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Desalination Project Cost Estimating and Management

Nikolay Voutchkov

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-0-8153-7414-5 (Hardback)

Library of Congress Cataloging-in-Publication Data

Library of Congress Cataloging-in-Publication Data
Names: Voutchkov, Nikolay, author.
Title: Desalination project cost estimating and management / Nikolay Voutchkov.
Description: Boca Raton : Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, 2018. | Includes bibliographical references.
Identifiers: LCCN 2018031237 | ISBN 9780815374145 (hardback : acid-free paper)
Subjects: LCSH: Saline water conversion--Costs. | Saline water conversion plants--Management.
Classification: LCC TD479.3 .V68 2018 | DDC 628.1/670681--dc23
LC record available at https://lccn.loc.gov/2018031237

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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.

Acknowledgments

I would like to express my appreciation to the fellow professionals, colleagues, and associates who have reviewed various portions of this book and have provided constructive comments and suggestions. Special note of gratitude to the many operators, desalination plant managers, equipment and membrane manufacturers, and public utilities in the United States, Australia, Japan, Bahrain, United Arab Emirates, Spain, Cyprus, Kingdom of Saudi Arabia, and other parts of the world who have contributed valuable cost and technology-related information used in this book.

Special appreciation is extended to Eng. Meshal Alawad for his support work on collection and analysis of cost information from desalination plants worldwide and on the development of the cost curves included in the book.

I gratefully appreciate the assistance of Ms. Emma Kaiser for her artistic contribution toward the preparation of the figures and graphs included in the book.

Finally, my deep and sincere gratitude to Dr. Boris Liberman, Chief Technology Officer of IDE, for his inspiration, encouragement, and impetus to write this book.

Author

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

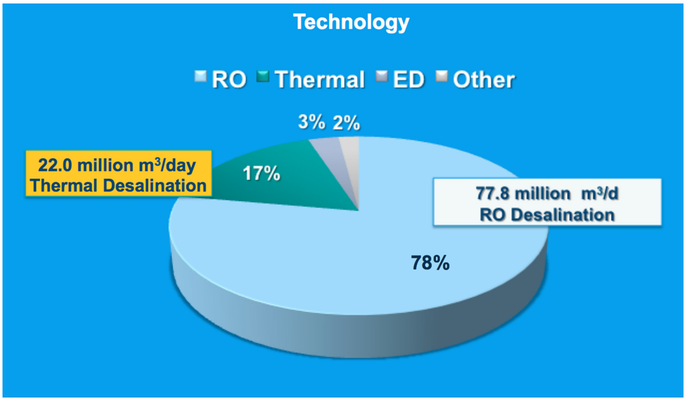

FIGURE 1.1 Breakdown of installed desalination plants worldwide by technology (2017).

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.

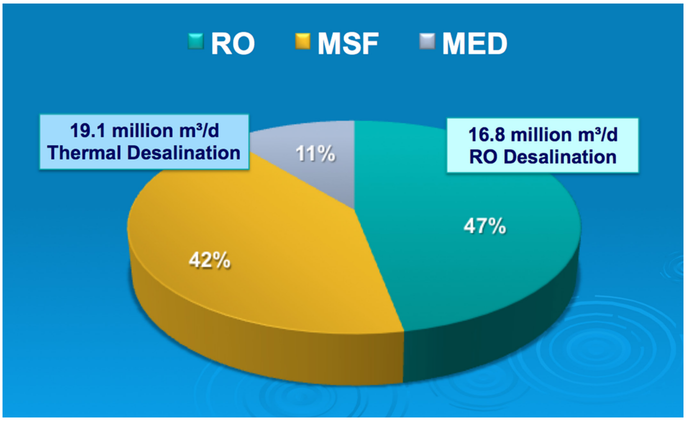

FIGURE 1.2 Breakdown of installed desalination plants in MENA by technology (2017).

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.

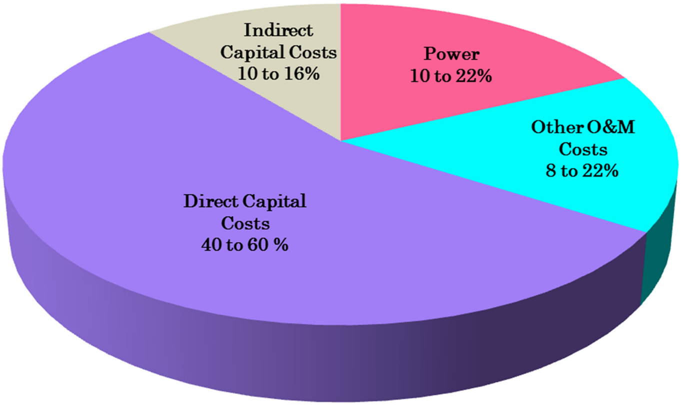

FIGURE 1.3 Typical cost of water breakdown for low-salinity BWRO plants.

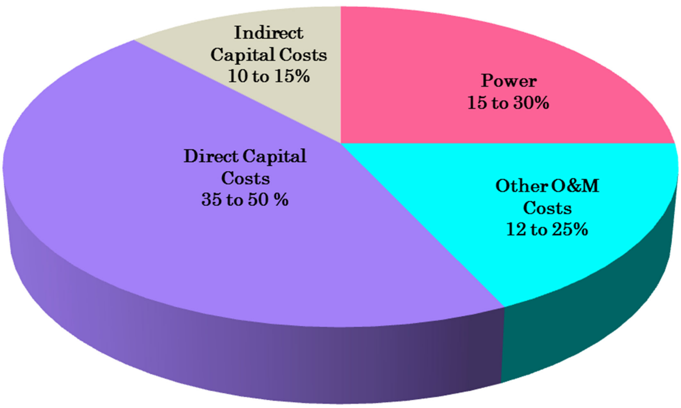

FIGURE 1.4 Typical cost of water breakdown for high-salinity BWRO plants.

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**

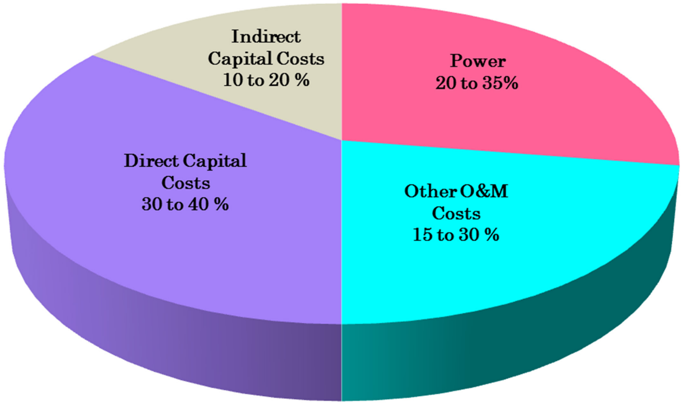

FIGURE 1.5 Seawater reverse osmosis plant – cost of water breakdown.

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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