This O&M cost component incorporates expenditures for replacement of pretreatment membranes (if membrane pretreatment is used); RO membranes; and cartridge filters. Annual membrane and cartridge filter replacement costs are proportional to the replacement frequency of these consumables, which in turn depends on the source water quality and plant design. Since often at the conceptual stage of the SWRO desalination project the number of cartridge filters is unknown, a rule of thumb that could be used for preliminary assessment of the total number of the cartridge filters needed for the plant is: 25 cartridge filters/1,000 m^3/day of plant fresh water production capacity.

In average, cartridge filters in well-designed and -operated SWRO desalination plants are typically replaced once every 2 to 3 months. In the case of plants with very high-quality source seawater or brackish groundwater collected using well intake, the frequency of cartridge filter replacement is once every 6 months. Under worst-case scenario, if the pretreatment system of the desalination plant does not work well cartridge filters may need to be replaced as frequently as once per week. Depending on the cartridge filter size, the unit cartridge filter cost is between US\$8 and US\$30 per filter.

The typical useful life of ultra- and microfiltration pretreatment membranes is 3 to 7 years, although some membrane suppliers provide membrane useful life warrantees for up to 10 years. Therefore, their annual replacement costs range between 10.0% and 33.3% of the initial installed membrane cost. The total number of membrane elements needed for seawater pretreatment varies from one model of membrane system to another and depends on unit membrane surface area and design flux. For conceptual cost estimates, if the actual model of pretreatment membranes is not selected yet and the system design is not completed, a rule of thumb that can be used for determining the total number of microfiltration (MF) or ultrafiltration (UF) pretreatment membrane elements is 40 UF/MF elements/1,000 m^3/day.

The useful life of first-pass seawater membranes is typically between 5 and 7 years, while the typical useful life of the second-pass brackish water reverse osmosis

(BWRO) membranes is 10 years. As a result, the typical annual average SWRO membrane replacement rate is 14.3% to 20.0% of their initial installed costs. A rule of thumb that can be applied for determining the total number of SWRO membrane elements in the first pass of the RO system is 80 SWRO elements/1,000 m^3/day and the total number of BWRO elements in the second pass of the RO system is 30 BWRO elements/1,000 m^3/day. These rules of thumb could be used in the early stages of desalination project development and conceptual cost estimating. It is preferable, however, for the membrane replacement costs to be determined based on the actual number of membrane elements which will be used for the project.

Both pretreatment and SWRO membranes are replaced when the membrane media fouls irreversibly to levels that require excessive power use for their operation or reduce membrane productivity of water quality below a certain acceptable threshold. Membranes are also replaced when they lose their integrity and cannot produce the target product water quality for a given project and their performance declines irreversibly. The unit costs for RO elements are shown in Table 4.8. The total membrane and cartridge filter replacement costs are typically in a range of US\$0.02/m^3 to US\$0.06/m^3.

5.7 WASTE STREAM MANAGEMENT

The main waste stream of every membrane seawater desalination plant is the RO system concentrate. Concentrate disposal costs include expenditures associated with operation and maintenance of the outfall facilities, concentrate injection wells, evaporation ponds, or mechanical evaporation equipment if such disposal methods are used. These costs may vary widely depending on the disposal method and project size.

In most applications, the ocean discharge of concentrate from desalination plants with open ocean intake is acceptable without any additional treatment and at minimal or no costs. In this case the concentrate disposal cost is typically only US\$0.005/m^3 to US\$0.0075/m^3 of product water.

For open ocean discharges from seawater desalination plants with beach well intakes, the concentrate disposal costs are dependent on the need to aerate the concentrate before its discharge to the ocean or to otherwise treat it if the concentrate exhibits toxicity or has other measurable environmental impacts and may vary in a range of US\$0.01/m^3 to US\$0.05/m^3 of product water.

For sanitary sewer discharge of the concentrate the conveyance costs are mainly driven by the volume of the concentrate, distance of the desalination plant to the point of discharge in the sewer system, the elevation of the point of discharge, and the sewer connection fees. Depending on the location, the sewer connection fees may vary in a wide range from none to several orders of magnitude larger than the conveyance costs. The sewer connection fees are usually related to the available capacity of the sewer facilities and the effect of the concentrate discharge on the operational costs of the wastewater treatment plant, which would provide ultimate treatment and disposal of the concentrate.

Seawater desalination plants generate a number of other waste streams in addition to the plant concentrate. The main waste streams are the pretreatment waste filter backwash and the spent RO membrane cleaning solution. In the case of membrane seawater pretreatment, the desalination plant generates two additional waste streams: chemically enhanced backwash (CEB) and spent pretreatment membrane cleaning solution.

The cost of waste disposal depends on the method of waste disposal used at the desalination plant and the size of the waste streams. In many applications worldwide all waste streams are returned to the ocean for disposal. Therefore, under best-case scenario no additional costs for waste disposal are incurred.

Frequently, the waste filter backwash along with the plant concentrate are the only two desalination plant process streams allowed to be discharged to the ocean, and the rest of the waste streams have to be conveyed to the sanitary sewer for disposal and further treatment. In this case, the expense of waste stream disposal is usually the sewer discharge fee established by the local wastewater collection and treatment agency. This cost may be between US\$0.005/m^3 to US\$0.02/m^3.

In many large seawater desalination plants, the spent filter backwash water has to be treated (typically by sedimentation) before discharge to the ocean. The residuals (sludge) generated during the filter backwash treatment are usually dewatered to solids content of 20% or higher via mechanical dewatering equipment (belt filter presses, centrifuges, or plate-and-frame presses) and disposed to a sanitary landfill. Depending on the capacity and distance of the available landfills in the area of the desalination plant, the waste stream disposal costs are between US\$0.010 and US\$0.020/m^3.

5.8 ENVIRONMENTAL AND PERFORMANCE MONITORING

Every desalination plant has discharge water quality monitoring requirements. These requirements may be applicable to the entire discharge and/or to the individual plant waste streams. In addition, in many environmentally sensitive areas the monitoring requirements encompass not only the discharge but the receiving water body (ocean, groundwater aquifer, or estuary) as well.

Depending on the complexity and frequency of the environmental monitoring required for permit compliance, the discharge monitoring costs could be substantial and should be taken under consideration in determining the overall plant O&M costs. Plant discharge monitoring costs may vary between US\$0.002/m^3 to US\$0.005/m^3.

Plant performance monitoring costs are expenses needed to measure and analyze key intake water quality constituents and process performance parameters (i.e., silt density index (SDI), turbidity, temperature, pH, salinity of plant feed water and the pretreated water, etc.). These O&M costs depend on the level of automation and plant complexity. Product water monitoring costs are expenditures associated with sample collection, laboratory analysis, and data management and reporting, which are required to be completed in order to comply with all applicable regulatory requirements associated with the product water supply. Typically, plant performance and product water quality monitoring costs are between US\$0.004/m^3 to US\$0.008/m^3.

5.9 INDIRECT O&M COSTS

Indirect O&M costs include annual expenditures for staff training, professional development and certification; expenditures for consumables and maintenance of plant service vehicles; administrative and utility/service (water, sewer, telephone, etc.) expenses; taxes associated with plant operations; operations insurance; contingency and other O&M reserve funds. These costs also incorporate the fees/profit for plant operation if a private contractor runs the plant. Typically plant indirect O&M costs vary in a wide range of 5.0% to 20.0% of the total O&M costs (US$0.02/m³ to US$0.06/m³).

5.10 OPERATION AND MAINTENANCE COST CURVES

This section incorporates graphs for the annual direct non-energy operation and maintenance costs for key facilities commonly used in seawater desalination plants. These costs are expressed in million US$ per year (adjusted to year 2018) and are presented as a function of the desalination plant intake or fresh water production costs. The plant facilities for which O&M cost curves are developed match these in Chapter 4 (Section 4.2).

Except for annual energy expenditures, the cost curves incorporate all other fixed and variable costs associated with operation and maintenance of the desalination plant facilities including: labor; chemicals (calculated for the average values of the applicable chemicals presented in Table 5.3); preventive and reactive maintenance and replacement of all treatment process related equipment and instrumentation; membrane and cartridge filter replacement; and operation and maintenance of all plant piping, valves, and service utilities and equipment. Separate cost curves are provided for indirect plant expenditures because they are impossible to assign to a particular plant treatment component, equipment, or technology.

5.10.1 Intake Structures and Piping – Annual O&M Cost

5.10.1.1 O&M Cost of Open Onshore Intakes

Figure 5.2 depicts the total direct, non-energy related annual O&M costs for onshore intakes based on the intake flow they collect. The onshore intake costs incorporate all expenditures for operating and maintaining intake structures, equipment, and instrumentation, and the associated labor for their operation, maintenance, and upkeep. Such costs encompass expenditures for operation of a sodium hypochlorite feed system for marine growth control. The cost curve also encompasses expenditures for dredging of the intake channel, lagoon, or forebay, which is commonly practiced once every 3 to 5 years for plants with open onshore intakes – the costs are based on 5-year intake dredging frequency pro-rated annually.

5.10.1.2 O&M Cost of Open Offshore Intakes

Figure 5.3 depicts the annual O&M costs for two types of the most commonly used offshore intake systems – intakes with high-density polyethylene (HDPE) pipelines

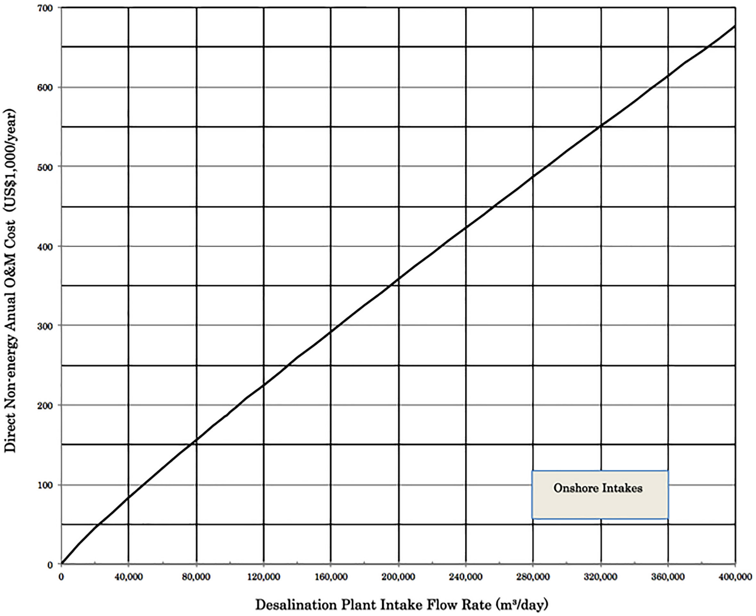

FIGURE 5.2 Annual O&M cost for open onshore intakes.

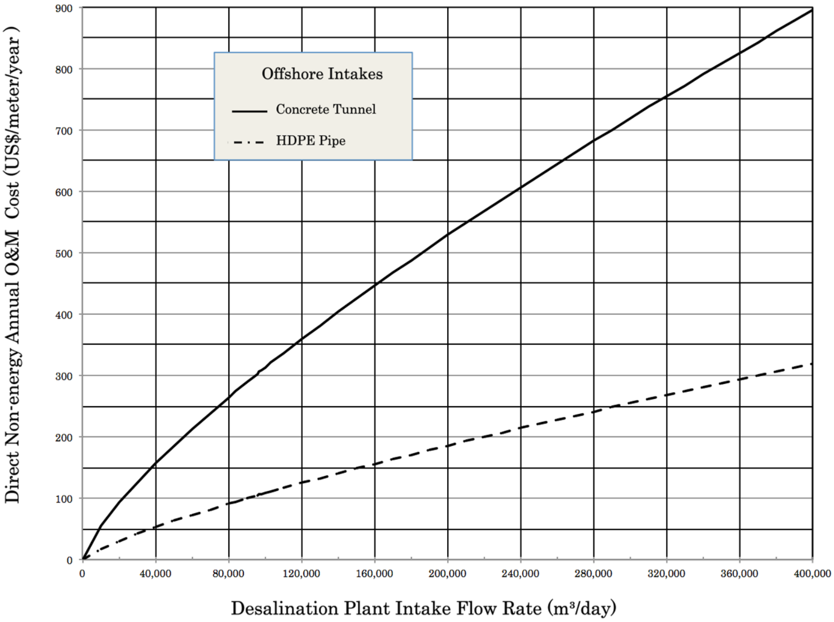

FIGURE 5.3 Annual O&M cost for open offshore intakes.

and concrete tunnels. In both cases the intake system includes concrete offshore intake towers, which are connected to an onshore intake pump station via one or more HDPE pipelines or one concrete tunnel, respectively. These costs are presented as a function of the plant intake flow and are expressed in dollars per meter of length of the intake conduit (HDPE pipeline or tunnel).

Similar to the O&M costs of onshore intakes, these annual expenditures include the operation and chemical costs of a sodium hypochlorite feed system for suppression of marine growth on the inner walls of the intake conduits.

The O&M costs would typically vary within 30% envelope from one location to another based on site-specific conditions such as water depth, coastal geology, and source water quality. Analysis of Figure 5.3 indicates that the operation of desalination plant intakes with deep tunnels is several times costlier than that of HDPE pipelines because of the more extensive and costly requirements for monitoring of the structural integrity of the intake tunnels and the significantly higher repair costs in the case of failure of the structural integrity of the tunnels.

5.10.2 INTAKE PUMP STATIONS – ANNUAL O&M COST

Figure 5.4 presents the annual O&M costs for intake pump stations with dry- and wet wells. The cost curves do not incorporate expenditures associated with the operations of the intake screens and the piping interconnecting the pump station and the downstream pretreatment facilities and the electrical costs to run the pumps.

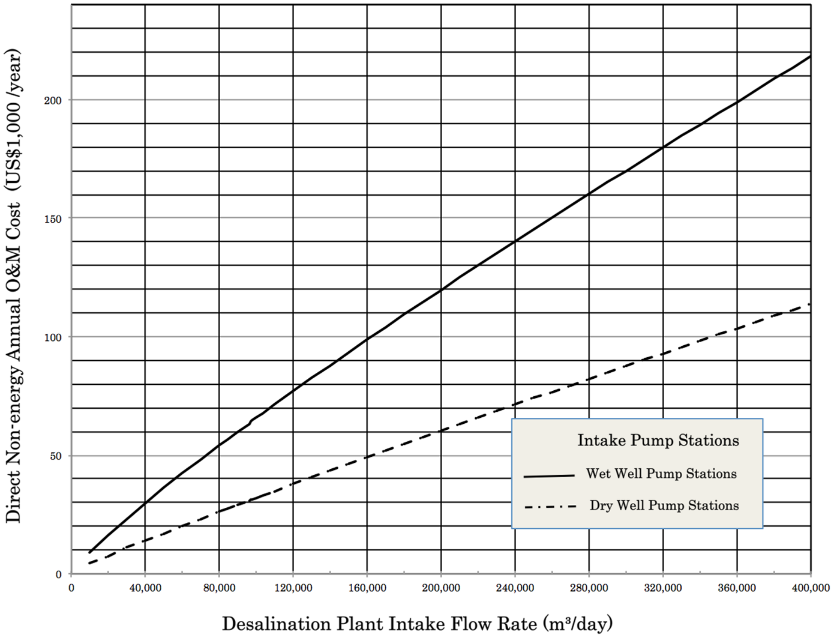

FIGURE 5.4 Annual O&M cost for intake pump stations.

It is important to note that the O&M costs for dry-well pump stations are lower than these for pump stations where the pumps are installed in wet wells because of the significantly lower maintenance expenditures for the intake pumps. In dry-well configuration, the intake pumps and their motors are located in a separate ventilated building and are protected from the impact of inclement weather, which extends their useful life – the pumps and service equipment experience less corrosion, and are easier to access for monitoring, maintenance, replacement, and repairs. Such lower O&M expenditures to some extent compensate for the higher construction costs associated with building dry-well intake pump stations (see Figure 5.4). In pump stations with wet-well configuration most of the key pump components (except for the motor) are installed in the source water and exposed to more corrosive environment.

5.10.3 BAND AND DRUM SCREENS – ANNUAL O&M COST

Figure 5.5 provides annual O&M cost estimates for band and drum screens as a function of plant intake flow. As shown in this figure, band screens are less costly to operate and maintain than drum screens for projects of the same size. Drum screens are significantly less advantageous than band screens in the case of jellyfish outbreaks because they require more complex and labor-intensive maintenance. The O&M costs for both band and drum screens include expenditures for disposal of the screenings to a sanitary landfill. The cost curves do not include the expenditures for energy used for the operations of the screens.

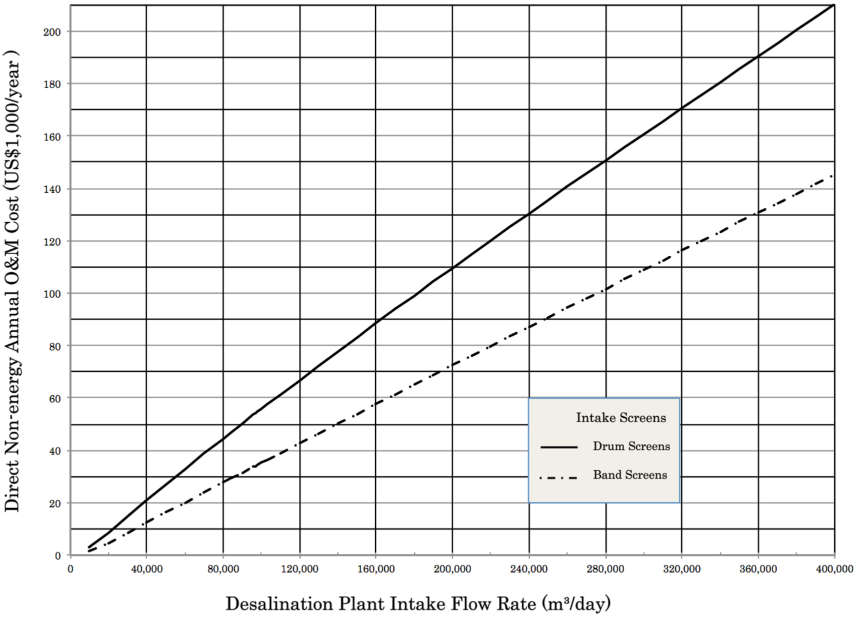

FIGURE 5.5 Annual O&M cost for drum and band intake screens.

5.10.4 WEDGEWIRE SCREENS – ANNUAL O&M COST

A cost curve for the annual O&M expenditures for wedgewire screens is shown in Figure 5.6. As seen from the comparison of this figure to Figure 5.5, in general, wedgewire screens are less costly to operate and maintain than band or drum screens because they do not have moving components, and do not generate screenings that require offsite hauling and disposal.

The O&M expenditures for wedgewire screens include an air compressor for periodic release of bursts of air on the inner side of the screens in a direction opposite to source water inflow to remove debris accumulated on the surface of the screens. Such costs also include annual inspections by divers and cleaning of the outside surface of the screens, as needed.

5.10.5 MICROSCREENS – ANNUAL O&M COST

Figure 5.7 depicts a budgetary cost graph for the operation and maintenance of microscreen systems (e.g., self-cleaning strainers or disk filters) as a function of the intake flow they are designed to process. The costs on this graph do not include the energy expenditures to pump water through the screens.

5.10.6 CARTRIDGE FILTER SYSTEM – ANNUAL O&M COST

A graph of the annual O&M costs for cartridge filtration systems is presented in Figure 5.8. The main component of the O&M costs is the replacement cost of the

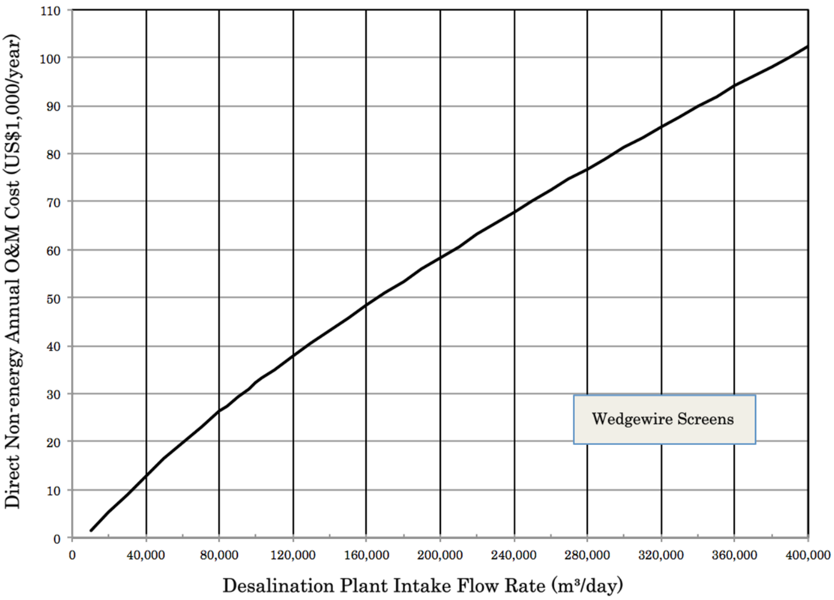

FIGURE 5.6 Annual O&M cost for wedgewire intake screens.

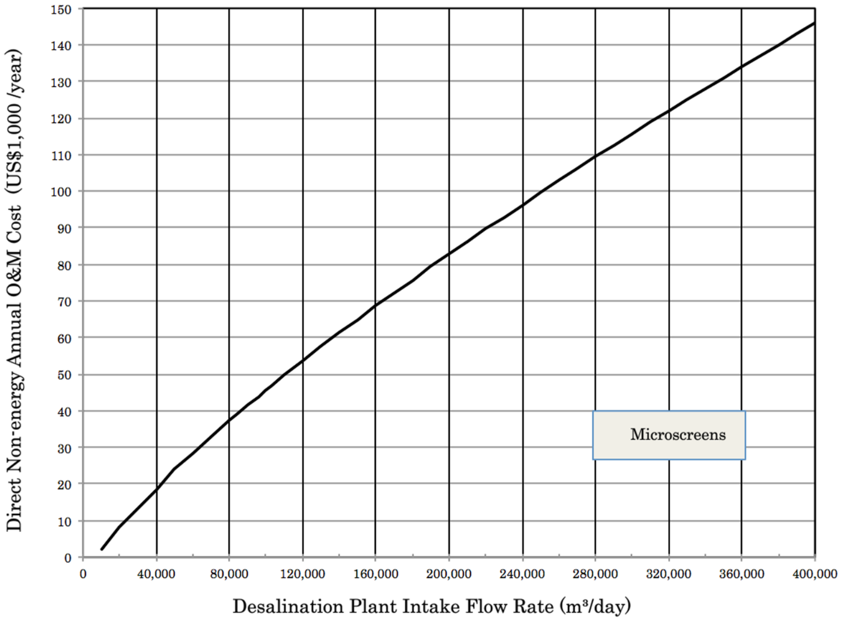

FIGURE 5.7 Annual O&M cost for microscreens.

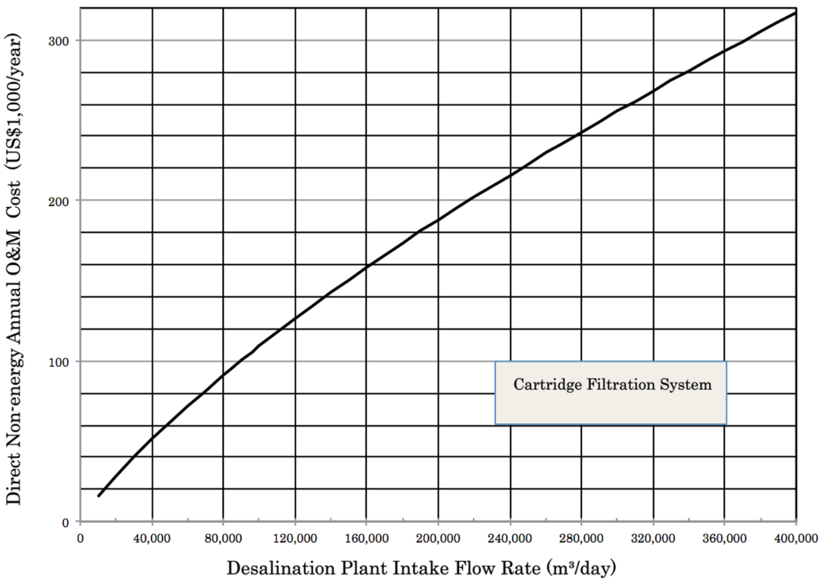

FIGURE 5.8 Annual O&M cost for cartridge filtration systems.

cartridge filters, which is based on a unit cartridge filter cost of US$10/cartridge filter and replacement frequency of once every 4 months. In addition, the cost graph incorporates labor expenditures associated with cartridge filter replacement and disposal costs for the spent cartridge filters.

Since both the unit cartridge filter costs and replacement rates can vary for the site-specific conditions of a given project, the O&M costs for cartridge filtration may vary in a range of 30% to 50% above or below the values presented in the figure. In some plants with a poorly performing pretreatment system the cartridge filters may need to be replaced once every week to two weeks, which will significantly increase the cartridge filter replacement costs.

It should be noted that in addition to the costs for replacement of the cartridge filters, Figure 5.8 is also reflective of the expenditures for the annual inspection of the cartridge filter vessels to verify their integrity and check for corrosion and the condition of the protective epoxy coating layer, as well as the maintenance of the differential pressure monitoring equipment and instrumentation across the cartridge filtration system.

5.10.7 LAMELLA SETTLERS AND DAF CLARIFIERS – ANNUAL O&M COST

Figure 5.9 shows the annual non-energy O&M costs for lamella settlers and DAF clarifiers. The cost curves encompass all expenditures for chemicals typically used for source seawater conditioning (e.g., ferric chloride and acid). In addition, the DAF cost curve encompasses the expenditures associated with the source water saturation with air (air compressors) as well as pumping costs for recirculation of 10% of the clarified water to the feed of the DAF units.

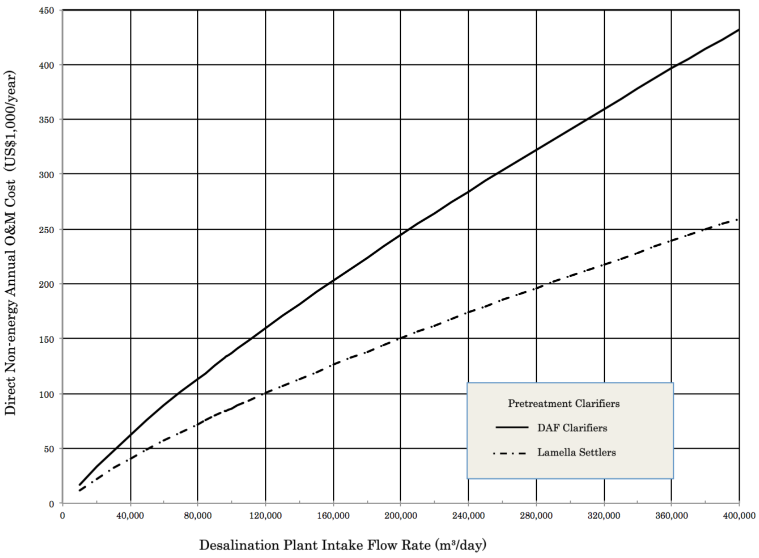

FIGURE 5.9 Annual O&M cost for DAF clarifiers and lamella settlers.

As indicated in Figure 5.9, lamella settlers are less costly than DAF clarifiers for the same volume of pretreated source water. Usually, lamella settling is more cost-effective for source waters with high source water turbidity variations and low content of hydrocarbons in the saline source water. DAF clarifiers are more widely used for pretreatment of source seawater of high algal content and/or elevated potential for oil and grease contamination. O&M experience to date shows that DAF clarifiers have not met performance expectations as effective clarification technology for mitigation of algal bloom impacts on desalination plant performance (see Voutchkov, 2017).

5.10.8 GRANULAR MEDIA PRETREATMENT FILTERS – ANNUAL O&M COST

Figure 5.10 depicts the annual O&M costs for gravity and pressure driven granular dual media filters in US$2018. These costs include both expenditures for chemical conditioning of the source seawater (coagulation and flocculation), and energy and labor expenditures for filter media backwashing, inspection, and refilling as needed.

The figure is reflective of the costs for down-flow dual media filters with a top layer of anthracite or pumice and a bottom layer of sand. As seen from Figure 5.10, pressure filters have a lower total non-energy annual O&M cost than gravity filters, for the same daily volume of pretreated saline source water, because they typically require less operator attention. However, if energy is added to the total O&M costs, the operation of pressure filters is usually more costly than that of gravity filters because of the additional energy expenditures for pressurization of the source seawater through the filtration media. Additional information on the O&M requirements

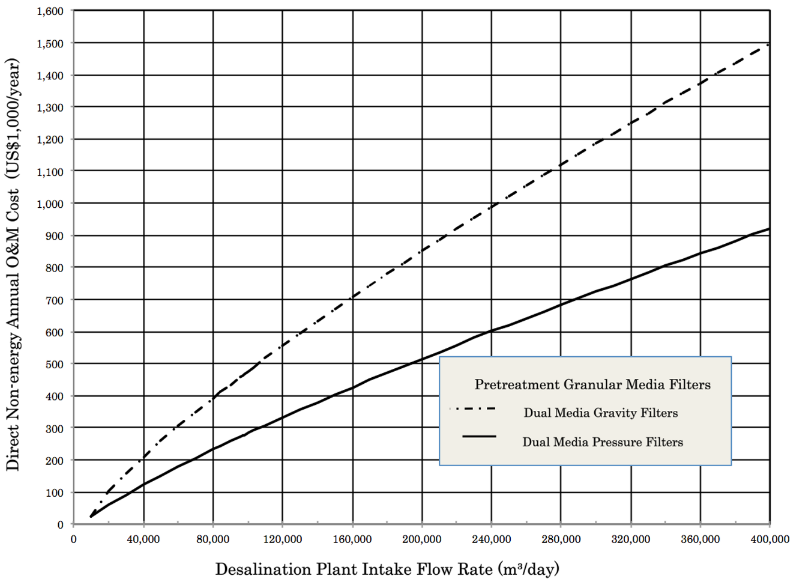

FIGURE 5.10 Annual O&M cost for granular dual media filters.

and differences of pressure and gravity granular media filters is provided elsewhere (Voutchkov, 2014).

5.10.9 MEMBRANE PRETREATMENT FILTERS – ANNUAL O&M COST

The membrane pretreatment costs presented in Figure 5.11 include all non-power expenditures (chemicals, membranes, equipment replacement and repair, etc.) associated with the operation of the membrane filtration system employed at the desalination plant as well as the operation of the filtration related services systems for conventional and chemically enhanced membrane filter backwashes, the periodic cleaning in place (CIP) of the membranes, as well as labor for pretreatment system operation, membrane replacement, and equipment repair.

Due to the lack of standardization of membrane module sizes, membrane rack configurations, operating pressures or vacuum, and membrane materials, it is difficult to develop a generic curve for the annual O&M costs for membrane pretreatment systems. Therefore, rather than a single cost curve, Figure 5.11 presents a range of year-2018 costs of membrane pretreatment for desalination plants as a function of the plant intake flow rate.

5.10.10 SWRO DESALINATION SYSTEMS – ANNUAL O&M COST

As described in detail in Chapter 4, three SWRO membrane system configurations are most widely used in practice at present: single-pass; full two-pass, and split-partial two-pass (see Figures 4.12, 4.14, and 4.16). The following sections present the non-energy direct annual O&M costs for these systems. Such costs

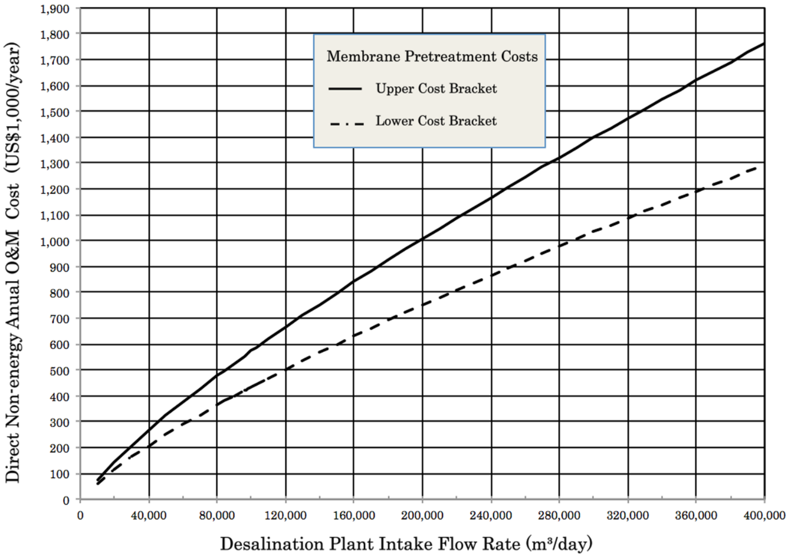

FIGURE 5.11 Annual O&M cost for membrane pretreatment filters.

encompass expenditures for operation and maintenance of the key system components (e.g., high-pressure pumps; energy recovery devices and booster pumps; chemical feed systems for addition of antiscalant, for dechlorination of the feed seawater to the RO membranes, and for pH adjustment; clean-in-place (CIP) system for cleaning of the RO membrane racks; and all auxiliary equipment and instrumentation). In addition, the annual O&M costs include expenditures for replacement of RO membranes.

The O&M costs presented in graphs 5.12 through 5.14 do not include expenditures for energy used for operation of the RO system. These graphs are reflective for the differences in RO system designs for different source water salinities such as permeate recovery and flux. The annual costs for plants processing seawater with salinity within the range of 35,000 or 46,000 mg/L could be determined by extrapolation.

5.10.10.1 Single-Pass SWRO Systems

The direct non-energy annual costs for operation and maintenance of single-pass SWRO desalination systems are shown in Figure 5.12.

Such systems are widely used for production of drinking water, especially when the source seawater is of relatively low salinity and the product water does not have to comply with stringent limits for removal of boron, bromides, chlorides, or sodium.

5.10.10.2 Full Two-Pass SWRO Systems

Figure 5.13 depicts the cost curves for full two-pass SWRO systems, which are widely used for desalination of high-salinity source seawater and/or to produce water of very low mineral content. More detailed explanation of the function of these systems is provided in Chapter 4.

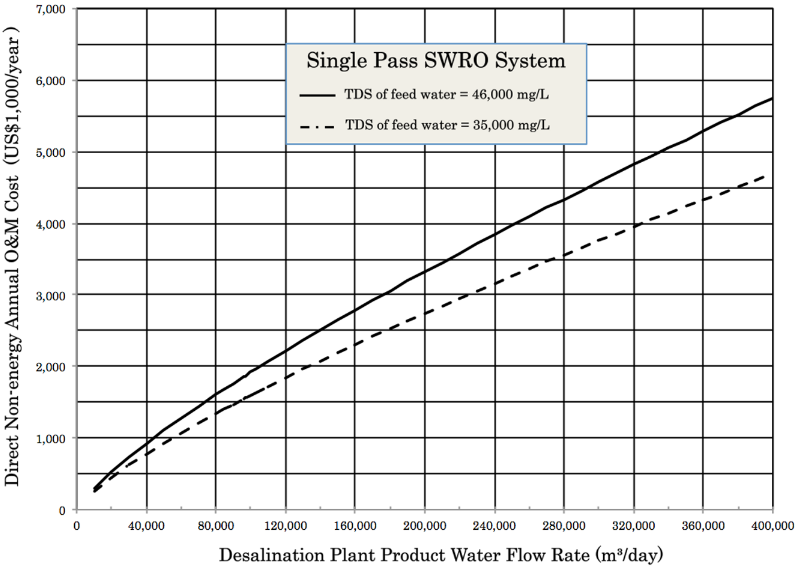

FIGURE 5.12 Annual O&M cost for single-pass SWRO systems.

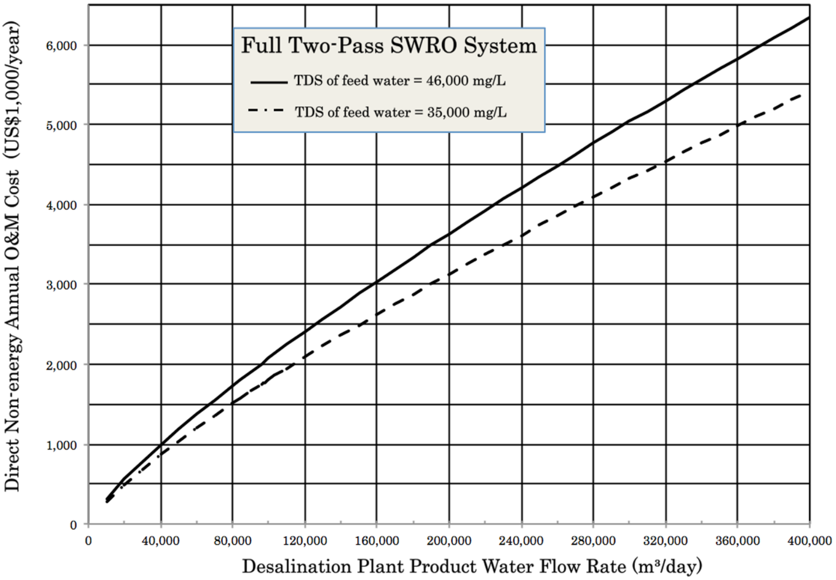

FIGURE 5.13 Annual O&M cost for full two-pass SWRO systems.

5.10.10.3 Split-Partial Two-Pass SWRO Systems

At present, split-partial two-pass systems with a collection of permeate from the front end of the membrane vessels of SWRO trains are the most commonly implemented in new desalination projects built over the last 10 years worldwide – Figure 5.14

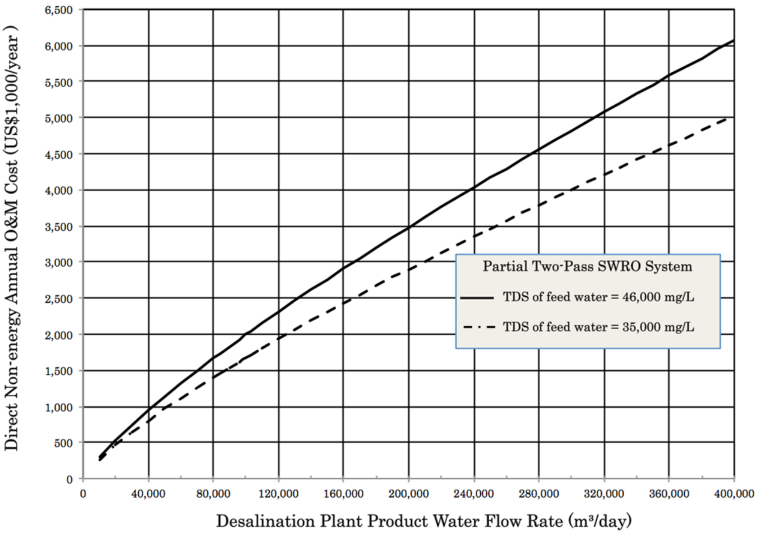

FIGURE 5.14 Annual O&M cost for split-partial two-pass SWRO systems.

depicts the O&M costs for such systems. As explained in Chapter 4, split-partial two-pass SWRO systems yield both capital cost savings and energy demand reduction as compared with full two-pass systems. Advanced configurations of split-partial two-pass systems are further discussed in Chapter 8 – Cost Management.

5.10.11 POST-TREATMENT SYSTEMS – ANNUAL O&M COST

Post-treatment of desalinated water encompasses two steps of conditioning of permeate produced by desalination plants – stabilization (e.g., addition of alkalinity and hardness) and disinfection. This section presents cost curves for the most commonly used permeate stabilization and disinfection facilities.

5.10.11.1 Post-Treatment – Stabilization

Figure 5.15 depicts non-energy cost curves for the two most commonly used post-treatment stabilization technologies: (1) addition of lime (calcium hydroxide) and (2) treatment of permeate with carbonic acid originating from liquid carbon dioxide followed by permeate processing through limestone (calcite) contact filters. Lime and carbon dioxide addition to the SWRO permeate is more commonly practiced worldwide due to the limited availability of limestone in some locations. However, usually the use of limestone contact filtration is the preferred method of stabilization because it is easier to operate and control. As seen from Figure 5.15, permeate stabilization by addition of carbon dioxide and limestone filtration is significantly less costly than lime/CO_2 stabilization. Key advantages and disadvantages of both permeate stabilization technologies are discussed elsewhere (Lahav et al., 2012).

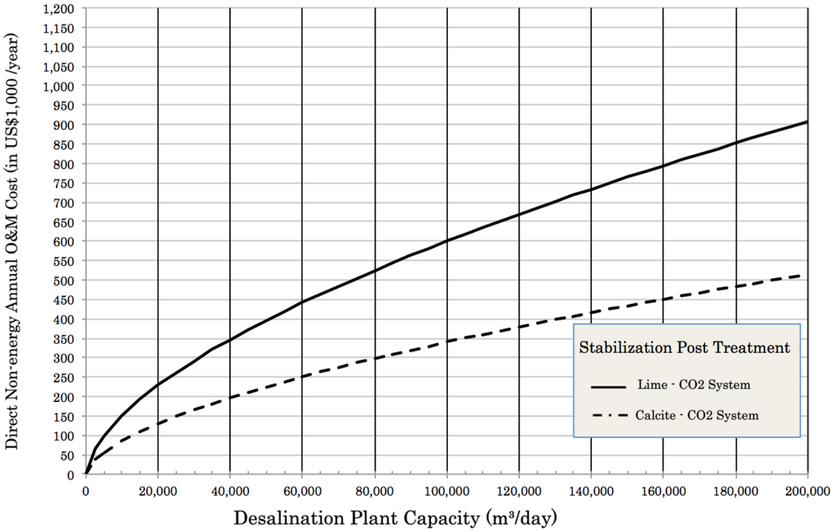

FIGURE 5.15 Annual O&M cost for lime and calcite stabilization systems.

5.10.11.2 Post-Treatment – Disinfection

After stabilization, desalinated water is usually treated with disinfectant to suppress pathogen growth in the distribution system and protect public health. The two most commonly used disinfectants for desalinated water are sodium hypochlorite and chlorine dioxide. Sodium hypochlorite could either be used in a liquid form as a 10%–15% solution or generated on site. Usually, the onsite generation of sodium hypochlorite is costlier than its use as a liquid solution. In the Middle East and other locations of the world with hot climate where the strength of liquid sodium hypochlorite is quickly diminished by the high ambient temperature, chlorine dioxide is the preferred disinfectant. Cotruvo et al. (2010) provide detailed discussions of the advantages and disadvantages of alternative disinfectants for desalinated water.

Figure 5.16 presents the non-energy annual O&M costs for using chlorine dioxide and bulk sodium hypochlorite for disinfection of desalinated water. These expenditures include the cost of the chemicals used for disinfection as well as the costs associated with the O&M of the chemical feed systems for the respective disinfectants. Since chlorine dioxide is always generated at the plant site, the O&M costs for this disinfectant include the labor, spare parts, and maintenance costs for the onsite chloride dioxide generation system. As seen from Figure 5.16, the use of sodium hypochlorite yields lower annual O&M expenditures, which explains why this disinfectant is the most widely used chemical at present worldwide.

5.10.12 OTHER DIRECT ANNUAL O&M COSTS

Figure 5.17 shows other direct annual O&M costs for facilities and equipment, which are not encompassed into the cost curves depicted in Figures 5.2 through 5.16. Such

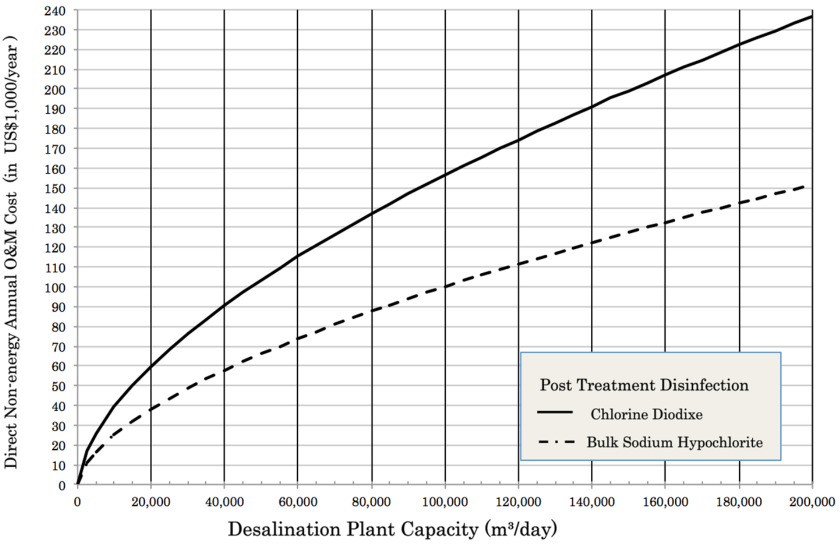

FIGURE 5.16 Annual O&M cost for chlorine dioxide and bulk sodium hypochlorite disinfection systems.

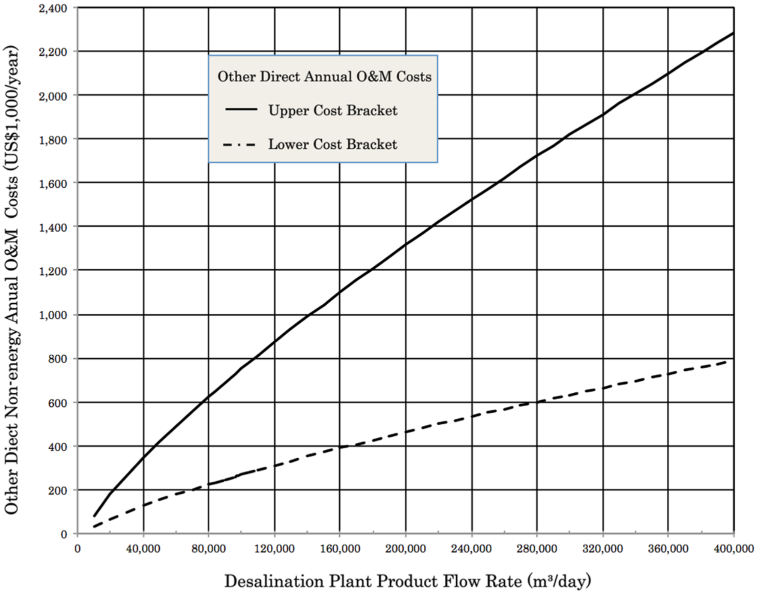

FIGURE 5.17 Other direct annual O&M costs.

costs include the expenditures for upkeep of all plant buildings, interconnecting plant piping and fittings, service air and water systems, high voltage electrical system and motor control centers, the plant automation and control system, and other plant support systems, which are components of the main water production process.

Because many of the costs listed above are site specific and vary significantly from plant to plant, Figure 5.17 depicts the other direct costs in a bracket format. The actual O&M expenditures are typically within the cost curve envelope, except for projects of unusual location, plant site configuration, product water quality requirements, power supply source, or other circumstances.

5.10.13 Indirect Annual O&M Costs

The key components of the indirect annual O&M costs are described in Section 5.9. Figure 5.18 provides a graphic representation of these costs based on actual SWRO desalination projects built worldwide over the last 10 years. As indicated previously, these costs are often influenced by many site-specific factors and therefore they are presented in a bracket format.

5.11 EXAMPLE OF DESALINATION PROJECT O&M COST ESTIMATE

Table 5.5 presents a conceptual annual O&M cost estimate for the 100,000-m^3/day seawater desalination project described in Chapter 4 – Section 4.7.1. Project Description. These costs total US$14.6 million per year. The O&M costs of the desalination plant are determined applying two different methods – “Rule-of-Thumb Range Method” and “Cost-Curve Based Method.”

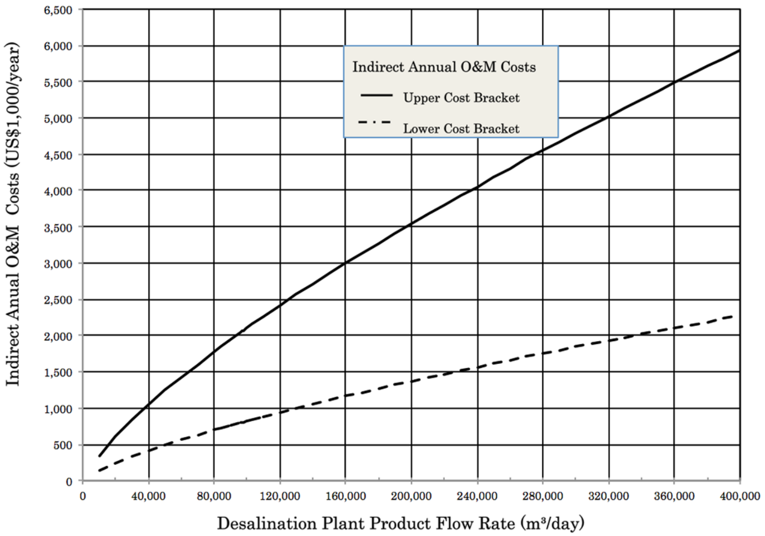

FIGURE 5.18 Indirect annual O&M costs.

TABLE 5.5

Projected Annual O&M Cost Breakdown by Fixed and Variable Components

	Annual O&M Costs		
Cost Item	**(US$/year)**	**(US$/m³) @ 100% Availability**	**(% of Total)**
	Variable O&M Costs		
1. Energy	7,446,000	0.204	51.0
2. Chemicals	1,095,000	0.030	7.5
3. Replacement of membranes and cartridge filters	885,000	0.024	6.1
4. Waste stream disposal	547,500	0.015	3.7
Subtotal – Variable O&M Costs	*9,973,500*	*0.273*	*68.3*
	Fixed O&M Costs		
5. Labor	1,095,000	0.030	7.5
6. Maintenance	1,733,750	0.0475	11.9
7. Environmental and performance monitoring	346,750	0.0095	2.3
8. Indirect	1,460,000	0.040	10.0
Subtotal – Fixed O&M Costs	*4,635,500*	*0.127*	*31.7*
Total O&M costs	US$14,609,000/yr	0.400/m³	100%

5.11.1 ANNUAL O&M COST ESTIMATE BASED ON "RULE-OF-THUMB RANGE METHOD"

The rule-of-thumb range method uses the ranges for the various cost components described in Sections 5.2 through 5.9. The following paragraphs describe the methodology used to determine the cost items listed in Table 5.5:

Item 1: "Energy" of US$7.446 million/year is calculated for the total energy use of the desalination plant of 3.40 kWh/m^3 and unit energy cost of US$0.06/kWh as defined in Chapter 4–3.40 kWh/m^3 × 100,000 m^3/day × 365 days × US$0.06/kWh = US$7,446,000/year. The breakdown of energy costs for the example project is shown in Figure 5.1.

Item 2: "Chemicals" of US$1.095 million is calculated for the low bracket of US$0.030/$m^3$ of the typical chemical cost range of US$0.030 to US$0.060/m^3, shown in Section 5.3. The low end of the range value was selected because the source water quality defined in Table 4.11 is very good and the consumption of conditioning chemicals is expected to be minimal.

Item 3: "Replacement of Membranes and Cartridge Filters" of US$885,000/year was determined using the rules-of-thumb values for the number of SWRO and BWRO membranes and cartridge filters defined in Section 5.6 and Table 4.8. The number of first-pass SWRO elements = 80 elements/1,000 m^3/day × 100,000 m^3/day = 8,000 SWRO elements. At useful life of 5 years, the annual replacement rate for these elements is: 8,000/5 years = 1,600 SWRO elements/year. At an average cost of SWRO element of US$425/element (range US$350–500/SWRO element – Table 4.8) the annual SWRO membrane element replacement cost is 1600 SWRO elements × US$425/element = US$680,000/year.

Similarly, the number of second-pass BWRO elements = 30 elements/1,000 m^3/day × 100,000 m^3/day = 3,000 BWRO elements. At useful life of 10 years, the annual replacement rate for these elements is: 3,000/10 years = 300 BWRO elements/year. At an average cost of BWRO element of US$350/element (range US$300–400/BWRO element – Table 4.8) the annual BWRO membrane element replacement cost is 300 SWRO elements × US$350/element = US$105,000/year.

Using the cartridge filter (CF) rule of thumb of 25 CFs/1,000 m^3/day × 100,000 m^3/day = 2,500 cartridge filters. At a replacement rate of 4 times per year (once every 3 months) the total annual number of CFs to be replaced is 2,500 × 4 times = 1,000. At an average cost of CF of US$10/CF (range US$8–14/CF – Section 5.6) the annual cartridge filter replacement cost is 2500 CFs × 4 replacements per year × US$10/CF = US$100,000/year.

When the annual replacement costs for SWRO elements (US$680,000/year), BWRO elements (US$105,000/year), and cartridge filters (US$100,000/year) are added together the total replacement cost is US885,000/year.

Item 4: "Waste Stream Disposal" – the annual cost for this item is determined using the rule of thumb presented in Section 5.7 – US$0.015/$m^3$/day ×

100,000 m^3/day × 365 days = US\$547,500/year. This unit cost is selected as the average value of the range of costs of US\$0.010 and 0.020/m^3/day for desalination plants which have a solids handling system for spent filter backwash water which includes mechanical dewatering and disposal of the sludge to a landfill.

Item 5: "Labor" annual O&M cost of US\$1.095 million is calculated for the average value of the rule-of-thumb range of US\$0.015 to 0.045/m^3/day (see Section 5.4) – US\$0.030/m^3/day × 100,000 m^3/day × 365 days = US\$1,095,000.

Item 6: "Maintenance" of US\$1,733,750/year is determined for the average value of the rule-of-thumb range of US\$0.025 to 0.070/m^3/day (see Section 5.5) – US\$0.0475/m^3/day × 100,000 m^3/day × 365 days = US\$1,733,750.

Item 7: "Environmental and Performance Monitoring" is calculated for the sum of the average values of environmental monitoring (US\$0.0035/m^3/day) and plant performance monitoring ((US\$0.0060/m^3/day) – US\$0.0095/m^3/day × 100,000 m^3/day × 365 days = US\$346,750.

Item 8: "Indirect Costs" of US\$1,460,000/year is determined for the average value of the rule-of-thumb range of US\$0.02 to 0.06/m^3/day (see Section 5.9) – US\$0.04/m^3/day × 100,000 m^3/day × 365 days = US\$1,460,000.

Review of Table 5.5 indicates that variable O&M costs are 68.3% of the total annual O&M cost. The unit O&M cost is determined for 100% of plant availability (i.e., the desalination plant producing 100,000 m^3/day during 365 days of the year). If the plant is designed for availability of 96% as indicated in the project description included in Chapter 4, the actual O&M cost will be higher because the plant is expected to have the same amount of annual expenditures (i.e., annual cost is prorated over a smaller annual volume of product water of 0.96 × 100,000 m^3/day = 96,000 m^3/day). As a result the actual unit O&M cost of the plant at 96% availability will be US\$0.40/m^3/0.96 = US\$0.417/m^3.

5.11.2 ANNUAL O&M COST ESTIMATE USING THE "COST-CURVE BASED METHOD"

The annual O&M cost of the 100,000-m^3/day desalination plant could also be determined using the cost curves presented in Section 5.10. In this case, the O&M cost has a different breakdown, shown in Table 5.6.

The cost-curve based method applies the cost curves for the various O&M cost components described in Section 5.10. The following paragraphs explain the methodology used to determine the cost items listed in Table 5.6:

Item 1: "Intake" of US\$250,000/year is calculated as a sum of the annual costs for the offshore intake facilities (intake tower and pipeline) presented in Figure 5.3 (US\$20,000/m.year @ 200 m = US\$40,000/year) plus the annual non-energy O&M costs for the intake pump station determined from Figure 5.4 (US\$130,000/year) and the costs for band screens identified

TABLE 5.6
Project Annual O&M Cost Breakdown by Plant Components

	Annual O&M Costs		
Cost Item	**(US$/year)**	**(US$/m³) @ 100% Availability**	**(% of Total)**
1. Intake	250,000	0.006	1.7
2. Pretreatment	1,123,000	0.031	7.7
3. Reverse osmosis system	3,380,000	0.093	23.1
4. Post-treatment	440,000	0.012	3.0
5. Other direct non-energy O&M costs	510,000	0.014	3.5
6. Energy costs	7,446,000	0.204	51.0
Subtotal - Direct O&M Costs	*13,149,000*	*0.360*	*90.0*
7. Indirect O&M costs	1,460,000	0.040	10.0
Total O&M costs	US$14,609,000/yr	0.400/m³	100%

using Figure 5.5 – US$80,000/year – all of which are established for plant intake flow of 220,000 m^3/day.

Item 2: “Pretreatment” of US$1,123,000/year is calculated as a sum of the annual costs for the cartridge filtration system presented in Figure 5.8 (US$202,000/year) plus the annual non-energy O&M costs for the gravity dual media filters from Figure 5.10 (US$921,000/year), all of which are determined for plant intake flow of 220,000 m^3/day. It should be noted that the total annual O&M costs of US$202,000/year include both the expenditures for purchasing cartridge filters (US$100,000/year) as well as the labor costs for their replacement four times per year, for disposal of the spent cartridge filters to a sanitary landfill, and for the inspection and repair of the cartridge vessels, and instrumentation and controls of the cartridge filtration system.

Item 3: “Reverse Osmosis System” of US$3,380,000/year is determined from Figure 5.13 for full two-pass SWRO system, source water salinity of 35,000 mg/L, and product water flow of 100,000 m^3/day.

Item 4: “Post-treatment” of US$440,000/year is calculated as a sum of the annual costs for the limestone/CO_2 stabilization system presented in Figure 5.15 (US$340,000/year) plus the annual non-energy O&M costs for bulk sodium hypochlorite disinfection system from Figure 5.16 (US$100,000/year) all of which are determined for plant product water flow of 100,000 m^3/day. It should be noted that the total annual O&M costs of US$202,000/year include both the expenditures for purchasing cartridge filters (US$100,000/year) as well as the labor costs for their replacement four times per year, for disposal of the spent cartridge filters to a sanitary landfill, and for the inspection and repair of the cartridge vessels, and instrumentation and controls of the cartridge filtration system.

Item 5: “Other Direct Non-energy Costs” of US$510,000/year is estimated from Figure 5.17 for plant product water flow of 100,000 m^3/day.

Item 6: “Energy Costs” value of $7,446,000/year is calculated using the unit power demand for the entire plant of 3.4 kWh/m^3 and plant production capacity of 100,000 m^3/day as already explained in the previous section.

Item 7: “Indirect O&M Costs” of US$1,460,000/year is calculated based on a reading from Figure 5.18 for plant product water flow of 100,000 m^3/day.

Comparison of the two methods for calculation of desalination plant annual O&M cost presented in Tables 5.5 and 5.6 indicates that they have yielded the same result – US$14,609,000/year. Either one of the two methods could be used successfully for preparing conceptual cost estimates. However, the rule-of-thumb range method could be used to determine the breakdown of the annual O&M costs into variable and fixed components, which is very useful when calculating the total cost of water production (see Chapter 6).

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6 Water Production Cost

6.1 INTRODUCTORY REMARKS

The cost of water production encompasses all expenditures associated with project implementation, operation, and maintenance and financing, and consists of fixed and variable components. The fixed water costs are expenditures associated with plant construction and with repayment of the capital investment in the plant (i.e., capital cost recovery); and of the portion of the annual O&M expenditures that are independent of the actual volume of water produced by the desalination plant (labor, maintenance, environmental and performance monitoring, and indirect O&M costs). The "variable cost of water" component incorporates O&M expenditures that are directly related and usually proportional to the actual volume of produced desalinated water (power, chemicals, replacement of membranes and cartridge filters, and waste stream disposal).

When the desalination plant is delivered under a build-own-operate-transfer (BOOT) contract between a public agency and a private contractor, the water tariff structure under which the water utility purchases water is typically reflective of the cost of the water structure described above. The tariff usually includes capacity payment components, which compensate the private contractor for the fixed cost associated with water production, and a commodity (output) tariff payment component, which provides compensation for the contractor's variable O&M expenditures.

6.2 FIXED COST COMPONENTS

6.2.1 Capital Cost Recovery

The capital cost for construction of the desalination plant is usually amortized over the term of repayment of the capital used to build the desalination plant (typically a period of 5–20 years). To determine the amortized value of the capital cost this cost is divided by a capital recovery factor (CRF) and by the plant's design capacity availability factor. The CRF is a function of the interest rate of the capital and the number of years over which the investment is recovered (i.e., the plant capital expenditures are repaid). The CRF can be calculated using the following formula:

$$\mathrm{CRF} = \frac{(1+i)^n - 1}{\left(i(1+i)^n\right)}$$

where:

n is the period of repayment of capital expenditures
i is the interest rate of the amortized investment

For example, the CRF for the hypothetical 100,000-m³/day desalination project discussed in Chapter 4, that has a capital cost of US$171.5 million, repayment period of 20 years, and amortization rate of 5.73%, is 11.756 (see Section 4.7 for project description). Therefore, the project's annual amortized (annualized) capital cost is US$171.5 million/11.756 = US$14,588,295/yr. The capital cost recovery portion of the cost of water for this example project is: US$14,588,295/yr./(100,000 m³/day × 365 days) = US$0.400/m³. Since the plant has a design capacity availability factor of 96%, the capital cost recovery charge will be increased accordingly to US$0.40/m³/(96%) = US$0.416/m³.

In many projects, the capital investment is a combination of equity and debt, which have different interest rates of return on investment. In addition, these interest rates may vary over the repayment period. As a result, the calculation of the capital cost recovery for such project may not be as straightforward as shown above, and typically requires the development of a financial model that reflects all specific features and terms of the various investments used for the project.

Development of a financial model for a given desalination project is usually the responsibility of the project developer/owner. If the project developer does not have adequate in-house capabilities to develop a financial model of the level of sophistication needed to obtain competitive financing, typically the developer/owner retains a specialized company to provide the necessary expertise.

6.2.2 OTHER FIXED COSTS

Besides capital cost recovery, the other fixed components of the water production cost are:

- Labor costs;
- Maintenance costs;
- Plant environmental and performance monitoring costs;
- Indirect O&M costs.

These costs are typically calculated by dividing the annual fixed O&M expenditures by the design average annual production capacity of the desalination plant and by the plant design capacity availability factor.

The fixed cost component of the total water production cost is independent of the actual amount of water that is produced by the desalination plant. Therefore, this cost has to be minimized as much as possible. Typically, labor cost is reduced by building the desalination plant with high level of automation and by employing a limited number of highly qualified operations staff. If such staff is not readily available in-house, it is highly recommended to consider retaining private company, which is specialized with the operation of desalination plants of similar size and technology.

Maintenance cost is minimized by selecting high-quality materials, equipment and piping, and by implementing proactive and systematic preventive maintenance program. Plant environmental and monitoring costs are reduced by using environmentally safe, low-cost concentrate disposal methods and by automation of most plant performance monitoring functions.

Indirect O&M cost is typically minimized by using highly qualified operations staff or by subcontracting plant operations to a private contract operation company specialized in desalination plant operations. Since the reduction of the other fixed water production costs requires higher capital expenditures and therefore, increases the capital recovery costs, the total fixed costs have to be optimized to find the most cost-effective balance between the two key fixed cost components.

6.3 VARIABLE COST COMPONENTS

The following O&M expenditures are considered variable cost of water components:

- Power;
- Chemicals;
- Replacement of membranes and cartridges;
- Waste stream disposal.

Power expenditure is the largest variable cost component and usually accounts for 25%–35% of the total cost of water. Depending on the power tariff structure, the fixed portion of the power costs, such as the electrical grid connection charges, may sometimes be accounted for as a portion of the fixed water cost component.

On the other hand, some of the maintenance costs, which traditionally are considered fixed costs (e.g., the preventive maintenance costs), may be accounted for as variable costs. This holds true especially for equipment whose routine maintenance/replacement schedule is based on the actual number of operating hours.

As indicated previously, chemical costs are related not only to the desalination plant source water and production flows, but to the source water quality as well. Usually, treatment of source water of good quality (low silt density index [SDI], turbidity and organic content) requires lower amount of pretreatment chemicals and less frequent membrane cleaning, which in turn yields lower plant chemical costs as well.

The difference between the chemical pretreatment and membrane cleaning costs for good and worst-than-average source water quality could be significant – often two to four times lower. This difference, however, has to be put in prospective. Since the chemical costs are usually less than 8% of the total water production costs, a two-fold chemical cost reduction due to improved source water quality may not amount to a very large reduction of the overall fresh water production cost.

Where source water quality makes a measurable cost difference, however, is the extent of reverse osmosis (RO) membrane fouling and the associated increase in membrane cleaning frequency, and the associated plant downtime. If the source water quality is poor and it requires very frequent membrane cleaning and replacement due to fouling, the excessive membrane maintenance needs typically result in plant production interruptions and ultimately in reduced overall plant capacity availability factor. In addition, the accelerated membrane fouling increases the average plant power consumption and costs associated with membrane cleaning.

Waste stream disposal costs usually are relatively small. However, in some cases operation of the concentrate disposal facilities could constitute a significant portion of the plant water production costs and malfunctioning of these facilities could reduce significantly plant capacity factor (e.g., can increase downtime). Therefore, the use of simple and environmentally sound methods of concentrate disposal such as co-discharge with power plant cooling water, sanitary sewer discharge, or direct open ocean discharge, when viable, are recommended over deep well injection discharge, evaporation pond disposal, or zero liquid discharge.

For desalination plants, which are already in operation, the variable water production costs are typically calculated by dividing the total annual variable O&M costs by the actual average annual fresh water production capacity of the desalination plant.

During the project planning phase, for the purposes of conceptual and budgetary cost estimates and determination of the water tariff of new desalination projects, the variable water costs are calculated by dividing the projected annual variable O&M expenditures by the design average annual plant water production flow and by the target availability factor.

6.4 WATER PRODUCTION COST

Historically, one of the key obstacles limiting the wider use of seawater desalination for the municipal water supply has been the high cost of water production. A number of cost-saving innovations in seawater desalination technology over the past 20 years have transformed this once costly option of last resort into a viable water supply alternative.

Table 1.3 presents the range of water production costs of medium and large size desalination projects constructed after year 2000. As seen in this table, at present the average industry-wide cost of production of desalinated water is US\$1.1/m^3. The table indicates that the cost of water varies significantly and overall could be divided into three brackets – low, medium, and high end.

Advances in seawater RO desalination technology during the past two decades, combined with transition to construction of large-capacity plants, and enhanced competition by using the BOOT method of project delivery have resulted in an overall downward cost of water production trend. While the water production costs have benefited from recent advances in desalination technology, the cost spread among individual desalination projects observed over the past 10 years is fairly wide (see Figure 6.1). Pinto and Marques (2017) present a cost of water summary for over 80 desalination projects built since the year 2000, a review of which confirms the significant difference in the cost of production of desalinated water in various regions of the world.

Most recently commissioned large seawater desalination projects worldwide produce desalinated water at an all-inclusive cost of US\$0.80–US\$1.5/m^3. However, the traditionally active desalination markets in Israel and Northern Africa (i.e., Algeria) have yielded desalination projects with exceptionally low first-year water production costs (410,000 m^3/day SWRO Plant in Sorek, Israel – US\$0.53/ m^3; 330,000 m^3/day Hadera Desalination Plant, Israel – US\$0.60/m^3; 500,000 m^3/day Magtaa SWRO Plant in Algeria – US\$0.56/m^3).

Cost of water production for seawater reverse osmosis (SWRO) desalination plants in Spain of plant capacity between 50,000 and 250,000 m^3/day, built over the past

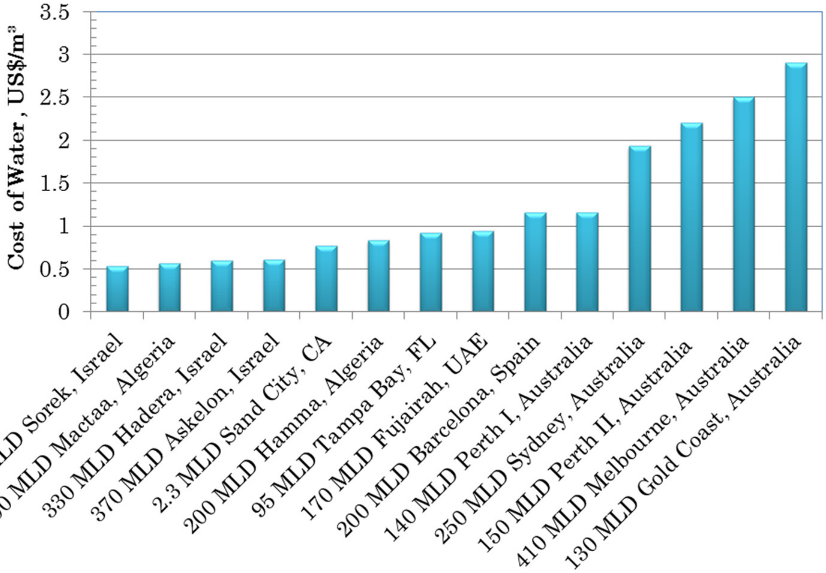

FIGURE 6.1 Cost of Water Production of Recent Seawater Desalination Projects. Note: 1 MLD = 1,000 m³/day.

25 years, varies between US\$0.74 to US\$0.84/m^3 (€0.63–0.72/m^3) (Lapuente, 2012). Adjusted for inflation to year 2018 US\$, this cost range is US\$0.87 to US\$0.98/m^3. Such cost is determined for unit cost of power of US\$0.0656/kWh (€0.0561/kWh). The Spanish desalination market is one of the most mature markets in the world and along with the Middle Eastern desalination market is indicative of the best-case realistic desalinated water production costs at present.

On the other end of the cost spectrum, some of the seawater desalination projects in Australia have been associated with the highest desalination costs observed over the past 20 years – i.e., the Gold Coast SWRO Plant in Queensland has a first-year cost of water of US\$2.8/m^3; and the Melbourne's Victorian Desalination Plant has a cost of US\$2.5/m^3. The actual cost of water paid by the public utilities purchasing water from the private developers of these plants has increased 1.5–2 times because the desalination plants along the east coast of Australia were put in standby shortly after their commissioning due to increased availability of low-cost conventional water sources following heavy rainfalls. The unit capital cost of the Victorian Desalination Plant (US\$7,200/m^3/day) is the highest cost on record in the history of desalination (Caldera and Breyer, 2017). This cost is over six times higher than the unit capital cost observed in the most competitive and mature desalination markets of the world – those of Spain and MENA which have yielded unit capital costs of mega-desalination projects in a range of US\$1,000 to 1,500/m^3/day (see Chapter 2).

While this extreme cost disparity of projects constructed recently has a number of site-specific reasons, the key differences associated with the lowest and highest-cost projects are related to five main factors: (1) desalination site location;

(2) environmental considerations; (3) labor market pressures; (4) method of project delivery, and (5) risk allocation between owner and private contractor responsible for project implementation.

6.4.1 IMPACT OF DESALINATION PLANT LOCATION ON THE COST OF WATER

In the case of the Australian desalination plants, many of the project sites were selected with a significant weight on "not-in-my-back-yard" considerations, which resulted in project locations situated at an overly long distance from the points of delivery of the desalinated water into the water distribution system. For example, due to its remote location, at the 410 MLD Melbourne (Victoria) Desalination Plant in Australia, the total costs of the desalinated water delivery system and the desalination plant power supply facilities (US$1.1 billion) are comparable to the costs of the desalination plant (US$1.7 billion).

The location and costs of the 250 MLD Sydney desalination project in Australia, which has fresh water production capacity similar to that of the 218 MLD Al Dur SWRO plant in Bahrain, have also been heavily influenced by the environmental concerns of local non-government organizations (NGOs) and the Australian social and environmental safeguard regulations. The project was constructed in an industrial zone of Sydney fairly far away from the point of delivery of the desalinated water to the city distribution system, which required the construction of costly water supply pipeline at the bottom of Botany Bay. The capital cost for this project, US$1.14 billion (US$865 million of construction and US$275 million of indirect costs), is 4.8 times higher than that of the 218 MLD Al Dur Plant and the cost of water is over two times higher.

6.4.2 IMPACT OF ENVIRONMENTAL ISSUES ON THE COST OF WATER

Locating desalination plant discharges for the referenced Australian desalination projects in the vicinity of marine species habitats with high sensitivity to elevated salinity, combined with very conservative designs which avoided public controversy and lengthy upfront environmental review process, resulted in the need to build complex concentrate discharge diffuser systems, which costs in most cases exceeded 30% of the total desalination project expenditures.

For comparison, most of the desalination plants yielding the lowest water production costs have concentrate discharges either located in coastal areas with very intensive natural mixing or are combined with power plant outfall structures which use the buoyancy of the warm power plant cooling water to provide accelerated initial mixing and salinity plume dissipation at very low cost. The intake and discharge facility costs for these plants are usually less than 10% of the total desalination plant costs.

In Australia, the United States, and Europe, NGOs have been able to exert significant influence on the environmental review process and legislation pertinent to desalination projects, and to pursue opportunities to reduce the size of the projects or in some cases to select location and environmental mitigation conditions for the projects, which have resulted in a measurable increase of the desalination project construction and operation costs, and ultimately of the cost of water.

In addition, under the influence of local NGOs the desalination plant developer for the Melbourne desalination plant was required to install green roofs on the main building as well as to incorporate low height structures, which increased the construction costs of many of the plant structures between two and five times as compared to the simple structures used for most desalination projects worldwide. In addition, the plant developer was required to use renewable power at a unit power cost, which is approximately 20% higher than the standard power supply rate available from the electrical grid. At a total power consumption of 90 MW, such an increase has resulted in a measurable increment in the total cost of water. The Melbourne desalination project has also incorporated the construction and maintenance of an ecological reserve in the vicinity of the plant. In summary, the costs associated with projects triggered by social and environmental safeguard regulations and pressures from local environmental NGOs have contributed measurably (25%–30%) to the project costs and resulted in the costliest project ever in the recent history of desalination worldwide.

Because of concerns for environmental impacts on the marine environment by the desalination plant intake and outfall, the 133 MLD Gold Coast SWRO desalination plant developer had to build very elaborate and costly intake and outfall structures, at a cost of US$280.6 million (approximately 50% of the total construction cost of the desalination plant of US$557.5 million and 33% of the total plant capital cost of US$838.1 million). For comparison, in most other desalination projects worldwide, intake and outfall costs are typically only 5%–12% of the total capital cost. The intake and outfall costs of the Gold Coast desalination plant are over two times higher than the entire capital costs of the Fujairah II desalination project (US$115 MM), which coincidentally has been built by the same turnkey contractor and has more elaborate pretreatment than the Gold Coast plant. In addition, the project developer had to complete elaborate intake and outfall environmental assessment impact studies, expenditures for which (US$35 million) were over 10 times higher than the expenditures to similar studies in MENA projects (US$0.5 to US$2.5 million).

The 200 MLD Carlsbad SWRO desalination project in California (US$490 million of capital costs; US$55.5 million of annual O&M costs and cost of water of US$1.67/m^3) is another example, where responding to political and legal pressures, and to very stringent social and environmental safeguard regulations have resulted in a significant increase in the desalination project cost. The project went through an 8-year permitting process, which involved numerous environmental studies and five lawsuits from environmental NGOs, all of which were dismissed in legal proceedings as baseless, and have resulted in project development expenditures of over US$60 million.

As indicated in the previous sections of this chapter, besides the US$60 million of environmental review-related expenditures, the project costs include US$28 million of capital expenditures for mitigation of environmental impacts from the intake operation and over US$50 million of expenditures associated with incorporating carbon footprint mitigation measures. In addition, these capital costs include the expenditures for defending (successfully) the project against five frivolous lawsuits, initiated by several NGOs, which contributed a total of US$4 million of additional capital costs to the project. In summary, approximately 30% of the project capital costs are associated with environmental review and mitigation-related activities, many of which were triggered by local NGO groups and which activities did not result in tangible and quantifiable environmental benefits for the marine and terrestrial environment.

It is interesting to note that ultimately, the design and configuration of the 218 MLD Al Dur SWRO Plant in Bahrain and the Carlsbad desalination plant are very similar (except for the intake, pretreatment, and discharge configurations which are actually more elaborate for the Al Dur plant). Based on environmental monitoring in the discharge area of both projects since the beginning of their operation, there is no difference in the actual environmental impacts of these projects, which brings up the question of the necessity for the elaborate environmental review and mitigation incorporated into the Carlsbad project and many other projects in Australia, the United States, and Europe.

Such observation underlines the benefits of the streamlined environmental review process in most Middle East and North Africa (MENA) countries, which is completed by qualified professionals and based on the enforcement of well-proven good practices in plant design and operation created based on over 50 years of experience in desalination in MENA.

Actual experience to date shows that the streamlined environmental review practices adopted in most MENA countries ultimately yield the same desalination plant intake, outfall, and desalination facility designs, and the same benefits and level of protection for the environment as the costly, politicized, and protracted environmental review process in many countries which have just entered into the development and implementation of large-scale seawater desalination projects such as Australia or some US states (e.g., California).

6.4.3 Impact of Labor Market on the Cost of Water

Labor market differences can have a profound impact on the cost of construction of desalination projects. The overlapping schedules of the series of large desalination projects in Australia have created a temporary shortage of skilled labor, which in turn has resulted in a significant increase in unit labor costs. Since labor expenditures are usually 30%–50% of the total desalination plant construction costs, a unit labor rate increase of 20% to as high as up to 100% could trigger sometimes unexpected and not frequently observed project cost increases.

Labor costs for construction, operation, and maintenance of desalination plants are very consistent within the MENA region and have limited differences from one country to another. Since labor costs in the region are usually 10%–15% of the total construction costs, the influence of local unit labor rates between MENA countries is minimal and do not have measurable impacts on the total costs for construction and O&M of desalination plants.

Local unit labor costs in many other parts of the world are highly variable and could be 3 to 30 times higher than the unit labor costs in MENA. Such differences have two impacts on desalination project costs: (1) labor costs are a higher percentage (25%–40% vs. 10%–15%) of the project construction costs; (2) these costs add to a substantive increase of the total project construction cost, and cost of water.

For example, the 218 MLD Al Dur SWRO plant in Bahrain has capital cost of US$236 million, O&M cost of US$27.2 million/year, and cost of water of US$0.89/m^3. A very similar size SWRO plant (200 MLD) in Barcelona, Spain, designed and built by the same turnkey contractor, has capital cost of US$380 million, O&M cost of US$52 million/year, and a cost of water of US$1.42/m^3. While the cost of labor for the construction of the Al Dur plant is 11% (US$26 million) of the plant capital cost, the cost of labor to build the Barcelona plant is 32% (US$121.6 million) of the total capital cost – e.g., it is 4.7 times higher.

Such difference is to a great extent attributed to the fact that unit labor rates in Europe are typically 4–6 times higher than those in the MENA region. For the Al Dur and Barcelona plants, the capital costs of the plants are approximately 42% and 50% of the cost of water. In terms of influence on product water costs, the construction labor component of the Al Dur SWRO project is therefore only US$0.04/m^3 (42% × 11% × US$0.89/m^3 = US$0.04/m^3); in the case of the Barcelona SWRO project, such cost of water contribution is US$0.23/m^3 (50% × 32% × US$1.42/m^3 = US$0.23/m^3) – or 5.75 times higher. In summary, if the Al Dur SWRO plant water cost is adjusted for unit cost of labor differences to determine the cost of water in Barcelona, the Al Dur cost of water will increase from US$0.89/m^3 to US$1.08/m^3 (21% increase).

An example further illustrating the significant difference in labor rates of MENA countries and other parts of the world is the 200 MLD Carlsbad SWRO desalination project in California, United States, which began operation in December 2015. The Carlsbad plant, despite the fact that it has half of the capacity of the Sorek facility and it is designed by the same turnkey contractor, is of 30% higher capital cost than Sorek – US$530 million vs. US$400 million, has 14% higher O&M cost (US$55.5 vs. US$48.5 million/year), and cost of water that is 2.8 times higher than that for the Sorek project (US$1.65 vs. US$0.59/m^3).

The unit costs of labor for the construction of the Carlsbad project are approximately 15 to 18 times higher than the rates in MENA countries, including Israel. In this case the cost of water differential due to the labor rate difference is US$0.46/m^3 – i.e., Sorek would have been US$1.05/m^3, if the California labor rates are used for the construction of Sorek.

Another very important factor, which varies dramatically outside of the MENA region, is the cost of other services associated with the project implementation – especially engineering, contractor procurement, and project oversight services. The costs of such services in MENA are 20 to 50 times lower than those in other countries. The main reasons for such differences are not only the lower hourly rates for consulting services in MENA, but also the significantllower level of oversight required in MENA than the rest of the world because MENA does not have as much regulatory requirements associated with review and certification of project deliverables and the government agencies administering the project contracts are much more experienced than the rest of the world because MENA countries have been implementing large desalination projects for over 50 years.

6.4.4 Impact of Method of Project Delivery on the Cost of Water

Without exception, the lowest cost desalination projects to date have been delivered under turnkey BOOT contracts where private sector developers share risks with the public sector based on their ability to control and mitigate the respective project-related risks. On the other hand, the most costly desalination projects worldwide have been completed under an "alliance" [a type of design-build-operate (DBO)] model implemented for the first time in Australia, where the public utility retains the ownership over the project assets but expects the DBO team to take practically all project-related risks.

In this case, DBO contractors take upon project risks over which they have limited or no control, by delivering very conservative designs, incorporating high contingency margins in the price of their construction, operation, and maintenance services; and by insuring these project risks at very high premiums. As a result, the projects delivered under such a structure carry very high contingencies and upfront insurance, and performance security payments which ultimately reflect on the overall increase of the cost of water production.

While under a typical BOOT project, the insurance and contingency costs are usually well below 20% of the total capital costs, projects with disproportionate transfer of risk to the private contractor result in built-in insurance and contingency premiums which exceed well over 30% of the total project capital costs. The cost-of-water impact of such risk-imbalanced projects is that benefits gained from using state-of-the-art technologies, equipment, and design are negated by overly burdensome insurance and contingency expenditures and a high cost of project funding. Chapter 7 provides additional discussion of key advantages and challenges associated with alternative methods of project delivery.

6.5 EXAMPLE OF DESALINATION PROJECT COST OF WATER ESTIMATE

Table 6.1 presents an example of the total cost of water production for the hypothetical 100,000 m^3/day SWRO desalination project described in Chapter 4.

The calculation of the capital cost recovery component of US\$0.40/m^3 is explained in Section 6.2.1. The remaining cost components in Table 6.1 are annual O&M expenditures. The methodology for calculating these cost components is provided in Chapter 5 – Section 5.11.1.

The total cost of water production for this project at 100% availability is estimated at US\$0.80/m^3 (see Table 6.1). Actual desalination plants, however, usually have less than 100% availability. Therefore, the cost of water has to be adjusted to account for the fact that for a portion of the time the plant will not deliver desalinated water to the final users (i.e., will not generate revenue from water sales) while incurring expenses associated with fixed plant costs.

Because the variable cost component is proportional to flow, the plant availability factor would not have an effect on the variable water cost component expressed as unit cost. However, the plant fixed unit cost will increase because the same amount of fixed expenses would need to be recovered at reduced water sales.

TABLE 6.1
Cost of Water Production for 100,000 m^3/day SWRO Project

Cost of Water Item	Cost of Water (US\$/m^3)	Cost of Water (% of Total)
Fixed Costs		
1. Capital cost recovery	0.400	50.0
2. Labor	0.030	3.8
3. Maintenance	0.0475	5.9
4. Environmental and performance monitoring	0.0095	1.2
5. Indirect	0.040	5.0
Subtotal – Fixed Costs	*0.527*	*65.9*
Variable Costs		
1. Energy	0.204	25.5
2. Chemicals	0.030	3.7
3. Replacement of RO membranes and cartridge filters	0.024	3.0
4. Waste stream disposal	0.015	1.9
Subtotal – Variable Costs	*0.273*	*34.1*
Total cost of water	0.80/m^3	100%

For the project example described in Chapter 4, the designed plant availability factor is 96% rather than 100%. In this case the actual annual average volume of desalinated water produced by the 100,000 m^3/day desalination plant will be: 100,000 m^3/day × 96% = 96,000 m^3/day. As a result, the fixed component of the desalination cost would increase from US\$0.527/m^3 to US\$0.549/m^3 (\$0.527/m^3/96% = \$0.549/m^3). Therefore, the total cost of water will increase from \$0.80/m^3 to \$0.549/m^3 + \$0.273/m^3 = \$0.822/m^3. This 2.75% increase of the desalination plant water production cost would account for the design plant availability factor and to recover plant fixed expenses during times the plant is not delivering desalinated water to the final user.

Plant availability has a significant impact on the cost of water for desalination plants. For example, based on actual experience with medium and large desalination plants in Spain (Lapuente, 2012), a decrease of plant availability from 95% to 80% results in an increase in desalinated water production cost by 15% (from US\$0.78/m^3 to US\$0.90/m^3) – see Figure 2.12.

The cost-of-water example presented above was developed under the assumption that the unit cost of electricity supplied to the desalination plant is US\$0.06/kWh, which is relatively low. In many parts of the world, electricity rates are two to three times higher. The increase of cost of electricity from US\$0.06 to 0.12/kWh will have a profound effect on water production costs. As per the example above, the plant annual cost of energy at US\$0.06/kWh is US\$0.204/m^3. This cost will increase to US\$0.408/m^3 at an electricity rate of US\$0.12/kWh. As a result (at 96% plant availability), the overall plant water production cost will increase from US\$0.822 to US\$1.026/m^3 (25% cost of water increase).

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7 Project Implementation and Costs

7.1 PROJECT DELIVERY ALTERNATIVES AND COSTS

Seawater desalination projects can be implemented using a number of contracting methods, which can be summarized into three key categories: design-bid-build (DBB), design-build-operate (DBO), and build-own-operate-transfer (BOOT). To date, the DBB method has been commonly used for procurement of small and medium size seawater desalination plants in Europe, the United States, and Israel, and for large-scale desalination projects in the Middle East.

Large and mega-size seawater desalination projects worldwide are typically implemented using the BOOT or DBO methods of delivery. Table 7.1 presents a list of the large-scale seawater desalination plants built in the last 10 years along with the method of project delivery for each plant.

The type of selected contracting method mainly depends on the type of owner (public agency or private entity); the project risk profile and owner's experience with similar projects; and the source of project funding – loans, grants, bonds, equity, or a mixture of these funding sources. The type of selected project delivery method often has a significant influence on project costs and therefore deserves considerable attention.

7.1.1 Design-Bid-Build (DBB)

7.1.1.1 Project Parties and Their Roles

Under this traditional method of project delivery, the desalination plant owner is typically a public entity (municipality or utility) that is responsible for the overall project implementation as well as for the project financing and long-term plant operation and maintenance.

Typically, for DBB projects, the owner retains a professional consulting engineer (owner's engineer) to prepare detailed technical specifications for the desalination plant, which are used to procure a construction contractor or contractors to build the project. The construction contractors complete their work under the supervision of the owner and the consulting engineer and their main responsibility is to implement the requirements indicated in the specifications. Contractors guarantee their fixed construction bid prices with a bid bond and provide payment and performance bond security.

This project delivery method can be implemented with or without the pre-purchase of the materials and equipment with a long-lead time for production and delivery to

TABLE 7.1
Large SWRO Plants Constructed over the Past 10 Years

Plant Name/ Location	Capacity (m^3/day)	In Operation Since	Project Delivery Method
Hamma, Algeria	200,000	2008	BOOT 25-year term
Barcelona, Spain	200,000	2009	DBO 2-year term
Sydney Water (Kurnell), Australia	250,000	2010	Alliance 20-year term
Ashdod, Israel	320,000	2011	BOOT 25-year term
Al Dur, Bahrain	218,000	2012	BOOT 25-year term
Adelaide, Australia	300,000	2013	DBO 25-year term
Hadera, Israel	330,000	2013	BOO 25-year term
Sorek, Israel	624,000	2013	BOOT 25-year term
Magtaa, Algeria	500,000	2014	BOOT 25-year term
Ras Al-Khair, Saudi Arabia	310,000	2014	BOOT 20-year term
Carlsbad, California, USA	200,000	2015	BOOT 30-year term
Al Ghubrah, Oman	190,000	2015	BOO 20-year term
Sadara Marafiq, Saudi Arabia	150,000	2016	BOO 20-year term
Minera Escondida, Chile	216,000	2017	DB
Ras Abu Fontas A3, Qatar	164,000	2017	BOO 10-year term

the construction site such as high-pressure pumps, large variable frequency drives, energy recovery system, and membranes. The main difference between the two alternatives is the time needed to complete the project. Pre-purchase of equipment is projected to reduce the overall time for completion of plant construction by 10% to 20%.

After the desalination plant construction is completed the plant owner takes over the project asset management and operates the plant with its own staff or employs a private O&M contractor under a service contract.

7.1.1.2 Construction Contractor Procurement Process

Under this project delivery scenario, the owner's engineer will create a complete set of detailed design drawings and specifications for all plant construction activities and will prepare construction contract bid documents. If the owner elects to pre-purchase long-lead items, the owner's engineer also assists with purchasing of these items. Once the owner approves the engineering design package, construction contractor(s) is procured based on a competitive bidding process. Table 7.2 summarizes the key activities of the construction contractor procurement process.

7.1.1.3 Key Advantages and Disadvantages

The key advantage of this delivery method for the owner is that they retain complete control over the plant ownership, design, and implementation. If the owner chooses to operate the desalination plant with an in-house staff, it also retains all opportunities to take advantage of cost savings that membrane technology advancements could yield in the long term.

Under the DBB method of project delivery, the owner can have close input and control throughout conceptual and detailed design, and construction. Since most owners are very familiar and experienced with the DBB method of project delivery, there is low contractual risk. In addition, the owner is likely to have access to lower cost funding than private contractors and therefore will be able to reduce the overall project expenditures.

Because of the accelerated development of membrane desalination technology, retaining ownership over the plant assets allows for the project owner to fully benefit from energy, membrane replacement, and chemical cost savings that stem from the use of new membranes, energy recovery systems, monitoring and control equipment, and instrumentation and controls that are expected to occur over the useful life of the project (25 to 30 years). In retrospect, such technology advancements over the last 25 years have yielded over 30% of energy use and 50% of membrane productivity gains. On the other hand, if a build-own-operate (BOO) or BOOT contract is executed, usually the first-year cost of water in this contract only increases over time because it is adjusted upwards for inflation at least once per year and unless there is an explicit mechanism in the contract for sharing of technology-related cost savings, the benefits of future desalination technology advancements will not be transferred to the owner.

TABLE 7.2
Construction Contractor Procurement Process under DBB Project Delivery

Activity	Duration (Months)
1. Development of detailed design drawings and specifications by the owner's engineer	4–6
2. Preparation of construction contractor bid package/s and request for proposal	2–3
3. Construction bid preparation and submittal	2–3
4. Bid review and selection and approval of construction contractor/s	1–2
Estimated Total Duration	**9–14**

The key disadvantages are that the owner takes practically all risks associated with project development (permitting and permit compliance, site availability and underground conditions, future power tariff changes, potential environmental damages and associated mitigation efforts); project implementation (faulty design, technology and equipment selection blunders, construction contractor deviations from engineering specifications; start up and commissioning risks and delays); and project financing.

Because the process of beginning facility construction is sequential to creating design drawings and specifications, the overall time needed to complete plant construction is likely to be the longer compared to a parallel design-build project implementation process. The process of handling change orders and resolving differences between the designer and the construction contractors is also usually longer than a design-build or BOO/BOOT approach of project delivery. The key potential challenges associated with the conventional DBB process of project delivery are:

- Finger-pointing between designers and contractors;
- Schedule delays;
- Construction cost overruns;
- Commissioning risk and its mitigation costs are usually owner's responsibility.

If a private O&M contractor is selected to operate the plant, because this O&M contractor typically does not participate in the design and construction of the plant facilities, often the private O&M contractor is willing to provide less comprehensive long-term performance guarantees than those offered by the original equipment manufacturer (OEM).

If the owner decides to operate the desalination plant with their own in-house staff, the owner also takes all risks associated with the long-term project operations and performance – such as the risks that the desalination plant may not be capable of: producing desalinated water at or above the design capacity and or target capacity availability factor; operating at or below the projected power demand, cartridge filter and membrane replacement rates, and chemical use; and of meeting all applicable product water quality and concentrate discharge regulations.

Since the owner is responsible for the project financing, it also carries the financial burden associated with the project, including reduction of the owner's available bonding capacity for funding and implementation of future projects.

This project delivery method is most suitable for owners that have prior experience with the permitting and implementation of seawater desalination projects and operation of desalination plants. For owners lacking such experience, the use of the design-bid-method of delivery is advisable for the implementation of small desalination projects with a low-risk profile, which would allow them to gain the necessary experience and develop in-house desalination plant O&M capabilities and expertise.

The DBB method of delivery is suitable for mature desalination markets where there is a large pool of skilled workforce and contractors for construction and operation of desalination projects. For example, in California, Florida, and Texas, where public water utilities have built extensive experience with operating brackish water desalination plants over the past 30 years, practically all new brackish water reverse osmosis (BWRO) desalination projects are delivered via the DBB method.

However, the seawater reverse osmosis (SWRO) desalination projects in these and other US states to date have all been delivered under the BOOT or DBO model because of the lack of experience with such projects by the public sector. As the public sector builds expertise and a readily available large pool of skilled SWRO plant operators are created in the future, the desalination project delivery model is likely to shift from DBO or BOOT to DB or DBB.

An example of such an evolution in procurement methods is the Kingdom of Saudi Arabia (KSA) where a majority of the projects to date have been delivered as DB or DBB, and operation and maintenance of the desalination plants is completed by a public utility created by the central government – the Saline Water Conversion Corporation (SWWC) of Saudi Arabia.

One benefit the DBB or DB method offers is that the owner retains the project assets, which could be sold during or at the end of the useful life of the desalination plant, and the proceeds from the sale could be used to fund project capacity and/or performance enhancements. Such sale of public assets to private owners/investors to generate cash is often referred to as privatization.

In a broader sense, privatization is defined as changing ownership or management of companies, water infrastructure assets (e.g., desalination plants, water storage, and conveyance facilities), or public services (bulk and/or retail water supply) from the government (public) sector to the private sector via management and operational contracts, leasing, financing, or total or partial sale of assets to the private sector.

7.1.2 Construction Manager at Risk (CMR)

7.1.2.1 Project Parties and Their Roles

This method of project delivery is a modification of the DBB approach and is based on the owner selecting a general construction contractor (construction manager – CM) based on qualifications early in the design phase, which allows the CM to be closely involved in the design and to contribute toward solving constructability and cost issues before the detailed project design is completed by the engineer and the project is released for construction. Toward the middle to the end of the design process, the owner and the CM establish a guaranteed maximum price (GMP) and afterwards, the CM is at risk (CMR) to meet this, not-to-exceed project construction price.

Under this project delivery scenario, the CMR and the owner's engineer would work together as a team to develop a constructible and biddable set of contract specifications for the project. The owner's engineer will still have the responsibility for the quality of the detailed project design documents. The CMR would be responsible for managing the overall project cost and schedule during the design phase of the project to such a point where a GMP price can be submitted by the CMR to the city.

The GMP proposal can be requested by the owner at any time during the design development phase, which maintains the validity of the cost, and schedule offers throughout the design. However, the final GMP is usually accepted by the CMR after the firm price and schedule bids are obtained from the construction contractors interested in the project.

If the CMR wishes to self-perform any work, the owner can request them to bid for this work along with the other construction contractors. If the CMR is successful, then they can self-perform/serve as the general contractor and if not, they would receive their fee during the construction phase to serve as the construction manager for the entire project and they will remain at risk for the delivery of the project at or below the GMP. In this case, the construction phase contracting mechanism for the CMR is recommended to be a cost plus fixed fee type with a guaranteed maximum price. However, a lump sum fee for the GMP would also be a viable option after the construction bids are received.

7.1.2.2 CMR Contractor Procurement Process

The CMR contractor procurement process includes the preparation of request for qualifications (RFQ) by the owner's engineer for CMR contractor, evaluation of CMR contractor statements of qualifications (SOQ), and selection of a contractor based on their qualifications and experience with the successful implementation of similar projects. The construction contractor procurement process under the CMR method of project delivery is presented in Table 7.3.

7.1.2.3 Key Advantages and Disadvantages

Under this project delivery method the owner would retain a high level of involvement and would have an enhanced control over the project costs and budget. Because the project costs are developed in an "open book" environment, the owner would be able to closely monitor these costs and direct the owner's engineer and the CMR contractor to modify the design if needed to fit the targeted cost expenditure and/or modify the project scope during the project design phase.

The main advantage of this method for the owner is that the CMR takes the risk of project cost overruns which otherwise would be a risk assigned to the owner. Typically, the owner will have the biggest cost advantage to negotiate the GMP with

TABLE 7.3

Construction Contractor Procurement Process under CMR Project Delivery

Activity	Duration (Months)
1. Development of CMR contractor request of qualifications (RFQ) by the owner's engineer and solicitation of CMR contractor	1–1.5
2. Preparation and submittal of statements of qualifications (SOQs) by interested CMR contractors	1–1.5
3. SOQ review and selection and approval of CMR contractor	1–1.5
4. Development of detailed design drawings and specifications by the owner's engineer with input from CMR contractor	4–6
5. Preparation of construction contractor bid package/s and of request for bids	2–3
6. Construction bid preparation and submittal	2–3
7. Bid review and selection and approval of construction contractor/s	1–2
Estimated Total Duration	**12–17**

the CMR when the design is 50% to 70% complete. Another anticipated advantage of this delivery method is a reduced overall project delivery schedule.

Some of the key potential disadvantages of the CMR process are that the project success would depend very closely on retaining the right construction manager and project implementation would require significant involvement by the owner's staff. In addition, the overall minimum time for contractor procurement is likely to be extended from 9 months for DBB to 12 months for CMR contractor procurement.

CMR method of project delivery is not commonly used in the delivery of seawater desalination projects but has been applied for the implementation of brackish water desalination projects in Florida, United States.

If the owner does not have CMR project-related experience it may be challenging for them to deliver this project under this procurement alternative. Usually, CMR project delivery is very beneficial when the project has significant construction risks where the early input of an experienced construction manager is critically important. In the case of the desalination projects, this method of delivery could be advantageous if the project involves complex construction, especially of the intake and outfall facilities, and the site-specific project location and conditions pose significant construction challenges.

7.1.3 Design-Build (DB)

7.1.3.1 Project Parties and Their Roles

Under this procurement method a single private entity (DB contractor) takes the responsibility for both the design and the construction of the desalination project. Such a contractor is also referred to as an engineering, procurement, and construction (EPC) contractor or a turnkey contractor. In this case, rather than developing a complete set of detailed drawings and specifications, the owner's engineer prepares a performance specification that defines what refurbishment activities will be needed and how the individual plant components (intake, pretreatment, RO system, post treatment, etc.) have to perform after the plant reactivation is complete. In addition, the performance specifications will address the minimum acceptable requirements in terms of the quality of materials for key equipment, piping, and instrumentation.

Compared to the DBB project delivery method where the entire design risk is allocated to the owner, with the BD method of delivery, the private turnkey contractor takes the risk on project design. In addition, the BD contractor had the constructability risk and performance risk, which they do not take under the DBB approach.

It should be pointed out that similar to the DBB method of project delivery, under the DB arrangement the owner takes on the operations risk. As a result, it is possible that the long-term O&M contractor who is a business entity unrelated to the DB contractor may not honor the same performance guarantees as those given by the DB contractors for such important factors as plant chemical and energy use, membrane replacement, and fresh water production capacity under extreme events (heavy algal blooms, high-intensity storms, or strong winds).

7.1.3.2 DB Contractor Procurement Process

The design-build contractor procurement process includes the development of performance specifications by the owner's engineer followed by preparation of procurement documents and bid advertisement. The contractor bids are opened and the DB contractor is selected based on the lowest cost bid. The key activities of the DB contractor procurement process and their duration are presented in Table 7.4.

7.1.3.3 Design-Build – Key Advantages and Disadvantages

The DB contractor has a clear responsibility to complete plant construction and commissioning such that it meets preset performance specifications; thus it is responsible for both cost-effective design and construction. This benefit minimizes problems associated with the division of responsibility and resolutions of faults.

The design-build method of project delivery is known to reduce the overall project cost and implementation schedule as compared to the traditional DBB approach because the DB contractor has to advance their design to a significant level during the bid process in order to develop a more competitive proposal. In addition, the engineering and construction entities are motivated to work very closely together in order to minimize internal losses due to engineering or construction errors and omissions. As a result, project overruns and schedule deviations are less likely.

Besides a shorter schedule and lower construction costs, another potential advantage of the DB over the DBB method of project delivery is that while the owner transfers engineering risk to the contractor, it still has the opportunity to control project design by the development of comprehensive performance specifications.

A potential disadvantage of the DB approach is that in the desire to generate the lowest construction cost bid, the DB contractor may compromise the quality of the engineering design and construction work by offering lower quality materials and less durable structures, instrumentation, and controls. While such a method of delivery can yield tangible construction cost reduction, at the same time it could also result in higher operation and maintenance costs.

TABLE 7.4
DB Contractor Procurement Process

Activity	Duration (Months)
1. Development of preliminary design and request for contractor qualifications by the owner's engineer	2–3
2. Preparation and submittal of statements of qualifications (SOQs) by potential DB contractors	1–1.5
3. Preparation of DB bid package and request for proposal, review of SOQs and prequalification of DB teams	2–3
4. DB bid preparation and submittal	2–3
5. Bid review and selection and approval of DB contractor	1–1.5
Estimated Total Duration	**8–12**

The DB method of project delivery is widely used in mature desalination markets, such as in Saudi Arabia, Oman, the United Arab Emirates, Europe, and Florida (United States). Such a method of project delivery is attractive to owners that have in-house staff and know-how for the operation and maintenance of desalination projects and where the government would like to retain the ownership of the country's water production facilities, usually because it considers such ownership of strategic importance. An example is the Saline Water Conversion Corporation of Saudi Arabia (SWCC), a public utility in KSA which has procured the majority of the country's large seawater desalination projects under this method of project delivery and which owns and operates these projects.

7.1.4 DESIGN-BUILD-OPERATE (DBO)

7.1.4.1 Project Parties and Their Roles

Similarly to the DBB method of project delivery, the DBO approach also involves asset ownership by a public entity or private offtaker (utility or municipality). Under this method of delivery, the owner is responsible for project development, permitting, and financing. A single turnkey private contractor is responsible for both plant design and construction (e.g., EPC services) and for long-term operation and maintenance.

The owner retains permitting risk and costs, and all environmental permits are issued on the owner's behalf. Permit noncompliance and liability, however, are backed by the DBO contractor via a letter of credit or other monetary instrument, and the DBO contractor is ultimately fiscally responsible to pay for penalties associated with permit noncompliance caused by contractor negligence, errors, and omissions. The DBO contractor is also required to obtain all government permits for construction of the project facilities and for plant operation.

Under the DBO method of project delivery, the owner's engineer develops detailed performance specifications and preliminary project design, which are then used to prepare tender and retain a DBO contractor that is responsible for the final process design, and for the detailed design, construction, startup, and commissioning, as well as for the long-term operation of the desalination plant. Usually the DBO contracting team consists of an engineer, a contractor, and a private operations company (operator).

The DBO contractor is paid not-to-exceed fee for their turnkey EPC and O&M services. During the EPC phase of the project such payment is completed monthly for the duration of the project implementation schedule guaranteed by the DBO contractor. Once project construction and commissioning are complete and the DBO contractor begins plant operation services, this contractor will be paid a pre-negotiated service fee monthly, which will include fixed and variable components.

The fixed fee component will be paid every month and will not depend on the actual amount of water purchased during this month, while the variable fee will be proportional to the produced and delivered monthly volume of product water. The owner pays for desalinated water only if it meets contractual product water quality and quantity requirements. Chemicals, power, and membrane replacement costs are paid by the owner to the DBO contractor up to their guaranteed maximum levels. If the contractor spends less than the guaranteed amounts of these consumables, then the annual savings from such reduced expenditures are usually shared between the owner and the DBO contractor.

A modified DBO approach used in Australia for delivery of several of their largest SWRO desalination projects is the "alliance" contracting concept. Under this delivery method, the owner (the public partner) and the private DBO contractor share responsibilities, risks, and rewards for project delivery and performance. For comparison, under the traditional DBO approach, used in the United States and elsewhere, the risks are clearly allocated to the respective parties responsible for project delivery, and commercial and legal penalties apply for failure to deliver on the contractual commitments of either party of the public-private partnership.

The project alliance agreement establishes predetermined cost, schedule, and performance targets, which both the public and the private partner collectively agree to meet at the beginning of the project. For targets that are not met, both parties share the risks and the losses associated with project implementation. For project areas where the actual performance and costs are lower than the initially set targets, both parties share the monetary benefits.

This "alliance" approach allows the private contractor to reduce its contingency component of the costs, thereby reducing the initial cost of services, and trade some of the project savings, which the contractor would otherwise keep, for a lower overall risk exposure. The "alliance" project delivery method gives an opportunity to the public agency to be more actively involved throughout the project implementation and to exercise more control over the final product. These benefits are traded for taking upon some of the project design and construction risks that are traditionally apportioned to the private DBO or BOOT contractor.

7.1.4.2 DBO Contractor Procurement Process

The overall process and time for procurement of the DBO contractor are very similar to that of the retaining DB contractor – see Table 7.5. In this case, more time is given to the potential DBO contractors to prepare their bids because the contractors will need to complete an initial design and equipment selection before they can develop an O&M plan and cost estimate.

TABLE 7.5

DBO Contractor Procurement Process

Activity	Duration (Months)
1. Development of preliminary design and of request for DBO contractor qualifications by owner's engineer	2–3
2. Preparation and submittal of statements of qualifications (SOQs) by potential DBO contractors	1–1.5
3. Preparation of DBO bid package and request for proposal, review of SOQs, and prequalification of DBO teams	2–3
4. DBO bid preparation and submittal	2–3
5. Bid review and selection and approval of DBO contractor	1–1.5
Estimated Total Duration	**9–12**

7.1.4.3 Key Advantages and Disadvantages

The key advantage of the DBO method of delivery as compared to the DBB project implementation approach is that the early coordination of the facility planning and design with the key construction activities and plant O&M requirements allows optimizing the desalination plant design and reducing life-cycle water production costs.

Another advantage for the public entity (utility or municipality), which would use the desalinated water, is that it retains the ultimate ownership of the desalination plant. In addition, under this method of delivery the owner transfers most of the plant O&M risks to a private operator that has the experience, workforce, and skills to manage these risks more cost-effectively.

The key disadvantage of the DBO method of delivery is that the public agency carries engineering and construction risks similar to those typical for the DBB approach of project delivery. Some of these risks are somewhat reduced because a number of the design concerns and potential construction deviations are diminished by the fact that the DBO contractor is closely involved in the project design. Another disadvantage is that the public agency carries the project's fiscal (i.e., financing) and permit compliance responsibilities and associated cost burdens.

7.1.5 Build-Own-Operate-Transfer (BOOT)

7.1.5.1 Project Parties and Their Roles

The main difference between this and the other methods of delivery described previously is that the public or private entity (also referenced as "offtaker") purchases water (a commodity) rather than a physical asset (the desalination plant) from a private turnkey BOOT contractor that is responsible for planning, permitting, designing, financing, constructing, commissioning, and operation of the plant for the duration of the contract. The project ownership is retained by the BOOT contractor.

The offtaker purchases water for a contractually agreed upon period of time ("contract term"), which could be as short as 2 to 5 years or as long as the length of the useful life of the desalination plant (25 to 30 years). Some contracts extend beyond the useful life of the facility, in which case the BOOT contractor is obliged to maintain and upgrade the plant at their cost so it can maintain guaranteed performance for the entire contract term. At the end of the contract term the desalination project assets are either transferred to the offtaker or retained by the turnkey contractor. In the latter case, the contract is also referred to as BOO (build-own-operate), rather than BOOT – because a transfer of project assets does not occur.

As indicated previously (see Chapter 4), BOOT projects are usually financed with a combination of equity and debt. The debt bond/commercial construction loan repayment obligations for these types of projects are typically revenue-based and are "non-recourse" to the private project company that delivers the project and the public agency purchasing the desalinated water, because the net worth of the owners of the project company and the public agency does not have to be used to provide security for debt repayment.

The public or private entity that is the final user of the desalinated water procures a turnkey BOOT contractor based on a performance specification developed by the owner's engineer. The BOOT contractor sells product water at a guaranteed price, quality, quantity, and point of delivery under a water purchase agreement (WPA), sometimes also referred to as "water supply agreement" (WSA). The key terms of a typical WPA are discussed in the following section.

Once the terms for payment of services are set by the WPA, the BOOT project owner/developer usually retains a turnkey contractor to provide all engineering, procurement, and construction services needed to build and commission the desalination plant, and a private O&M contractor to operate the plant over the entire term of the WPA. Often, the BOOT project owner/developer may also serve as an EPC and/or O&M contractor and may provide a portion of or the entire amount of equity needed to finance the project.

The WPA, EPC, and O&M contracts in combination with other entitlements, such as environmental and construction permits; land purchase or lease agreement; power purchase agreement; agreement for access to source water/water rights; and agreement for concentrate and waste disposal services, and are used as a proof of control of the BOOT contractor over the project cash flow, which is necessary to secure private financing for the BOOT project.

The financing costs associated with the project are a direct function of the strength of the BOOT project's contracts and the financial and operating strength of the entity purchasing the water and the EPC and O&M contractors. Well-structured BOOT projects with good WPA, EPC, and O&M contracts and willing participants typically can be financed with 80% debt and 20% equity. If the project structure is strong and the project risk profile is favorable, a lower percentage of equity (e.g., 10%) may be found adequate by the project lenders.

The WPA guarantees water delivery to the user of the desalinated water (public or private entity) at predetermined quantity, quality, and availability over the entire term of the agreement. On the other hand, this agreement guarantees a predetermined payment for the delivered water to the BOOT contractor and thereby secures a revenue stream that the BOOT contractor can pledge to obtain project financing. The key provisions recommended to be incorporated in a well-structured water purchase agreement in order to minimize the project financing cost and therefore, the overall cost of water production, are:

- *"Take-or-pay" clause*: By which the water purchasing entity (offtaker) agrees to purchase a minimum amount of water at any given time and/or pay for the fixed costs of water incurred by the BOOT contractor, if the desalination facility is put on "standby."
- *Firm water purchase obligations*: The contract should not contain provisions that allow the purchasing entity to unilaterally terminate or substantially revise the contract in the future.
- *Provisions to assign water contract to lenders:* The financial institutions that will provide equity and debt funds for project implementation should have the right and ample opportunity to cure project default if the BOOT contractor fails to perform its obligations under the WPA.
- *Firm and clear water tariff structure*: The WPA should have a water tariff structure that provides adequate coverage of the fixed water production

costs and includes water cost escalation factors tied to third-party commodity (power, chemicals, labor, etc.) price adjustment indexes and foreign currency exchange fluctuations.

- *Change in law clause*: Which allows the BOOT contractor to adjust the water tariff in order to reflect the additional costs that the BOOT contractor will incur in order to comply with future environmental and/or other regulations that have material impact on the water production costs.
- *Unambiguous water quality standards*: The WPA should contain clear specifications of the product water quality and quantity; the plant capacity availability factor; the location/s of water delivery; and the procedures for measurement of the delivered water flow and monitoring of the quality of the desalinated water.
- *Liability for third-party claims*: The WPA should have provisions protecting equally both the BOOT contractor and the water purchaser from claims from the ultimate water consumers. In most cases, the BOOT contractor sells the water to a wholesale water supply agency, which in turn conveys and distributes the product water to the actual consumers. The BOOT contractor can only be required to be liable for the product water quality at the point of delivery to the wholesale agency and cannot take the responsibility for changes in water quality caused by malfunction of the wholesale supplier's distribution system and conveyance facilities. On the other hand, the BOOT contractor should carry liability for impacts on the wholesale supplier's distribution system, if the BOOT contractor supplies inferior out-of-spec product water quality, which is the cause of such impacts.

Water purchase agreements have a number of other provisions, which aim to define contractual division of responsibilities and risks between the BOOT contractor and the water purchaser. These provisions may vary from project to project, but in general have to be such that the project risks are apportioned between the BOOT contractor and the water purchaser commensurate with their ability to control and mitigate the risks and to deliver water to the ultimate consumer at the lowest overall cost and competitive market price.

7.1.5.2 BOOT Contractor Procurement Process

Overall process and time for procurement of the BOOT contractor are very similar to that of DB and DBO contractors (refer to Table 7.6).

7.1.5.3 Key Advantages and Disadvantages

The key advantage of the BOOT method of project delivery is that the offtaker will not be responsible for environmental permitting of the desalination plant and will not need to expend significant capital resources and raise funding for the project, which may reduce the offtaker's borrowing capacity for future projects.

The offtaker will pay a predetermined cost of water and if the BOOT method of project delivery is used for the expansion or refurbishment of an existing desalination

TABLE 7.6
BOOT Contractor Procurement Process

Activity	Duration (Months)
1. Development of performance specifications and of request for BOOT contractor qualifications by the owner's engineer	2–3
2. Preparation and submittal of statements of qualifications (SOQs) by potential BOOT contractors	1–1.5
3. Preparation of BOOT bid package and request for proposal, review of SOQs, and prequalification of BOOT teams	2–3
4. BOOT bid preparation and submittal	2–3
5. Bid review and selection and approval of BOOT contractor	1–1.5
Estimated Total Duration	**9–12**

plant they own, the offtaker may be able to receive cash for the existing plant's assets, which could then be used by the offtaker to invest in other projects (e.g., building a new school or other water or wastewater facilities) – World Bank, 2014.

Key potential disadvantages for the public utility, which is the offtaker of the desalinated water, are the comparatively higher overall water production costs and the loss of control over plant ownership (Vining et al., 2005). Higher overall water production costs may result from the fact that the BOOT contractor would have to use equity for project funding which is usually more costly (8% to 25% interest rate) than grants and low-cost (2% to 5%) government funding sources and municipal bonds; and that besides the profit margins for the private O&M and EPC contractors, the water cost will also include a BOOT contractor project fee which is usually 2% to 5% of the capital cost of the project.

Usually, the return on equity expectation for a given project depends on the project risk profile. The main five financial risks for desalination projects are: (1) potential for bankruptcy of the private project developer; (2) unfavorable (unstable) economy in the host country; (3) tariff adjustment uncertainty; (4) rate of return (profitability) restrictions; and (5) availability problems of the private capital (Ameyaw et al., 2017).

As shown in Table 7.1, most of the large seawater desalination facilities built over the past 10 years, or currently undergoing construction, are delivered under public-private partnership arrangement using the BOOT method of project implementation.

The BOOT project delivery is preferred by municipalities and public utilities worldwide that do not have experience with the implementation and operation of seawater desalination projects, because it allows a cost-effective transfer to the private sector of the risks associated with the number of variables affecting the cost of desalinated water, such as intake water quality, and its sometimes difficult to predict effects on plant performance; permitting challenges; startup and commissioning difficulties; fast-changing membrane technology and equipment market; and limited public sector experience with the operation of large seawater desalination facilities (Rebeiz, 2012).

7.2 PROJECT IMPLEMENTATION SCHEDULE AND PHASING

7.2.1 Project Duration

A detailed project implementation schedule has to be developed during the design phase of the seawater desalination project. The desalination plant construction schedule should as a minimum include the following information:

- The total duration of the project implementation;
- Duration and start date of contractor mobilization and site preparation;
- Duration and start date of the project engineering and design;
- Duration and start date of procurement and installation of high-pressure RO pumps, energy recovery equipment; high-pressure stainless steel piping; RO membrane elements, and any other significant long-lead time items, which procurement, installation or start up requires over three months;
- Duration and start date of construction of intake facilities, intake and discharge interconnecting piping; pretreatment system; RO system and post-treatment facilities;
- Duration and start date of plant commissioning and start up;
- Duration and start date of desalination plant acceptance testing.

Table 7.7 presents a typical length of desalination project design and construction as a function of the plant size. The actual length of the desalination plant project design and construction may vary from the indicative periods indicated in Table 7.7 depending on the site-specific project scope and conditions.

Some construction activities may take longer than the duration indicated in the table, especially if most of the construction has to be completed in adverse weather conditions; if the plant footprint is too compact; if the construction staging area is very limited; and/or the access to the site and hours of the day and days of the week

TABLE 7.7
Typical Length of Desalination Project Implementation

Plant Size (m^3/day)	Design Period (Months)	Construction Period (Months)	Start-up and Commissioning (Months)	Total (Months)
Less than 1,000	1–2	2–3	1–2	4–7
5,000	2–3	4–6	1–2	7–11
10,000	2–4	6–8	1–2	9–14
20,000	3–5	8–10	2–3	13–18
40,000	3–6	14–16	2–3	19–25
100,000	5–8	18–20	3–4	26–32
200,000	6–10	20–24	3–4	28–36

Note: Accelerated implementation of some of the activities is possible but is likely to result in cost increase.

during which construction is allowed are burdened with significant constraints due to noise, traffic, air pollution, or other regulatory requirements.

Some of the construction activities may be accelerated by work in multiple shifts and by pre-purchasing some of the long-lead equipment, and piping. However, such project acceleration measures usually result in an increase in the overall plant construction costs.

7.2.2 PROJECT PHASING

The desalination projects with the highest and lowest costs have a very distinctive difference in terms of project phasing strategy. While the large high-cost projects incorporate single intake and discharge tunnel structures built for the ultimate desalination plant capacity (which often equals two times the capacity of the first project phase), the desalination projects on the low-end of the cost spectrum use multiple-pipe intake systems constructed mainly from high-density polyethylene (HDPE) or glass reinforced plastic (GRP) that have the capacity commensurate with the production capacity of the desalination plant. Additional multiple intake pipes and structures are installed as needed at the time of plant expansion for these facilities.

While the single-phase construction of desalination plant intake and outfall structures dramatically reduces the environmental and public controversy associated with the plant capacity expansion at a later date, this “ease-of-implementation” benefit typically comes with an overall cost penalty.

The notion that the larger costs associated with building complex intake and outfall concrete tunnels in one phase will somehow be offset by economies of scale usually does not yield the expected overall project cost savings. The main reason is the fact that the cost of 100 meters (300 linear feet) of deep concrete intake or discharge tunnel is over four times higher than the cost of the same capacity intake or discharge constructed from multiple HDPE or GRP pipes located on the ocean bottom, while the economy of scale from one-stage construction is usually less than 30%.

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8 Cost Management

8.1 INTRODUCTORY REMARKS

As indicated in Figure 1.5, seawater reverse osmosis (SWRO) desalination plant construction costs and power use together contribute 50% to 75% of the total cost for fresh water production. Over 70% of the plant construction costs and energy are typically associated with the design and operation of the SWRO system. Therefore, the main focus of desalination project cost management is to reduce reverse osmosis (RO) system construction and energy costs.

Dramatic improvements of the membrane element materials and energy recovery equipment over the past 20 years, coupled with enhancements in the efficiency of RO feed pumps and reduction of the pressure losses through the membrane elements, have resulted in a reduction in the use of power to desalinate seawater to less than 3.5 kWh/m³ of produced fresh water and to decrease plant construction costs several times. While the conventional SWRO technology used at present is at a mature stage of development, further improvements in SWRO membrane structure and productivity as well as advancements of innovative SWRO system configurations hold significant potential for further cost and energy reduction.

8.2 COST AND ENERGY USE FACTORS AND THEIR MANAGEMENT

Construction costs and energy use for seawater reverse osmosis desalination vary in a wide range and depend upon a number of factors (see Table 8.1). Specific impacts of these factors on the cost of production of desalinated water are discussed in detail in Chapter 2.

Over the past decade, the desalination industry has successfully adopted a number of cost management approaches and technological innovations to control construction and energy costs. They include evolutionary improvements of the SWRO membrane permeability and salt rejection; refinements of the isobaric chamber and turbocharger type energy recovery equipment and systems; SWRO system configuration modifications aimed at increasing the overall RO system recovery, reducing energy losses within the feed water distribution piping and vessels; implementation of fewer, larger size desalination trains and pumps, and use of larger diameter membrane elements (Migliorini and Luzzo, 2004; NRC, 2008; Li et al., 2008; Choules et al., 2007, Voutchkov, 2013).

One of the key issues associated with optimizing SWRO system construction expenditures, energy use, and operation costs is the quality of pretreated water fed to this system. Over the past 20 years, industry understanding of key mechanisms in seawater pretreatment for membrane desalination has evolved significantly (Passow, 2002a,b; Laine et al., 2003; Goosen et al., 2004; Yiantsios et al., 2005; Leparc et al., 2007;

TABLE 8.1
Key Desalination Plant Cost and Energy Use Factors

Factor	Construction Cost and Energy Saving Technology Trends	Potential for Cost and Energy Savings as Percent of Industry Average
Source water temperature	Use of warmer source water (collocation with power generation plants)	3%–5%
Source water salinity	Use of lower-salinity source water or blend of seawater and brackish water	Over 50%
Membrane element and system energy and productivity losses	Use of higher productivity elements. Application of lower energy & cost RO system configurations. Adoption of larger diameter (16 to 19-inch vs. 8-inch) SWRO elements	5%–15%
High-pressure RO feed pump efficiency	Maximizing pump and motor efficiency by the use of large pumps serving multiple RO trains	5%–10%
Recovery of energy from RO concentrate	Use of isobaric chamber type technologies	10%–15%

Mosset et al., 2008; Choules et al., 2009; Knops and Lintelo, 2009). Gradually, the desalination industry is adopting the use of seawater membrane pretreatment which is believed to allow for producing higher quality seawater, which in turn can facilitate more cost-effective RO system design and operations (Pearce, 2007; Sommariva et al., 2009; Villacorte et al., 2009; Voutchkov, 2017).

Key cost management innovations are discussed in the following sections of this chapter.

8.3 ALTERNATIVES FOR REDUCING DESALINATION PLANT ENERGY USE AND COSTS

The optimum design of a given desalination plant in terms of energy and costs revolves around the optimum design of the SWRO system. As indicated in Chapter 2, the optimum RO system design that ultimately yields the lowest cost of production of desalinated water is dependent on a number of site-specific factors such as: source and product water quality specifications; cost of construction labor and materials; O&M labor and chemical costs; unit power costs; membrane element costs; plant size, location, and type of power supply; and so on. Therefore, a universal optimum SWRO system design does not exist, and plant design optimization always needs to be completed based on the site-specific project requirements and constraints. Depending on certain prevailing site-specific factors, there are a number of different practical approaches for minimization of RO system energy and costs, which have found industry-wide acceptance and use:

- Collocation of desalination and power plants;
- Use of high-productivity/low-energy membrane elements;
- Use of large-diameter RO membrane elements;
- Hybrid RO membrane configuration;
- Use of RO systems for high-recovery plant design;
- Split-partial two-pass RO system with front permeate second pass;
- Use of large size high-efficiency pumps;
- Energy recovery by pressure exchangers.

8.3.1 COLLOCATION OF DESALINATION AND POWER PLANTS

Desalination of warmer source seawater usually requires less energy for membrane separation than using seawater of ambient temperature. This potential energy reduction benefit could be applied by using warm water discharges from coastal power plants as a source water for desalination.

Coastal power generation plants often use seawater of ambient temperature for cooling of their electricity generation units. The cooling water discharged from a typical power generation station is usually 4°C to 15°C warmer than the ambient ocean water. Taking under consideration that energy needed for salt separation is reduced with 5% to 8% for every 10°C of elevated seawater temperature in the temperature range of 12°C to 40°C, using warmer seawater can result in measurable energy reduction (see Figure 2.13).

Under a desalination plant – power station collocation configuration, the intake of the seawater desalination plant is connected to the discharge canal of the power plant to collect a portion of the cooling water of this plant for desalination (see Figure 8.1). The collocation configuration allows using the power plant cooling water both as a source water for the seawater desalination plant and as a blending

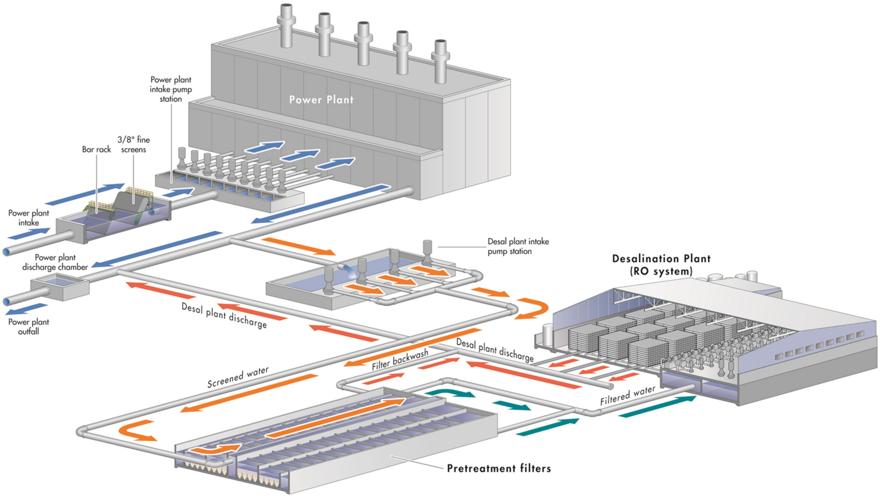

FIGURE 8.1 Typical configuration of collocated desalination plant.

water to reduce the salinity of the desalination plant concentrate prior to its discharge to the ocean.

Collocation of SWRO desalination plants with existing once-trough cooling coastal power plants could yield four key benefits: (1) the construction of a separate desalination plant outfall structure is avoided, thereby reducing the overall project capital costs; (2) the salinity of the desalination plant discharge is reduced as a result of the mixing and dilution of the membrane concentrate with the power plant discharge, which has ambient seawater salinity; (3) because a portion of the discharge water is converted into potable water, the power plant thermal discharge load is decreased, which in turn lessens the negative effect of the power plant thermal plume on the aquatic environment; and (4) the blending of the desalination plant and the power plant discharges results in accelerated dissipation of both the salinity and the thermal discharges (AWWA, 2011; WRRF, 2016).

Usually, coastal power plants with once-trough cooling systems use large volumes of seawater. Because the power plant intake seawater has to pass through the small diameter tubes (typically 10-mm or less) of the plant condensers to cool them, the plant discharge cooling water is already screened through bar racks and fine screens similar to those used at surface water intake desalination plants. Therefore, a desalination plant whose intake is connected to the discharge outfall of a power plant usually does not require the construction of a separate intake structure, intake pipeline, and screening facilities (bar racks and fine screens). Since the construction cost of a new surface water intake structure for a desalination plant is typically 5% to 30% of the total plant construction expenditure, power plant collocation could yield significant construction cost savings (AWWA, 2007).

While for most collocated SWRO desalination plants, additional source seawater screening may not be needed prior to pretreatment, in cases where the power plant screenings are discharged in the outfall upstream of the point of intake of the desalination plant, such additional screening would be necessary. Therefore, it is of key importance to select a location on the power plant outfall to connect the desalination plant intake such that no power plant intake screenings are present in the discharge.

In addition, the distance between the point of entrance of the desalination plant concentrate into the power plant outfall pipe and the point of discharge of the outfall pipe into the ocean has to be long enough for the concentrate and remaining power plant cooling water to mix completely.

It should be pointed out that using warmer water for desalination could have certain disadvantages associated with the accelerated bio-growth of marine bacteria on the surface of the SWRO membrane elements, which could result in the need for more frequent membrane cleaning, especially if the source seawater temperature is already higher than 25°C (AWWA, 2011).

In addition, use of warmer water would result in production of RO permeate (and fresh product water) of higher salinity, boron and bromide content, and may require additional treatment if the desalination plant has to meet stringent product water quality requirements. A summary of key issues that would need to be taken under consideration in order to determine the feasibility of collocation of a SWRO desalination plant with a power generation plant for the site-specific conditions of a given project are presented in Table 8.2.

TABLE 8.2
Issues and Considerations of Desalination Plant Collocation

Advantages

- Capital cost savings by avoiding construction of new intake discharge outfall.
- Decrease of the required RO system feed pressure and power cost savings as a result of using warmer water.
- Reduction of marine organism impingement and entrainment because the desalination plant does not collect additional seawater from the ocean.
- Reduction of impact on marine environment as a result of faster dissipation of thermal plume and concentrate.
- Reduction of the power plant thermal discharge to the ocean because a portion of this discharge is converted to potable water.
- Use of already disturbed land at the power plant minimizes environmental impact.

Disadvantages and Feasibility Considerations

- Use of warmer seawater may accelerate membrane biofouling.
- RO membranes may be exposed to iron, copper or nickel fouling from power plant condensers.
- Source seawater has to be cooled if its temperature increases above 40°C in order to protect RO membrane integrity.
- Permeate water quality diminishes slightly with the increase of source water temperature.
- Use of warmer water would result in lower boron rejection.
- RO plant source water screening may be required if the power plant disposes off its screenings through their outfall and the point of disposal is upstream of the desalination plant intake.
- Desalination plant operation may need to be discontinued during periods of heat treatment of the power plant facilities.

Therefore, collocation is more likely to be feasible for locations where the ambient seawater is relatively cold (ocean water temperatures of 18°C or lower occur seasonally) (AWWA, 2011). Examples of such locations are the coastal seawater desalination projects in northern California as well as most of the large desalination projects in Australia, which have deep intakes and collect seawater, the temperature of which during the winter season often reaches levels of 12°C to 16°C.

Collocation has been implemented on a large-scale for the first time at the 95,000 m^3/day Tampa Desalination Plant in the US, which has been in continuous operation since 2008; the 200,000 m^3/day Carlsbad Seawater Desalination Plant in California, and over a dozen seawater desalination plants in other parts of the world (WRRF, 2013).

One important issue associated with the feasibility of the collocation configuration is that the power plant discharge volume has to be significantly larger than the volume of the concentrate discharged by the desalination plant. The minimum mixing ratio between the power plant cooling water and concentrate would be site specific and would depend on the ambient mixing conditions in the discharge zone; the source seawater salinity, the desalination plant recovery and concentrate density; and the temperature of the thermal discharge. For example, in the case of the Tampa Bay desalination project, the mixing ratio between the power plant discharge and desalination plant concentrate is typically over 70:1 (Voutchkov, 2011).

The negatively buoyant discharge of the desalination plant can have a significant positive impact on the reduction of the area of the thermal footprint of the power plant discharge. For example, for a typical mixing ratio between the power plant flow and the desalination plant flow of 4:1 to 6:1, and temperature difference of the two discharge streams of 3°C to 5°C, the footprint of the power plant discharge is reduced by 40% to 60% as a result of the negative buoyancy effect of the desalination plant discharge, which has salinity of 65,000 to 70,000 mg/L, on the positively buoyant power plant cooling water discharge.

It should be pointed out that while desalination plant collocation may eliminate the need for construction of separate intake screening facilities for the desalination plant, this plant will still require seawater pretreatment by granular media or membrane filtration because the water quality of the power plant discharge is typically inadequate to be used directly for membrane separation in the reverse osmosis system.

8.3.2 Use of Lower Salinity Source Water

In reverse osmosis, the membrane desalination system's energy demand for salt separation is proportional to the salinity of the source water. Therefore, desalination of lower salinity source water results in lower energy demand for fresh water production. From this prospective, desalinating brackish water is preferable if such a saline water source is readily available.

If brackish water sources at a given location are not adequate to produce a desired volume of fresh water, then the available brackish water could be blended with seawater to reduce the source water salinity of a seawater desalination plant and therefore decrease the overall energy used for desalination. While this approach is not commonly practiced at present, it holds significant potential benefits under the right circumstances.

Besides brackish source water, concentrate from brackish water desalination plants (desalter brine) could also be used as feed water to a seawater desalination plant in order to reduce feed water salinity (see Figure 8.2). Such an approach has already found practical implementation at a 10,000 m^3/day desalination plant located in the city of Eilat, Israel, and is under consideration for implementation in Orange County and San Diego County, California, USA.

The key components of such a regional integrated desalination system include: (1) inland brackish water desalination plants, (2) a regional brine interceptor/collector, and (3) a centralized coastal seawater desalination plant. The purpose of the regional brine collector is to convey the concentrate from the inland desalters to the regional seawater desalination plant, where this concentrate is used as supplemental feed water to the source seawater used for desalination.

Although Figure 8.2 depicts a combination of seawater desalination plants collocated with a coastal power generation plant, this approach could be used for SWRO plants with conventional intakes and outfalls as well. Use of concentrate from brackish water desalination plants as feed water to a seawater desalination plant is mutually beneficial for both plants.

Usually, inland brackish water desalination plant capacity is limited by lack of suitable discharge locations for the plant concentrate. If the seawater desalination

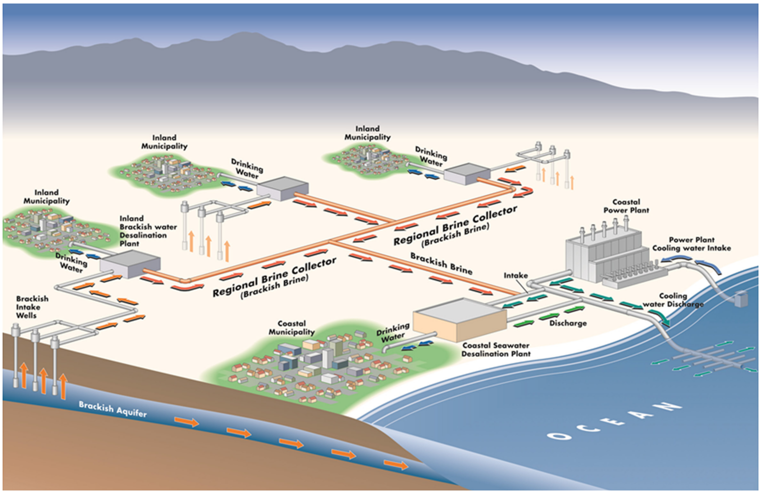

FIGURE 8.2 Integrated inland desalter brine disposal and seawater desalination.

plant can accept brackish water desalination plant concentrate and process it, then the brackish water desalination plant capacity could be increased beyond the threshold driven by brackish brine discharge limitations, and the desalination plant source salinity could be reduced at the same time.

This regional concentrate management approach has a number of benefits. Brine from inland desalters using brackish ground water sources typically does not contain pathogens (bacteria, Giardia, Cryptosporidium, etc.) and therefore, it could be a safe and suitable source of water for seawater desalination. As a result, rather than being disposed as a waste product to the ocean or to deep aquifers, brackish water concentrate could be reused for drinking water production.

In addition, brine from inland desalters usually has an order of magnitude lower total dissolved solids concentration than seawater (i.e., 2,000 to 5,000 mg/L vs. 33,500 to 40,000 mg/L). As a result, mixing of brine and seawater will reduce the overall salinity of the source water fed to the seawater desalination plant, and therefore, it will decrease the total amount of energy needed to desalinate seawater.

Typically, brine from inland desalters contains antiscalants, which under a regional treatment configuration will allow it to reduce or to completely eliminate the expenditures for the addition of such chemicals at the seawater desalination plant and will increase desalination plant fresh water recovery. Increased recovery means producing more fresh water from the same amount of feed water, which in turn yields lower unit desalinated water production costs.

Because the brackish water desalter brine will be put to beneficial use, rather than being a disposal burden, it will become a valuable resource, which will reduce the operational costs of the brackish water desalters and at the same time will enhance the affordability of seawater desalination.

Brine from inland desalters, if practical, is often discharged to existing wastewater outfalls for final disposal. Diverting brine from wastewater treatment plant

(WWTP) ocean outfalls would enhance their available outfall capacity and thereby could decrease wastewater treatment and disposal costs, especially if the WWTP capacity is limited by outfall discharge capacity availability.

As an added benefit, operating SWRO plants at a higher recovery, as a result of integrated brine management, would result in reduction of the overall discharge volume and salinity of the SWRO plants, which in turn could yield potential environmental benefits in the mixing zone of the WWTP discharge.

It should be pointed out that at present there are commercially available technologies to reduce the volume of brackish water desalination plants to zero liquid discharge (ZLD) levels and therefore to eliminate the need for liquid discharge of the brine generated by inland desalters. However, experience with full-scale commercially available ZLD technologies, such as evaporators-crystallizers, indicates that the cost of construction and operation of such ZLD facilities are comparable to the capital and operation costs of the brackish desalination plants.

It should be noted that while ZLD facilities for disposal of brine from inland desalters are very costly, ZLD may be more cost attractive than the regional concentrate management if the distance between the inland desalters and the coastal desalination plant are significant. Therefore, the most viable alternative for concentrate management from inland desalters should be determined based on a detailed lifecycle cost analysis for various technologies, including ZLD, near-ZLD, and regional concentrate disposal alternatives.

Another opportunity for reduction of the energy and cost needed for desalination is to feed highly treated secondary effluent or RO reject from a wastewater treatment plant into the feed water of a SWRO desalination plant. Because the discharge from advanced water reclamation plants has an order of magnitude lower salinity than the source seawater, the SWRO system's feed water salinity and energy cost for desalination could be reduced significantly. Such a treatment process is referenced as joint desalination and water reuse. An example of such a joint desalination and water reuse facility is the Hitachi's Remix system, which has been extensively tested at the 40,000 m^3/day Water Plaza Advanced Treatment Plant in Japan (Kurihara and Takeuchi, 2018 – see Figure 8.3).

At present, joint desalination and reuse is in its infancy and its practical implementation to date has been exclusively for industrial water supply. The use of joint desalination and water reuse systems for production of drinking water requires further development as well as promulgation of regulations for direct potable reuse.

However, as direct potable reuse matures and gains worldwide acceptance in the next 10 years, joint desalination and water reuse facilities are likely to become an attractive low-energy alternative for production of desalinated water. The benefits and potential challenges of joint desalination and reuse plants in terms of efficiency, reliability, costs, and product water quality are currently undergoing a thorough investigation in demonstration plants in Japan and South Africa.

Another recent trend aiming at the collection of lower salinity aquifers is the selection of the open intake of the seawater desalination plant at a location where fresh water aquifer formation exits at the bottom of the ocean. If they exist, unconfined terrestrial fresh water aquifers in many cases exits the ocean near the coast in a localized manner.

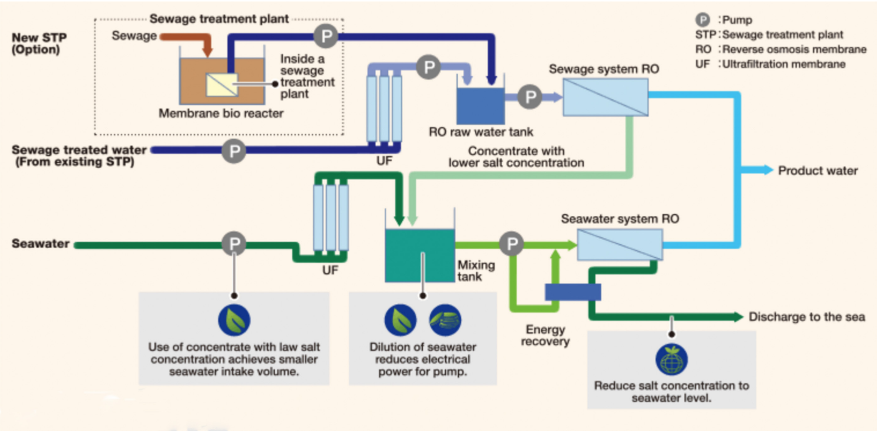

FIGURE 8.3 Water treatment system for joint desalination and reuse.

Such a location is relatively easy to identify because the salinity of the seawater within several hundred meters of the exit area is often 10% to 30% lower than the ambient open ocean seawater salinity. Installing intake in such locations has two main benefits: (1) it captures lower salinity seawater at practically all times and (2) it has minimum environmental impact because such areas do not attract seawater marine organisms.

It is important to point out that fewer marine organisms can adapt to low-salinity water conditions of fresh water aquifer discharge into the ocean than to the higher-salinity conditions of the concentrate discharged from desalination plants. Therefore, locations where fresh water aquifers exit into the ocean bottom are scarce of marine life and collection of water from such locations by open intakes minimizes environmental impacts.

8.3.3 Use of Higher Productivity/Lower Energy SWRO Elements

A key factor that has contributed to the dramatic decrease of seawater desalination energy use and costs over the past 10 years is the advancement of the SWRO membrane technology. Today's high-productivity membrane elements are designed with several features that yield more fresh water per membrane element than any time in the recent history of this technology: higher surface area, enhanced permeability, and denser membrane packing. Increasing active membrane leaf surface area and permeability gains significant productivity using the same size (diameter) membrane element. Active surface area of the membrane elements is typically increased by membrane production process automation, by denser membrane leaf packing, and by adding membrane leafs within the same element.

In the second half of the 1990s, the typical 8-inch SWRO membrane element had a standard productivity of 5,000 to 6,000 gallons per day (gpd) at a salt rejection of 99.6%. In 2003, several membrane manufacturers introduced high-productivity seawater membrane elements that are capable of producing 7,500 gpd at a salt rejection of 99.75%. Just one year later, even higher productivity (9,000 gpd at 99.7% rejection) seawater membrane elements were released on the market. Over the past 10 years SWRO membrane elements combining productivity of 10,000 to 16,000 gpd and high-salinity rejection have become commercially available and have gained wide project implementation.

The newest membrane elements provide flexibility and choice, and allow users to trade productivity and pressure/power costs. The same water product quality goals can be achieved in one of two general approaches: (1) reducing the system footprint/construction costs by designing the system at higher productivity, or (2) reducing the system's overall power demand by using more membrane elements, designing the system at lower flux and recovery, and taking advantage of the newest energy recovery technologies which further minimize energy use if the system is operated at lower (35% to 45%) recoveries.

8.3.4 USE OF LARGE-DIAMETER RO MEMBRANE ELEMENTS

The total active surface area in a membrane element is also enlarged by increasing membrane size/diameter. Although 8-inch SWRO membrane elements are still the "standard" size most widely used in full-scale applications at present, larger 16-inch, 18-inch, and 19-inch size SWRO membrane elements have become commercially available over the past five years and have already found full-scale implementation in over two dozen SWRO projects worldwide (Bergman and Lozier, 2010, Voutchkov, 2013).

Large size RO membrane elements are aimed to respond to the recent desalination industry trend toward construction of large and extra-large (mega) desalination projects. In 2009, such projects constituted approximately 40% of the total new commissioned desalination capacity worldwide. In 2016 and 2017, large and extra-large desalination projects amounted to 78% of the total new installed desalination capacity worldwide (GWI, 2017).

Large-diameter RO elements have 4 to 10 times higher membrane area and unit production than conventional size 8-inch membranes, which reduces significantly the number of RO system components (membranes, vessels, piping, fittings, instrumentation, RO trains, O-rings, brine seals, and pumps) and decreases the total footprint of the RO system. Other potential benefits include reduced maintenance and improved reliability because of the fewer element connections (O-rings and brine seals).

8.3.4.1 Commercial Products

At present, a number of membrane manufacturers offer large-diameter RO membrane products. Table 8.3 summarizes key performance parameters of commercially available large-diameter membrane elements for seawater desalination. This table incorporates products from five key manufacturers of large-diameter membranes – Dow/Filmtec, Hydranautics, Toray, Toray Advanced Materials Korea – TAK (formerly, Woongjin Chemicals), and Koch Membrane Systems (KMS). The first three membrane manufacturers have participated in a consortium, which in 2003/2004

TABLE 8.3
Large-Diameter SWRO Membrane Elements

Membrane Element Model	Nominal Diameter *x* Length (in)	Nominal Surface Area (sq. ft.)	Feed Spacer Thickness (mm)	Permeate Flow at Standard Test Conditions (gpd)	Nominal Salt Rejection at Standard Test Conditions (%)	Weight, Dry (lbs)	Weight, Wet (lbs)
DOW/Filmtec							
SW30HRLE-1725	16×40	1,725	0.71	32,000	99.75 (91% Boron)	125	150
Hydranautics (Nitto Denko)							
SWC4 1640	16×40	1,600	0.76	26,000	99.80 (93% Boron)	114	139
SWC5 1640	16×40	1,600	0.76	34,000	99.80 (92% Boron)	114	139
Toray							
TM840C–160	16× 40	1,600	0.71	26,700	99.75 (93% Boron)	145	167
TM840E-160	16×40	1,600	0.71	30,000	99.75 (91% Boron)	145	167
Toray Advanced Materials Korea (TAK) (Formerly, Woongjin Chemical/Seehan)							
CSM RE16040 -SHN	16×40	1,600	0.71	24,600	99.75	132	145
CSM RE16040 -SHF	16×40	1,600	0.71	36,000	99.70	132	145
CSM RE16040 -SR	16×40	1,600	0.71	24,400	99.60	132	145

(Continued)

TABLE 8.3 (CONTINUED)
Large-Diameter SWRO Membrane Elements

Membrane Element Model	Nominal Diameter *x* Length (in)	Nominal Surface Area (sq. ft.)	Feed Spacer Thickness (mm)	Permeate Flow at Standard Test Conditions (gpd)	Nominal Salt Rejection at Standard Test Conditions (%)	Weight, Dry (lbs)	Weight, Wet (lbs)
Koch Membrane Systems (TFC – MegaMagnum(1) and MegaMagnum Plus(2) Membranes)							
18061-SW-3050(1)	18×61	3,050	0.70	53,000	99.75	200	250
18061-HF-3050(1)	18×61	3,050	0.70	69,500	99.70	200	250
19061-SW-3525(2)	19×61	3,525	0.70	60,800	99.75	300	360

had developed a “standard” large element of 16-inch diameter and 40-inch length under the guidance of the US Bureau of Reclamation (USBR, 2004).

While the 16-inch elements of the manufacturers listed in Table 8.3 have few differences, they are commoditized in size and diameter and could be used interchangeably in the same membrane vessel. TAK did not participate in the USBR-led consortium but have adopted the 16-inch “standard” for their large size RO membranes.

Koch Membrane Systems have independently developed large RO elements of 18-inch diameter and 61-inch length (“MegaMagnum”), which are not compatible in size and length with the other large size membrane elements available on the market today. In November 2009, Koch introduced 19-inch × 61-inch brackish water and seawater RO elements, which have enhanced production capacity (“MegaMagnum Plus” models 19061-HR-3525 and 19061-SW-3525, respectively).

8.3.4.2 Diameter, Length, Membrane Area, and Productivity

Dow/Filmtec, Hydranautics, Toray, and TAK have adopted the “standard” 16-inch by 40-inch membrane size developed by the USBR-led consortium of membrane manufacturers (USBR, 2004). While the consortium considered the feasibility of 20-inch or larger vessels, the USBR study concluded that the preferred diameter large membrane element is 16 inches based on the fact that cost savings decrease and manufacturing risks increase asymptotically for membrane systems with larger diameter elements.

The consortium has selected 40-inch length of the 16-inch elements for several reasons: (1) this size element has exactly 4 times higher surface area as compared to 8-inch elements; (2) the length of the 16-inch pressure vessels for 5 and 7 elements will be the same as that of existing 8-inch pressure vessels, which would facilitate the retrofit of 8-inch RO installations with larger vessels within the same RO building.

GrahamTek, a Singapore-based company, has developed two enhancements to 16-inch RO systems: (1) a patented flow distributor located on the inlet and outlet ends of the vessels to achieve a more uniform distribution of the source seawater flow within the membrane element feed spacer and (2) electromagnetic field (EMF) inducing coils embedded in the pressure vessels to enhance membrane flux and suppress membrane scale formation and biofouling.

Each integrated flow distributor has 45°-angled and evenly distributed holes to control the angle of entry and flow velocity in the membrane spacers. The electromagnetic field created in the vessels generates net movement in the direction of the concentrate stream through the membrane surface, thereby increasing permeability as well as inhibiting scale formation.

The two technological enhancements are claimed by GrahamTek to have the following benefits: (1) use of lower quality water for desalination; (2) operation at up to two times higher flux which allows to reduce the total number of elements needed to produce target permeate flow; (3) lower membrane scaling rate due to diminished concentration polarization on the membrane surface as a result of the more uniform spacer flow distribution, the scrubbing effect of micro-bubbles created by the flow distributors, and the electromagnetic field; and (4) reduced scale formation and biofouling.

In 2003, KMS developed a series of large-diameter RO membrane elements with 18-inch diameter and 61-inch length ("MegaMagnum"). These elements have over 7 times larger membrane area and fresh water production capacity as compared to the traditional 8-inch elements (3,050 sq. ft. vs. 400 sq. ft.). Up to five 18-inch membrane elements can be installed into one large pressure vessel. As a result, one 5-element vessel with 18-inch MegaMagnum RO membrane can produce approximately 5 times more permeate flow than one 7-element vessel with 8-inch membranes.

The 19-inch KMS MegaMagnum Plus RO elements, introduced in November 2009, have a membrane area of 3,525 sq. ft., which is 8.8 times higher than that of a standard 8-inch element. Productivity of one 5-element vessel with MegaMagnum Plus elements is over 6 times higher than that of a 7-element vessel with 8-inch membranes.

The 18-inch KMS MegaMagnum elements have approximately 30% greater filtration area than the 16-inch RO membranes provided by other vendors. Similarly, the 19-inch MegaMagnum Plus elements have over 50% higher filtration area than the 16-inch RO elements.

8.3.4.3 Membrane Materials and Performance

All membrane manufacturers use the same membrane flat sheet (leaf) materials for their large size RO elements and their 8-inch elements. They also employ the same feed/brine spacer configuration and thickness. As a result, large size membrane elements are produced with the same performance characteristics (rejection, standard production capacity, permeability, feed spacer size, etc.) as their 8-inch equivalents.

Recent site-by-site studies of 8-inch and large-diameter membrane elements for water reclamation and seawater desalination applications (Hallan et al., 2007; Ng et al., 2008; Johnson et al., 2009; Bergman and Lozier, 2010) indicate that the latest generation large size elements perform equally well in terms of salt rejection, permeability, flux, and fouling rate.

The outer shell of the membrane elements is produced by the same filament winding process for both 8-inch and large size elements. However, the outer wrap of the large size elements is stiffer and thicker in order to obtain a stiffer shell laminate.

8.3.4.4 Seal Carrier

This membrane element component (also called anti-telescoping device) is positioned at both ends of the fiberglass wrapped spiral-wound element and its main function is to support the downstream side of the membrane leafs and to prevent them from telescoping due to pressure differential across the element.

The seal carriers of the large size elements are several times thicker than those of their 8-inch counterparts because they are exposed to significantly higher loads. Hydranautics seal carriers for 16-inch elements incorporate vents, which allow for the removal of air from the annular gap between the outside of the element and the pressure vessel wall and thereby prevent over-pressurization and damage of the RO elements.

8.3.4.5 Element Interconnection

In all large size elements the permeate seals at each membrane-to-membrane connection are reduced from two to one. A single O-ring between each of the two elements is used instead. Taking under consideration the reduction in the total number of membrane elements and the fact that only one instead of two O-rings are used to connect the elements, the total number of O-rings relative to the standard 8-inch elements is reduced seven-fold. This reduction would have a beneficial effect on the potential O-ring leakage, which is one of the most frequent causes for RO membrane system performance integrity loss.

The Toray 16-inch elements have an "axial labyrinth" seal between the membranes (patent-pending), which avoids the need of installing radial seals on each element, reduces friction during loading/unloading, facilitates air displacement, and controls bypass flow.

The 16-inch Dow/Filmtec RO elements are available with interlocking devices similar to their 8-inch equivalents. However, the permeate coupler is eliminated in favor of a permeate seal locked on the end cap. This configuration simplifies membrane loading and eliminates the difficulties associated with the routine probing of the elements. It also reduces the pressure drop created by the coupler internal to the product water tube. The membrane elements are coupled via interlocking tabs located on the complimentary upstream and downstream end caps. A pair of modules is locked by rotating the newly loaded element approximately 30°. Aligned markings on the end cap perimeter allows the verification of the membrane locking visually.

In the 18-inch MegaMagnum elements, coupling between elements is accomplished by an external sleeve design. The coupling unit is locked within a cavity that is an integral part of the two-element seal plates. The coupling is external to the core tube, which allows a large cross-section O-ring to be used for connecting two elements. The elements are joined together at the outer surface of the seal plates by several fastener keys.

8.3.4.6 Brine Seal Location

Typical 8-inch elements use a radially loaded cup seal between the inside wall of the pressure vessel and the element. Such configuration would create excessively high friction for large elements and would make membrane element loading more difficult. Therefore, all membrane suppliers use a brine seal configuration where the seal is moved to the face of the seal plate. With this configuration, the flow path within the large RO elements is identical to the 8-inch membranes but without the significant drag force against the pressure tube walls.

8.3.4.7 Membrane Element Costs

At present, the costs of large size RO membrane elements per unit filtration area are higher than these of 8-inch elements. Membrane materials used for 8-inch and larger diameter elements are identical and both standard and large size elements are typically designed at similar flux and produce approximately the same volume of permeate per square foot of membrane area. However, the size of the core tube and membrane element wrapping are larger and the production costs of rolling larger size elements are higher. As a result, the price of large size membrane element per unit production capacity is higher.

For example, based on recent bids for large size projects, the unit cost of an 8-inch SWRO element with standard permeate flow production capacity of 7,000 gpd is US$400 to US$550/8-in element (i.e., US$57.1/1,000 gpd to US$78.6/1,000 gpd – avg. US$67.9/1,000 gpd). The typical price of a 16-inch SWRO element with permeate production capacity of 30,000 gpd at standard test conditions is US$2,200 to US$2,500/16-in element (US$73.3/1,000 gpd to US$83.3/1,000 gpd – avg. US$78.3/1,000 gpd). Thus, on average, large SWRO membrane elements are expected to cost 15% more than 8-inch elements for the same size plant. A similar unit cost difference between 8-inch and 16-inch elements is expected for brackish and seawater applications as well. This difference is reflective of the higher production costs of large size membrane elements.

8.3.4.8 Membrane Vessels

Four manufacturers currently offer membrane vessels for larger size elements:

- Protec Arisawa (formerly Beakaert);
- Pentair Codeline;
- ROPV;
- BEL.

All of these manufacturers can produce fiber-reinforced plastic pressure vessels for brackish water and water reuse applications. However, they are significantly more reluctant to manufacture and guarantee performance of membrane vessels for seawater applications for several reasons:

- Complexity of production of suitable end-cap assemblies due to their very high operation loads.
- Several times higher production costs than 8-inch vessels;
- Significantly lower profit margins as compared to 8-inch vessels.

The forces on the vessels and end caps are proportional to the square of the vessel diameter. As a result, the vessel wall and end-cap thickness and weight are four to six times higher than those of 8-inch vessels. For example, the estimated weight of an end-cap assembly designed for SWRO vessels meeting American Society for Testing and Materials (ASTM) code requirements is 145 pounds and cannot be handled manually. For comparison, the end-cap assembly for an 8-inch SWRO vessel is 25 pounds and can be installed singlehandedly by one operator.

Because of the higher end-cap weight loads, vessel manufacturers have adopted the use of the configuration and design of the existing 8-inch seawater end caps and shimming for the large-diameter pressure vessels offered for brackish water desalination and water reuse applications.

However, the design and production technology of large-diameter end caps for seawater applications are still in its early stages of development, and the membrane vessel suppliers do not have industry standards or in-house experience with manufacturing of such end caps and shimming. Therefore, the traditional membrane vessel manufacturers have to order custom-made end caps for seawater vessels they deliver. The specialty manufacturers of such end caps have several times higher profit margin expectations than the profit margins the vessel suppliers can sustain from the sale of large vessels.

As a result, none of the membrane vessel manufacturers listed above currently maintains a standard production line for large-diameter seawater desalination vessels and if the vessel manufacturers take such orders, these vessels are custom-made, and the vessel end caps are subcontracted to specialty manufacturers. Therefore, the time for production and delivery of such vessels is significantly longer than that for standard 8-inch vessels (usually 12 months or more).

The limitations and very high costs associated with the manufacturing of large-diameter vessels and end caps; the potential desalination plant worker safety risks associated with the use of non-standard end caps with unproven track record, which the vessel suppliers are usually required to take by the end user; and the slow response of the desalination industry to adopt the use of large- diameter RO elements are some of the key reasons why the pressure vessel industry has not yet embraced the commercial production of vessels for large size SWRO elements.

A very important cost-benefit consideration for all large size pressure vessels today is that they are only offered in end-port and side-port configurations (i.e., no multiple-port configuration large-diameter pressure vessels are currently available on the market). Taking under consideration that the use of 8-inch multiple-port configuration provides significant savings of high-quality stainless steel piping as compared to end- and side-port configurations, this disadvantage of large-diameter systems diminishes their overall cost benefits.

As indicated previously, the vessels for large size RO membranes have significantly thicker and heavier walls and end caps than those for 8-inch elements. As a result, the vessel costs for these elements are higher than 8-inch vessels. For example, the cost of a 7-element 8-inch pressure vessel for a large SWRO project is typically in a range of US$1,400/vessel to US$1,800/vessel (avg. US$1,600/vessel).

A 4-element, 16-inch pressure vessel costs US$7,000 to US$9,000/vessel (avg. US$8,000/vessel). Taking under consideration that one 7-element, 8-inch SWRO vessel has a standard production capacity of 49,000 gpd and a 4-element 16-inch vessel would produce 120,000 gpd, the average vessel cost per unit production capacity for an 8-inch vessel is US$32.7/1,000 gpd while a 16-inch vessel is US$66.7/1,000 gpd. This analysis indicates that the use of 16-inch vs. 8-inch elements will cost on average two times more for SWRO plants of the same size. The vessel cost difference for large brackish water and water reclamation projects is expected to be in a range of 50% to 80% higher.

8.3.4.9 RO Train Number, Size, and Configuration

It should be pointed out that economies of scale from the use of large RO elements can only be obtained when the number of the RO trains of a plant with large elements is smaller than the number of RO trains using 8-inch elements. For example, for the 50 MGD brackish water, water reclamation and SWRO plants, the USBR study team (USBR, 2004) have selected the size of the individual large element trains of 47,300

m^3/day (12.5 MGD), 37,850 m^3/day (10 MGD), and 31,530 m^3/day (8.33 MGD), respectively, and have compared it against a 15,780 m^3/day (4.17 MGD) 8-inch train (i.e., in all cases the 16-inch RO trains were at least two times smaller than the 8-inch RO trains). This allowed the USBR team to conclude that for this size plant, use of large RO elements will have a clear life cycle cost advantage as compared to an 8-inch element-based system.

Cost-benefit analysis for RO systems with an identical number of RO trains would have shown an unfavorable outcome. For example, a RO system of a 200,000 m^3/day SWRO plant with ten 8-inch 20,000 m^3/day element trains will likely cost 10% to 30% more than the same size plant with ten 20,000 m^3/day 16-inch RO element trains despite the fact that fewer elements and vessels are used. In order for the 16-inch RO system to become more competitive than the 8-inch RO system, the large element RO system would have to have at least two times fewer trains than the 8-inch system.

The main reason for this disparity is the fact that the costs for large RO elements per unit production capacity are 10% to 20% higher than the costs of 8-inch elements and the costs for membrane vessels are approximately two times higher. The main cost savings that can offset these significantly higher membrane and vessel costs can mainly come from the shorter length stainless steel interconnecting piping and fewer fittings (valves, elbows, etc.) and instrumentation, and lower number of racks resulting from the use of fewer RO trains.

Because the cost of high-quality stainless steel piping, instrumentation, and RO racks is approximately 25% of the total cost of the RO system, and the RO trains and vessels are over 50% of these costs, in order for the cost penalty associated with the use of larger elements and vessels to be compensated by the savings from the use of fewer trains, the number of large membrane trains would need to be at least two times smaller than the number of 8-inch RO trains.

In the case of the 200,000 m^3/day plant, in order for a large RO element system to be more competitive than an 8-inch system of the same capacity (i.e., 200,000 m^3/day), it has to have five RO trains or less (i.e., each train would have to have capacity of at least 40,000 m^3/day). The problem with such a large RO train capacity for this size plant is that when one train is taken out of service for cleaning, the plant would lose 20% of its production capacity.

In order for the plant to maintain its overall production capacity during an RO train shutdown, the RO system design flux has to be selected conservatively (i.e., plant design flux is such that the other RO trains can be operated at 20% higher than design flux) and the train transfer pumps, high-pressure pumps, and energy recovery devices have to be oversized. These additional costs, however, will greatly negate the benefits of the use of larger trains.

It should be pointed out that the cost-benefit analysis and threshold of beneficial use of large-diameter over 8-inch elements would be project specific and constraints such as space availability and land costs may become an important factor that would make large element RO systems more attractive for plants of capacity lower than 100,000 m^3/day. However, under the present economics of large element vessels, for plants smaller than 100,000 m^3/day it is likely that the use of 8-inch elements would be more cost beneficial and an economy of scale derived from the use of fewer trains and interconnecting piping and fittings can be obtained by the use of larger size individual 8-inch trains rather than by using large size RO elements.

The benefits associated with economies of scale that 8-element systems can yield are limited to plants of approximately 200,000 m^3/day and therefore, large element RO systems would have a clear cost advantage mainly for larger plants. A typical 8-inch RO train of a large desalination plant contains 100 to 200 vessels and 700 to 1,600 membrane elements. Even feed flow distribution beyond 200 vessels per train is very difficult to achieve and not practiced. The complexity of fabricating, transporting, and installing large size RO racks also becomes more complex with an increase in train size. At present, these hydraulic, construction, and physical constraints limit the maximum production capacity of individual RO trains with 8-inch elements to 20,000 to 25,000 m^3/day per RO train.

The large number of connections, elements, pressure vessels, and seals significantly reduces the cost benefits derived from the economy of scale for large and mega desalination projects. Full-scale experience to date indicates that very little economy of scale could be achieved when constructing 8-inch RO desalination plants with a production capacity larger than 200,000 m^3/day.

From a practical point of view, large size RO membrane trains can be constructed with a capacity of 50,000 to 100,000 m^3/day per RO train. While trains larger than 100,000 m^3/day are possible to build, their use would face the same economy-of-scale limitations as the 8-inch RO trains have at present but at a higher threshold. In summary, the use of large size elements would move the economy-of-scale threshold of 200,000 m^3/day associated with 8-inch elements to up to 800,000 m^3/day, if larger elements are used.

Depending on the RO membrane supplier, one large membrane vessel houses 4 to 7 membrane elements. Table 8.4 presents a typical one-vessel configuration of large-diameter RO elements offered by key membrane suppliers. Analysis of this table indicates that a single vessel can produce between 600 to 1,900 m^3/day of permeate depending on the membrane supplier and configuration.

Currently, the largest SWRO project in the world, the 410,000 m^3/day Sorek desalination plant in Israel, is configured with RO racks that have vertically installed vessels with 16-inch elements (see Figure 8.4). This vertical configuration minimizes the size of the otherwise heavy RO train support structure and further reduces RO system costs.

In addition, such configuration is considered to be more beneficial because it arrests internal movement of the elements within the membrane vessel under conditions of pressure surges, and thereby minimizes breakages of O-rings and pipeline interconnectors. All other large-diameter full-scale RO projects in operation to date are configured with membrane vessels installed horizontally on membrane racks.

8.3.4.10 Large Size Element Loading and Unloading

As compared to 8-inch elements, the large RO elements cannot be loaded manually because of their heavy weight (115 to 145 lbs dry and 136 to 167 lbs wet) for 16-inch elements and 200 lbs dry/250 lbs wet for 18-inch elements. End caps for large element vessels are also several times heavier than those for 8-element vessels [145 lbs (for SWRO systems) vs. 25 lbs] and require special handling equipment.

TABLE 8.4
Typical Production Capacity of One Large RO Vessel

		Product Water Capacity per Vessel (MGD)	
Membrane Manufacturer/ Membrane Element Size	**Typical Number of Elements per Vessel**	**BWRO & Water Reuse**	**SWRO**
Dow/Filmtec 16-in × 40-in	7	0.28–0.30	0.22
Hydranautics 16-in × 40-in	4	0.12–0.15	0.10–0.14
Toray 16-in × 40-in	7	0.28	0.19–0.21
Woongjin Chemical 16-in × 40-in	4	0.15	0.10–0.15
KMS – MegaMagnum 18-in × 61-in	5	0.33–0.43	0.26–0.35
KMS – MegaMagnum Plus – 19-in × 61-in	5	0.40–0.50	0.30–0.40

Note: 1 MGD = 3785 m³/day.

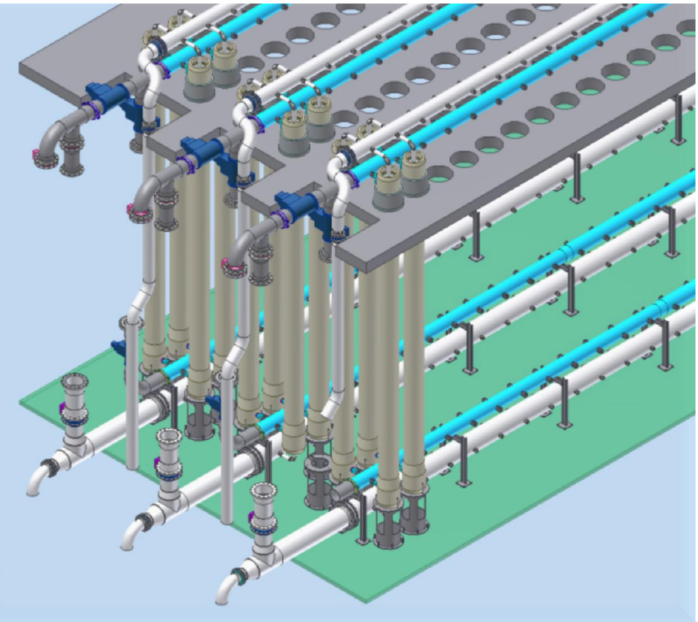

FIGURE 8.4 Vertical 16-inch vessels of Sorek SWRO plant.

Membrane manufacturers differ by the methods and equipment they have developed for large size membrane lifting, staging, and loading. Some manufacturers (Hydranautics and TAK) have developed proprietary loading/unloading devices for their systems. The 16-inch elements of the Sorek SWRO desalination plant are installed from the bottom of the vessel via a loading mechanism specifically designed for this purpose (see Figure 8.5).

Toray has developed a patented wheel-mounted material lift to load the elements. This lift is fully motorized and can be operated by a single operator. KSM also offers an automatic loading device to accommodate the loading of its 18-inch and 19-inch elements. Dow/Filmtec also has a patented loading system, which includes a lightweight cradle that attaches to anchors placed in the end face of the pressure vessel. KSM large elements are designed to be connected in series and therefore they can only be loaded and unloaded from one side of the pressure vessels.

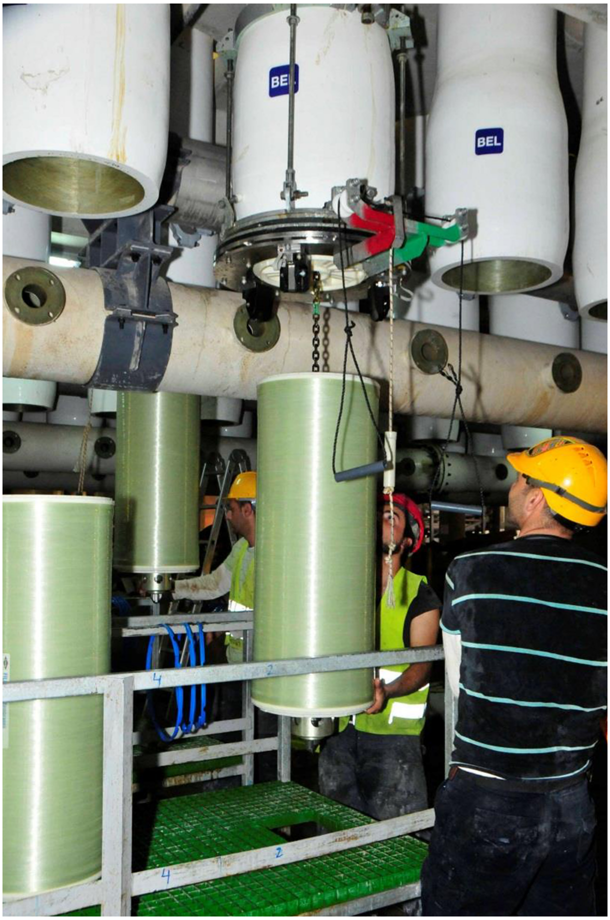

FIGURE 8.5 Sorek SWRO plant loading of 16-inch element.

The large elements of all other membrane manufacturers are designed for loading from both ends of the vessel. Full-scale experience shows that the time a two-people crew needs to load a 7-elment/8-inch vessel is approximately the same as the loading or unloading time for large size 5-element vessel – approximately 15 to 20 minutes.

8.3.5 Hybrid Membrane Configuration

At present, hybrid membrane configuration combining SWRO elements of different productivity and rejection within the same vessel is widely used to reduce energy use and water production costs (see Figure 8.6).

Usually, in SWRO systems using standard spiral-wound RO membrane elements all of the feed seawater is introduced at the front of the membrane vessel and all permeate and concentrate are collected at the back end. As a result, the first (front) membrane element is exposed to the entire vessel feed flow and pressure, and operates at productivity per square meter of element (flux) significantly higher than that of the subsequent membrane elements.

With a typical configuration of seven elements per vessel and ideal uniform flow distribution to all RO elements, each membrane element would produce one-seventh (14.3%) of the total permeate flow of the vessel. However, in actual conventional SWRO systems, the flow distribution in a vessel is uneven and the first membrane element usually produces over 25% of the total vessel permeate flow, while the last element only yields 6% to 8% of the total vessel permeate (see Figure 8.7).

The decline of permeate production (flux) along the length of the membrane vessel is mainly due to the increase in feed salinity and associated osmotic pressure as the permeate is removed from the vessel while the concentrate rejected from all elements remains in the vessel until it exits the last element. In addition, as the first element produces over 25% of the permeate flow it also uses over 25% of the pressure/energy available for desalination. This energy is lost with permeate generated by the first RO element, instead of being available to obtain maximum performance efficiency of the remaining six RO elements in the pressure vessel.

Since a disproportionately large amount of energy is expended too early in the desalination process and the remaining six downstream RO elements are

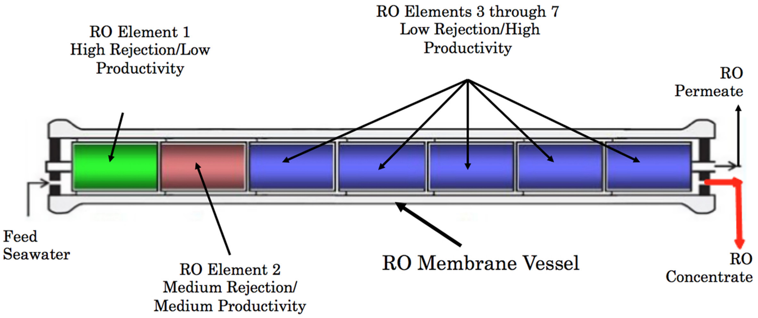

FIGURE 8.6 Hybrid membrane configuration.

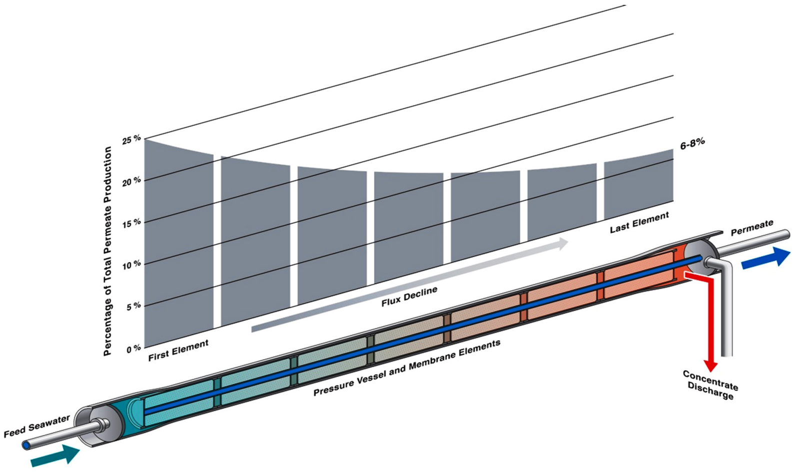

FIGURE 8.7 Typical distribution of permeate production within membrane vessel.

underworked, the overall energy efficiency of permeate production by the pressure vessels in conventional SWRO systems is not at an optimum level. In addition, because the first element processes the largest portion of the feed flow, it also receives and retains the largest quantity of the particulate and organic foulants contained in the source seawater, and is most impacted by fouling.

The remaining feed water that does not pass through the first RO element and the concentrate from this element enters the feed channels of the second RO element of the vessel. Therefore, this element is fed with higher salinity feed water and lower feed pressure (energy) – since some of the feed energy has already been used in the first RO element to produce permeate. As a result, the permeate flow rate (flux) of the second element is lower and the concentrate polarization on the surface of this element is higher than that of the first RO element.

The subsequent membrane elements are exposed to increasingly higher feed salinity concentration and elevated concentrate polarization, which results in a progressive reduction of their productivity (permeate flux). As flux through the subsequent elements is decreased, accumulation of particulate and organic foulants on these elements diminishes and biofilm formation is reduced. However, the possibility for mineral scale formation increases because the concentration of salts in the boundary layer near the membrane surface increases. Therefore, in conventional SWRO systems, fouling caused by accumulation of particulates, organic matter, and biofilm formation is usually most pronounced on the first and second membrane elements of the pressure vessels, while the last two RO elements are typically more prone to mineral scaling than the other types of fouling.

Desalination would be more energy efficient if the feed flow to the pressure vessel is distributed more evenly to all seven RO elements in the vessel. A novel membrane configuration design to obtain more even flux distribution is achieved by combining three different models of membranes with different permeability within the same vessel instead of using the same model of RO elements throughout the vessel (which is a typical configuration for conventional SWRO systems). This design was perfected and proven by Dow Filmtec as Inter-Stage Design (ISD) and over the last 10 years has been implemented in many SWRO desalination plants worldwide (Mickols et al., 2005).

On the example shown in Figure 8.6, the first (lead) element in ISD configuration, which receives the entire seawater feed flow of the vessel, is a low-permeability/high salt rejection element (i.e., Dow Filmtec SW30 XHR-400i). Because of its low permeability, this element produces only 14% to 18% (instead of 25%) of the permeate flow produced by the entire vessel, thereby preserving the feed energy for more effective separation by the downstream RO membrane elements in the vessel.

The second RO element in the pressure vessel is of a standard (average) permeability (i.e., Dow Filmtec SW30 XLE-400i) and salt rejection, and produces approximately 14% to 16% of the total flow, while the remaining five elements in the vessel are of the same high-permeability/low-rejection model (i.e., Dow Filmtec SW30 ULE-400i). This 1-1-5 combination of low-permeability/high-rejection and high-permeability/low-rejection elements results in a more even distribution of flux and pressure along the vessel and typically yields 5% to 15% energy savings, reducing the fouling rate of all membrane elements.

8.3.6 RO SYSTEMS FOR HIGH-RECOVERY PLANT DESIGN

A recent trend aimed at the reduction of the cost for fresh water production is the use of SWRO system configurations that allow an increase in the overall recovery of the desalination plant from a typical range of 40% to 50% to a range of 55% to 60%. Two recently developed high-recovery SWRO systems, which have significant potential for improving the overall plant recovery, are the FEDCO's Multistage Dual Turbocharger (MSDT) system (Figure 8.8) and the Hitachi's E-REX system (Figure 8.9). Both system configurations aim at maximizing permeate recovery by uniform distribution of flux among all of the membrane elements within the SWRO vessels.

8.3.6.1 Multi-Stage Dual Turbocharger (MSDT) High-Recovery SWRO System

The MSDT system, which incorporates one high-pressure feed pump (HPP) and two-stage SWRO configuration, is designed to achieve uniform flux distribution of all seven elements within the membrane vessels by reducing the feed pressure to the

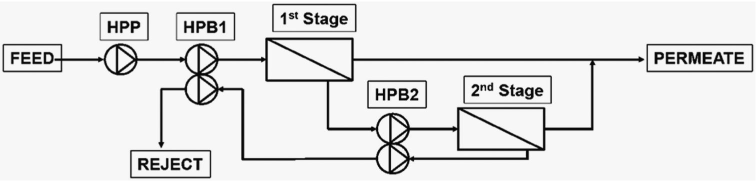

FIGURE 8.8 High-recovery SWRO system with Multistage Dual Turbochargers (MSDT).

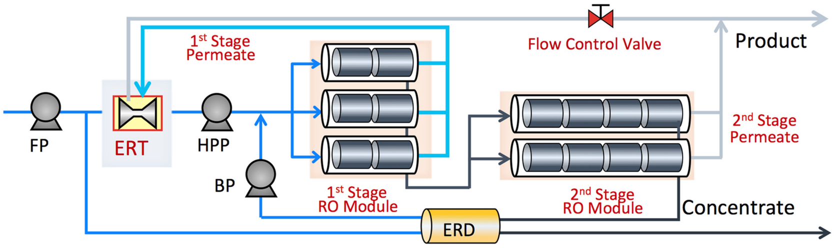

FIGURE 8.9 Process schematic of E-REX high-recovery desalination system.

first stage of SWRO elements and operating these elements at relatively low recovery and flux (Barrassi, 2018). The concentrate from the first-stage SWRO elements is then treated through a second set of SWRO elements to obtain a total SWRO system recovery of 55% to 60%. Each of the two SWRO stages is equipped with high-pressure boosters (HPB1 and HPB2).

Based on full-scale testing of the high-recovery system depicted above, the energy used by the SWRO system for seawater salinities of 35,000 and 43,000 mg/L was 2.1 and 2.9 kWh/m^3, respectively. Such energy use is comparable to that of conventional SWRO systems with pressure exchangers operating at SWRO system recovery, with the key difference being that the sustainable recovery of the MSDT system is 30% to 40% higher (e.g., 55% to 60% vs. 42% to 45%).

Designing the plant intake and pretreatment systems for such significantly higher recoveries allows significant capital and cost of water production savings for new plants or enhances the existing plant fresh water production capacity at relatively low capital investment.

8.3.6.2 E-REX High-Recovery SWRO System

The E-REX system is an innovative reverse osmosis desalination technology, which uses patented two-stage RO system configuration to significantly increase the recovery of this system and to thereby reduce the size, construction, and operating costs of the desalination plant's intake, pretreatment, and discharge facilities by 30% to 50% (Kitamura and Miyakawa, 2017). This system consists of three key components: (1) first-stage RO module, that contain only two elements per vessel and has a feed flow that is typically 1.5 to 3 times smaller than the feed flow per vessel of a typical conventional SWRO system; (2) energy recovery turbine installed on the permeate line from the first-stage RO module, which creates 10 to 20 bars of backpressure on this permeate thereby reducing the flux, fouling, and concentrate polarization of the first-stage RO elements; and (3) second-stage RO module which typically has only four membrane elements in a series and processes the concentrate from the first-stage RO module.

As shown in Figure 8.9, similar to conventional SWRO systems, the feed flow to the first-stage RO module of the E-REX system is pumped by a high-pressure pump (HPP) and the concentrate generated by the second-stage RO module is processed through an energy recovery device (ERD), which typically is a pressure exchanger type.

The permeate from the first-stage RO module is directed to an energy recovery turbine (e.g., turbocharger – ERT) installed to operate in the series with the high-pressure pump and to boost the pressure of this pump with 10 to 20 bars. The backpressure of the first-stage permeate line is controlled by a flow control valve.

One of the key unique features of this technology is the two-stage configuration of the SWRO treatment system, which allows the permeate backpressure on the membranes of the first stage of the SWRO system, which is generated by an energy recovery device (turbocharger), to create even distribution of feed and permeate production flows of all membrane elements included in the two stages of the system, which in turns increases the overall membrane productivity and the recovery of the SWRO system, while reducing the total energy used for desalination.

The E-REX system configuration allows the reduction of the feed flow and permeate flux of the front two SWRO elements by two to three times as compared to that in conventional SWRO systems, thereby reducing the fouling and concentration polarization of the front elements, which results in beneficial decrease of the transmembrane pressure and increase of the overall productivity of the SWRO system.

Depending on the source seawater salinity and temperature, as well as the configuration of the two stages of the SWRO system, the overall desalination system recovery can be increased from 45–50% to 60–65% for seawater of salinity of up 35,000 mg/L (i.e., typical Pacific and Atlantic Ocean waters) and from 40–45% to 55–60% for the high-salinity waters of the Mediterranean sea (39,000 to 41,000 mg/L); and the Red Sea and Arabian Gulf (42,000 to 46,000 mg/L).

Despite the slight (4% to 6%) increase in the capital costs of the SWRO desalination system due to the two-stage configuration of this system and the addition of the energy recovery turbine on the first-stage permeate line, the overall desalination plant construction costs are reduced because of the significant capital cost savings from the use and operation of smaller-size intake, pretreatment and discharge facilities, and SWRO energy recovery system.

The capital cost savings stem from the fact that a desalination plant which has an E-REX SWRO system is designed and operated at 30% to 40% higher overall plant recovery than conventional reverse osmosis desalination plants. As a result, a desalination plant with an E-REX SWRO system is 10% to 20% more energy efficient, and 10% to 20% less costly in terms of both capital investment as well as annual operation and maintenance expenditures than conventional SWRO desalination plants with the same fresh water production capacity.

A significant additional benefit of the E-REX system is the reduced fouling rate of the SWRO membranes. The E-REX system configuration evens out the flux of all RO membrane elements in the first- and second-stage vessels; reduces in the flux and fouling of the front elements over two times and increases the productivity of the back (second stage) elements approximately two times. As a result, the E-REX configuration increases the recovery of the SWRO system approximately 1.5 times (from 40% to 60%) as compared to conventional 7-element configuration (Figure 8.10).

Since the flux of the first-stage RO elements is proportional to the difference between the feed and the backpressures, for a typical feed pressure to the RO system of 68 bars for high-salinity ocean water (e.g., Arabian Gulf and Red Sea) and backpressure of 20 bars, the flux of the first two elements is reduced by 1.45 times

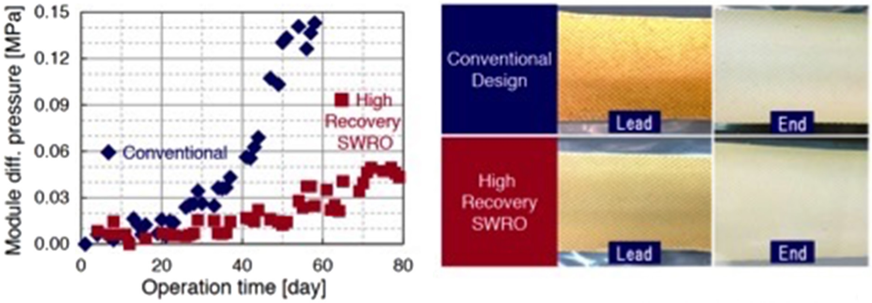

FIGURE 8.10 Fouling rate test results from side-by-side study of conventional and E-REX desalination systems on Red Sea source water.

(68 bars/(68 bars – 20 bars) = 1.42) as compared to the flux of the first two elements in a conventional 7-element per vessel RO system.

Because the RO membrane fouling rate is exponentially related to flux, a 1.42-times flux reduction would result in over 4-times decrease of the membrane fouling rate. Such a fouling rate decrease was clearly illustrated during the 6-month side-by-side testing of conventional RO and E-REX RO systems on Red Sea water (see Figure 8.10) - Kitamura and Miyakawa, 2017.

8.3.7 SPLIT-PARTIAL TWO-PASS RO SYSTEM WITH FRONT PERMEATE TREATMENT

At present, most new SWRO desalination systems are designed with a split partial second-pass configuration described in Chapter 4, because this configuration allows reducing the size of the second-pass RO system and the overall fresh water production costs. An advanced split-partial second-pass system where permeate collected from the front end of the SWRO vessels is treated through a second pass as depicted in Figure 8.11.

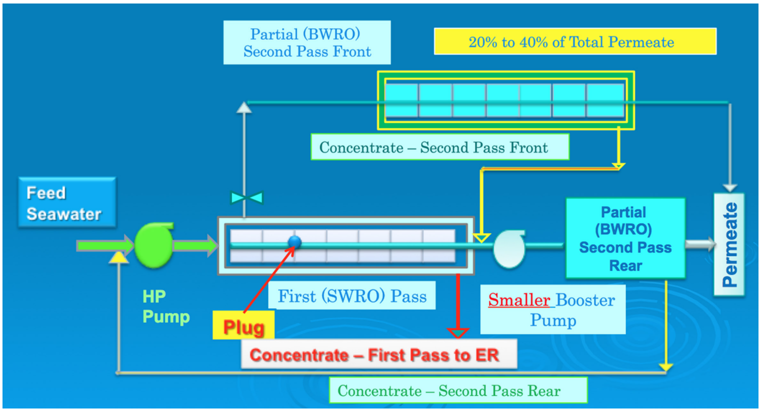

FIGURE 8.11 Split partial two-pass system with front and rear second pass.

The split partial second-pass system shown on this figure has some features that improve the flux distribution of the SWRO membrane that are similar to these of the E-REX system in terms of function and benefits: (1) permeate plug installed inside on the permeate tube of the second SWRO element, which effectively creates a two-stage first-pass SWRO system and helps balance the flux in the first two membrane elements; (2) brackish water RO membrane system installed on the front end permeate line with flow control valve that has two beneficial functions – one – it allows for the creation of 10 to 15 bars of backpressure on the front two elements in order to reduce their flux, and two – uses this backpressure to produce a very high-quality first-stage permeate.

In summary, the permeate plug creates two-element first SWRO stages similar to the first stage of the E-REX system, while the brackish RO system on the front permeate line serves a function similar to that of the energy recovery turbine. While the energy created by the backpressure is used by the ERT of the E-REX system to booster the feed pressure to the first-stage RO module by 10 to 20 bars, the energy created by the 10 to 15 bars of backpressure in the front and rear second-pass configuration shown in Figure 8.10 is used to pressurize the front-permeate into the second-pass front BWRO system.

8.3.8 Increased High-Pressure Pump Efficiency

One approach for reducing total SWRO system energy demand and water production costs, which is widely applied throughout the desalination industry today, is to use larger and higher efficiency high-pressure centrifugal pumps which serve multiple RO trains rather than the conventional approach of dedicating smaller-size pumps to the individual RO trains. The energy savings associated with the use of larger pumps stem from the fact that the efficiency of multistage centrifugal pumps increases with their size (pump flow). For example, under a typical configuration where an individual pump is dedicated to each desalination plant RO train, high-pressure pump efficiency is usually in a range of 80% to 83%. However, if the RO system configuration is such that a single high-pressure pump is designed to service two RO trains of the same size, the efficiency of the high-pressure pumps could be increased to up to 85%.

Proven design that takes this principle to the practical limit of centrifugal pump efficiency (≈ 90%) is implemented at the Ashkelon seawater desalination plant in Israel, where two duty horizontally split high-pressure pumps are designed to deliver feed seawater to 16 SWRO trains at guaranteed long-term efficiency of 88%.

A continuous plant operational track record over the past 10 years shows that the actual efficiency level of these pumps under this configuration is close to 90%. A similar high-pressure pump-RO membrane rack approach is used on a number of other recent desalination projects, such as the Sydney Water, Perth I and II, Cape Preston, and Adelaide SWRO desalination plants in Australia, and a number of desalination plants in Spain, Israel, and the Middle East.

A current trend for smaller desalination facilities (plants with fresh water production capacity of 250,000 gpd or less) is to use positive displacement (multiple-piston) high-pressure pumps and energy recovery devices, which often are combined into a single unit. These systems are configured to take advantage of the high efficiency of the positive displacement technology that reach 94% to 97%.

8.3.9 IMPROVED ENERGY RECOVERY

Advances in the technology and equipment allowing the recovery and reuse of the energy applied for seawater desalination have resulted in a reduction of 80% of the energy used for water production over the last 20 years. Today, the energy needed to produce fresh water from seawater for one household per year (~2,000 kW/yr.) is less than that used by a typical 18 cubic feet refrigerator for the same size household.

Energy recovery systems working on the pressure exchange principle (isobaric chambers) have found widespread application over the last 10 years and the use of these systems has reduced the desalination power costs with approximately 10% to 15% as compared to the last generation of energy recovery technologies dominating the market before the year 2005. The pressure exchangers transfer the high pressure of the concentrated seawater directly into the RO feed water with an efficiency exceeding 95%. Future lower energy RO membrane elements are expected to operate at even lower pressures and to continue to yield a further reduction in the cost of desalinated water.

Figure 8.12 depicts the configuration of a typical pressure exchanger-based energy recovery system. After membrane separation, most of the energy applied for desalination is contained in the concentrated stream (brine) that also carries the salts removed from the seawater. This energy-bearing stream is applied to the back side of pistons of cylindrical isobaric chambers, also known as pressure exchangers (shown as vertical cylinders on Figure 8.11). These pistons pump approximately 45% to 50% of the total volume of seawater fed into the RO membranes for salt separation. Since

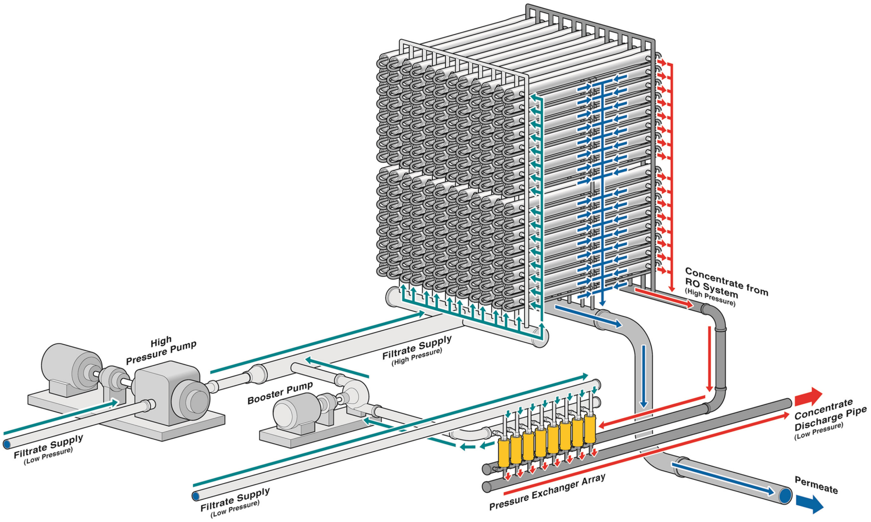

FIGURE 8.12 Pressure exchanger energy recovery system.

a small amount of energy (4% to 6%) is lost during the energy transfer from the concentrate to the feed water, this energy is added back to the feed flow by small booster pumps to cover for the energy loss. The remaining (45% to 50%) of the feed flow is conveyed by the high-pressure centrifugal pumps.

Harnessing, transferring, and reusing the energy applied for salt separation at very high efficiency (93% to 96%) by the pressure exchangers allows a dramatic reduction of the overall amount of electric power used for seawater desalination. In most applications, a separate energy recovery system is dedicated to each individual SWRO train. However, some recent designs include configurations where two or more RO trains are serviced by a single energy recovery unit.

8.4 RECENT AND FUTURE DESALINATION TECHNOLOGY ADVANCES

Near and long-term desalination technology advances are projected to continue to yield further decrease in costs of production of desalinated water. Some of the technologies with a high cost-reduction potential are discussed below. A comprehensive review of future desalination technologies and state-of-the-art desalination research is provided elsewhere (Burn and Gray, 2016; Bazargan, 2018).

8.4.1 Nanostructured Membranes

A recent trend in the quest for lowering the energy use and fresh water production costs for SWRO desalination is the development of nanostructured (NST) RO membranes, which provide more efficient water transport as compared to existing conventional thin-film membrane elements.

The salt separation membranes commonly used in RO desalination membrane elements today are dense semi-permeable polymer films of random structure (matrix), which do not have pores. Water molecules are transported through these membrane films by diffusion and travel on a multi-dimensional curvilinear path within the randomly structured polymer film matrix. This transport is relatively inefficient in terms of membrane film volume/surface area and substantial energy is needed to move water molecules through the RO membranes. A porous membrane structure, which facilitates water transport, would improve membrane productivity.

NST membranes are RO membranes which contain either individual straight-line nanometer-size channels (tubes/particles) embedded into the random thin-film polymer matrix, or are entirely made of clustered nano-size channels (nanotubes). NST membrane technology has evolved rapidly over the past 10 years and recently developed nanostructured membranes either incorporate inorganic nanoparticles within the traditional membrane polymeric film or are made of highly-structured porous film which consists of densely packed arrays of nanotubes. These nanostructured membranes reportedly have much higher specific permeability than conventional RO membranes at practically the same high salt rejection. In addition, nanostructured membranes have a comparable or lower fouling rate than conventional thin-film composite RO membranes operating at the same conditions, and they can be designed for enhanced rejection selectivity of specific ions.

For example, a US membrane supplier NanoH$_2$O, recently acquired by LNG has developed thin-film nano-composite (TFN) membranes, which incorporate zeolite nanoparticles (100 nanometers in diameter) into a traditional polyamide thin membrane film. These new TFN membranes have been commercially available for seawater applications since September 2010. The new membrane elements have 10% to 20% higher productivity than other currently available RO membranes or operate at approximately 10% to 15% lower energy use while achieving the same productivity as standard RO elements.

Recently, researchers worldwide have focused on the development of RO membranes made of vertically aligned densely packed arrays of carbon nanotubes (CNT) which have the potential to enhance membrane productivity up to 20 times as compared to the state-of-the-art desalination membrane elements available on the market at present. While CNT-based desalination membranes are not commercially available as of yet, it is very likely that such membranes will be released for full-scale application over the next 5 to 10 years.

Recently, grapheme has been the focus of significant research efforts because compared to nanotubes and carbon fiber it has a higher aspect ratio and surface area, which infers higher permeability and salt rejection, and lower fouling propensity (Hilal and Wright, 2018).

Nanostructured membranes hold the greatest potential to cause a quantum leap in desalination cost reduction because theoretically they can produce up to 20 times more fresh water from the same membrane surface area than the state-of-the-art SWRO membranes commercially available on the market at present. Such a dramatic decrease in the membrane surface area needed to produce the same volume of desalinated water could reduce the physical size and construction costs of membrane desalination plants over two times and bring this cost of production of desalinated water production to the level of that of conventional water treatment technologies.

A potential challenge with higher productivity membrane elements is that their efficiency and productivity will decrease proportionally to the rate of membrane fresh water productivity (membrane permeate flux) because of the accelerated membrane fouling. Therefore, the development of higher productivity membranes would likely require the modification of the membrane structure, geometry, and the configuration of the entire SWRO system to combat the accelerated fouling and scaling processes that accompany the use of membrane of fluxes that are significantly higher than those of SWRO systems with conventional membrane elements – 12 to 16 Lmh. A step forward in this direction is the use of close-circuit desalination systems lowers the membrane fouling rate by the slow increase in RO system recovery rate via concentrate recirculation loop (Stover, 2005; Warsinger et al., 2016; Stover and Efraty, 2012).

8.4.2 FORWARD OSMOSIS (FO)

In forward (direct) osmosis, a solution with osmotic pressure higher than that of the high-salinity source water (“draw solution”) is used to separate fresh water from the source water through a membrane. A forward osmosis process holds the potential to reduce energy use for salt separation. A number of research teams in the United

States and abroad are working on the development of commercially viable FO systems. These systems mainly differ in chemical composition of the draw solution and the method of recovery of the draw solution from the desalinated water.

Existing conventional thin-film composite RO membranes are not suitable for FO applications mainly due to their structure, which leads to low productivity. Development of high-productivity low-cost FO membrane elements of standard size is currently one of the greatest challenges and most important constraints in creating commercially-viable FO systems that could ultimately replace existing RO systems while reusing most of the existing RO system equipment. Most of the existing full-scale installations applying forward osmosis have been used mainly for industrial reuse. The use of this technology for drinking water applications is under development but from a total energy use point of view may not provide a significant competitive advantage to RO because of the high energy demand needed to separate the draw solution from the FO permeate to an extent where this permeate can meet potable water quality requirements.

Several companies such as Modern Water, Hydration Technology Innovation, and Trevi Systems have developed commercially available FO membrane desalination technologies, which to date have only found application for treatment of wastewaters from oil and gas industry and high-salinity brines. The Trevi systems FO technology is of potential interest because it uses draw solution that can be reused applying solar power – it is the main innovative technology considered for the ongoing solar power–driven desalination research led by Masdar in United Arab Emirates (UAE).

The main potential benefit of the development of commercially viable FO technologies for the production of desalinated water is the reduction of the overall energy needed for fresh water production by 20% to 35%, and those energy savings could be harvested if the draw solution does not need to be recovered and the salinity of the source water is relatively high. Such energy reduction could yield a cost of water reduction of 10% to 15%, especially for non-drinking water production applications.

8.4.3 MEMBRANE DISTILLATION (MD)

In membrane distillation, water vapor is transported between a “hot” saline stream and “cool” fresh water stream separated by a hydrophobic membrane. The transport of water vapor through the membrane relies on a small temperature difference between the two streams. There are several key alternative MD processes, including air-gap, vacuum, and sweeping-gas membrane distillation.

The sweeping-gas MD has been found to be more viable than the other alternatives. A sweeping-gas is used to flush the water vapor from the permeate side of the membrane, thereby maintaining the vapor pressure gradient needed for continuous water vapor transfer. Since liquid does not permeate the hydrophobic membrane, dissolved ions/non-volatile compounds are completely rejected by the membrane.

The separation process takes place at normal pressure and could allow achieving approximately two times higher recovery than seawater desalination (80% vs. 45% to 50%). It is also suitable for further concentration of RO brine from desalination plants (i.e., concentrate minimization). Membranes used in MD systems are different from the conventional RO membranes – they are hydrophobic polymers with micrometer-size pores. However, flux and salt rejection of these membranes are usually comparable to these of brackish water RO membranes.

Currently, MD enjoys a fairly high academic interest because of its very high recovery (as compared to RO) and lower energy use (as compared to conventional thermal evaporation technologies). The viability of this technology hinges upon the development of contactor geometry that provides an extremely low-pressure drop and on the creation of membranes which have high-temperature limits. Because of its current limitations, membrane distillation holds promise mainly for concentrate minimization and for fairly small-size applications (Alkhudhiri et al., 2012).

At present, MD systems are commercially available from Memsys, which have focused the advancement of this technology application mainly for treatment of produced water waste streams from the oil and gas industry. Other companies, such as Memstill, Keppel Seghers, and XZERO MD have recently commercialized MD systems mainly for industrial wastewater treatment and reuse applications. The main cost savings that can result from the application of this technology for large-scale desalination plants is lowering the cost of fresh water production from highly saline seawaters such as those of the Arabian Gulf and the Red Sea and the costs for concentrate management and disposal for brackish desalination plants by 15% to 20%.

8.4.4 ELECTROCHEMICAL DESALINATION

Developed by Evoqua (formerly Siemens) under a Challenge Grant from the Government of Singapore, this continuous electrochemical desalination process is based on a combination of ultrafiltration pretreatment, electrodialysis (ED), and continuous electrodeionization (CEDI) and is claimed to desalinate seawater to drinking water quality at only 1.5 kWh per cubic meter. This energy consumption is lower than the energy use of conventional SWRO desalination systems.

The electrochemical desalination has two key advantages as compared to RO desalination: (1) it does not require high pressure for desalination and therefore the equipment and materials used for the process are mechanically and structurally less demanding and therefore less costly; (2) the ED process is more efficient by its nature, because it separates and moves a much smaller mass of material (ions of salts) through low-pressure membranes as compared to RO membrane separation where a much larger number of water molecules are moved through thicker and more robust and complex high-pressure membranes. Although thermodynamically the theoretical amount of minimum energy needed for separation is the same, the auxiliary energy use inherently is lower when a process moving smaller mass of matter is used.

This process is currently under full-scale development and has been able to achieve energy consumption of 1.8 kWh/m^3 when desalinating seawater of salinity of 32,000 mg/L at 30% recovery (Shaw et al., 2011). The process operates at low pressure (2.8 to 3.4 bars), the equipment can be produced from plastic, and the membranes used for ED and CEDI are chlorine resistant. The potential reduction of desalinated water costs this technology can yield is 5% to 15%.

8.4.5 Capacitive Deionization (CDI)

This technology is based on ion transport from saline water to electrodes of high ion retention capacity, which transport is driven by a small voltage gradient. The saline water is passed through an unrestricted capacitor type CDI module consisting of numerous pairs of high-surface area electrodes. Anions and cations contained in saline source water are electrosorbed by the electric field upon polarization of each electrode pair by a direct current (DC) power source. Once the maximum ion retention capacity of the electrodes is reached, the de-ionized water is removed and the salt ions are released from the electrodes by polarity reversal.

The main component, which determines the viability of the CDI, is the ion retention electrodes. Based on research to date, carbon aerogel electrodes have shown to be suitable for low-salinity applications. This technology holds promise mainly for RO permeate polishing and for low-salinity brackish water applications. The fresh water system recovery for such applications is over 80%.

With recent development of a new generation of highly efficient lower-cost carbon aerogel electrodes, CDI may out-compete the use of ion exchange and RO for generation of high-purity water. Several commercially available CDI systems are available on the market (Enpar, Aqua EWP, Voltea). However, these systems have found applications mainly for small brackish water desalination plants and mainly industrial applications due to the limited specific ion adsorption of current carbon materials.

The technology holds promise because it could theoretically reduce the physical size and capital costs of desalination plants by over 30%. Current carbon electrode technology, however, limits salt removal to only 70% to 80%, uses approximately two times more energy than conventional RO systems, and is subject to high electrode cleaning costs due to organic fouling. New electrode materials as grapheme and carbon nanotubes may potentially offer a solution to the current technology challenges.

8.4.6 Biomimetic Membranes

Development of membranes with a structure and function similar to those of the membranes of living organisms (i.e., diatoms) may offer the ultimate breakthrough for low-energy desalination (specific energy use below 2.0 kWh/1,000 gallons). In these membranes water molecules are transferred through the membranes through a series of low-energy enzymatic reactions instead of by osmotic pressure. The permeability of such membranes could theoretically be 5 to 1,000 times higher than that of currently available RO membranes (Giwa et al., 2017).

Aquaporins are an example of such membrane structures. They are proteins embedded in the cell membrane of many plant and animal tissues and their primary function is to regulate the flow of water and serve as “the plumbing system for cells.” While an osmotic pressure driven exchange of water between the living cells and their surroundings are often the key mechanism for water transport, aquaporins provide an alternative mechanism of such transport.

Aquaporins selectively conduct water molecules in and out of the cell, while preventing the passage of ions and other solutes. Also known as water channels, aquaporins are integral membrane pore proteins. Some of them also transport other small, uncharged solutes, such as glycerol, CO_2, ammonia, and urea across the membrane, depending on the size of the pore. However, the water pores are completely impermeable to charged species such as protons.

One key advantage of aquaporine-based membranes, which is not found in conventional RO membranes, is that they combine both the ability to have high permeability and to exhibit high salt rejection at the same time (Tang et al., 2012). Conventional SWRO elements have an inverse relationship between permeability and salt rejection. The smaller the molecular pores the higher the salt rejection of the RO membranes but the lower the membrane permeability and vice versa. So practically, it is not possible to create a SWRO membrane that has high salt rejection and high productivity at the same time.

Currently, researchers in the United States, Singapore, and Australia are focusing on advanced research in the field of biomimetic membranes and the development of stable commercial products is underway (Tang et al., 2012). Although this research field is expected to ultimately yield high-reward benefits (e.g., overall desalinated water cost and energy use reduction over two times), currently it is in early stages of development – further research is focused on the formation and production of aquaporin structures, which are incorporated into robust and durable commercial membranes (Shahzad et al., 2017).

At present, the National University of Singapore's (NUS) Environmental Research Institute is working on the development and commercialization of biomimetic membranes, which have aquaporins inserted into the selective permeable layer of conventional RO membranes and UF and NF membranes. The aquaporins are installed into spherical artificial vesicles referred to as polymersomes, which are incorporated on the surface of the conventional membranes. Such aquaporin enhanced membranes are expected to operate low feed pressures (5 to 15 bars) and to yield significant energy savings and enhanced fresh water production.

8.5 POTENTIAL IMPACT OF FUTURE TECHNOLOGIES ON DESALINATION COSTS

The advance of the reverse osmosis desalination technology is closest in dynamics to that of the computer technology. While conventional technologies, such as sedimentation and filtration, have seen modest advancement since their initial use for potable water treatment several centuries ago, new more efficient seawater desalination membranes, membrane technologies, and equipment improvements are released every several years. Similar to computers, the RO membranes of today are many times smaller, more productive, and cheaper than the first working prototypes. The future improvements of the SWRO membrane technology are forecasted to encompass:

- Development of membranes of higher salt and pathogen rejection and productivity; reduced trans-membrane pressure, and fouling potential;
- Improvement of membrane resistance to oxidants, elevated temperature, and compaction;
- Extension of membrane useful life beyond 10 years;

- Integration of membrane pretreatment, advanced energy recovery, and SWRO systems;
- Integration of brackish and seawater desalination systems;
- Development of new generation of high-efficiency pumps and energy recovery systems for SWRO applications;
- Replacement of key stainless steel desalination plant components with plastic components to increase plant longevity and decrease overall cost of water production;
- Reduction of membrane element costs by complete automation of the entire production and testing process;
- Development of methods for low-cost continuous membrane cleaning which reduces downtime and chemical cleaning costs;
- Development of methods for low-cost membrane concentrate treatment, inplant and offsite reuse, and disposal.

Although no major technology breakthroughs are expected to bring the cost of seawater desalination further down dramatically in the next several years, the steady reduction of desalinated water production costs coupled with increasing costs of water treatment driven by more stringent regulatory requirements are expected to accelerate the current trend of increased reliance on the ocean as an attractive and competitive water source.

This trend is forecasted to continue in the future and to further establish seawater desalination as a reliable drought-proof alternative for many coastal communities worldwide. These technology advances are expected to ascertain the position of SWRO treatment as viable and cost-competitive processes for potable water production and to reduce the cost of desalinated water by 20% in the next 5 years and by up to 60% in the next 20 years (see Table 8.5).

8.6 CONCLUDING REMARKS

Over the past decade seawater desalination has experienced an accelerated growth driven by advances in membrane technology and material science. Recent technological advancements such as pressure exchanger based energy recovery systems,

TABLE 8.5

Forecast of Desalination Energy Use and Costs for Medium and Large Plants

Parameter for Best-in Class Desalination Plants	Year 2017	Within 5 Years	Within 20 Years
Total electrical energy use (kWh/m^3)	3.5–4.0	2.8–3.2	2.1–2.4
Cost of water (US\$/m^3)	0.8–1.2	0.6–1.0	0.3–0.5
Construction cost (US\$/MLD)	1.2–2.2	1.0–1.8	0.5–0.9
Membrane productivity (m^3/membrane)	28–48	55–75	95–120

higher efficiency RO membrane elements, nanostructured RO membranes, innovative membrane vessel configurations, and high-recovery SWRO systems are projected to further decrease the energy needed for seawater desalination.

The steady trend of reduction of desalinated water production energy and costs coupled with increasing costs of conventional water treatment and water reuse driven by more stringent regulatory requirements are expected to accelerate the current trend of reliance on the ocean as an attractive and competitive water source. This trend is forecasted to continue in the future and to further establish ocean water desalination as a reliable drought-proof alternative for many coastal communities worldwide.

Besides the factors which are likely to spur the growth of the use of seawater desalination for fresh water production worldwide, there are a number of factors that are likely to have inhibiting impact on the global growth of seawater desalination. Such factors include environmental concerns and associated environmental impact mitigation cost expenditures; "not-in-my-back yard" (NIMBI) reaction of concerned citizens driving plant location away from technically viable sites; rising energy costs; and the latest trends in adopting direct potable reuse instead of seawater desalination for large-scale regional water supply due to lower overall fresh water production costs (Gude, 2016).

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Glossary

Aerobic: Containing oxygen.

Ambient: Surrounding or background.

Ambient seawater: Seawater in the open ocean used for desalination.

Anaerobic: Not containing oxygen.

Anthropogenic: Caused by human activity.

Antiscalant: A chemical that inhibits scale formation on the SWRO membranes.

Aquifer: Underground formation that is saturated with water.

Bactericide: A chemical capable of destroying bacteria.

Biocide: Chemical used to inactivate microbiological organisms (e.g., chlorine).

Biodegradation: Breakdown of substances in the water by microorganisms.

Biomass: Living organic matter.

Biofouling: Membrane fouling caused by the excessive growth and accumulation of microorganisms and their secretions on the membrane surface.

Brackish water: Water with total dissolved solids concentration of 1,000–10,000 mg/L.

Brine: The concentrated stream separated from the source seawater during the desalination process. Usually the concentrate from SWRO desalination has 1.5–2.5 times higher TDS concentration than the source seawater.

Collocation: Location of desalination plant on existing power generation station and connection of desalination plant intake and outfall to the cooling water discharge of the power generation station.

Concentrate: Same as brine.

Contaminant: An undesirable substance contained in the source seawater, permeate, or concentrate.

Desalination, desalting: A process that removes dissolved solids (salts) from seawater.

Diffuser: Offshore end portion of outfall which consists of discharge ports configured to maximize the mixing of the desalination plant discharge with the ambient receiving waters.

Double-pass RO system: A RO system that consists of two sets of RO trains (units) configured in a series in which permeate from the first set of RO trains is processed through the second set of RO trains.

Feed water: Influent water that is fed into a treatment process/system.

Filtrate: The purified water that is produced by the membrane pretreatment system.

Flux: The rate of water flow across a unit of membrane surface area expressed in liters per hour per square meter (L/hr/m^2 or Lmh).

Fouling: The gradual accumulation of contaminants on and/or within the RO or pretreatment membrane surface that inhibits the passage of water, thus decreasing membrane permeability and productivity.

Hardness: Concentration of calcium and magnesium salts in water.

Inorganic: Commonly also referred to as mineral, includes all matter that does not originate from living organisms (animals, plants, bacteria, etc.).

Intake: The facility through which source water is collected to produce fresh water in desalination plant.

Ion: An atom or group of atoms/molecules that has a positive charge (cation) or negative charge (anion) as a result of having lost or gained electrons.

Ion strength: A measure of the overall electrolytic potential of a solution.

Langelier saturation index (LSI): A parameter indicating the tendency of a water solution to precipitate or dissolve calcium carbonate.

Mass transfer coefficient: A coefficient quantifying material passage through a membrane.

Membrane: A thin film of polymer material permeable to water and capable of separating contaminants from the source seawater as a function of their chemical and physical properties when a driving force is applied. Microfiltration and ultrafiltration membranes have measurable porous structures and physically remove particles and microorganisms larger than the size of the membrane pores. Ultrafiltration membranes also remove molecules larger than a specified molecular weight. Reverse osmosis membranes remove both soluble and particulate matter from the source water.

Membrane element: An individual membrane unit of standard size and performance.

Membrane system: A complete system of membrane elements, pumps, piping, and other equipment that can treat feed water and produce filtrate (UF and MF systems) or permeate (RO systems).

Microfiltration: Filtration through membranes of pore size between 0.1 and 0.5 μ.

Mitigation: Prevention of significant environmental impact and/or repair of such impact on aquatic habitat exposed to desalination plant discharge. Often mitigation involves restoration of existing habitat or creation of new habitat similar to the one that is impacted on the same or different location.

Near-shore discharge: Disposal on the desalination plant waste streams through structure (channel, pipe, weir, etc.) located on the shore or within several hundred meters from the shore in the tidal zone.

Offshore discharge: Disposal of desalination plant waste streams via long outfall structure extending beyond the tidal zone.

Open intake: Intake collecting source water directly from the water column of surface water body.

Organic: Organic matter is a broad category that includes both natural and man-made molecules containing carbon and hydrogen. All organisms living in water are made up of organic molecules.

Osmosis: The naturally occurring transport of water or other solvent through a semi-permeable membrane from a less concentrated solution to a more concentrated solution.

Osmotic pressure: A pressure applied on the surface of semi-permeable membrane as a result of the naturally occurring transport of water from the side of the membrane of lower salinity to the side of the membrane with higher salinity.

Percent recovery: The ratio of pure water (filtrate or permeate) flow to feed water flow of filtration system. In SWRO systems this is the ratio between permeate and feed water. In ultrafiltration (UF) and microfiltration (MF) systems it is the ratio of filtered water and feed water.

Permeability: The capacity of membrane material to transmit flow. Expressed as the membrane flux normalized for temperature and pressure and expressed in liters per square meter per hour per bar (Lmh/bar); also named specific flux.

Permeate: Purified water of low mineral content produced during the reverse osmosis separation process. Permeate is the portion of the feed seawater that passes through the RO membranes.

pH: The negative logarithm of the hydrogen-ion concentration. A solution of a pH lower than 7 is acidic, while one with pH higher than 7 is alkaline.

Pressure filtration: Filtration aided by imposing pressure differential across an enclosed filter vessel.

Pressure vessel: A housing containing membranes in a preset configuration that operates under pressure. For SWRO systems, pressure vessels are plastic or metal tube-shaped devices that house 6–8 SWRO elements.

Pretreatment: Process that includes one or more source water treatment technologies (e.g. screening, coagulation, sedimentation, filtration, chemical addition, etc.) which aim to remove foulants from the source seawater prior to SWRO separation in order to protect the membranes and improve desalination plant performance.

Product water: Low-salinity (fresh) water usually with TDS concentration of 500 mg/L or less produced by the desalination plant and suitable for distribution system delivery. In order for the desalination plant permeate to be converted to product water it has to be disinfected and conditioned for corrosion and predetermined water quality requirements.

Reject: Same as brine (concentrate) or spent pretreatment filter backwash water.

Reverse osmosis: Pressure driven movement of water through a semi-permeable membrane from the side of the membrane with more concentrated solution to that of a less concentrated solution.

Salinity: The concentration of total dissolved solids in water.

Salt passage: The ratio of the concentration of salt/s (ion/s) in permeate and the concentration of the same salt/s (ion/s) in the feed seawater. Typically, salt passage is expressed as a percentage of the feed water concentration of the salt/s.

Salt rejection: The ratio of salt/s (ion/s) removed (rejected) by the RO membrane to the salt/s (ion/s) of the source water. Salt rejection is equal to 100% minus the salt passage.

Scale: Mineral deposits formed on the surface of membrane and/or membrane matrix as a result of concentration (saturation) of the mineral/s to a level at which they form insoluble amorphous or crystalline solids.

Scale inhibitor: See Antiscalant.

Semi-permeable membrane: Membrane that has structure that allows small molecules, such as water, to pass while rejecting a large portion of the salts contained in the feed water.

Silt density index (SDI): A dimensionless parameter widely used to quantify the potential of seawater to cause particulate and colloidal fouling of RO membranes.

Spiral-wound element: An RO or NF membrane element which consists of membrane leaves wound around a central permeate collection tube and including feed and permeate spacers, anti-telescoping devices, and a brine seal.

Stage: A set of pressure vessels installed and operated in parallel.

Subsurface intake: Intake located below the ground surface collecting source water from groundwater aquifer. Examples of subsurface intakes are vertical, horizontal, and slant wells and infiltration galleries.

Suspended solids: Particulate solids suspended in the water.

Total dissolved solids, salinity: Measure of the total mass of all dissolved solids contained in the water.

Total suspended solids: The concentration of filterable particles in water (retained on a 0.45 μ filter) and reported by volume.

Train: A membrane system that consists of a rack housing a number of pressure vessels that have a common feed, permeate and concentrate piping and control equipment, and can be operated independently. The RO system or pressure-driven MF or UF membrane system consists of multiple trains operating in parallel.

Turbidity: A measure of concentration of suspended solids in water which is determined by the amount of light scattered by these solids.

Ultrafiltration: Filtration through membranes of pore size between 0.01 and 0.05 μ.

Uniformity coefficient: The ratio of the 60th percentile media grain diameter to the effective size of the filter media.

Vacuum filtration: Filtration through MF or UF membrane created in enclosed filter vessel by applying vacuum.

Viscosity: A tendency of fluid to resist flow (movement) as a result of molecular attraction (cohesion).

Zero liquid discharge (ZLD): Concentrate management alternative in which the concentrate is converted from liquid phase to solid phase (salt residual) by evaporation, freezing, or other means allowing crystallization of the salts contained in the concentrate.

Zone of initial dilution (ZID): Area around the discharge of desalination plant with diameter determined by the distance at which the concentration of the TDS of the mix between concentrate and ambient water reaches 10% of the TDS level of the ambient water.

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