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WATEREUSE RESEARCH

Renewable Energy Technologies and Energy Efficiency Strategies

Guidebook for Water Desalination and Reuse Systems to Optimize Energy Use and Reduce Green House Gas Emissions

WateReuse Research Foundation

Renewable Energy Technologies and Energy Efficiency Strategies

About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high-quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's subscribers, water and wastewater agencies, and other interested organizations.

Renewable Energy Technologies and Energy Efficiency Strategies

Guidebook for Water Desalination and Reuse Systems to Optimize Energy Use and Reduce Green House Gas Emissions

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Contents

Figures

Tables

Acronyms and Abbreviations

AC	alternating current
AFC	alkaline fuel cell
AOP	advanced oxidation process
APP	axial piston pumps
ARRA	American Recovery and Reinvestment Act
AWT	advanced water treatment
BCRS	brine concentration and recovery system
BEP	best efficiency point
BNR	biological nitrogen removal
CARROT	Climate Action Registry Online Tool
CCAR	California Climate Action Registry
CCD	closed circuit desalination
CCX	Chicago Climate Exchange
CDI	capacitive deionization
CDM	Clean Development Mechanism
CEDI	continuous electrodeionization
CERCLA	Comprehensive Environmental Response and Liability Act
CIGS	copper indium gallium diselenide
CONVAS	conventional activated sludge
CPV	concentrator photovoltaic
CREB	Clean Renewable Energy Bond
CSP	concentrating solar power
CWA	Clean Water Act
DC	direct current
DNA	deoxyribonucleic acid
DST	decision support tool
DW	drinking water
DWEER	dual work exchanger energy recovery
EBOP	electrical balance of plant
ED	electrodialysis
EDR	electrodialysis reversal
EPC	engineering, procurement, and construction
ERD	energy recovery device

ESPC	energy savings performance contracts
ESS	energy storage systems
FO	forward osmosis
GEO	Geothermal Exchange Organization
GFD	gallons/square foot/day
GGRT	Greenhouse Gas Reporting Tool
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	global warming potential
GWR	ground water replenishment
HD	humidification–dehumidification
HVAC	heating ventilation and air conditioning
ICLEI	International Council for Local Environmental Initiatives
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power provider
IPR	indirect potable reuse
ISO	International Organization for Standardization
ITC	investment tax credit
ITP	Industrial Technologies Program
LCZ	lower convecting zone
MBOP	mechanical balance of plant
MBR	membrane bioreactor
MCDI	membrane–CDI
MCFC	molten carbonate fuel cell
MD	membrane distillation
MED	multieffect distillation
MEH	multieffect humidification
MEMS	multieffect multistage
MF	microfiltration
MGD	million gallons per day
MLSS	mixed-liquor suspended solids
MPN	most probable number
MSF	multistage flash
MVC	mechanical vapor compression

NCZ	nonconvecting zone
NEPA	National Environmental Pollution Act
NPDES	National Pollution Discharge Elimination System
NYSERDA	New York State Energy Research and Development Authority
O&M	operation and maintenance
OEEP	Operational Energy Efficiency Program
PACE	property assessed clean energy
PAFC	phosphoric acid fuel cell
PEFC	polymer electrolyte fuel cell
PEM	polymer electrolyte membrane
PSAT	pump system assessment tool
PSB	polysulfide bromide flow battery
PPA	power purchase agreement
PSIM	pump system improvement modeling
PTC	production tax credit
PV	photovoltaic
PWE	pressure or work exchanger
PWT	Pelton wheel turbine
PX	pressure exchanger
QECB	qualified energy conservation bond
RDSI	renewable and distributed systems integration
REC	Renewable Energy Credit/Certificate
ReEDS	Regional Energy Deployment System
REPI	renewable energy production incentive
RNA	ribonucleic acid
RO	reverse osmosis
ROI	return on investment
RPS	renewable energy portfolio standard
RRTP	reverse-running turbine pump
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act
SEGIS	solar energy grid integration systems
SOFC	solid oxide fuel cell
SOP	standard operating procedure
SRT	sludge retention time
SWRO	seawater RO

TBP	turbo-booster pump
TDS	total dissolved solids
TVC	thermal vapor compression
UCZ	upper convecting zone
UF	ultrafiltration
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
UV	ultraviolet
VC	vapor compression
VFD	variable frequency drive
VRB	vanadium redox flow battery
WBSCD	World Business Council for Sustainable Development
WRI	World Research Institute
WRP	water recycling plant
ZBR	zinc bromine flow battery

Foreword

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse research topics including:

- Definition of and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's primary funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and other funding relationships.

The overall objectives of this project were to develop a comprehensive knowledge base for utilities in the United States, with the most updated developments in energy minimization and renewable energy techniques, and to prepare an easy-to-understand guidebook based on the relevant practical lessons learned by global researchers, organizations and utilities.

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Executive Summary

Purpose and Objective

The purpose of this guidebook is to provide utilities and water treatment practitioners with energy minimization strategies and renewable energy utilization guidelines. The guidebook is primarily focused on desalination using reverse osmosis (RO) and advanced water treatment (AWT) technologies. The overall objectives of this project were to develop a comprehensive knowledge base for utilities in the United States, with the most updated developments in energy minimization and renewable energy techniques, and to prepare an easy-to-understand guidebook based on the relevant practical lessons learned by global researchers, organizations, and utilities. The guidebook was developed as part of WateReuse Research Foundation Project WRF-08-13. The guidebook delineates analytical and quantitative guidelines for technologies to reduce energy use, overall facility costs, and greenhouse gas (GHG) emissions from AWT processes used in water reuse and desalination.

Research Approach

The project consisted of three major phases: (1) literature review, (2) utility case studies, and (3) guidebook development. During Phase 1 of the project, a thorough literature review of energy minimization strategies and renewable energy implementation for desalination and water reuse facilities was undertaken. During Phase 2 of the project, desalination and water reuse utilities with conventional and renewable energy resource utilization were surveyed. Information pertaining to the challenges and lessons learned in the process, energy minimization approaches, and renewable energy implementation was obtained. During Phase 3 of the project, information gathered from the literature review and utility survey were used to prepare this guidebook on energy minimization and renewable energy implementation strategies.

Findings and Conclusions

Energy usage can impact a utility in several areas of operation. Reducing energy consumption can lead to both reduced energy costs and GHG emissions. A combination of several strategies needs to be considered to reduce energy consumption. These strategies include improved system design, utilization of high-efficiency pumping, implementation of energy recovery devices (ERDs), and non-process-related conservation. Pumping consumes the largest energy for desalination using RO. All the energy minimization strategies and technologies are well developed and proven. Implementation of energy-efficient strategies can result in significant energy savings for the treatment plant. Development of an energy core team that understands the energy usage of the utility will be key to implementing these strategies. Implementation of energy efficiency programs should be performed with an energy audit to assess baseline energy consumption. Energy minimization approaches need to be considered during the initial design phase of the project, plant operation, retrofits and process modification, plant expansion, and treatment scheme upgrades.

Utilization of renewable energy technologies depends on the geography, technology, and means of handling variability, and solving economic scale-up and permitting issues. Technologies such as solar photovoltaic, concentrating solar power, wind turbines, geothermal energy, and biogas cogeneration are well developed but are still expensive to implement without the availability of funding, grants, and incentives. Return on investment (ROI) is a key criterion and decision maker for the implementation of renewable energy technologies at the utility scale.

A well-thought-out energy minimization plan that includes renewable energy utilization will reduce energy costs, positively impact the environment, and show a strong commitment to environmental stewardship and conservation of natural resources.

Chapter 1

Introduction

1.1 Water Demand and Consumption

The production of potable water has become a worldwide concern today. Less than 3% of the earth's 330 million cubic miles of water is freshwater and it is very unevenly distributed across the planet. For many communities, projected population growth and demand exceed freshwater resources (Greenlee et al., 2009). It is estimated that more than 1 billion people are without clean drinking water and approximately 2.3 billion people live in regions with water shortages (Service, 2006). As a result of demographic expansion, many areas in the world face the challenge of meeting ever-increasing water demands.

Global water consumption trends project more than 750 billion m^3 per year of water consumption by 2025 for North America alone (USGS, 2005). In the United States, the highest water consumption is in California, where more than 45,000 million gallons per day (MGD) of water is withdrawn predominantly for irrigation, thermoelectric power generation, and public supply (USGS, 2005). To cope with this increasing water demand, many municipalities and other water suppliers are turning toward more energy-intensive seawater desalination and water reclamation to supplement dwindling freshwater sources.

1.2 Desalination and Water Reuse

Desalination and water reuse technologies have been successfully implemented to provide additional freshwater production for communities (USEPA, 2004; Gleick, 1996; Sandia National Labs, 2003; Gleick, 2006). In the United States most desalination facilities are designed to achieve a total dissolved solids (TDS) content of 500 mg/L or less in the product water (permeate), for which reverse osmosis (RO) technology is predominantly used (Greenlee et al., 2009). The majority of plants in Saudi Arabia, the United Arab Emirates (UAE), and other Middle East countries use thermal processes, such as multistage flash (MSF), multieffect distillation (MED), and vapor compression (VC), producing TDS of less than 50 mg/L (Ettouney et al., 1999; Greenlee et al., 2009).

A forecast by the *Economist* magazine of global desalination technology utilization predicted that the global capacity of RO technology will outpace that of thermal desalination facilities (*The Economist*, 2008). Domestically, desalination accounts for approximately 0.4% of total water production capacity. More than 75% of U.S. desalination capacity is used to treat brackish groundwater or river water. Coastal and arid states including Florida, California, Texas, and Arizona have the highest installed desalination capacities in the U.S (Wangnick and GWI, 2005).

When water reuse is concerned, meeting stringent drinking water regulations requires the use of AWT technologies. Examples of AWT technologies being used or considered for both water and wastewater applications include ozonation, ultraviolet (UV) disinfection, and membrane processes (Chang et al., 2008). Membrane processes can involve a combination of low-pressure (microfiltration, ultrafiltration, membrane bioreactors) and high-pressure membrane processes (reverse osmosis).

AWT technologies are also used for indirect potable reuse (IPR) applications. IPR is the practice of taking recycled water that meets all regulatory requirements for nonpotable use, treating it further with several AWT technologies to meet potable water standards, and adding it to an untreated potable water supply. Indirect potable reuse typically refers to a combination of microfiltration (MF)/ultrafiltration (UF) followed by RO and UV disinfection. For advanced water treatment and reuse, the capital expenditure in the United States is predicted to grow by 19.5% over the next six years (Water Desalination Report, 2009). The cumulative installed water reuse capacity for IPR is expected to be almost 1.06 billion gallons per day by the year 2016 (Water Desalination Report, 2009).

Energy consumption in desalination and water reuse processes is of particular concern because of the rising cost of electricity. Although equipment costs have been decreasing as a result of technological advancements, the cost of energy continues to escalate. For example, because of significant reductions in membrane equipment and material costs over the last 20 years, energy consumption is now the second largest fraction of unit water cost in RO applications (Chang et al., 2008). Improving the energy efficiency of desalination and water reuse processes requires that a comprehensive understanding of energy consumption by the different equipment be developed. Key to improving the energy efficiency of desalination and water reuse processes is understanding their important characteristics, such as determining the primary energy-consuming equipment, water quality, and operating parameters that are influencing energy consumption.

Until recently, conventional fossil-fuel-based power plants have been utilized as the primary source for supplying energy to desalination and water reuse plants. However, the use of fossil fuels for generating power has spurred environmental concerns, specifically with GHG emissions. Thus, there are a large number of energy minimization approaches and renewable energy alternatives being developed, investigated, and implemented around the globe for desalination and water reuse applications.

1.3 Objectives of the Guidebook

The objective of this guidebook is to provide utilities and water treatment practitioners with strategies for energy minimization and renewable energy utilization.

This guidebook was developed to answer the following questions:

- What are the steps and methods to reduce energy consumption for various membrane-based desalination and advanced water treatment processes?
- What are the resources and tools available in pursuing energy efficiency at a treatment facility and in renewable energy resource implementation?
- What are the steps required for utilizing renewable energy resources?
- What are the challenges faced during implementation of renewable energy technologies?

1.4 Organization of the Guidebook

This guidebook is organized into the following chapters:

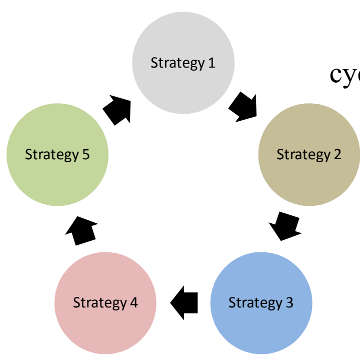
- Chapter 1: Introduction
- Chapter 2: Planning
- Chapter 3: Implementation of Energy-Efficient Strategies
- Chapter 4: Utilization of Renewable Energy Resources

Each chapter comprises objective, essential components for implementation, implementation steps, resources, and tools. Information obtained from the utility survey and literature review was utilized to develop the guidebook contents. Information from the utility survey and case studies is provided as Appendix A. More detailed descriptions of the process and energy minimization strategies are provided in Appendix B. Detailed descriptions of renewable energy utilization and GHG emissions are provided in Appendix C.

1.5 How to Use the Guidebook

The strategies provided in the guidebook are best utilized during the concept development and design phase of a project, but the guidelines can also be implemented during routine process operations and maintenance periods. The guidebook can be utilized for new treatment facility design, upgrades, and retrofits to existing treatment facilities to improve energy efficiency. Every chapter and its contents are provided with a resource section with information on tools available for design and implementation, resource guides, technology updates, and vendor information.

1.6 Purpose of Icons



Each chapter in the guidebook is provided with a basic cycle figure that consists of the components and strategies that need to be considered for energy minimization and renewable energy utilization. Consideration of all the components in a holistic manner will provide the best benefits to the user.

The light bulbs in the chapters suggest important information that needs to be considered in developing energy minimization and renewable energy utilization strategies.

The magnifying glass provides further resources and tools for the various components of the guidebook. The resources contain Webpage links that can be accessed to gather additional useful information on a particular topic.

Chapter 2

Planning

In this chapter, key components required for planning energy minimization and renewable energy utilization in a treatment plant are discussed. Steps required for energy efficiency management and renewable resource utilization are outlined. Additional resources for planning and auditing energy efficiency management and renewable resource utilization are provided at the end of the chapter.

2.1 Benefits of Implementing Energy Efficiency and Renewable Energy Utilization

Many benefits can be among the drivers for implementing these changes at a treatment plant:

- *Financial savings:* Reducing energy consumption will result in significant cost savings for the utility in terms of its energy bill.
- *Reduced GHG emissions:* Implementation of renewable energy resources will result in lower GHG emissions by reducing the consumption of fossil-fuel-based electricity.
- *Meeting state and federal energy-reduction targets:* Reduction of energy consumption will result in meeting targets set by local and federal authority for energy utilization.
- *Environmental stewardship:* Utilization of renewable energy resources will result in a clean and sustainable environment for the public.
- *Improved customer relations:* By implementing green initiatives and carbon-neutral treatment, facilities will improve utility–customer relationships.

2.2 Steps to Energy Efficiency and Renewable Energy Utilization

The steps that are typically followed for energy efficiency and renewable energy utilization are summarized in Figure 2.1. These steps are management, collection, implementation, monitoring and reporting, and continual improvement. These steps are then further expanded on in the subsections.

1) Manage

- Form an energy efficiency management team
- Devise a plan

2) Collect

- Perform energy audit
- Gather funding and incentive options

3) Implement

- Energy efficiency programs
- Renewable energy utilization

4) Monitor and Report

- Energy improvement
- GHG emissions

5) Continually Improve

- Capital and O&M improvements
- Standard Operating Procedures (SOPs)

Figure 2.1. Steps involved in energy efficiency and renewable energy utilization.

Step 1. Manage

The first step is to create an organizational structure, such as a core management team, to manage and be accountable for any efficiencies or recommendations decided on. This team should consist of an energy program manager and staff who will be actively engaged in achieving the determined goals.

- *Energy program manager:* The energy program manager will have the responsibility and management authority for implementing energy improvement programs and renewable energy resource utilization from start to finish.
- *Energy team:* The core team should consist of personnel who have knowledge of utility processes and energy usage and will help communicate the importance of energy improvement to utility staff. By creating a core energy team, you will have people to focus on monitoring energy efficiency and implementation goals. The energy team should consist of personnel who can assist during design, operation, and maintenance of the treatment plant.
- *Construct a plan:* Utilize the program manager and energy team to develop methods to improve energy management, implement renewable energy resources within a specific timeline, and develop a plan for periodic monitoring of energy efficiency and GHG emissions of the plant.

Step 2. Collect

The second step is to collect energy consumption data from the plant. Collection of data should be performed through an energy audit. Information collected through the energy audit can be used to set up a baseline for energy consumption and necessary energy improvements. Although considering energy efficiency management and renewable energy resource utilization, the collection step should also include an assessment of various financial options that are available for successful implementation of the schemes.

- *Energy audit:* Have the energy team perform an energy audit to determine the baseline energy demand and consumption of the plant. The energy audit can be used to identify areas that require the greatest attention. Walk-through process audits provide an initial assessment of energy savings and determine if a detailed process audit should be undertaken at a facility. Detailed process audits are an extension of the walk-through audit and can be performed by an electricity utility representative, water or wastewater agency staff, or an external energy audit specialist. Various tools for performing an energy audit are provided in the additional resources section at the end of this chapter.
- *Funding options:* The energy team can also identify funding options and incentives available for implementing renewable energy at the facility and set a budget for energy improvement and renewable energy utilization. Various funding options available are discussed in Chapter 4 of the guidebook.

Step 3. Implement

The third step is the identification of the correct technologies for energy efficiency and renewable energy and their implementation at the utility. Identification of strategies for the implementation of selected energy-efficient schemes is discussed in Chapter 3. Identification and strategies of renewable energy utilization are provided in Chapter 4. In implementing the strategies, consider the following:

- Options available for renewable energy utilization
- Implementation of monitoring and report systems for measuring and tracking energy efficiency and renewable energy utilization

Step 4. Monitor and Report

The fourth step involved is monitoring and reporting the information collected from the various processes and for calculating GHG emissions. Various tools available for monitoring and reporting are provided in the additional resources section at the end of this chapter.

- *Monitor:* Initiate a program to monitor energy metrics continuously. This may occur on a periodic basis—for example, a planned annual update. Monitoring may also be performed continuously through existing SCADA (supervisory control and data acquisition) and data management systems.
- *Energy improvement:* Report improved energy efficiency and cost savings.
- *GHG emissions:* Report GHG emissions of the entire plant and their associated processes.

- *Public outreach:* Disseminate information on the energy efficiency achieved and the renewable energy utilized. This information should include energy efficiency before and after implementation of energy efficiency programs and GHG emission amounts before and after utilization of renewable energy resources.

Step 5. Continually Improve

The final step is to continually improve the established goals for energy management and renewable resource utilization. Development of an energy policy will result in the utility's commitment to improved energy use and management of resources. The energy policy should be developed specifically for the utility to accomplish these goals.

- *Continuous improvement:* To ensure that all future capital improvements and operation and maintenance (O&M) upgrades continue to meet energy efficiency requirements and goals, a continuous improvement process needs to be carried out.
- *Standard operating procedures (SOPs):* SOPs set in place standard practices for evaluating energy efficiency of all capital additions and O&M improvements.

Additional Resources

Guidebooks

Handbooks for energy efficiency:
http://www.energy.ca.gov/reports/efficiency_handbooks/index.html (last accessed July 11, 2011).

> Information is provided on energy accounting, financing public sector energy projects, energy auditing, guidelines for hiring an energy service company and guidelines for hiring a construction manager.

Energy management guidebook for wastewater and wastewater utilities:
http://www.epa.gov/region6/water/energymgt/energy_mgt_guidebook_wastewater.pdf (last accessed July 11, 2011).

> This guidebook provides a methodology for energy monitoring, energy minimization, and energy improvement for public utilities.

Energy best practice guidebook for water and wastewater utilities:
http://www.werf.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/ContentDisplay.cfm&CONTENTID=10245 (last accessed July 11, 2011).

> This guidebook provides guidelines on energy use estimation, energy baseline calculations, management and technical best practices for water treatment, wastewater treatment, and collection and distribution systems.

Energy Auditing

Determining baseline energy use:
http://water.epa.gov/infrastructure/sustain/baseline_energy.cfm (last accessed July 12, 2011).

> By determining baseline energy use, utility managers and operators can better understand their electricity providers' rate structure and understand how current operations impact energy consumption. The Web link provides information on protocols for conducting energy audits, an energy self-assessment tool and funding resources for implementing energy efficient strategies.

Energy audit manual for water and wastewater facilities:
http://www.cee1.org/ind/mot-sys/ww/epri-audit.pdf (last accessed July 12, 2011).

> The energy audit manual provides information on conducting walk-through and process audits, process energy conservation measures (ECM), and monitoring and follow-up procedures on energy management for water and wastewater facilities.

Energy management tool to track and assess water consumption:
http://www.energystar.gov/index.cfm?c=evaluate_performance.bus_portfoliomanager (last accessed July 12, 2011).

> This energy management tool can be used to track and assess energy and water consumption across the entire portfolio of buildings in a utility. The portfolio manager can be used to estimate the energy consumption of buildings and the carbon footprint of the utility.

Software tools for energy efficiency best practices:
http://www1.eere.energy.gov/industry/bestpractices/software.html (last accessed July 12, 2011).

> The Industrial Technologies Program (ITP) of the Department of Energy provides free software tools to identify and analyze the energy of systems and savings opportunities.

Auditing tools and protocols:
http://cfpub.epa.gov/compliance/resources/policies/incentives/auditing/ (last accessed July 12, 2011).

> Auditing policies and protocols for utilities under various programs, such as the Safe Drinking Water Act (SDWA), Clean Water Act (CWA), Comprehensive Environmental Response and Liability Act (CERCLA), can be found at this Web link.

Monitoring and Reporting

Climate Action Registry Online Tool (CARROT):
http://www.climateregistry.org/tools/carrot.html (last accessed July 12, 2011).

> CARROT is a Web-based tool that is used for calculating and monitoring GHG emissions at the utility. CARROT uses built-in emission factors and conversion factors to automate calculation of GHG inventories and improve consistency and comparability. Users input annual energy usage data (i.e., kWh of electricity, or MMBtu of natural gas) and CARROT calculates the associated GHG emissions.

Electronic Greenhouse Gas Reporting Tool (e-GGRT):
http://www.epa.gov/climatechange/emissions/ghgrulemaking.html (last accessed July 12, 2011).

> The EPA issued the Mandatory Reporting of Greenhouse Gases Rule (74 FR 5620), which requires reporting of greenhouse gas (GHG) data and other relevant information from large sources and suppliers in the United States. The purpose of the rule is to collect accurate and timely GHG data to inform future policy decisions. In general, the Rule is referred to as 40 CFR Part 98 (Part 98). Implementation of Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP).

GHG monitoring guidelines:
http://www.commerce.wa.gov/DesktopModules/CTEDPublications/CTEDPublicationsView.aspx?tabID=0&ItemID=7797&MId=944&wversion=Staging (last accessed July 12, 2011).

> An assessment of GHG tools currently available is provided in a report prepared for the Department of Commerce of the state of Washington. The assessment compares various GHG tools for mobile and nonmobile source emissions and provides guidelines for selecting the right monitoring tool.

GHG emissions and management tool (opsGHG):
http://www.esp-net.com/Products/opsiEnvironmentalisupTMsup/opsiGHGisupTMsup/tabid/200/Default.aspx (last accessed July 12, 2011).

> The opsGHG software helps utilities meet the challenges of GHG monitoring by delivering streamlined tracking, managing, and reporting of direct and indirect greenhouse gas emissions. The software links together with the rest of an environmental information management system to give powerful and complete emissions data management, all from one centralized, Web-accessible source.

Carbon dioxide (CO2) emissions from the generation of electric power in the United States:
http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html (last accessed July 12, 2011).

> This report was prepared jointly by the staff of the U.S. Department of Energy and the U.S. Environmental Protection Agency.

Calculation of GHG emissions from energy use:
http://www.cleanerandgreener.org/resources/pollutioncalculator.html (last accessed July 12, 2011).

GHG emissions can be calculated using the tool provided based on the total energy consumption of the utility in kWh.

Chapter 3

Implementation of Energy-Efficient Strategies

In this chapter, various energy-minimization guidelines for desalination and AWT technologies are provided. The chapter consists of typical energy consumption rates for desalination and AWT treatment processes per unit of water produced. System design, pumping efficiency improvement, utilization of ERDs, energy-saving membranes, membrane configuration, and non-process-related energy components are discussed in detail in the subsections.

Several strategies in combination will need to be used to minimize energy consumption.

Components of the energy minimization of desalination and AWT processes are shown in Figure 3.1. Maximum energy efficiency will be obtained when all the components are considered in a holistic manner. It is critical to understand the distribution of energy by various treatment processes to determine avenues for energy minimization. Distributions of energy for typical desalination and AWT processes are provided in the next two subsections.

3.1 Rates of Energy Consumption by Different Treatment Processes

Understand the distribution and magnitude of energy consumption rates among treatment process components.

Energy consumption rates for different types of desalination and water treatment facilities are listed in Table 3.1. The energy consumption for the seawater desalination and AWT plants listed in Table 3.1 correspond to a plant with process components shown in Figures 3.2 and 3.3, respectively. For a brackish-water desalination plant, groundwater is typically treated directly using brackish-water RO membranes with only cartridge filtration as pretreatment. For wastewater treatment, the process train would typically include primary and secondary treatment. For AWT facilities, the process train would typically include MF/UF, RO, and UV/hydrogen peroxide. Detailed descriptions of various desalination technologies and AWT processes are provided in Appendix B, Sections 1 to 4. Detailed information on energy consumption for desalination and AWT plants is provided by Cooley and Wilkinson (2011). Additional information on energy consumption by various treatment processes is provided in Appendix B, Section 5.

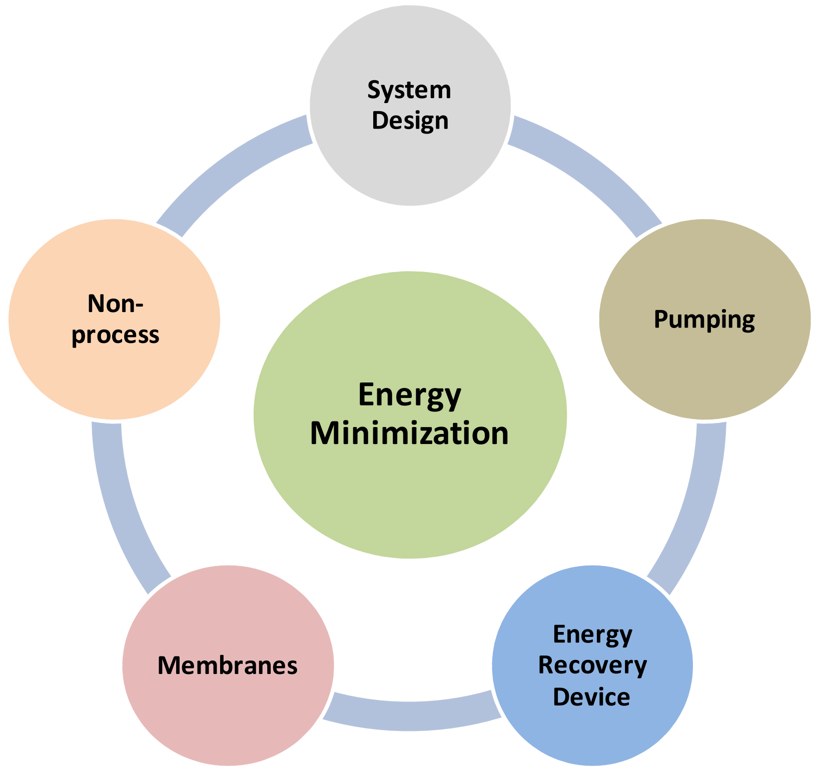


Figure 3.1. Energy minimization for desalination and advanced water treatment requires a holistic approach.

Table 3.1. Typical Energy Consumption for Various Types of Plants (Data Obtained from Utility Survey) in Kilowatt-Hours Consumed per Cubic Meter (kWh/m^3) of Treated Water Produced

Plant Type	Energy Consumption
Seawater desalination	3–4 kWh/m^3
Brackish water desalination	~ 1 kWh/m^3
Wastewater treatment[1]	~0.6 kWh/m^3
Advanced water treatment[2]	~ 1 kWh/m^3

[1]Conventional wastewater treatment plant.

[2]Treatment of secondary/tertiary effluent with RO and UV processes.

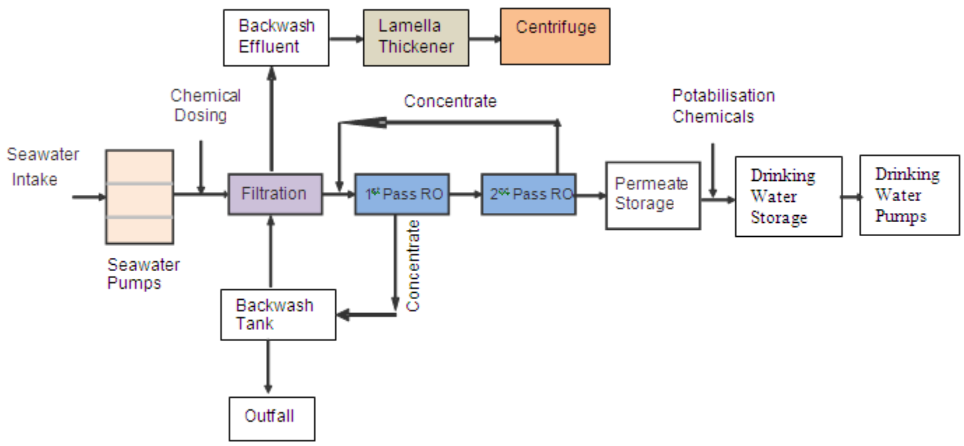


Figure 3.2. Process flow schematic of typical seawater desalination plant.

3.2 Examples of Energy Consumption for Large-Scale Desalination and Advanced Water Treatment Plants

Typical distributions of energy for seawater desalination, brackish water desalination, and advanced wastewater treatment are shown in Figures 3.4, 3.5 and 3.6, respectively. Process train configurations for the energy distribution pie charts correspond to typical plants described in Figures 3.2 and 3.3. For the various types of treatment schemes, energy consumption due to pumping requirements is highest. For desalination, high pressure pumping consumes the maximum energy.

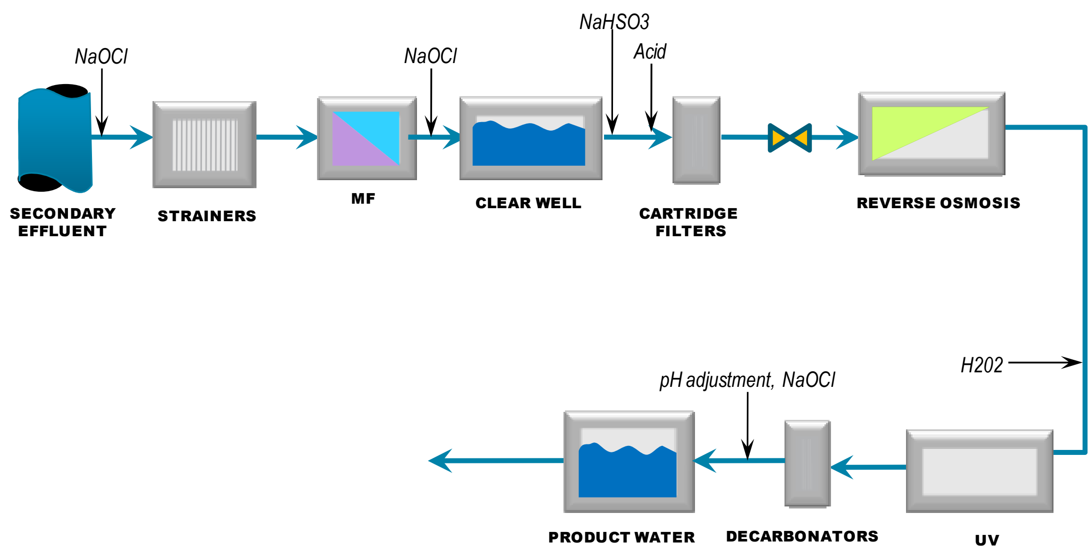


Figure 3.3. Process flow schematic of typical AWT plant.

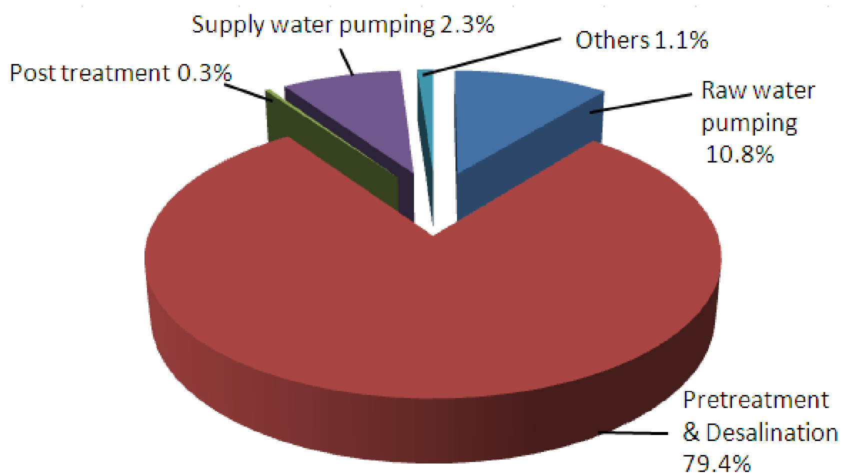


Figure 3.4. Typical distribution of energy for surface seawater RO desalination. (Data obtained from utility survey—Appendix A.) Supply water pumping refers to treated water distribution. Total energy consumption ~3.4 kWh/m^3. *Note:* Distribution of energy does not equate to 100% for these data.

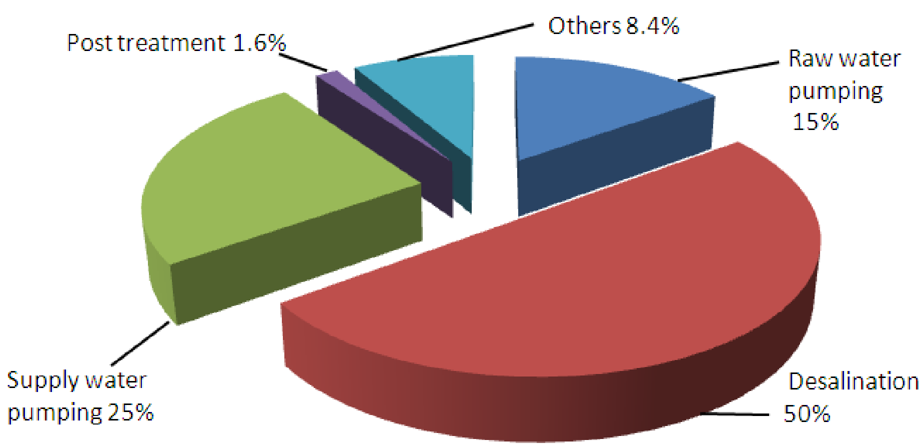


Figure 3.5. Typical distribution of energy for brackish groundwater RO desalination. Total energy consumption ~ 1 kWh/m^3 (Chang et al., 2008).

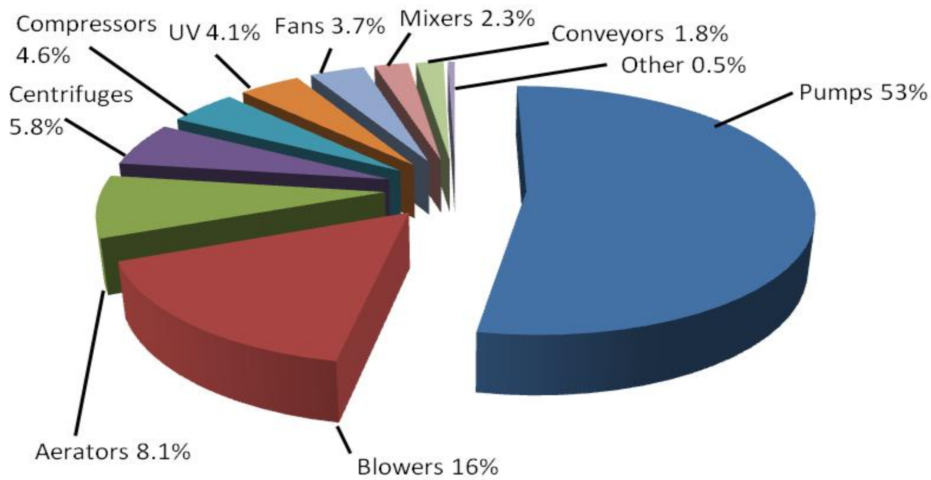


Figure 3.6. Typical distribution of energy for advanced water treatment. Total energy consumption ~1 kWh/m^3. (Data obtained from utility survey.)

3.3 Strategies for Energy Minimization

Strategies that need to be considered for energy minimization are detailed in the following pages. The reader will be led through a series of tables to help narrow down best strategies for meeting energy-minimization objectives. Table 3.2 provides an overview of the energy-minimization strategies that need to be considered for a selected application process. These components include

- System design and process optimization
- Pumping efficiency
- Selection of ERDs for desalination processes
- Selection of membranes for pretreatment and desalination
- Selection and optimization of advanced oxidation processes for AWT
- Selection of nonprocess heating, ventilation, and air conditioning (HVAC) and lighting

All energy-minimization strategy components are impacted during the design phase and should be considered during the project conceptual stage.

For seawater and brackish water desalination, energy minimization is achieved by proper system design, efficient pumping, utilization of ERDs, selection of membranes, and efficient utilization of nonprocess components.

AWT typically consists of MF/UF membranes followed by RO and UV/hydrogen peroxide. Advanced water treatment can also utilize a membrane bioreactor (MBR) treating raw wastewater or primary effluent, followed by RO and UV/hydrogen peroxide. For AWT technologies, maximum energy efficiency is obtained through system design/process modification and efficient pumping. For AWT technologies involving membranes (MF/UF, MBR), proper selection of membranes also reduces energy. Strategies that need to be considered for energy minimization are detailed in the following pages. Each of the strategy components listed in Table 3.2 is elaborated on in the following subsections, which will help readers narrow down the best strategy options for meeting their energy-minimization objectives.

3.3.1 System Design and Process Optimization

System design and process optimization component parameters for energy-efficient operations are provided in the following subsections.

3.3.1.1 Seawater Desalination System Design and Process Optimization Strategies

System and process optimization strategies for energy-efficient operation of specific parameters during seawater desalination are listed in Table 3.3. A general discussion of enhanced RO system design covering staging, passes, high-efficiency pumping, energy recovery, advanced membrane materials, and the application of innovative technologies is provided in Appendix B, Section 5.

Fouling of membrane elements results in higher feed pressure requirements for the same operational flux. Thus, selection of the optimum membrane flux results in reduced fouling and operating pressures. Selection of the optimum number of membrane stages and passes is dependent on the treated water quality that is desired. Single-stage design results in lesser pressure drop across the system, resulting in a lower feed pressure requirement than for a two-stage or multistage design. Selection of a single-pass or multipass system should be based on the treated water quality that is desired. For higher rejection of specific compounds in seawater, such as boron, a multipass design is essential. Co-location of the desalination plant with a power plant results in the utilization of warmer feed water, which eventually results in a lower feed pressure requirement for the RO membranes. Detailed descriptions of energy minimization through system design are provided in Section 5.3.1 of Appendix B.

Table 3.2. Energy-Minimization Strategy Components That Need to Be Considered for Specific Application Processes

Application Process	System Design/Process Optimization	Pumping	ERD	Membranes	Nonprocess
		Desalination			
Seawater	✓	✓	✓	✓	✓
Brackish water	✓	✓	✓	✓	✓
		AWT			
MF/UF	✓	✓		✓	✓
MBR	✓	✓		✓	✓
UV	✓	✓			✓
Ozone	✓	✓			✓

Table 3.3. Strategies for Efficient System Design and Process Optimization for Seawater RO Desalination

Parameter	Energy Efficiency Strategy for RO Systems—Seawater Desalination	Outcome
Membrane flux	Selection of the best membrane flux based on feed water quality.	Reduced membrane fouling and operating pressures.
Array configuration	Determination of the optimum combination of RO membrane element, array, stages and passes.	Reduced energy consumption due to reduced membrane feed pressure.
Number of stages	Utilization of single-stage design when applicable with seven or eight elements in a pressure vessel.	Reduced energy consumption compared to two-stage design because of lower pressure drop across RO trains. Up to 2.5% lower power requirement.
Number of passes	Utilization of first-pass front-end element permeate as feed to second pass. Utilization of membranes with highest salt rejection in the first pass.	Reduced feed pressure requirement for second pass.
Process control system	Utilization of energy-optimal set points for controlling concentrate valve position and feed flow rate.	Ability to achieve energy-optimal operation of RO system close to theoretically predicted energy consumption curves.
Process performance monitoring	Monitoring and recording of operating data to monitor process performance.	Reduced energy consumption due to lower feed pressure requirement as a result of early fouling detection.
Co-location	Co-location of desalination plant with existing power plant.	Reduced energy consumption by utilizing warmer water discharged from condensers in power plant. Up to 5–8% lower feed pressure requirement .

Source: Wilf and Bartels, 2005; Zhu et al., 2009; Voutchkov, 2004; data obtained from Utility Survey

3.3.1.2 Brackish Water Desalination System Design and Process Optimization Strategies

System and process optimization strategies for energy-efficient operation during brackish water desalination are listed in Table 3.4. Similarly to seawater desalination, system design and process optimization strategies are based on the selection of optimum flux, array design, process control monitoring, and process control. In addition, utilization of new types of pressure vessels results in lower energy consumption. Detailed descriptions of energy minimization through system design are provided in Section 5.3.1 of Appendix B.

Table 3.4. Strategies for Efficient System Design and Process Optimization for Brackish Water RO Desalination

Parameter	Energy Efficiency Strategy for RO Systems—Brackish Water Desalination	Outcome
Membrane flux	Selection of the best membrane flux based on the feed water quality.	Reduced membrane fouling and operating pressures that result in lower energy consumption.
Array design	Determination of the optimum combination of RO membrane element, array, stages, and passes.	Reduced energy consumption due to reduced membrane feed pressure.
RO pressure vessel design	Utilization of center port design for element instead of side port design.	Reduced energy consumption due to reduced feed pressure requirement as a result of reduced flow path within pressure vessel. Up to 15% reduction in feed pressure requirement.
Process performance monitoring	Monitoring and recording of operating data to monitor process performance.	Reduced energy consumption due to lower feed pressure requirement as a result of early fouling detection.
Process control system	Utilization of energy-optimal set points for controlling concentrate valve position and feed flow rate.	Ability to achieve energy-optimal operation of RO system close to theoretically predicted energy consumption curves.

Source: Zhu et al., 2009; Wilf and Hudkins, 2010; Data Obtained from Utility Survey

3.3.1.3 Advanced Water Treatment System Design and Process Optimization Strategies

MF/UF Systems

System and process optimization strategies for energy-efficient operation of MF/UF membranes are listed in Table 3.5. For MF/UF systems, maximum energy efficiency is obtained from pretreatment, efficient operation of the pumps, and selection of the membrane. Selection of proper pretreatment for the MF/UF process will reduce the backwash frequency. Fouling of the MF/UF membranes leads to higher backwash and cleaning frequency. Higher backwash frequency will result in higher energy consumption as a result of associated pumping requirements. Heating the cleaning chemical solution also results in higher energy consumption. Further information on MF/UF systems is provided in Section 4.1 of Appendix B.

Table 3.5. Strategies for Efficient System Design and Process Optimization for MF/UF Processes

Parameter	Energy Efficiency Strategy for MF/UF	Outcome
Pretreatment	Selection of pretreatment to effectively reduce organic and particulate loading to membranes.	Decreased membrane fouling. Longer cleaning intervals.
Membrane flux	Selection of best membrane flux based on the feed water quality. Utilization of low-fouling membranes based on membrane surface chemistry.	Decreased membrane fouling. Longer cleaning intervals.
Backwash optimization	Utilization of optimized backwash and back pulse frequency.	Reduced energy requirements for pumping backwash water.
Air scour optimization	Restriction of air scouring when influent water quality is poor.	Reduced energy requirements from minimizing air scouring frequency.
Hydraulic loading	Operation of membrane trains based on feed flow rate. Shutdown of certain trains during low-flow conditions.	Optimized energy consumption from operation at highest pump efficiency.

MBR Systems

System and process optimization strategies for energy-efficient operation of MBR systems are listed in Table 3.6. MBRs are specialized applications of low-pressure membranes modified for municipal wastewater treatment. In an MBR process, a combination of low-pressure membrane filtration and the activated sludge process is involved. Further information on MBR is provided in Section 4.1 of Appendix B.

Selection of optimum fine screens upstream of the MBR process can minimize the sludging (plugging or fouling) of membrane fibers with fibrous materials. Primary clarification can also be utilized upstream of the MBR process to reduce organic loading. The primary sludge produced from the clarifiers can then be utilized for energy production if anaerobic digesters are utilized at the treatment plant.

In certain design configurations (with primary clarifiers), aeration basins can be designed for operation at lower mixed-liquor suspended solids (MLSS) concentrations. This mode of operation reduces the solids recycle flow by 50%, reducing energy associated with pumping and oxygen transfer. This lower MLSS design may be limited, however, to sites where plant footprint area is not an issue, because this design and operating strategy will require a larger footprint area for the bioreactors.

When anaerobic digesters are available/utilized at the treatment plant, the biological treatment process can be designed with a lower sludge retention time (SRT) of 12 to 15 days depending on the water temperature. This design would ensure complete nitrification as well as minimizing process air consumption related to endogenous decay. Operation at lower SRT would also result in higher secondary sludge production, which can then be utilized for energy production through anaerobic digestion and use of the biogas produced.

Additional Resources

Design considerations for MBR systems:
http://www.gewater.com/products/equipment/mf_uf_mbr/mbr/design_considerations.jsp. (last accessed July 12, 2011).

Table 3.6. Strategies for Efficient System Design and Process Optimization for MBR Processes

Parameter	Energy Efficiency Strategy for MBR	Outcome
Pretreatment	Selection of pretreatment to effectively reduce organic loading to membranes.	Decreased membrane fouling. Longer cleaning intervals. Reduced process aeration requirements.
Balance of solids	Operation at lower MLSS when using large aeration basin.	Reduced solids recycle flow rate. Reduced pumping energy and aeration.
Air scour optimization	Application of intermittent/cyclic air scouring.	Reduced energy requirements in membrane tank.
Aeration	Utilization of fine-bubble diffusers.	Optimized oxygen transfer efficiency. Reduced aeration energy.
Blowers	Utilization of single-stage, multistage, or turbo blowers.	Maximized energy efficiency.

Source: Hribljan, 2007; Chang et al., 2008; Wallis-Lage and Levesque, 2011

Table 3.7. Strategies for Efficient System Design and Process Optimization for UV and AOP

Parameter	Energy Efficiency Strategy for UV Systems	Outcome
UV dose control, oxidant dose control, and monitoring	Adjustment of lamp power based on flow rate, level of treatment (dose), and water quality (UV transmittance). For AOP process using oxidant and UV, control the oxidant dose and residuals required.	Reduced energy consumption during lower flow rate, lower level of treatment, and higher UV transmittance conditions. Reduced chemical consumption for oxidant due to optimization of applied dose which has an overall GHG emissions reduction when considering reduced chemical usage.
UV contactor	Selection of the UV contactor with lowest energy consumption, hydraulic head loss and pumping requirement.	Reduced energy consumption due to lower electricity requirements for the UV lamps and reduced pumping requirements from lower hydraulic head loss.
Lamp configuration	Selection of the best lamp configuration to avoid UV emission losses due to self-absorption, refraction.	Reduced energy consumption due to transmission losses.

Source: Chang et al., 2008.

UV Systems

System and process optimization strategies for energy-efficient operation of UV systems are listed in Table 3.7. For UV systems, dose control and selection of UV type and configuration will result in the lowest energy consumption. Additional information on UV systems is provided in Section 4.2 of Appendix B.

Additional Resources

UV system information and case studies:
http://www.trojanuv.com/uvresources (last accessed July 12, 2011).
http://www.calgoncarbon.com/uv/disinfection.html (last accessed July 12, 2011).
http://www.freshwatersystems.com/c-157-uv-systems.aspx (last accessed July 12, 2011).

Table 3.8. Strategies for Efficient System Design and Process Optimization for Ozonation Processes

Parameter	Energy Efficiency Strategy for UV Systems	Outcome
Dose control	Adjustment of ozone dosage based on flow rate, level of treatment, and water quality.	Reduced energy consumption during lower flow rate, lower level of treatment, and better water quality.
Ozone generator and dielectrics	Selection of the number and size of ozone generator units to match expected water flow and dose range for operation at best efficiency point. Optimization of ozone generator cooling water flow and system to maximize the ozone generator efficiency.	Reduced energy by implementing these energy efficiency strategies.
Ozone diffusers and contactor	Selection of ozone gas diffusers that provide the most efficient transfer of gas into the water to achieve required dose. Design and selection of ozone off-gas destruct system for energy efficiency.	Reduced energy consumption by utilization of efficient ozone diffusers and contactor design to maximize the ozone transfer efficiency.
Air and oxygen enrichment compressor design	Utilization of smaller compressors.	Reduced energy consumption by utilization of low oxygen production rates.

Source: Chang et al., 2008.

Ozone Systems

System and process optimization strategies for energy-efficient operation of ozone systems are listed in Table 3.8. For ozonation systems, maximum energy minimization is obtained from dose control and efficient system design for ozone generators and compressors. Additional information on ozonation systems is provided in Section 4.3 of Appendix B.

Additional Resources

Ozone information:
http://www.degremont-technologies.com/dgtech.php?rubrique68 (last accessed July 12, 2011).

3.3.2 Pumping Strategies for Energy Efficiency

Pumping strategies for energy efficiency are common to desalination and AWT processes. Pumping energy is predominantly consumed in operation of pretreatment pumps, feed pumps to the system, product water transfer pumps, chemical feed pumps, and water distribution pumps. Pumps and motors have significant energy demand, capital investment, and maintenance requirement. Proper selection and maintenance will reduce energy costs and improve reliability. Additional information on high-efficiency pumping is provided in Section 5.3.2 of Appendix B.

The following strategies should be considered to obtain the highest possible pumping efficiency:

Sizing pump and motor equipment

- Size pumps based on the intended flow rate. Operating pumps at lower than design capacity leads to higher energy consumption. Pumps should be operated at or near their best efficiency point (BEP).
- Utilize large pumps with a centralized design to feed several trains of treatment processes instead of using several pumps to feed treatment processes.
- To size down pump capacity, replace the pump and motor with a downsized model, replace the impeller with a lower-capacity one, trim the outside diameter of the existing impellers, install a variable-frequency drive (VFD) to control load requirements, and add a smaller pump to reduce intermittent operation of a larger existing pump.

Verifying energy-efficient operation of pumps and motors

- Energy efficiency of existing pumps and motors should be verified every 3 months.
- Motor efficiency can be maintained by periodic monitoring of ventilation and temperature control required for optimal operating conditions as provided by manufacturer.
- Replacement of inefficient motors with higher-efficiency motors is an effective method for improvement in energy reduction.

Typical information needed while choosing pumps and considering maintenance is listed in Table 3.9. Following a maintenance schedule will result in improved energy efficiency. An example of energy efficiency obtained by replacing older pumps and motors with newer ones for a large-scale AWT plant is shown in Table 3.10.

Table 3.9. Considerations for Pump Design and Efficient Maintenance Strategies

Required Equipment Information	Conditions to Consider
Pump style	Flow rate (capacity) fluctuations
Manufacturer pump curves	Replacement of bearing and seals
Actual (operating) pump curves	Lubrication
Pump stages required	Cavitation on pumps, impellers, and bearing
Pump rated head	Out-of-alignment conditions
Pump and motor speed	Excessive noise or vibrations
Full load current requirement (A)	Significant flow rate and pressure fluctuations
Rated and actual (operating) pump discharge	Leaks
Operating schedule	Replacement of older, less efficient motors
Constant speed or variable speed	Benefits of variable-speed drive and pumping operation

Table 3.10. Improvement in Energy Efficiency from Replacing Older Pumps with Newer Pumps

Pump	Existing Efficiency, %	Improved Efficiency, %
Hot water pump	37	59
Cold water pump	48	59
MF Feed Pump	36	65
MF Filtrate Pump	50	63
RO Feed Pump	59	70
RO Transfer Pump	63	70

Source: Data obtained from Utility Survey.

Utilization of Variable Frequency Drives (VFDs)

- VFDs have a soft start, allow precise control of motors and processes, enhance the efficiency of motors, and significantly reduce energy demand.
- VFDs can be used to eliminate over pumping during product water feed and transfer operations.
- VFDs can be used to accommodate the variability in feed pressure with time without the necessity to throttle high-pressure pumps or ERDs. This variability may be due to feed water salinity changes, temperature change, RO membrane fouling, and RO membrane age.

Additional information on VFDs is provided in Section 5.3.2 of Appendix B.

Additional Resources

Pump System Assessment Tool (PSAT):
http://www1.eere.energy.gov/industry/bestpractices/software_psat.html (last accessed July 12, 2011).

> PSAT is a free online software tool to help utility users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings. The tool also enables users to save and retrieve log files, default values, and system curves for sharing analyses with other users. The software can be accessed using the PSAT Web link.

Pump System Improvement Modeling Tool (PSIM):
http://www.pumpsystemsmatter.org/content_detail.aspx?id=110 (last accessed July 12, 2011).

> PSIM is a free educational tool focused on helping you better understand the hydraulic behavior of pumping systems. With the challenges of today's marketplace, your fluid handling systems must be both cost effective and energy efficient. It is essential that users evaluate the total pump system in their designs.

Estimation of electric motor load and efficiency:
http://www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf (last accessed July 12, 2011).

> Methods for estimating electric motor load and efficiency are provided by a document from the Department of Energy.

Motor Systems Initiative tool kit:
http://www.cee1.org/ind/mot-sys/mot-sys-tools.php3 (last accessed July 12, 2011).

> The Motor Systems Initiative has developed a tool kit to help motor program representatives and contractors promote a variety of motor-related efficiency improvements. The tool kit includes both technical tools (software, checklists, guidelines, etc.) and promotional tools targeting the interests of a variety of audiences, such as maintenance, operation, and management personnel.

Department of Energy (USDOE) Motor Challenges Program:
http://www1.eere.energy.gov/industry/bestpractices/techpubs_motors.html (last accessed July 12, 2011).

> Guidance documents on technology, economics and maintenance and repair of motors can be found in the USDOE Web link.

California Public Utilities Commission:
http://www.cpuc.ca.gov/PUC/Water/oeep/ (last accessed July 21, 2011).

> Guidance documents on the water–energy nexus and the Operational Energy Efficiency Program (OEEP) for efficient pump design and operation for energy minimization.

3.3.3 Selection of Energy Recovery Devices

Recovery of energy is crucial in making desalination of high-salinity water economically feasible. Utilization of ERDs can reduce energy consumption up to 30% for seawater desalination. For brackish water desalination, ERDs are used as interstage (in between first- and second-stage) booster pumps. Thus, the feed pressure requirement of the feed pump (in front of the first stage) is reduced, thereby reducing overall energy consumption. The fraction of energy recovered depends on the type and efficiency of the equipment used. Comparison of ERDs and a thorough discussion of each type of ERD is provided in Section 5.3.3 of Appendix B.

Additional Resources

Pressure and work exchanger:
http://www.energyrecovery.com/index.cfm/0/0/33-Overview.html (last accessed July 12, 2011).
http://www.flowserve.com/Products/Energy-Recovery-Devices/Work-Exchangers (last accessed July 12, 2011).

Turbines:
http://www.flowserve.com/Products/Energy-Recovery-Devices/Turbines (last accessed July 12, 2011).
http://www.fedco-usa.com/prod_products_high.html (last accessed July 12, 2011).
http://www.fedco-usa.com/prod_products_low.html (last accessed July 12, 2011).

White Papers and ERD implementation:
http://www.energyrecovery.com/index.cfm/0/0/55-White-Papers.html (last accessed July 12, 2011).
http://www.flowserve.com/Services-and-Solutions/Engineering-and-Technical-Services (last accessed July 12, 2011).
http://www.fedco-usa.com/techpapers_main.html (last accessed July 12, 2011).
http://www.fedco-usa.com/comparisons_main.html (last accessed July 12, 2011).

Table 3.11. Strategies for Efficient System Design and Process Optimization for Desalination Using Different Membrane Types and Configurations

Parameter	Energy Efficiency Strategy for RO Systems—Membrane Type and Configurations	Outcome
Combination of brackish water RO–seawater RO elements	Utilization of high-rejection brackish water RO elements (or) high-permeability seawater RO elements in the first stage. Second stage consisting of standard seawater RO elements.	Reduced energy consumption by 5%.
Combination of RO or NF membranes in array	Utilization of computer models to determine feed pressure reduction when a combination of NF and RO membranes are used within a single array or pressure vessel.	Reduced energy consumption.
Two-pass nanofiltration	Utilization of nanofiltration membranes in a two–pass configuration.	Reduced energy consumption by 12%.

Source: Subramani et al., 2011.

3.3.4 Selection of Membranes

Selection of membrane type can reduce energy consumption during desalination by reducing the feed pressure requirement. Parameters that need to be considered for proper selection of membranes to reduce energy consumption are listed in Table 3.11. Utilization of a combination of brackish water and seawater RO elements within a pressure vessel is an established method. Utilization of novel membrane materials (nanocomposites, carbon nanotubes, biomimetics) and innovative processes (such as forward osmosis) shows promise for reducing energy consumption, but limited data are currently available on these novel materials and technologies. Additional information on new-generation membrane types that can reduce energy consumption is provided in Section 5.3.4 of Appendix B.

Additional Resources

Two-pass nanofiltration:
http://www.lbwater.org/pdf/desal_lbmethod.pdf (last accessed July 12, 2011).
http://www.lbwater.org/pdf/desalination/desalination_test_plan.pdf (last accessed July 12, 2011).

Nanocomposite membranes:
http://www.nanoh2o.com/Technology.php5 (last accessed July 12, 2011).

Carbon nanotube membranes:
http://www.poriferanano.com/our-technology.html (last accessed July 12, 2011).
http://www.nanoasisinc.fogcitydesign.com/news.html (last accessed December 14, 2011).

Biomimetic membranes:
http://aquaz.dk/aquaporin_membrane_technology.asp (last accessed July 12, 2011).

Forward osmosis:
http://www.yale.edu/env/elimelech/News_Page/files/membrane_technology_jan2007.pdf (last accessed July 12, 2011).
http://www.htiwater.com/technology/forward_osmosis/index.html (last accessed July 12, 2011).
http://www.technologyreview.com/energy/26916/ (last accessed July 12, 2011).
http://www.filtsep.com/view/18901/modern-water-to-build-first-commercial-forward-osmosis-desalination-plant/ (last accessed December 14, 2011).

3.3.5 Selection of Nonprocess Heating, Ventilation, and Air Conditioning and Lighting

Strategies for efficient design and maintenance of HVAC and lighting systems are listed in Table 3.12. Utilization of newer HVAC and lighting systems can reduce building energy use by 10 to 40%. Implementation of programmable thermostats, prevention of AC loss, regular maintenance of air filters, use of energy-efficient lamps, and motion sensors can substantially reduce building HVAC energy consumption.

Table 3.12. Strategies for Efficient Design and Maintenance of HVAC and Lighting Systems

HVAC	Lighting
Alter settings of system seasonally	Installation of occupancy sensors
Installation of high efficiency equipment	Replacement of incandescent lights with fluorescent systems
Utilization of programmable thermostats	Replacement of older lighting with energy efficient lamps
Prevention of solar entry and AC loss	
Regular cleaning of air filters	

Additional Resources

Energy-efficient technologies in your buildings:
http://www1.eere.energy.gov/calculators/buildings.html (last accessed July 12, 2011).
http://www.energystar.gov/index.cfm?c=tools_resources.bus_energy_management_tools_resources (last accessed July 12, 2011).

Chapter 4

Utilization of Renewable Energy Resources

In this chapter, various renewable energy resources and parameters that need to be considered for implementation in desalination and water reuse are reviewed. The chapter provides steps required for developing renewable energy resource utilization and a discussion of various technologies available, financing options, and design considerations. Components involved in renewable energy utilization on a large scale are shown in Figure 4.1. Additional information on renewable energy resources is provided in Appendix C.

Understand the benefits and challenges of renewable energy resource implementation.

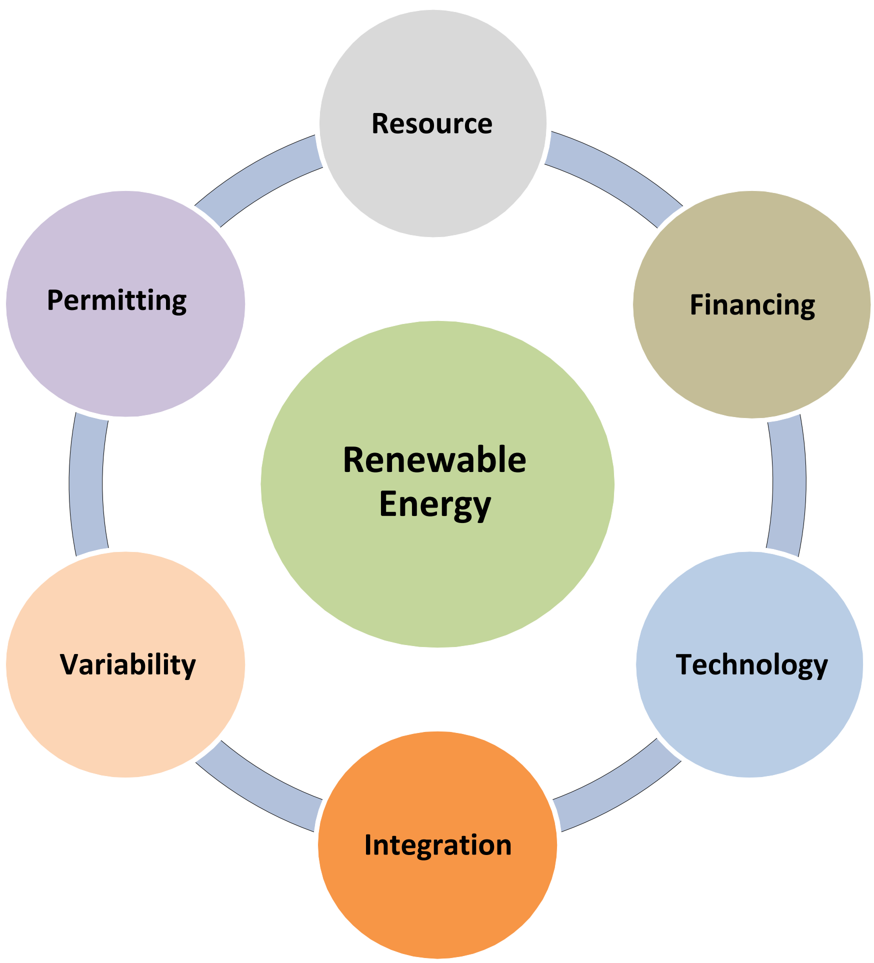


Figure 4.1. Components involved in renewable energy utilization on a large scale.

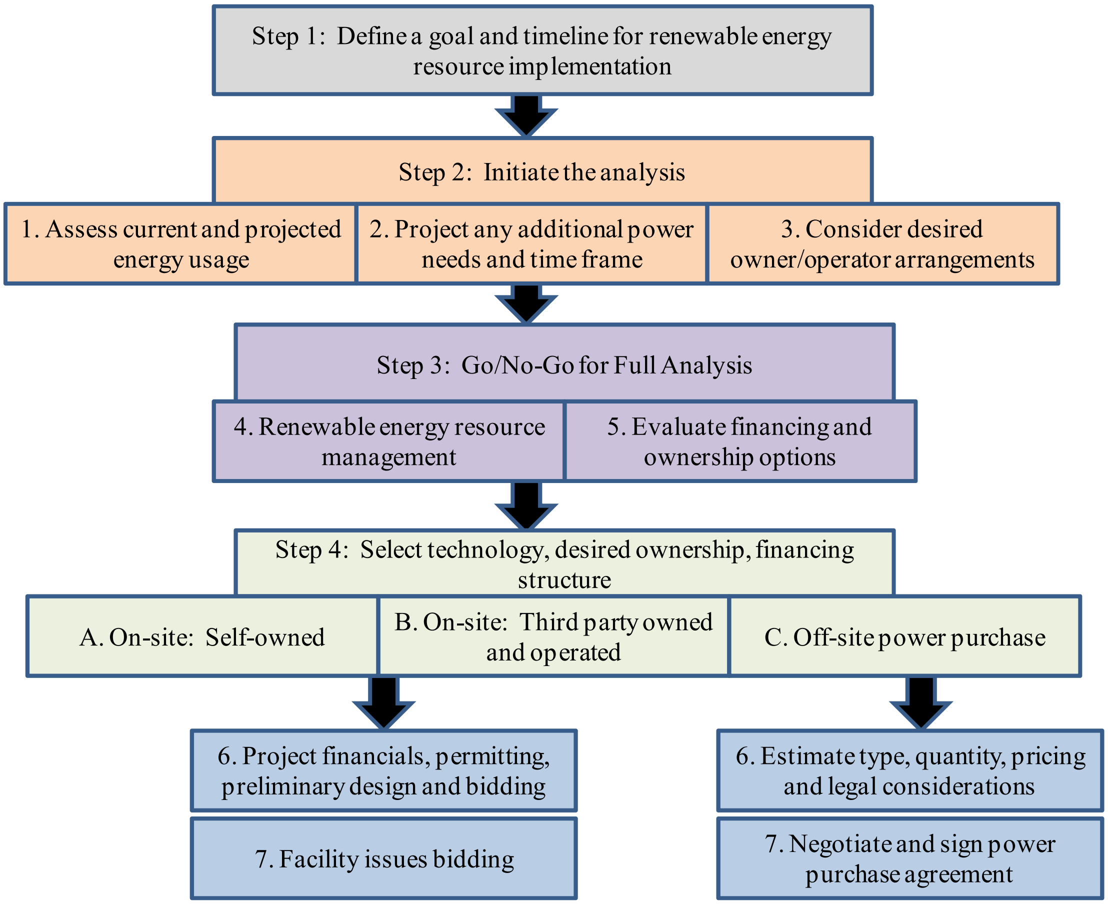


Figure 4.2. Typical process for developing a renewable energy project.

4.1 Steps in Renewable Energy Resource Implementation

Utilization of renewable energy is a stepwise process. Typical components involved in implementing renewable energy resources are shown in Figure 4.2.

Step 1

The first step is to define a goal for implementation of renewable energy to supply partial or complete power requirements. It will also be necessary to define a timeline for implementation of renewable energy resource utilization.

Step 2

The second step is to assess current and projected energy usage, current and projected future energy costs, and desired characteristics of a renewable energy system. Details of assessing current and project energy usage should include the following:

- Facilities must first understand their total annual energy consumption, the make-up of that power mix (e.g., is the facility already paying for renewables as part of the power utility's mix?), and the current cost of that power.

- Then projections must be made to understand any additional power needs and the anticipated time frame, as well as the anticipated cost escalations of grid-provided power.
- Finally, a critical step is to understand the characteristics or goals of desired renewable energy purchases. For example:
    - Does the facility wish to provide visible proof of its environmental stewardship? If so, an on-site renewable project may be desirable.
    - Does the facility wish to incentivize cutting-edge renewable technologies? If so, a less proven technology might be desirable.
    - Does the facility wish to be energy- or carbon-neutral? If so, minimally a mix of off- and on-site renewable energy should be considered.
    - Does the facility have cost as the principal driver? If so, the financial options that capture the greatest incentives, and possibilities such as purchasing renewable energy from large-scale off-site projects, may be more desirable.
    - Does the facility wish to avoid owning and operating the renewable energy assets? If the facility wishes to own and operate renewable energy assets, on-site leasing of land, seeking renewable power purchase agreements, and procuring and training its own operators may be considered.

DECISION POINT 1: A facility should decide whether or not to contract with an outside entity to provide a basic pre-feasibility study of renewable energy options. The remaining steps can be self-performed or contracted out.

Step 3

The third step is to understand renewable energy resource availability and financing options. Details for assessing renewable energy resources and finance should include the following:

- Assess the availability of on-site land or surface area (roofs, concrete tank tops) for renewable energy locations and the desirability of each location for this purpose.
- Assess resources, because renewable energy availability depends on the location. Estimate availability using resource maps, on-site surveys, and available software. For biomass energy, a regional survey of available sources within affordable driving range (typically 50 miles) will be necessary, as well as a comparison of pricing for alternative uses of that biomass.
- Assess options for off-site energy. Unless additional off-site land is already owned by the plant, this option typically would involve the purchase or lease of land, as well as the construction of associated infrastructure (primarily the grid interconnect), and finally, the wheeling of power from the local electrical grid. When this option is considered, it is typical to contract with a third party for the full ownership, operation, and wheeling of power. The plant owner may purchase part or all of the power that is generated through a power purchase agreement with that provider.
- Initial investment of renewable energy can be substantial.
- Funding options available from renewable energy providers and incentives from state and federal government need to be considered for a renewable energy project. However, many of these incentives are available to tax-paying entities only. Thus, the ownership of the renewable energy—public or private—may significantly impact the financial viability of the project.

- Two broad financing options are typically taken by a facility owner for the addition of renewable energy:
  - Self-owned: The utility owns the renewable energy technology and the associated components for power generation. However, if the facility owner is a public entity, this option may be more expensive.
  - Third-party owned: The power is purchased by the utility through a power purchase agreement. This option might be for a facility located either on or off site. This option does not necessarily require a new renewable plant to be constructed; a utility might decide to buy excess capacity from an existing renewable energy plant, or an already planned renewable energy plant. This option can allow for cost benefits (1) through the ability of the private party to claim state and federal incentives, and (2) through the economies of scale of a larger off-site project.

DECISION POINT 2: Based on the resource assessment and financing options available, a facility should decide at this point whether or not to initiate a full analysis for renewable energy utilization.

Step 4

The fourth step is to select a technology, type of ownership, and financing structure.

- Based on the resource availability and funding options available, select a renewable energy technology that is available commercially and well proven.
- While selecting a technology, determine footprint requirements to accommodate the renewable energy technology (if on site).
- Based on decisions made earlier, select the ownership and financing structure desired. If the utility decides to own and operate the facility itself, it will then need to determine and implement the staffing requirements to do so. Hire or continue the services of a contractor, who will work with the utility's project manager to
  - Estimate the infrastructure requirement for the technology selected, the physical footprint required, and the type of integration (on-site grid or off-site grid connected). Calculate the budget and ROI.
  - Determine the total capital and operation and maintenance (O&M) cost of the project.
  - Estimate ROI on funding options available.
  - Determine tariffs, regulations, and permits.
- Identify regulations and permitting requirements based on the location of the plant.
- Develop preliminary design sufficient for bid and prepare bid documents.

DECISION POINT 3: Utility issues bid for engineering, procurement, construction, ownership, and operation with the intent to own and operate the facility itself or utilize third-party ownership. After negotiation of the type of financing structure, the facility issues bidding for construction of the project.

4.2 Resource Availability

Renewable Energy Resource Maps

Selection of the best renewable energy resource varies with location. Determine renewable energy resource availability by utilizing resource maps**.**

Renewable energy resource maps are readily available at the National Renewable Energy Laboratory (NREL) Web site. Web links to resource maps are provided in the Additional Resources section. The resource maps can be utilized to determine renewable energy potential based on the location of the utility in the United States.

Additional Resources

Solar radiation resource map:
http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/ (last accessed July 12, 2011).

Wind energy resource map:
http://www.windpoweringamerica.gov/wind_maps.asp (last accessed July 12, 2011).

Photovoltaic solar resource map:
http://www.nrel.gov/gis/solar.html (last accessed July 12, 2011).

Concentrating solar power resource map:
http://www.nrel.gov/gis/solar.html (last accessed July 12, 2011).

Wind energy resource map:
http://www.nrel.gov/gis/wind.html (last accessed July 12, 2011).

Geothermal energy resource map:
http://www.nrel.gov/gis/images/geothermal_resource2009-final.jpg (last accessed July 12, 2011).

4.3 Financing and Incentives

Utilities have several options for procuring renewable energy systems. They can choose to purchase the equipment up front, using conventional financing options such as municipal leases. Financing options and incentives available for utilities to implement renewable energy are described in this section. Additional information on cost of renewable energy resources is provided in Section 2.11 and Section 2.12 of Appendix C.

1. *Clean Renewable Energy Bond (CREB) Program:* Local governments, electric cooperatives, and municipal utilities can issue bonds and repay only the principal. The lender receives a tax credit instead of the traditional interest. Available since 2008.
   - The amount of bonds allocated is limited and an application has to be filed with the IRS to receive an allocation. The IRS requires significant time to authorize, structure, price, and close the application.
   - CREB remains one of the cheapest sources of debt financing.

2. *Performance Contracting:* Allows utilities to fund renewable energy facilities through loan or lease arrangements. Typically performance contracting is used for energy conservation measures, but it can also be used with renewable energy installations. A long-term (10–25 years) contractual agreement is established between the contractor and the utility agreeing to the terms of performance.
    - All aspects of financing are provided by a qualified third-party financial institution.
    - A contractual agreement is entered into by the contractor and the utility, agreeing to the terms of performance. Typically this involves the utility agreeing to pay a price per kWh with future escalation clauses, and the contractor guaranteeing a certain level of performance with penalty clauses for any shortfalls.
    - The utility uses operating funds (the appropriated maintenance and energy budget) to pay back the capital improvement and associated costs. Any excess savings are usually retained by the utility.
    - After the contract performance period, all associated savings are transferred to the utility. System ownership will be defined by the financial arrangement and defined in the contractual agreement.
    - Any capital provided up front by the utility can help shorten the length of the contract and improve terms for the utility.
    - The utility owns the Renewable Energy Credits/Certificates (RECs) generated from on-site renewable energy implementation, and the utility may sell the credits on the open market.
3. *Third-Party Ownership with a Power Purchase Agreement:* Provides utilities with the ability to utilize benefits for renewable energy through service contracts while avoiding the risks associated with direct ownership.
    - The utility enters into a contract with the vendor, typically known as an independent power provider (IPP), to have it install a renewable energy system and deliver a set amount of power at an agreed price. This is known as a power purchase agreement (PPA). Typically PPAs have a number of contractual elements, and unless PPA contractual expertise is available within the utility, the services of a neutral power consultant may be desirable to negotiate these on good terms for the utility.
    - The renewable energy equipment provider enters into an agreement with a financial institution and then engineers, procures, and constructs the plant.
    - The renewable energy plant may be located either on or off site, depending upon the amount of power desired, the availability of land and the energy resource, the most attractive location for associated infrastructure, permitting, and the total financial implications. For on-site energy, a land lease agreement with the IPP may be needed.
    - Because municipal utilities may not claim many of the available federal and state incentives, the vendor providing the renewable energy system can claim incentives. This option typically results in a lower total cost per kWh.
    - The third party (vendor providing the renewable energy system) is responsible for operating and maintaining the on-site renewable energy facility.
4. *Financial Incentives:* Financial incentives for renewable energy provide small incremental benefits that help reduce the total cost of a project over its life cycle. These may include renewable energy credits, net metering, state public benefit funds, state clean energy funds, utility rebate programs, federal investment tax credits, grants in lieu of tax credits, state grants, and accelerated depreciation.

5. *Renewable Energy Credits/Certificates:* RECs come from the adoption of renewable energy portfolio standards (RPS) set by individual states and represent nonpower attributes of 1 MWh generated from a qualifying energy source. RECs can be traded to help electric utilities reach the generating goals imposed under RPS. In states with open REC markets, a REC is priced at the difference between the utility power rate and the actual cost of generation from a renewable energy source, making them competitive with conventional power sources.
6. *Investment Tax Credit:* Business energy investment tax credit (ITC) provides corporate tax credits, as a percentage of total expenditures, for the installation of new solar (thermal and electric), wind, biomass, and geothermal (thermal and electric) energy, fuel cells, solar hybrid lighting, and microturbines. The credit amount varies by technology and is subject to certain caps.
7. *Renewable Energy Production Incentives:* Renewable energy production incentive (REPI) complements the ITC and provides direct revenue to the generating entity based on performance. Qualifying new renewable energy installation received 2.2 cents/kWh in 2011 for the first 10 years of system operation.

Direct financial incentives are more volatile, depending on yearly appropriations, and can vary significantly with time. The utility should always check availability and eligibility of financial incentives, as they could have a significant impact on the economics of the project.

Additional Resources

Database of State Incentives for Renewables and Efficiency (DSIRE):
http://www.dsireusa.org/Index.cfm?EE=0&re=1 (last accessed July 12, 2011).

> DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency. Established in 1995 and funded by the U.S. Department of Energy, DSIRE is an ongoing project of the N.C. Solar Center and the Interstate Renewable Energy Council.

USDOE Loan Guarantee Program:
http://lpo.energy.gov/ (last accessed July 12, 2011).

Energy savings performance contracts:
http://www1.eere.energy.gov/femp/financing/espcs.html (last accessed April 5, 2012).

> Energy savings performance contracts (ESPCs) allow Federal agencies to accomplish energy savings projects without up-front capital costs and without special Congressional appropriations.

Types of financing programs:
http://www1.eere.energy.gov/wip/solutioncenter/financialproducts/financingprograms.html (last accessed July 12, 2011).
http://www.energystar.gov/index.cfm?c=business.EPA_BUM_CH4_Financing (last accessed July 12, 2011).

Information on various types of financing programs, such as state and municipal revolving loan funds, third party loans, energy savings performance contracts (ESPC), property-assessed clean energy (PACE), on-bill repayment, energy-efficient mortgages, power purchase agreement, FHA power saver, and qualified energy conservation bonds (QECBs) can be found at these Web links.

Performance contracting:
http://www.energystar.gov/ia/partners/spp_res/Introduction_to_Performance_Contracting.pdf (last accessed July 12, 2011).

Innovative financing solutions:
http://www.energystar.gov/ia/business/COO-CFO_Paper_final.pdf. (last accessed July 12, 2011).

4.4 Technology

4.4.1 Commercial Technologies

4.4.1.1 Solar Photovoltaics

Principle

The solar photovoltaic (PV) process converts sunlight directly into electricity. A PV cell consists of two or more thin layers of semiconducting material. When the semiconducting material is exposed to sunlight, electrical charges are generated and this can be conducted away by metal contacts as direct current (DC). An inverter is used to convert DC to alternating current (AC). The amount of energy produced by a panel depends on several factors. These include the type of collector, the tilt and azimuth of the collector, the temperature, and the level of sunlight and weather conditions. Additional information on solar PV is provided in Section 2.2 of Appendix C.

System Components

- PV arrays, which convert light energy to DC electricity
- Inverters, which convert DC to AC and perform important safety, monitoring, and control functions
- Various wiring, mounting hardware, and combiner boxes
- Monitoring equipment

Types of Cells

- Photovoltaic cells can be either monocrystalline silicon cells, polycrystalline silicon cells, or amorphous (thin film) cells.
- Monocrystalline cells are made of very pure monocrystalline silicon, whereas polycrystalline cells are produced using numerous monocrystalline grains. Thin films are made by spreading amorphous silicon on large plates.
- Polycrystalline cells are the least expensive and are the most common type of cell used currently. Monocrystalline cells are favorable for large projects because of their

higher energy yield, but this option is the most expensive. Thin films are less costly but are also less efficient, resulting in larger panels for the same power production.

- Thin film amorphous silicon is less expensive but is the least efficient when compared to CIGS (copper indium gallium selenide). Thin film CdTe (cadmium telluride) is considered less expensive than thin film silicon PV cells for multi-kilo watt systems..
- Concentrating PV adds lenses to concentrate light over solar cells.
- Typical area required by cells for 1 kW electricity generation is 10 to 14 square meter for monocrystalline and polycrystalline cells and 16 to 23 square meter for thin film cells (AEE, 2010).

Types of PV Systems

The electrical output from a single cell is small. Hence, multiple cells are connected together and encapsulated in glass to form a module or panel. The PV panel is the principal building block of a PV system, and any number of panels can be connected together to give a desired electrical output. Typical design parameters for solar PV systems are listed in Table 4.1. PV systems can be either ground-mounted or roof-mounted. Important aspects of each of these two types of systems follow.

Ground-Mounted Systems

- Ground-mounted systems are the least expensive based on a $/DC-W basis.
- System can be installed using a fixed-tilt, single-axis, or dual-axis tracking system. Fixed-tilt systems are installed at a specified tilt and are fixed at that tilt for the life of the system.
- Single-axis tracking systems have a fixed tilt on one axis and a variable tilt on the other axis. The system is designed to follow the sun in its path through the sky.

Table 4.1. Design Parameters for Solar PV Modules

Parameter	Description
Cell efficiency	Percentage of solar energy falling on PV cells that is converted into electrical energy
Module efficiency	Combination of cell efficiency placed into a module
Energy yield	Output in kilowatt hours (kWh) over time
Typical module size	175–200 W: 1 m × 1.5 m
Common types of modules	Polycrystalline, monocrystalline, amorphous silicon (thin film)
Module lifetime	Polycrystalline ~ 40 years; monocrystalline ~ 50 years; amorphous silicon ~ 20 years

- Single-axis tracking systems allow solar radiation to strike the panel at an optimum angle for a larger part of the day than for a fixed-tilt system.
- Single-axis tracking systems can collect up to 30% more electricity per capacity than fixed-tilt systems, but have higher O&M and installation costs.
- Dual-axis tracking systems allow tracking on two axes, thereby providing for both diurnal and seasonal shifts in the azimuth of the sun striking the earth. Though more expensive, these systems have the highest efficiencies.

Roof-Mounted Systems

- Roof-mounted systems are relatively more expensive than ground-mounted systems.
- Roof-mounted systems are more convenient because of less shading.
- In a roof-mounted system, a typical flush-mounted crystalline silicon panel can achieve power densities on the order of 1 DC-W/ m^2. For rack-mounted systems a power density of 0.8 DC-W/m^2 can be achieved (Lisell and Mosey, 2010).

Additional Resources

Solmetric solar path calculator:
http://www.solmetric.com/pvdesigner.html (last accessed July 12, 2011).

> A Solmetric solar path calculator enables you to quickly and easily draw a roof outline, specify setbacks and keep-out regions, incorporate shade measurements at specific locations on a roof, use drag-and-drop modules, size strings, check inverter limits, and calculate the AC energy production for your system. It includes extensive world-wide databases of modules, inverters, and historical weather.

PVWATTS:
http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/ (last accessed July 12, 2011).

> PVWATTS is a performance calculator for grid-connected PV systems. PVWATTS can be used for locations accessible through links on the map provided in the Web link, or through a text list for U.S. sites. or for sites outside the United States, through text lists by region. Researchers at the National Renewable Energy Laboratory developed PVWATTS to permit nonexperts to quickly obtain performance estimates for grid-connected PV systems.

Tools for renewable energy utilization:
http://www.energycommunity.org/default.asp?action=71 (last accessed July 12, 2011).

4.4.1.2 Concentrating Solar Power (CSP) Systems

Principle

CSP systems are based on heating a heat-transfer fluid using mirrors, which is used to generate steam and run a turbine and generator to generate electricity. The main types of CSP are summarized in Table 4.2 and then described in more detail by type.

Table 4.2. Major Types of CSP Systems

Type	Description
Power tower	Mirrors are used to concentrate sunlight on top of a tower where molten salt is housed. The molten salt's heat is used to generate steam and run a turbine that drives a generator to produce electricity.
Linear concentrator	Long horizontal mirrored pipes are used to collect sunlight and focus it on a linear receiver tube containing oil. The heated oil is used to generate superheated steam, which is used to run a turbine that drives a generator to produce electricity.
Dish/engine system	A mirrored dish is used to heat fluid that expands a piston to produce mechanical power.

Types of Concentrating Solar Power (CSP) Systems

Three major types of CSP systems exist. They are power towers, linear concentrators, and dish/engine systems.

Power Tower

- A large field of flat sun-tracking mirrors (heliostats) are used to focus and concentrate sunlight onto a receiver on the top of a tall tower.
- A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity.
- Common heat-transfer fluids used are water and molten salt. When molten salt is used as the heat-transfer fluid, thermal storage is possible, allowing the system to generate electricity in cloudy weather and at night.

Linear Concentrator

- Long curved rectangular mirrors are used to focus sunlight on receiver tubes, which are used to heat a fluid (oil or molten salt) that in turn heats water and generates steam.
- The steam is used to generate electricity through a turbine and generator.
- Two major types of linear concentrators are parabolic trough and Fresnel reflector systems. In parabolic troughs, the receiver tubes are positioned along the focal line of each parabolic mirror. In Fresnel reflector systems, one receiver tube is positioned above several mirrors to allow the mirrors greater mobility in tracking the sun.
- Similarly to the power tower, when molten salt is used as the heat-transfer fluid, thermal storage is possible, allowing the system to generate electricity in cloudy weather and at night.

Dish/Engine System

- A dish/engine system uses a mirrored dish similar to a very large satellite dish.
- The dish-shaped surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat and transfers it to the engine generator. The most common type of heat engine used today is a Stirling engine.

- The dish/Stirling engine system uses the fluid heated by the receiver to move pistons and create mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity.

Additional Resources

Modeling tools for CSP systems:
http://www.nrel.gov/csp/troughnet/models_tools.html#dview (last accessed July 12, 2011).

> The Web link provides information about models and software tools used to analyze parabolic trough power plant technology. The tools provided are SolTrace, TRNSYS, Solar Advisor Model (SAM), Receiver Model, and JEDI.

Tool for estimating energy and environmental impacts of CSP:
http://www.nrel.gov/analysis/reeds/ (last accessed July 12, 2011).

> The Regional Energy Deployment System (ReEDS) model is a computer model that optimizes the regional expansion of electric generation and transmission capacity in the continental United States over the next 50 years. The Web link presents an overview of this NREL-developed tool, as well as relevant data and related publications.

Concentrating Solar Power Research:
http://www.nrel.gov/csp (last accessed July 12, 2011).
http://www.nrel.gov/learning/re_csp.html (last accessed July 12, 2011).
http://www1.eere.energy.gov/solar/csp_program.html (last accessed July 12, 2011).
http://www.eere.energy.gov/basics/renewable_energy/csp.html (last accessed July 12, 2011).

TroughNet Parabolic Trough Solar Power Network:
http://www.nrel.gov/csp/troughnet (last accessed July 12, 2011).

> TroughNet is a technical resource for evaluation of parabolic trough solar power plant technologies.

System and Component Testing:
http://www.nrel.gov/csp/troughnet/testing_standards_reports.html (last accessed July 12, 2011).

4.4.1.3 Wind Energy

Principle

Wind turbines convert the kinetic energy of the wind into electricity. The blades of a wind turbine capture the wind's kinetic energy to spin a rotor that is used to generate electricity. The power of the wind is a function of the density of air, the area of the wind mill blades, and the cube of wind speed. Additional information on utilization of wind energy is provided in Section 2.4 of Appendix C.

Components of Wind Turbines

The primary components of a wind turbine are the turbine, nacelle, and tower.

Turbine

- The wind turbine consists of two or three blades made of high-density wood, Plexiglas, or a composite material. The blades develop an imbalance between the lift and drag forces to capture the wind's energy.
- Turbine aerodynamics, material composition, and size are fundamental issues in wind power system design. Regardless of system size, turbine price ranges from 10 to 40% of the total system cost (NYSERDA, 2005).

Utility-Scale Turbine

- Corresponds to large turbines (900 kW to 2 MW per turbine). Intended to generate bulk energy for sale in power markets.
- Typically installed as large arrays. Turbines connected to utility electricity grid through a transformer. Most common form of wind energy generation in the United States.

Industrial-Scale Turbine

- Corresponds to medium-sized turbines (50 kW to 250 kW per turbine). Intended for remote off-grid operation along with diesel generation or load-side generation to reduce on-site demand for higher-cost grid power and to reduce peak loads.
- Direct sale of energy to utility grid may or may not be allowed under individual state laws and utility regulations.

Residential-Scale Turbine

- Corresponds to small turbines (400 W to 50 kW). Intended for remote power, battery charging, or net-metering-type generation.
- Small turbines can be used with solar photovoltaics, batteries, and inverters to provide constant power at remote locations where access to electrical grid power is limited.

Nacelle

- Nacelles house a gearbox, a generator, control electronics, and a yaw mechanism.
- The spinning rotor blades are coupled to a shaft and generator through a gearbox.
- An induction generator is the most widely used for commercial applications and supplies electricity to the grid.
- The control electronics is used to sense wind speed, wind direction, rotor (turbine) speed, and generator load. When wind speed changes, the control electronics adjusts rotor speed and blade pitch to maximize power capture. When wind speeds are too high, the control electronics depowers the turbine to avoid damage.

Tower

- The tower supports the blades and nacelle and withstands vibrations and cyclic stresses associated with wind. Towers for commercial large-scale installations range from 30 to 120 m in height.
- The tower also shelters the power line connections between the generator and the transformer and electricity grid.

Considerations for Wind Energy Utilization

Factors that need to be considered for wind energy utilization are discussed in this section.

- *Understand your wind resource by checking wind speed:* Annual average wind speed of 11 to 13 mph is recommended.
- *Determine the distance from the existing transmission lines:* Infrastructure for transmission of electricity from a wind farm can become expensive if new transmission lines need to be installed.
- *Availability of land:* A large amount of land is required for setting up wind farms. Determine land ownership requirements before design.
- *Understand economics:* Securing investment capital, joint ownership, and federal/state incentives can cut costs significantly.
- *Determine zoning and permitting expertise:* Obtain expertise on wind power generation and integration.
- *Determine O&M needs:* Obtain O&M needs from wind turbine manufacturers.

Additional Resources

How Wind Turbines Work:
http://www1.eere.energy.gov/windandhydro/wind_how.html (last accessed July 12, 2011).
http://www1.eere.energy.gov/windandhydro/ (last accessed July 12, 2011).
http://www.powernaturally.org/ (last accessed July 12, 2011).

Wind Energy Tools:
http://www.nrel.gov/learning/ep_wind.html (last accessed July 12, 2011).
http://www.nrel.gov/analysis/analysis_tools_tech_wind.html (last accessed July 12, 2011).
http://www.nrel.gov/docs/fy05osti/36971.pdf (last accessed July 12, 2011).
http://swera.unep.net/index.php?id=data_search&action_method=external_archive_query&datatype=4,70&geoarea=-1&energycategory=87&orderby=geoarea (last accessed July 12, 2011).

4.4.1.4 Geothermal Energy

Principle

Geothermal energy sources are classified in terms of the measured temperature as low (<100 °C), medium (100–150 °C), and high temperature (>150 °C). Geothermal energy is usually extracted with ground heat exchangers. The extracted heat is used directly for electricity production or for heat pump applications. Additional information on geothermal systems is provided in Section 2.5 of Appendix C.

Based on the type of application, geothermal energy can be utilized for direct use, for electricity production, or as heat pumps.

Direct Use

- Heat is produced directly from soil or from hot water in the earth. A well is drilled into the geothermal reservoir to provide a steady stream of hot water.
- A mechanical system is used to bring the hot water up to the surface and is directly used, for example, to heat water for pools and aquaculture, or for space heating.

Electricity Production

- Earth's heat is used to generate electricity. Heat from the earth's magma in the form of steam is used to generate electricity via a turbine and generator.
- Dry steam, flash steam, and binary systems are three configurations for thermal energy recovery for mechanical power conversion.
- Dry steam power plants draw from underground sources of steam, which is directly used to run a turbine/generator unit.
- Flash steam power plants are the most common and use geothermal reservoirs of water with temperatures greater than 360 °F (182 °C). When water flows up, it is partially converted into steam because of decreasing pressure. The steam is then separated from the water and used to power a turbine/generator.
- Binary cycle power plants operate on water at lower temperatures of about 225 to 360 °F (107–182 °C). Binary cycle plants use the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to turn a turbine.

Heat Pump

- Heat pumps are used to heat and cool buildings. Over broad areas of the United States, near-surface soils maintain a temperature between 50 and 60 °F

(10 and 16 °C). This temperature is warmer than the air above it in the winter and cooler in the summer, and can make heat pump applications economically competitive with fossil-fuel heating systems, and especially competitive with electrical heating and ambient-cooled air conditioning.

- In the winter, the heat pump removes heat from a ground-coupled heat exchanger and "pumps" the heat into the indoor air delivery system. In the summer, the process is reversed, and the heat pump moves heat from the indoor air into the heat exchanger.
- Geothermal heat pumps consume much less energy than conventional heating systems because they draw heat from the ground.

Additional Resources

Geothermal Energy Utilization:
http://www.nrel.gov/learning/re_geothermal.html (last accessed July 12, 2011).
http://www.nrel.gov/analysis/tech_geo_analysis.html (last accessed July 12, 2011).
http://www1.eere.energy.gov/geothermal/ (last accessed July 12, 2011).

4.4.1.5 Biogas

Principle

Biogas refers primarily to the methane and carbon dioxide generated during sludge anaerobic digestion in tanks of wastewater treatment plants. In the aerobic digestion process, microorganisms convert organic material to biogas in the absence of oxygen.

Generation of Electricity

The biogas is used to generate electricity using a fuel cell, gas engine, or gas turbine. Fuel cells are electrochemical cells that produce electricity from fuel. Additional information on fuel cells is provided in Section 2.6 of Appendix C. When the fuel reacts with an oxidizing agent, electricity is produced.

- Applications include grid-connected power generation, cogeneration of power and heat, off-grid power supply, emergency power, and distributed generation.
- Based on efficiency, type of electrolyte used, and operating temperature, different types of fuel cells exist. They are polymer electrolyte membrane (PEM), direct methanol, alkaline, phosphoric acid, molten carbonate, solid oxide, and regenerative.
- Net electrical efficiency can attain 42 to 47%. Low-temperature systems are less efficient than intermediate- and high-temperature systems.

Biogas is also used to generate power using a gas engine or gas turbine. Further information on the use of biogas for electricity generation is provided in Section 2.7 of Appendix C. The principal concern with the use of biogas is that it must be cleaned of siloxanes prior to use, which can be an expensive process, depending upon the quality of the product gas. Piston-actuated gas engines have a lower efficiency but a higher tolerance for contaminants, whereas gas turbines have higher efficiencies but almost no tolerance for contaminants.

- Utilization of biogas in gas engine systems is typically referred to as cogeneration because of the simultaneous generation of power.
- Overall cogeneration plant efficiencies using a gas engine can reach more than 90% and leads to energy savings of approximately 40% compared to separate power and heat generation equipment.
- The primary components of a gas engine are an engine/generator unit and heat exchangers for utilization of waste heat.
- Power plant electrical switch and control systems distribute the electricity and manage the engine. Hydraulic equipment controls the heat distribution.

Additional Resources

Fuel Cell Technology:
http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/index.html (last accessed July 12, 2011).

Biogas Cogeneration:
http://www.gepower.com/corporate/ecomagination_home/biogas.htm (last accessed July 12, 2011).

4.4.2 Leading Renewable Energy Providers

4.4.2.1 Solar Photovoltaic

Today there are many solar photovoltaic providers, some specializing in manufacturing panels or mounting systems, others operating as engineering, procurement, and construction (EPC) contractors, and yet others vertically integrated. The number of providers grows every day, with more companies entering the market as solar PV becomes more widely accepted and affordable.

Industry Associations Provide Tools to Identify Local Providers:
www.findsolar.com (last accessed July 21, 2011).

> The result of a partnership between the American Solar Energy Society (ASES) and Cooler Planet, it provides a business directory of solar providers plus other tools to help assess, procure, and finance solar systems.

http://seia.org/cs/membership/member_directory (last accessed July 21, 2011).

> The Solar Energy Industries Association is the national trade association for the solar industry. The 1,000-member directory has a search feature to locate providers by state, business type, or keyword.

In addition, most photovoltaic panel manufacturers have networks of project developers and authorized installers. Some prominent names include the following:

Suntech:
http://am.suntech-power.com (last accessed July 21, 2011).

> The largest silicone PV manufacturer in the world, yet they only provide panels through their partner network.

First Solar:
http://www.firstsolar.com (last accessed July 21, 2011).

> Constantly ranked among the largest world manufacturers of PV modules.

Sharp:
http://www.sharpusa.com/SolarElectricity.aspx (last accessed July 21, 2011).

> With probably the oldest PV manufacturer, Sharp also perform sales through their independent certified installers.

Among the installers and vertically integrated solar providers, some key players are the following:

SunPower Corp.:
http://us.sunpowercorp.com/ (last accessed July 21, 2011).

> A vertically integrated firm providing solar panels.

SunEdison:
http://www.sunedison.com/ (last accessed July 21, 2011).

> Now a subsidiary of MEMC, SunEdison is an international developer of solar projects focused on the commercial and utility markets.

Solar City:
www.solarcity.com (last accessed July 21, 2011).

> Full service provider of residential and commercial systems, servicing Arizona, California, Colorado, Hawaii, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Texas, and Washington, DC.

REC Solar:
http://www.recsolar.com/ (last accessed July 21, 2011).

> One of the largest in the nation by watts installed, REC Solar services Arizona, California, Colorado, Hawaii, New Jersey, and Oregon offering turn-key solutions from residential to utility systems.

4.4.2.2 Concentrating Solar Power

Solarlite:
www.solarlite.de (last accessed July 21, 2011).

> Manufacturer and supplier of solar thermal parabolic trough plants. At small scales they can generate process heat instead of electricity.

Abengoa Solar:
www.abengoasolar.com/corp/web/en/index.html (last accessed July 21, 2011).

> Provides solar thermal technologies to meet industrial heat and steam requirements.

Sopogy:
http://sopogy.com/ (last accessed July 21, 2011).

> Provides micro CSP systems for distributed power generation, process heat and solar air conditioning.

Amonix:
http://amonix.com/ (last accessed July 21, 2011).

> Designer and manufacturer of concentrated photovoltaic (CPV) commercial solar power systems.

SolFocus:
www.solfocus.com/en/ (last accessed July 21, 2011).

> Supplier of concentrator photovoltaic (CPV) systems.

4.4.2.3 Wind Turbines

Wind systems vary greatly in size, and choosing the appropriate turbine is highly dependent on site characteristics, wind resources, and power needs. Small systems with rated output from a few kW up to 50 kW come in varied shapes and sizes and are used in residential and localized industrial applications (e.g., water pumping or telecommunications). Then there are medium turbines in the range of 50 to 250 kW that can serve larger commercial facilities, buildings, and large farms, as well as off-grid systems. Larger turbines (900 kW to 2 MW) are mainly used in utility-scale arrays and seldom used as a standalone solution.

Small:

Windspire Energy Inc.
http://windspireenergy.com (last accessed July 21, 2011).

> Offers a vertical axis wind system rated at 1.2 kW that eliminates the need for large towers and is suitable for urban environments.

Southwestern Windpower:
http://www.windenergy.com/ (last accessed July 21, 2011).

> Leader in small turbines (3 kW and under).

Bergey Windpower:
www.bergey.com/ (last accessed July 21, 2011).

> A long-established manufacturer with two well-known products rated at 1 and 10 kW.

Gaia-Wind:
www.gaia-wind.com (last accessed July 21, 2011).

> Offers a two-bladed 11 kW turbine. Based in the UK.

Endurance Wind Power:
www.endurancewindpower.com (last accessed July 21, 2011).

> Manufacturer offering several models from 5 to 50 kW.

Enertech:
http://www.enertechwind.com/index.html (last accessed July 21, 2011).

> Manufacturer of a 40 kW turbine widely used in the United States.

Medium:

Northern Power Systems:
http://www.northernpower.com/ (last accessed July 21, 2011).

Offers a 100 kW and a new 2.3 MW direct drive turbine.

Polaris America:
www.polarisamerica.com/ (last accessed July 21, 2011).

Has an ample turbine portfolio with a Small product line going from 10 to 50 kW and a Large line sized at 100, 500, and 1,000 kW.

Large:

Siemens: Supplier of high quality wind turbine blades and wind turbines to all parts of the world.
http://www.energy.siemens.com/mx/en/power-generation/renewables/wind-power/wind-turbines/ (last accessed July 21, 2011).

GE Wind Energy:
http://www.ge-energy.com/wind (last accessed July 21, 2011).

A branch of General Electric's Energy business, ranks near the top of the wind turbine suppliers by market share. GE's product portfolio goes from 1.5 to 4 MW for both on- and offshore applications.

Vestas:
www.vestas.com/en/ (last accessed July 21, 2011).

The largest supplier of utility-scale turbines, with a broad portfolio that expands from 850 kW up to a 7-MW turbine for offshore applications.

4.4.2.4 Geothermal

The use of geothermal energy to generate electricity is limited to sites with very specific characteristics (superheated aquifers reachable by current drilling technology), and so far, feasible installations have only happened on the large scale. In the United States, the average geothermal plant capacity is close to 50 MW.

The major developers of geothermal systems in the United States are the following:

Ram Power Corp.:
www.ram-power.com (last accessed July 21, 2011).

Provider of geothermal energy project development and infrastructure.

Calpine Corp.:
www.calpine.com (last accessed July 21, 2011).

Provider of geothermal energy project development and infrastructure.

Geothermal energy can also be harnessed to aid heating and cooling processes by the use of geoexchangers, which are much more versatile in both size and the underground conditions required to make them viable. There are many providers of geoexchange technology, and most come together at the Geothermal Exchange Organization (GEO).

In addition, the following Web link has a useful search feature designed to aid in locating member companies based on expertise, services provided, and geographic location:

http://www.geoexchange.org/index.php?option=com_content&view=article&id=273&Itemid=5 (last accessed July 21, 2011).

4.4.2.5 Bioenergy

GE:
http://www.gepower.com/prod_serv/products/recip_engines/en/index.htm (last accessed July 12, 2011).

Supplier of biogas cogeneration engines.

Cenergy:

http://www.2g-cenergy.com/index.html (last accessed July 12, 2011).

Provider of biogas cogeneration engines.

Ballard Power Systems:
www.ballard.com (last accessed July 12, 2011).

Supplier of fuel cell technology.

Hygrogenics:
www.hygrogenics.com (last accessed July 12, 2011).

Supplier of fuel cell technology.

Lynntech:
www.lynntech.com (last accessed July 12, 2011).

Supplier of fuel cell technology.

UTC Power:
www.utcpower.com (last accessed July 12, 2011).

Supplier of fuel cell technology.

4.5 Integration

Growing concerns over climate change and adoption of state-level renewable portfolio standards and incentives, with accelerated cost reduction, will make renewable energy technologies a larger part of energy portfolios during the coming decades. It should also be noted that climate change could result in unexpected changes in renewable energy resource availability. For example, changes in wind patterns need to be considered in addressing integration of renewable energy resources.

Utility-scale renewable energy systems are typically connected to existing electricity grids. As the market share of renewable energy grows, stability and operation of the electricity grid will be increasingly critical. Some aspects that need to be considered during grid integration of renewable energy technologies are provided in this section with an overview of integration challenges, methods, and considerations for grid integration. Further information on integration can be found in the additional resources section at the end of this section.

4.5.1 Integration Challenges

- Electricity supply and demand must be met to operate an efficient power station. Integration challenges are predominant for solar PV and wind technologies because of their variability in generating electricity.
- Variability of electricity production from solar and wind technologies leads to increased complexity of operating the electricity grid.
- Several states and utilities in the United States have grid interconnection standards. Some of these standards inhibit the connection of renewable energy technologies (mostly solar PV systems) to the electricity grid.

4.5.2 Integration Methods

4.5.2.1 Solar PV Systems

- Solar PV systems are integrated with the electricity grid through inverters and transformers. The inverters are used to convert DC to AC and the transformers are used to convert low voltage to high voltage before feeding into the main electricity grid.
- When solar PV systems are implemented, use of several inverters in parallel should be considered, so that failure of an inverter does not prevent electricity from being transmitted to the main grid.

4.5.2.2 Wind Turbine

- Electricity produced from wind turbines is collected in a medium-voltage (25–35 kV) power collection system. Wind turbines are typically located 1 to 10 miles from high-voltage transmission lines in order to minimize costs associated with interconnection.
- Transformers located adjacent to the wind tower are used to convert the low-voltage power from the turbine to the higher voltage of the electricity collection system.
- Substations are typically used for passing electricity from wind turbines to the utility grid. Plant isolation breakers and power quality monitors are present in the substation to protect the grid and wind turbines. A system of switches and overhead infrastructure is used to connect the substation to the utility's power lines.

4.5.3 Considerations for Grid Integration

- Distributed photovoltaic systems design and technology requirements can be used to develop a set of conceptual system designs to integrate solar PV systems to the electricity grid.
- Solar energy grid integration systems (SEGIS) can be used to incorporate advanced functionality and integration with the electricity grid.
- Utility models and analysis and simulation tools can be used to review current utility studies, models, and software applications that are used in grid planning.
- Cyber security analysis can be used to examine the potential security implications of high penetration of renewable electricity supply, which will require high levels of information technology and control systems.
- Consider power systems planning and emerging practices suitable for evaluation of the impact of high-penetration solar PV and wind energy systems.
- Utilize prototype field tests to evaluate key characteristics of a new renewable energy technology system that maximizes grid value.
- Differences between intermittent PV and solar power systems, as compared to base load geothermal power systems, play a role in evaluating integration issues.

Additional Resources

Solar Photovoltaic System Integration:
http://www1.eere.energy.gov/solar/segis.html (last accessed July 12, 2011).
http://www.nrel.gov/docs/fy09osti/45061.pdf (last accessed July 12, 2011).
http://www.nrel.gov/docs/fy08osti/42675.pdf (last accessed July 12, 2011).
http://www.nrel.gov/docs/fy08osti/42292.pdf (last accessed July 12, 2011).

Wind System Integration:
http://www.nrel.gov/wind/systemsintegration/data_resources.html (last accessed July 12, 2011).
http://www.nrel.gov/wind/systemsintegration/capabilities.html (last accessed July 12, 2011).
http://www.nrel.gov/wind/systemsintegration/faqs.html (last accessed July 12, 2011).
http://www.nrel.gov/wind/systemsintegration/projects.html (last accessed July 12, 2011).
http://www.nyserda.org/publications/wind_integration_report.pdf (last accessed July 12, 2011).

4.6 Handling Variability

Handling variability of renewable energy resources is a key criterion for implementation. When variability is of concern, two types of methods are employed: (1) use of hybrid designs, and (2) utilization of storage technologies.

4.6.1 Hybrid Designs

- The application of a hybrid design allows the use of multiple renewable technologies depending on the location and resources available.
- Hybrid designs consist of a combination of solar and wind technologies to allow the capture of maximum sun in the summer and maximum wind in the winter.

4.6.2 Storage

One hurdle to widespread adoption of renewable power is reliability. Sources of renewable energy, such as the sun and wind, are not consistently available. Energy generation capacity in excess of instantaneous demand may not be utilized, whereas excess demand results in an unacceptable lack of energy availability. Renewable energy storage provides a means of load balancing. Although all renewable energy storage systems result in a net loss of energy, their use allows energy to be transferred from low peak to high peak, which increases its value, and allows energy to be available on demand (firm power), thereby avoiding grid instability. These advantages of renewable energy storage increase the reliability of renewable power, making it a more viable replacement for conventional sources of power.

- There are currently seven main types of renewable energy storage available at a utility scale: batteries, pumped-storage hydroelectricity, compressed air storage, flywheels, supercapacitors, hydrogen fuel cells, and seasonal thermal storage.
- Of all the energy storage technologies, pumped hydro storage is the most established and is currently cost effective for its purpose. In fact, pumped storage hydroelectricity accounts for 3% of the world’s electricity. In addition, it can achieve one of the highest cycles per lifetime at one of the lowest costs. Pumped hydro, however, is constrained by geologic features. Other technologies that rely on specific geologic formations include compressed air energy storage and some forms of thermal storage.
- Costs of batteries, while similar, can be highly dependent on the cost of input materials, which fluctuates in the market. Batteries can be implemented at all locations. There are more than half a dozen types of batteries that show varying degrees of promise, including polysulfide bromide flow batteries, vanadium redox flow batteries, zinc bromine flow batteries, sodium sulfur batteries, lithium ion batteries, traditional lead–acid batteries, and metal–air batteries.
- Polysulfide bromide flow batteries (PSBs), vanadium redox flow batteries (VRBs), and zinc bromine flow batteries (ZBRs) are collectively known as flow batteries. These typically share similar features such as cycles/lifetime, discharge time, and energy density.
- VRBs have an efficiency of 85%, which is higher than the 75% of PSBs and ZBRs. Although NaS batteries have a high energy density, they are currently very expensive to operate because they must be kept at 300 °C. Lithium ion batteries also have a high energy density; they are slightly more efficient than NaS batteries and can achieve more cycles per lifetime.
- Lead–acid batteries are one of the few proven battery technologies. However, their price is highly sensitive to the price of lead, and at the conclusion of their useful life

they require extensive recycling. Of the batteries, VRB, lead–acid, and NaS batteries are being utilized at a commercial level.

- Other technologies, such as flywheels and supercapacitors, are not ideal for storage for longer than a few seconds or minutes. These technologies, however, provide superior electricity quality and can come online almost instantaneously, providing bridging power between two longer-term sources of electricity.

Additional Resources

Integration and storage:
http://www.oe.energy.gov/renewable.htm (last accessed July 12, 2011).

> This Web link provides information on renewable and distributed systems integration (RDSI) and focuses on integrating renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system.

Energy storage systems program:
http://www.sandia.gov/ess/ (last accessed July 12, 2011).

> This Web link provides information on the energy storage systems (ESS) program. The goal of ESS is to develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions, that will increase the reliability, performance, and competitiveness of electric generation and transmission in utility-tied and off-grid systems.

Handing wind power variability:
http://www.nrel.gov/docs/fy06osti/39955.pdf (last accessed July 12, 2011).

> This Web link provides information on grid impacts of wind energy variability and recent assessments from a variety of utilities in the United States.

4.7 Permitting

4.7.1 Approach

Project permitting is a critical function for the success of any energy generation project. Every state has a unique approach to permitting, but there are some general guidelines that can be followed in getting off on the right foot. The California Association of Resource Conservation Districts guide has identified 11 key activities required to successfully navigate the permitting process that can lead to a successful desalination project with renewable energy generation sources on or adjacent to the site.

- *Careful project design:* Design your project with regulation in mind to minimize rework and costly delays.
- *A thorough project description for regulators:* The more effectively you describe your work, the less likely you will be to get show-stopper questions or delays due to lack of project understanding.

- *Contact agencies early:* Permitting can easily become a long-drawn-out process, so get started as soon as possible. Learn the rules that regulators have set up and get to know your regulators well.
- *Involve the public and media:* Controlling your message is important, and you do not want the press or others dictating your project's motives and image. Involve the public early, be forthright, and work to communicate your message well to the press to enlist them as an ally.
- *Positive, nonadversarial position:* The permitting process can be challenging with many conflicting views on the project. Diplomacy and courtesy will get you much further than animosity.
- *Pay attention to details:* Follow the rules, be prompt with responses and meeting with regulators, and do not cut corners. Somebody always pays in the end.
- *Be willing to negotiate:* A variety of public interests may be imposed on your project that you may not have conceived of earlier. Staying sensitive to regulator and public needs, within reason, will help keep your project moving forward.
- *Ask questions of regulators if there is any uncertainty:* The more accurate and complete your formal submittals are to your permit agencies, the less likely regulators are to pick your submissions apart. Frequent questioning also sends the message that you really want to comply with the rules that the regulator is administering.
- *Get everything in writing:* Misunderstandings can be minimized by taking extra time to carefully manage all correspondence and get it properly documented. You also develop a documented record of responsiveness and compliance, which can smooth the resolution of follow-on questions, support continuity through personnel changes, and so forth.
- *Minimize project impacts:* Although every project has budget constraints, understanding the regulations and actively working to minimize negative impacts on and off site will go a long way in navigating the permitting process.
- *Frequent, proactive follow-up:* Follow-up with permitting agencies will result in ensuring that all new permitting requirements are met before the construction of the plant.

4.7.2 Typical Permits Required for Desalination

Every state has a unique approach to permitting. By applying the approach just discussed to a particular region, an organization can be well served. A list of permits that would typically be required in the California market follows. Any on-site power generation through renewable energy supplies or future offshore, directly connected systems would need to comply with and be incorporated into these permits. The federal permits identified here will be pertinent throughout the United States and should be considered carefully. Because federal regulations generally serve as templates for state regulations, this California permit profile will also exemplify many regulatory steps for most other states.

- California Regional Water Quality Board
    - National Pollution Discharge Elimination System (NPDES)

- Federal Clean Water Act Section 401 permit for discharges onto waters of the United States

- California Air Resources Board: Greenhouse gas emissions
- California Environmental Quality Act: Environmental impact report
- California Fish and Game: CEQA review and potential 404 permitting
- California Coastal Commission: Coastal development permit: permits for projects installing infrastructure in coastal areas
- U.S. Army Corps of Engineers: Wetlands permits or Section 10 permits for projects "working to erect structures in or affecting navigable waters," which include all waters affected by tidal influence or otherwise navigable
- U.S. Fish and Wildlife Service: Endangered Species Act compliance (Sections 7 and 10)
- National Environmental Pollution Act: NEPA environmental report
- California Rivers and Harbors Act: Permit

Additional Resources

Permitting guidance manual for desalination:
http://www.twdb.state.tx.us/rwpg/rpgm_rpts/2003483509.pdf (last accessed July 12, 2011).
http://www.hdrinc.com/sites/all/files/content/articles/article-files/3623-a-decision-framework-for-desalination-options-in-south-central-texas.pdf (last accessed July 12, 2011).
http://www.water.ca.gov/desalination/pud_pdf/Desal_Handbook.pdf (last accessed July 12, 2011).
http://www.watereducation.org/userfiles/TomLuster.pdf (last accessed July 12, 2011).

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Appendix A

Utility Case Studies

The objective of the utility case studies was to obtain information on energy utilization, energy minimization strategies, and renewable energy utilization. Nine different facilities utilizing conventional and renewable resources were surveyed during the study. A comparison of reuse and desalination plants surveyed is shown in Table A.1. Utilities surveyed were located in the United States, Singapore, and Australia. The size of the seawater desalination plants ranged from 3,470 to 13,880 m^3/h (22 to 88 MGD), the size of brackish water desalination plants ranged from 552 to 1,261 m^3/h (3.5 to 8 MGD), and the size of water reuse plants ranged from 1,734 to 4,731 m^3/h (11 to 30 MGD).

Treated water from all brackish water and seawater desalination plants is used for potable purposes. Treated water from reuse plants is used for groundwater replenishment, indirect potable reuse (irrigation), or industrial (boiler feed) applications. An example of feed and treated water quality obtained from a water reuse and seawater desalination plant is provided in Table A.2. Typical process flow schematics of treatment plants utilized for reuse and seawater desalination are shown in Chapter 3 (Figures 3.2 and 3.3). A summary of energy minimization strategies employed and renewable energy implementation lessons learned follows.

Table A.1. Comparison of Energy Consumption Rates for Utilities Surveyed

Utility	Type of Plant	Capacity m^3/h (MGD)	End Use	Feed TDS	Permeate TDS	Specific Energy Consumption, kWh/m^3
1	Reuse	4,731 (30)	GWR, IPR	850 mg/L	30 mg/L	—
2	Reuse	1,734 (11)	Industrial, IPR	552 mg/L	26 mg/L	0.98
3	Reuse	3,469 (22)	IPR	712 mg/L	< 150 mg/L	—
4	Seawater desalination	5,993 (38)	DW	37,000 - 40,000 mg/L	< 200 mg/L	3.6
5	Seawater desalination	10,410 (66)	DW	36,700 mg/L	275 mg/L	3.3
6	Seawater desalination	13,880 (88)	DW	40,500 mg/L	< 80 mg/L	3.5
7	Seawater desalination	3,943 (25)	DW	< 28,500 mg/L	< 360 mg/L	3.9
8	Brackish water desalination	552 (3.5)	DW	2,300 mg/L	< 320 mg/l	0.94
9	Brackish water desalination	1,261 (8)	DW	2,000 mg/L	< 150 mg/L	1

Table A.2. Feed and Treated Water Quality for Reuse and Seawater Desalination Treatment Plants

Parameters	Feed Water to Advanced Water Treatment Plant	Treated Water—Reuse	Raw Seawater	Treated Water—Seawater Desalination
pH	7	5.7	7.7	6.9
Alkalinity, mg/L as CaCO3	340	18	94	3
Conductivity, µS/cm	1,600	50	53,600	413
Total dissolved solids, mg/L	850	30	35,600	275
Sodium, mg/L	185	8.2	10,700	98
Potassium, mg/L	18	NA	490	5
Calcium, mg/L	50	0.051	424	2
Magnesium, mg/L	26	0.017	1,370	5
Iron, mg/L	0.3	< 0.1	0.005	<0.05
Silica, mg/L	20	0.47	0.12	<0.05
Sulfate, mg/L	140	< 2	2,740	11.8
Chloride, mg/L	200	5	19,700	164
Phosphate (mg/L as PO4)	10	NA	<0.015	<0.003
Nitrate (mg/L as NO3)	NA	0.19	0.172	<0.009
Boron (mg/L)	NA	NA	4.7	0.88

NA=data not available.

A.1 Energy Consumption

The distribution of energy consumption during wastewater treatment is shown in Figure A.1. Energy consumption was calculated through SCADA systems and energy audits. A process flow schematic of a treatment plant is shown in Figure A.2.

A summary of energy consumption information provided is as follows:

A.1.1 Water Reuse Plants

- The reuse plants surveyed consisted of advanced treatment processes including MF, RO, and UV. The total energy consumption was on the order of 1 kWh/m^3.
- The greatest energy consumption was due to the operation of pumps (more than 50% of total energy consumption). After pumps, blowers (16% of total energy consumption) and aerators (8% of total energy consumption) also consume large amounts of energy.

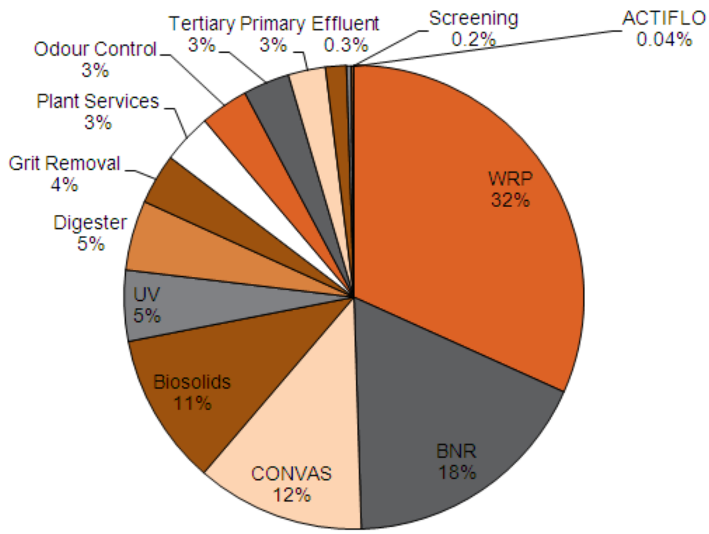

Figure A.1. Energy use by process during wastewater reuse. CONVAS is conventional activated sludge; BNR is biological nitrogen removal; WRP is water recycling plant.

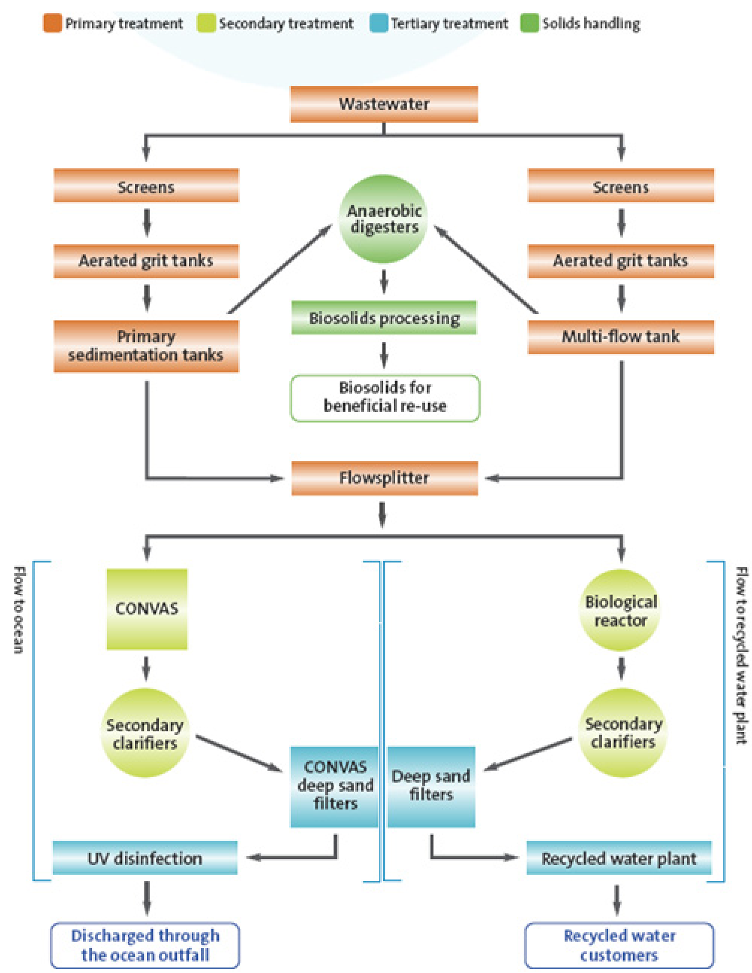

Figure A.2. Process flow schematic of wastewater treatment and recycled water plant, for which energy consumption is provided in Figure A.3.

A.1.2 Seawater Desalination Plants

Typical energy consumption in a seawater RO desalination plant is shown in Table A.3. Energy consumption with flow rate for a seawater RO desalination plant is shown in Figure A.3.

- The total energy consumption was on the order of 3–4 kWh/m^3. The energy consumption fluctuated significantly when the capacity of the plant varied. Energy consumption was lowest when the plant was operated at maximum capacity.
- The greatest energy consumption was due to the operation of high-pressure energy pumps for desalination (more than 75% of total energy consumption).

Table A.3. Typical Energy Consumption of Various Components during Seawater Desalination

Component	Specific Energy Consumption, kWh/m^3
Raw water pumping	0.39
Pretreatment and desalination	2.865
Post-treatment	0.012
High-service pumping station	0.3
General (buildings, heating, cooling)	0.04
Total energy consumption	3.607

A.2 Reported Energy Minimization Strategies

The following is a list of strategies reported by the utilities surveyed:

- Monitoring of energy efficiency of pumps (pump efficiency curves) to determine if the pumps and motors are operating close to the best efficiency point.
- Replacing older pumps and motors with newer premium efficiency models.
- Installation of VFDs to control motor speed and reduce energy consumption.
- Utilization of smaller RO trains and larger high pressure pumps led to minimization of energy consumption for seawater desalination.
- ERDs (Pelton wheels, pressure exchangers) for seawater desalination were installed in the first pass and were more than 90% efficient in recovering the pressure from brine.
- ERDs (turbochargers) for brackish water desalination were installed between the first and second stage to operate as booster pumps. No significant energy minimization was obtained by using ERDs for brackish water treatment.

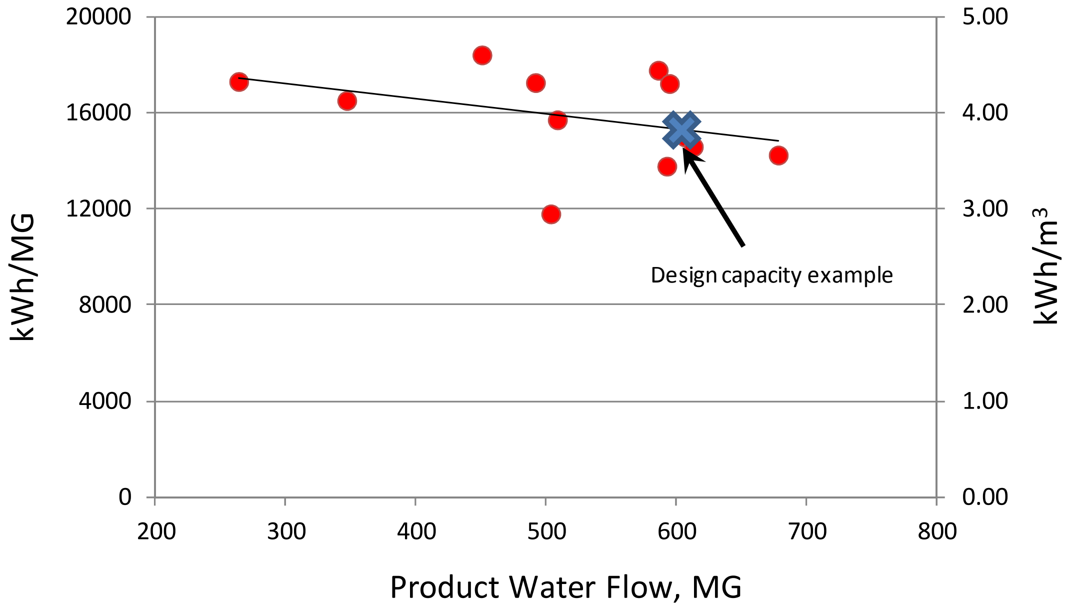

Figure A.3. Overall energy consumption for seawater desalination as a function of product water flow for one utility. The mark "X" denotes an example of design capacity. Energy consumption is higher when the plant is operating below design capacity.

A.3 Renewable Energy Utilization

A comparison of renewable energy utilization opportunities and drivers for the utilities surveyed is shown in Table A.4. Challenges encountered by the utilities for renewable energy utilization is shown in Table A.5.

- Solar PV and biogas cogeneration were the two types of renewable energy utilization (on site) for water reuse plants. Renewable energy provided 20% of the total energy consumption for the plants.
- Wind farms (off site) were utilized for the seawater desalination plants surveyed. Renewable energy provided 100% of the total energy consumption for the plants.
- All types of renewable energy utilized were connected to the utility grid and power was supplied to the plant through the utility grid (in addition to any on-site generation).
- Key drivers for renewable energy utilization were the funding available and social responsibility (reduced GHG emissions).
- All the utilities received funding from government and utility power providers in the form of direct funding, power purchase agreements, incentives, and rebates.
- Key challenges for implementation of renewable energy were ROI, footprint requirements, and integration of renewable energy with utility grid. There were no hurdles due to permitting requirements.

- ROI was a key challenge for the utilities that implemented renewable energy. Footprint requirements were high for installing solar PV panels. Solar PV panels were installed on concrete tanks where appropriate.
- Integration of renewable energy power to utility electricity grid was a challenge. When solar PV panels were utilized, several inverters were connected in parallel to ensure a constant supply of power to the electricity grid and maintain load.

Table A.4. Comparison of Renewable Energy Utilization Opportunities and Drivers for Utilities Surveyed

Utility	Type of Plant	Renewable Energy	% Use of Renewable	Onsite/Offsite	Funding/Incentives	Drivers
1	Reuse	Solar PV	20%	On site—grid-connected	Energy utility	Subsidized, sustainability, social resp.
2	Reuse	Biogas cogeneration	20%	On site—grid-connected	Government funds	Subsidized, sustainability, social resp.
3	Reuse	None	0%	None	Not determined	—
4	Seawater desalination	Wind	100%	Off site—grid-connected	Government funds	Subsidized, sustainability, social resp.
5	Seawater desalination	Wind	100%	Off site—grid-connected	Government funds	Subsidized, Sustainability, social resp
6	Seawater desalination	None	0%	—	—	—
7	Seawater desalination	None	0%	—	—	—
8	Brackish water desalination	Future consideration	0%	Considering on-site solar PV/CSP	Not determined	Subsidized, sustainability, social resp.
9	Brackish water desalination	Future consideration	0%	Considering o-nsite solar PV	Not determined	Subsidized, sustainability, social resp.

Table A.5. Comparison of Renewable Energy Implementation Challenges for Utilities Surveyed

Utility	Plant Type	ROI	Funding	Footprint	Integration	Permitting
1	Reuse	Minus	Plus	Minus	Minus	Plus
2	Reuse	Minus	Plus	Plus	Minus	Plus
3	Reuse	ND	ND	ND	ND	ND
4	Seawater desalination	Minus	Plus	Plus	Plus	Plus
5	Seawater desalination	Minus	Plus	Plus	Plus	Plus
6	Seawater desalination	ND	ND	ND	ND	ND
7	Seawater desalination	ND	ND	ND	ND	ND
8	Brackish water desalination	Minus	ND	ND	ND	ND
9	Brackish water desalination	Minus	Minus	Plus	ND	ND

Notes: Plus denotes that the parameter was favorable for renewable energy implementation. Minus denotes that the parameter was unfavorable for renewable energy implementation. ND=Not decided on implementation of renewable energy.

Appendix B

Energy Consumption and Minimization Strategies

B.1 History of Desalination

Desalination in the form of distillation was first utilized aboard ships to avoid the possibility of depleting onboard fresh water supplies (Seigal and Zelonis, 1995). During the 17th century, Japanese sailors used a distillation technique where water was boiled in pots and bamboo tubes were used to collect the evaporated water (Desalination in History, 2005). Advanced distillation technology started developing in the late 18th century (Greenlee et al., 2009). Some of the first attempts at commercial desalination plants included those installed in Tigne, Malta in 1881 and in Jeddah, Saudi Arabia in 1907 (Desalination in History, 2005). The first countries to use desalination on a large scale for municipal drinking water production were in the Middle East. Seawater distillation plants were first developed in the 1950s, and in the 1960s, the first industrial desalination plant was opened in Kuwait (Greenlee et al., 2009). In the late 1960s, membranes began to enter the desalination market, and the first successful RO plants used brackish water as feed (Reverse Osmosis*,* 1993).

Over the past 40 years, dramatic improvements in RO membrane technology have elevated RO to be the primary choice for new desalination facilities. Since the 1960s and 1970s, developments in both distillation and membrane technology have led to exponential growth in world desalination capacity (Greenlee et al., 2009). Today, more than 15,000 desalination plants are in operation worldwide. The Middle East holds approximately 50% of the world's production capacity. In 2005, Israel opened the world's largest RO seawater desalination facility, with a production capacity of more than 85 MGD (Sauvet-Goichon, 2007). The distribution of desalination production capacity by process technology is shown in Figure B.1 (a) and Figure B.1 (b) for the world and the United States, respectively. For the world, membrane and thermal technologies have an equal share of production capacity. But, in the United States, a major proportion of desalination production capacity is due to the application of RO (about 69%). The use of thermal technologies such as MED and MSF is less than 2% combined.

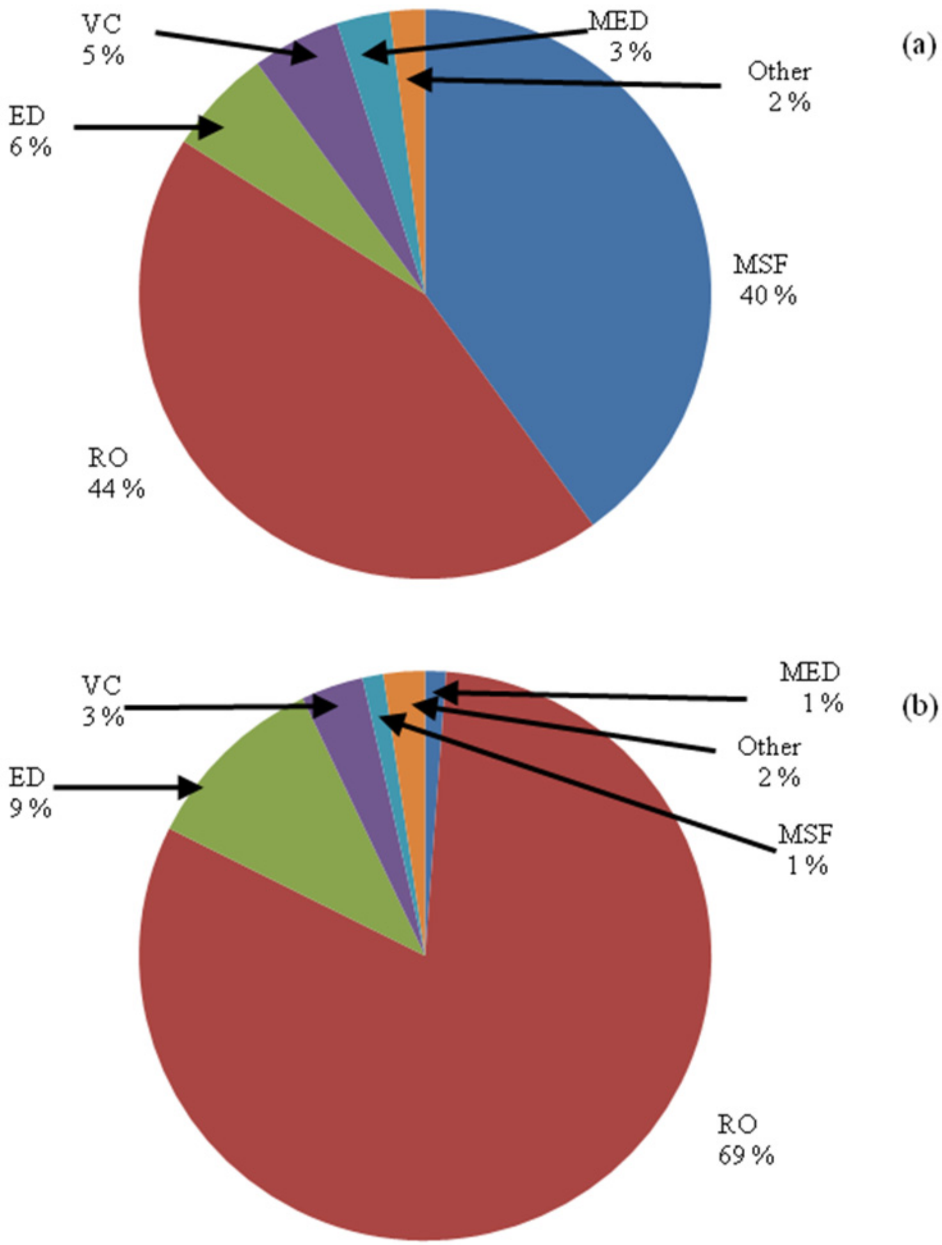

Figure B.1. Distribution of desalination production capacity by process technology for (a) the world and (b) the United States.
Adapted from Greenlee et al., 2009; Murakami, 1995; Zhou and Tol, 2005.
Note: **MED = multieffect distillation; MSF = multistage flash; RO = reverse osmosis; ED = Electrodialysis; VC = vapor compression.**

B.2 Desalination Technology Background

Desalination technologies can be broadly categorized into two major categories: thermal and membrane. A classification of the major desalination processes is shown in Figure B.2. A brief description of the various processes involved is provided in the following subsections.

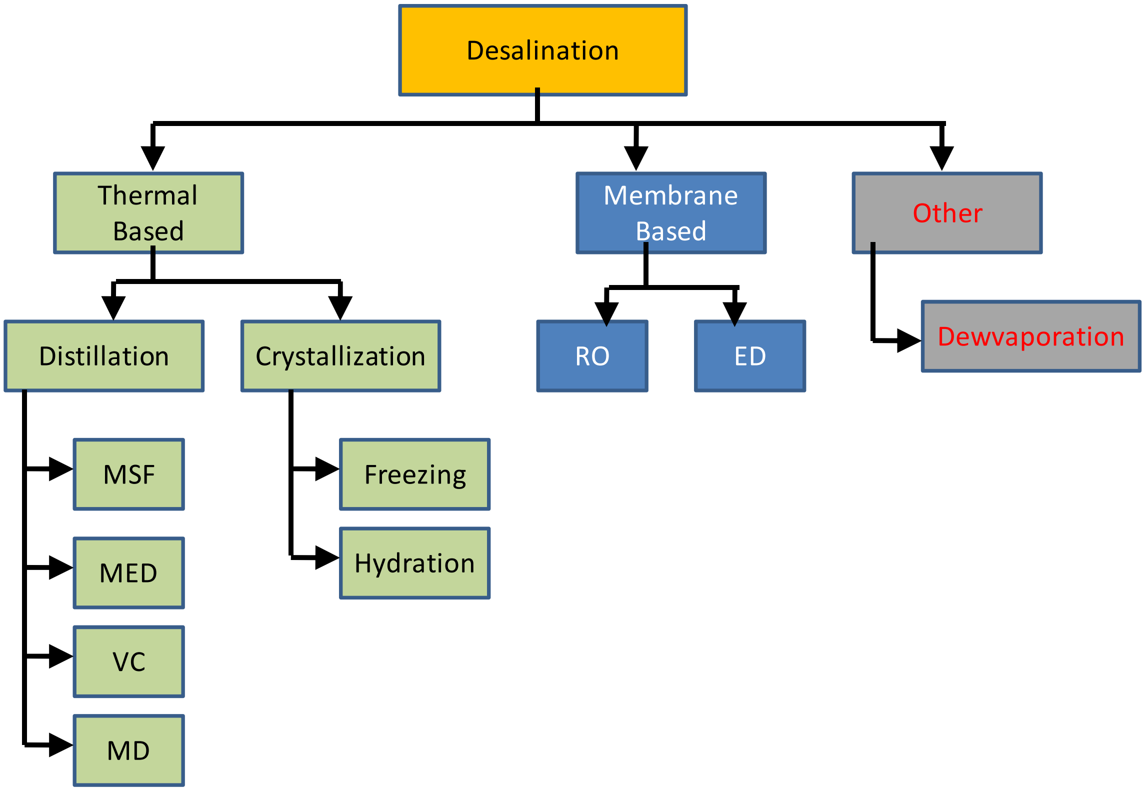

Figure B.2. Classification of major desalination processes.

B.2.1 Thermal-Based Desalination

The principle of thermal-based desalination processes depends on phase transition by energy addition or removal to separate fresh water from saline water. The most important thermal distillation processes are multistage flash (MSF) and multieffect distillation (MED). Other thermal distillation processes are vapor compression (VC) and membrane distillation (MD). Freezing and hydration are crystallization processes based on heat. Thermal-based distillation processes are described in brief in the following subsections.

B.2.1.1 Multistage Flash

The MSF process has been the predominant process for the desalination industry, which has a market share close to 60% of the total world production capacity (He and Yan, 2009). A schematic of the MSF process is provided in Veolia Water's Web site (Veolia Multistage Flash, 2011). This process is based on the generation of vapor from seawater or brine through sudden pressure reduction when seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at a temperature greater than 100 °C. The maximum temperature is limited by the salt concentration to avoid scaling. A low-temperature heat source can be utilized, and construction of equipment is simple in the MSF process. Due to the use of a small number of connection tubes, leakage problems and maintenance work are less than for other thermal-based processes. Also, evaporation and condensation are performed in many stages, thereby increasing efficiency.

The specific energy consumption for the MSF process is between 2.6 and 3.94 kWh/m^3 (10 and 15 kWh per 1000 gal) of water (Loupasis, 2001; Veerapaneni et al., 2007).

B.2.1.2 Multieffect Distillation

In the MED process, vapors are generated by the absorption of thermal energy by seawater (Gemma et al., 2006). A schematic of the MED process is provided at Veolia Water's Web site (Veolia Multi-effect Distillation, 2011). The steam generated at one stage or by one effect can heat the salt solution at the next stage, as the next stage is at a lower temperature or pressure. Similarly to the MSF process, the performance of the MED process depends on the number of stages or effects. MED plants normally use an external steam supply at a temperature greater than 100 °C. In a typical large plant, the presence of 8–16 effects is possible. The conventional MED process is the oldest method used to desalinate seawater in large quantities. Model MED units use horizontal or vertical falling evaporators in seawater desalination (Darwish et al., 2006). The low-temperature horizontal MED process is thermodynamically the most efficient of all thermal processes currently in use (Ophir and Lokiec, 2005). Major features of the MED process include the simultaneous transfer of latent heat on both sides of the heat transfer surface, utilization of aluminum tubes that permit a large heat transfer area, and short start-up periods with little time loss for heating up. The specific energy consumption for the MED process is between 1.84 and 2.63 kWh/m^3 (7 and 10 kWh per 1000 gal) of water (Loupasis, 2001; Veerapaneni et al., 2007).

B.2.1.3 Vapor Compression

VC desalination can be either thermal vapor compression (TVC) or mechanical vapor compression (MVC). The operation principle for the generation of distilled water from salt water is the same as for the MED process. Also, in the TVC and MVC processes, after initial vapor is generated from the saline solution, the vapor is thermally or mechanically compressed to achieve additional production. A schematic of the VC process is provided at Veolia Water's Web site (Veolia Vapor Compression, 2011). The VC process takes advantage of the principle of reducing the boiling point temperature by reducing the pressure. Methods used to condense water vapor to produce sufficient heat to evaporate incoming seawater are a mechanical compressor and a steam jet. Units have been built in a variety of configurations to promote the exchange of heat to promote evaporation (Kalogirou, 2005). The low-temperature VC process is a simple, reliable, and efficient process requiring only power. The use of a high-capacity compressor allows operation at temperatures below 70 °C, which reduces the potential for scale formation and corrosion. In general, the VC process is used for small-scale desalination plants. The power consumption for large units is approximately 7.89 kWh/m^3 (30 kWh per 1000 gal) of product water (Khawaji et al., 2008).

The performance of MSF and MED processes is directly proportional to the number of stages or chambers. These processes require more energy than membrane technologies but can produce water with much lower total dissolved solids (TDS) concentrations than membranes: less than 25 mg/L for thermal systems compared to 500 mg/L from many membrane systems (USBR, 2003). Although the energy requirement is independent of the feed water salinity, scaling caused by the accumulation of mineral deposits on heat exchange surfaces can disrupt the performance of MED systems by restricting water flow and reducing heat transfer efficiency (Khawaji et al., 2008). As a result, MSF systems that do not initiate evaporation on heat-exchange surfaces have increased in popularity. As of 2005, the largest MSF desalination facility in operation, with a treatment capacity of 18,927 m^3/h, was located in the United Arab Emirates (Cooley et al., 2006). According to a 2005 inventory (Wangnick and GWI, 2005), MED processes compose

15% of the thermal distillation market and are typically used to meet small municipal or industrial needs at capacities of 47 to 473 m^3/h (Wangnick and GWI, 2005).

B.2.1.4 Membrane Distillation

MD is a thermally driven, membrane-based process (Li and Sirkar, 2005). MD combines membrane technology and evaporation processing in one unit. It involves the transport of water vapor through the pores of hydrophobic membranes via the temperature difference across the membrane. A schematic of the working principle for the MD process is shown in Figure B.3. The temperature difference results in a vapor pressure difference, leading to the transfer of the produced vapor through the hydrophobic membrane to the condensation surface. Membrane materials that have been considered for the MD process include polytetrafluoroethylene, polyvinylidene fluoride, polyethylene, and polypropylene. Typical values for the porosity are 0.06–0.85; for the pore size, 0.2–1.0 µm; and for the thickness, 0.06–0.25 mm. For almost three decades, MD has been considered an alternative to conventional desalination technologies such as MSF and RO. These two techniques involve high energy and high operating pressure, respectively, which result in excessive operating costs. MD offers the attraction of operation at atmospheric pressure and low temperatures (30–90 °C), with the theoretical ability to achieve 100% salt rejection. When MD is coupled with solar energy, geothermal energy, or waste heat, it can achieve cost and energy efficiency. However, the industry has not fully embraced MD for several reasons: low water flux (i.e., productivity) and a shortage of long-term performance data due to the wetting of the hydrophobic microporous membrane (Mathioulakis et al., 2007). Innovative materials that offer microporous membranes with desired porosity, hydrophobicity, low thermal conductivity, and low fouling are essential to bring MD closer to commercialization. Opportunities therefore beckon membrane researchers to improve the flux in the process and increase its durability by fabricating highly permeable superhydrophobic membranes and/or modifying the MD module configurations. The specific energy consumption for MD systems has been reported to be about 43 kWh/m^3 (166 kWh per 1000 gal) of water (Walton et al., 2004).

B.2.1.5 Freezing

Desalination by freezing is categorized as a crystallization processes. Although desalination by freezing has been proposed as a method for several decades, only demonstration projects have been built to date (Qiblawey and Banat, 2008). Freezing is a separation process related to the solid–liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, ice crystals of pure water are formed within the salt solution. These ice crystals can be washed and remelted to obtain pure water. In a direct freezing process, the refrigerant is mixed directly with the brine. In an indirect process, the refrigerant is separated from the brine by a heat transfer surface. The process is essentially a conventional compressor-driven refrigeration cycle with the evaporator serving as the ice freezer and the condenser as the ice melter. Theoretically, freezing has certain advantages compared to distillation. These include a lower theoretical energy requirement, minimal potential for corrosion, and little scaling or precipitation (Qiblawey and Banat, 2008).

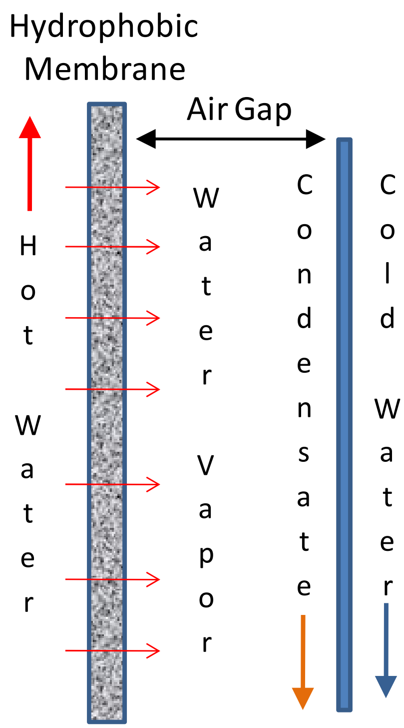

Figure B.3. Schematic of MD process.

B.2.1.6 Hydration

Desalination by hydration involves the formation of gas hydrates. Gas hydrates are crystalline aggregations of hydrogen-bonded water molecules around a central gas molecule (McCormack and Andersen, 2005). These crystalline compounds generally form under moderately elevated pressures, but are known to have freezing points at least as high as 12 °C. The hydration process is similar to a direct contact freezing process utilizing a secondary refrigerant. In the freezing section, gas and water are mixed and the hydrates precipitate. The crystals are physically separated from the remaining brine, washed, and melted. The gas volatilizes away from the water and is recovered for reuse. An advantage of the process is that it could operate at a higher temperature than a conventional freezing process, potentially decreasing the energy requirements of the plant.

B.2.1.7 Reverse Osmosis

Membrane-based desalination processes typically involve the use of RO membranes. In an RO process, the osmotic pressure is overcome by applying an external pressure higher than the osmotic pressure. Thus, water flows in the direction opposed to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration (Wilf and Bartels, 2005). No heating or phase separation is necessary for a RO process. Some of the dissolved minerals and salts may pass through the membrane, but at a much lower rate than water, resulting in the concentration of the remaining solution. The flow of water through the membrane depends on the pressure gradient across the membrane, whereas the flow of dissolved ions or salts depends on the concentration gradient. As the feed water pressure increases, the water flow increases but the salt flow does not, improving the quality of the product water (assuming that the salt concentration difference across the membrane does not increase). Over time and as technology has advanced, the performance of RO membranes has improved.

Early RO membranes were made from cellulose acetate (Wilf and Bartels, 2005). These membranes offered reasonably high flux rates and salt rejection capabilities, but were not effective outside a narrow range of water quality characteristics. New generation RO membranes are made of polymeric materials (e.g., polyamide) and can offer wider ranges of operating temperature and pH, thus providing more flexibility. However, a substantial degree of physical and chemical pretreatment is still required to reduce fouling of RO membranes (Wilf and Bartels, 2005). Periodic cleaning must also be performed to maintain production capacity through the prevention of scaling and foulant accumulation. RO membrane modules are either spiral-wound or hollow-fiber (Wilf and Bartels, 2005). Hollow-fiber membranes normally push feed water from the outside of the membrane into the center of the fiber. Spiral-wound membranes are assembled from flat-sheet membranes: two membrane sheets are separated by feed water and carrier spacers that provide process water and convey permeate water to a central collector line. An illustration of the spiral wound membrane is shown in Figure B.4. The design configuration and operating characteristics of these pressure vessels depend on feed water quality, treatment objectives, and capacity requirements. Pressure vessels can contain one or many membranes and exist in staged single, parallel, tapered, or numerous other array configurations. The energy consumption for RO processes is primarily due to the power required by the feed pressure pumps, which is directly proportional to the feed water salinity. The specific energy consumption of an RO process for treating seawater is between 2.63 and 4.2 kWh/m^3 (10 and 16 kWh per 1000 gal) (Veerapaneni et al., 2007).

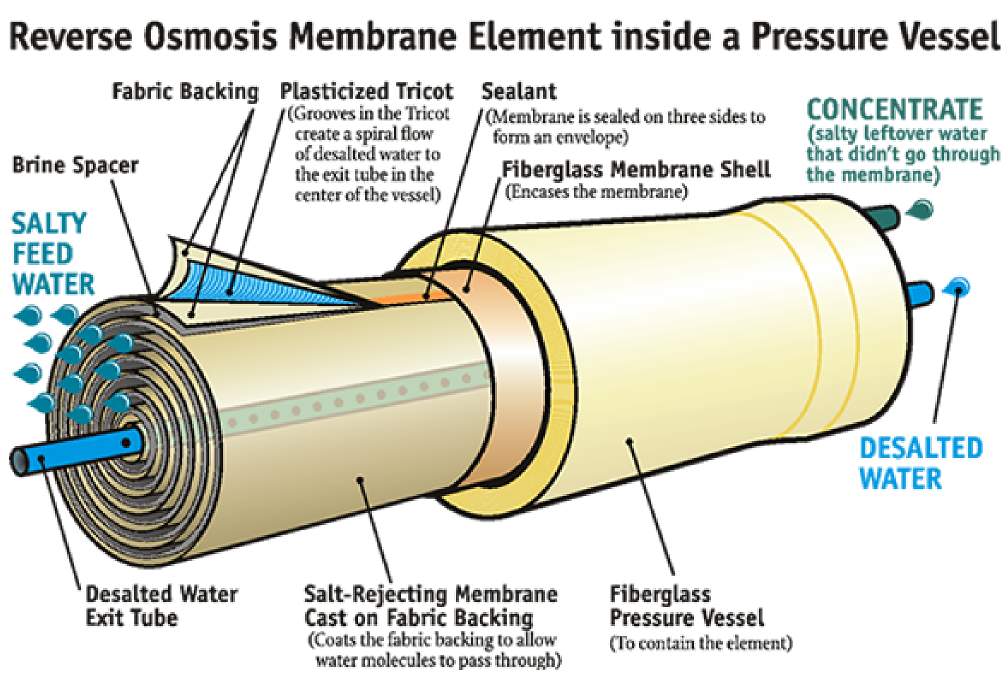

Figure B.4. Schematic of reverse osmosis membrane element (USBR, 2011).

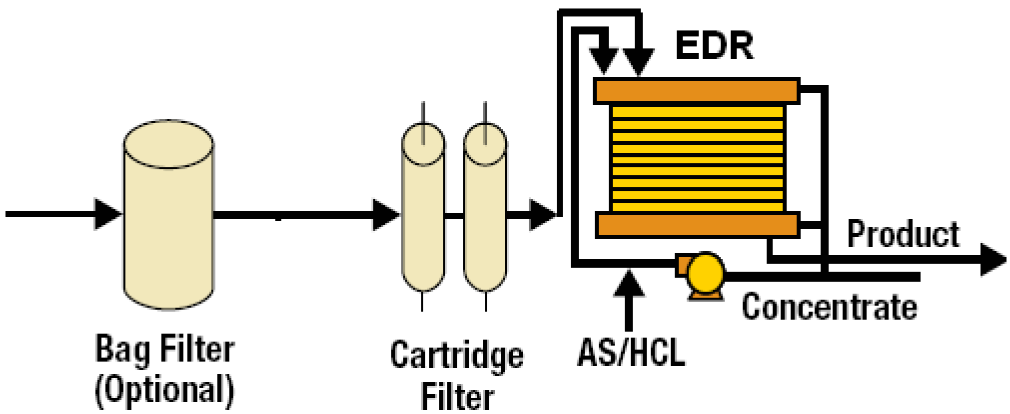

Figure B.5. Schematic of EDR treatment train.

B.2.1.8 Electrodialysis

Electrodialysis (ED), commercially introduced in the 1950s, removes dissolved salts by the application of an electrical potential difference. Positively and negatively charged ions are separated from a solution by oppositely charged electrodes and cation- or anion-permeable membranes (Kalogirou, 2005). Inverters frequently reverse the polarity of the system to prevent scaling. ED systems require less pretreatment than RO systems and have a higher percentage recovery than thermal distillation systems (i.e., produce more product water and less brine). However, energy requirements of the ED process are directly proportional to the salinity of the feed water. As a result, ED is commonly used to treat brackish waters with lower dissolved solids concentrations (Mathioulakis et al., 2007). The development of a modification to the ED system–electrodialysis reversal (EDR)–has further increased the performance of these systems. An illustration of the EDR process is shown in Figure B.5. EDR systems are functionally similar to the ED process but can operate on more turbid feed water, have higher water recovery than RO, and are less prone to biofouling than RO systems. Nevertheless, energy requirements still hinder the widespread acceptance of ED or EDR for the purification of seawater. The specific energy consumption of the EDR process for brackish water has been reported to be 1.26 kWh/m^3 (4.8 kWh per 1000 gal) (Chang et al., 2008).

B.2.1.9 Dewvaporation

Dewvaporation is a specific process of humidification–dehumidification desalination, which uses air as a carrier-gas to evaporate water from saline feeds and form pure condensate at constant atmospheric pressure (He and Yan, 2009). The heat needed for evaporation is supplied by the heat released by dew condensation on the opposite side of a heat transfer wall. Because external heat is needed to establish a temperature difference across the wall, and because the temperature of the external heat is versatile, the external heat source can be from waste heat, from solar collectors, or from fuel combustion. The unit is constructed out of thin water wettable plastics and operated at atmospheric pressure. The standard dewvaporation continuous contacting tower is a relatively new, nontraditional, and innovative heat–driven process using air as a carrier gas and remaining at atmospheric pressure throughout the device. The external heat source can be low-temperature solar, waste heat, or combustible fuels. In comparison to desalination using conventional techniques, a dewvaporation process utilizing waste heat can provide reduced energy consumption.

B.3 Comparison of Desalination Technologies

A comparison of common desalination technologies is presented in Table B.1. The advantages of membrane processes over thermal processes include lower capital cost and energy requirements, lower footprint and higher space/production ratio, higher recovery ratio, minimal interruption of operation during maintenance, less vulnerability to corrosion, and better rejection properties for microbial contaminants. The advantages of thermal processes over membrane processes include a proven and established technology, higher quality of product water, and less impact from feed water quality changes. The higher product water quality with thermal desalination technologies can also be used to achieve higher feed and permeate water blend ratios, thereby reducing the required capacity of the particular desalination technology.

Table B.1. Comparison of Common Desalination Techniques (Ettouney et al., 1999)

Process	Recovery	Permeate TDS	Advantages	Disadvantages
RO	30–60% recovery with single pass	< 500 mg/L for seawater	Lower energy consumption	Higher costs for chemical and membrane replacement
	Higher recoveries possible with multiple passes	< 200 mg/L for brackish water	Relatively lower investment cost	Adequate pretreatment a necessity
			Modular design	Membranes susceptible to biofouling
			Removal of contaminants other than salts	Minimum membrane life expectancy around 5–7 years
			Simple operation and fast start-up	
			Maintenance does not require entire plant shutdown	
			High space/production capacity	
ED	85–94% recovery possible.	140 - 600 mg/L	Energy usage proportional to salts removed and not volume-treated	Only suitable for feed water up to 12,000 mg/L TDS
			Higher membrane life of 7–10 years	Bacterial contaminants not removed
			Operational at low to moderate pressures	Periodic cleaning of membranes required
MSF	25–50% recovery in high–temperature recyclable	< 50 mg/L	Large capacity designs	Large capital investment required
	MSF plant.		Proven, reliable technology with long operating life	Energy-intensive process
			Reduced scaling	Large footprint requirement
			Minimal pretreatment required	Maintenance requires entire plant shutdown
			Plant process and cost independent of salinity level	Recovery ratio is low
				High level of technical knowledge required
			Heat energy can be sourced by combining with power generation	
MED	Up to 65% recovery is possible.	<10 mg/L	Large capacity designs	High energy consumption

Process	Recovery	Permeate TDS	Advantages	Disadvantages
VC	50% recovery possible.	<10 mg/L	Minimal pretreatment required Reliable process with minimal requirements for operational staff Heat energy can be sourced by combining with power generation . Very high-quality product water Developed process with low consumption of chemicals Relatively low energy demand . Lower temperature requirements reduce potential for scale and corrosion . Relatively lower capital and operating costs Portable designs allow flexibility	High capital and operational cost High quality materials required, as process is susceptible to corrosion Product water requires cooling and blending prior to being used for potable water need. Start-up requires auxiliary heating source to generate vapor Limited to small plants Compressor needs higher levels of maintenance

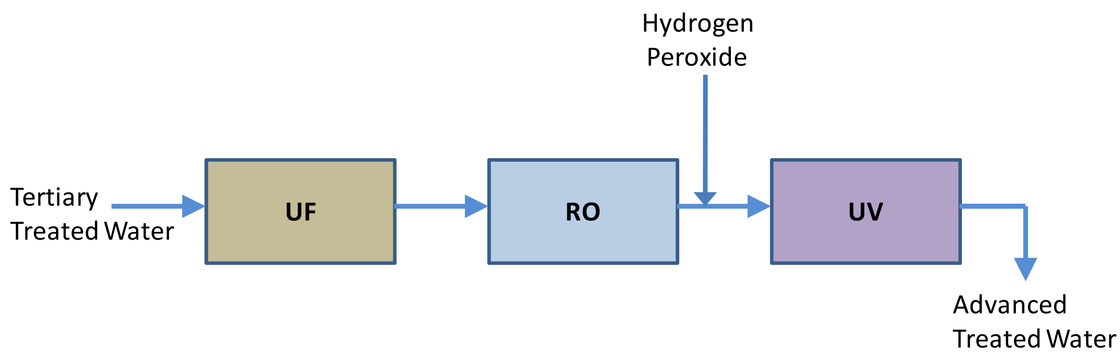

Figure B.6. Illustration of an advanced water treatment system (MWH, 2006).

B.4 Water Reuse Technology Background

Water reuse and advanced water treatment technologies consist of a combination of membrane and disinfection technologies to produce water for either indirect or direct potable reuse. An example of an advanced water treatment process used for producing water for indirect potable reuse in San Diego is shown in Figure B.6. The system uses a combination of UF and RO to remove suspended solids, organics, and TDS from the tertiary treated wastewater stream. The permeate stream from the RO process is further treated using a combination of UV and hydrogen peroxide. Advanced oxidation is necessary to achieve additional reduction of *N*-nitrosodimethylamine (a nitrogenous disinfection by-product) beyond what can be accomplished using membranes.

B.4.1 Low-Pressure Membrane Systems

In an advanced water treatment system, low-pressure membranes are typically used as pretreatment. Low-pressure membranes generally employ either MF or UF. MF membranes have pore sizes in the range of 0.05 to 5 µm, whereas UF membrane have slightly smaller pores ranging from 0.002 to 0.1 µm (Jacangelo and Buckley, 1996). MF and UF membranes may be used in either a spiral-wound, tubular, or hollow-fiber element design, with hollow-fiber being the most prevalent for municipal applications (Chang et al., 2008). The permeate water flux for low-pressure membranes is dependent on site-specific water turbidity, pump sizing, and acceptable levels of transmembrane pressure (Chang et al., 2008). A typical process schematic for low-pressure membranes is shown in Figure B.7. Raw water is first passed through a prescreen to remove large particles that may damage the membrane fibers or pumps. Based on the system configuration, a feed pump supplies water to the membrane bank and supplies the driving pressure through the membrane, or there is a vacuum pump that draws the water through the membranes, which are submerged in a tank. The permeate is stored in a finished water storage tank from which it can be sent to additional treatment processes in water reuse applications. Air scouring may be employed during the backwash to further clean the membranes. Some systems are also operated in cross-flow operation mode (Chang et al., 2008).

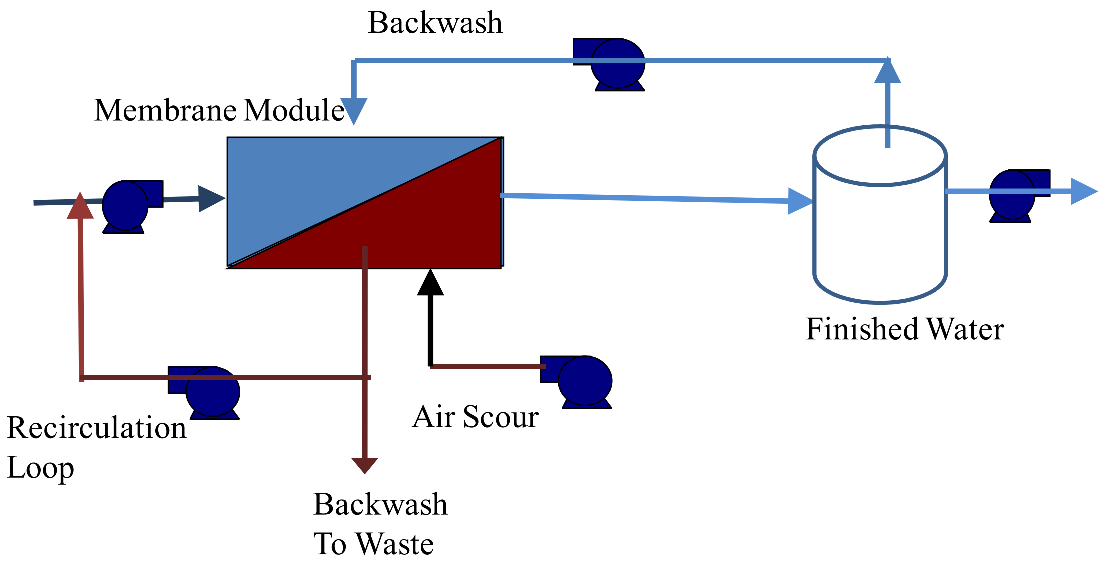

Figure B.7. General process schematic for low-pressure water treatment membrane systems (Chang et al., 2008).

MBR are specialized low-pressure membranes modified for municipal wastewater treatment. In an MBR process, a combination of low-pressure membrane filtration and the activated sludge process is involved. A schematic of the MBR process is shown in Figure B.8. The principal difference from MF and UF membranes is that MBRs require aeration during the filtration process to reduce the amount of fouling caused by the high concentration of suspended solids typical in municipal wastewaters. In an MBR process, aeration and anoxic zones are typically used ahead of the membrane process in order to achieve higher nutrient removal. The effluent from MBRs can be further treated using RO, followed by disinfection using UV and hydrogen peroxide.

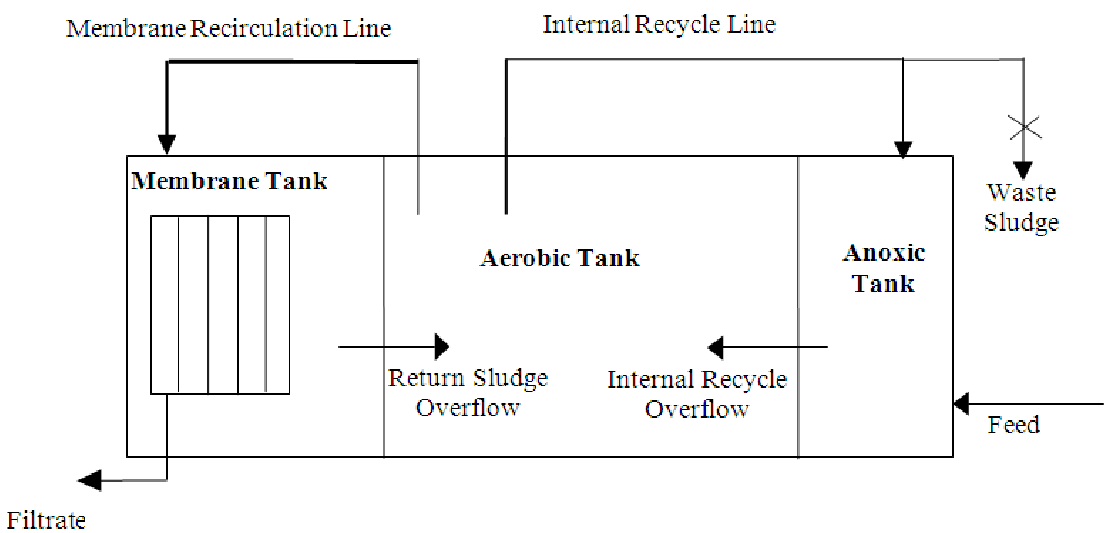

Figure B.8. General process flow schematic of MBR process.

B.4.2 UV Disinfection

An UV disinfection system transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA). When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. The effectiveness of UV disinfection depends on the characteristics of the wastewater, the intensity of the UV radiation, the amount of time the microorganisms are exposed to the radiation, and the UV reactor configuration (Chang et al., 2008).

The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either low-pressure or medium-pressure mercury arc lamps with low or high intensity. The optimum wavelength to effectively inactivate microorganisms is in the range from 250 to 270 nm. The intensity of the radiation emitted by the lamp dissipates as the distance from the lamp increases. Low-pressure lamps emit essentially monochromatic light at a wavelength of 253.7 nm. Medium-pressure lamps are often used in large facilities. They have approximately 15 to 20 times the germicidal UV intensity of low-pressure lamps. The medium-pressure lamp disinfects faster and has greater penetration capability because of its higher intensity. However, these lamps operate at higher temperatures with significantly higher energy consumption. Low-pressure UV systems are generally 40 to 50% more energy-efficient than medium-pressure systems, but the large number of low-pressure lamps required may result in higher maintenance and capital costs.

B.4.3 Ozonation

Advanced water treatment can also be accomplished using ozone as part of the treatment process (Chang et al., 2008). The ozonation process includes four steps: feed-gas preparation, ozone generation, ozone contact, and off-gas treatment. A typical process layout for ozonation in water treatment is shown in Figure B.9. The feed gas is typically passed through a desiccator to reduce the gas water content and achieve minimum moisture content of the feed gas. Ozone is produced by applying a high-voltage alternating current (6–20 kVAC) across a dielectric discharge gap that contains the feed gas. On-site generation is required, as ozone is highly unstable. The feed gas stream typically contains approximately 0.5 to 3% weight of ozone. The ozone gas stream is diffused into the feed water using a downflow contact basin. The contact basin may be a diffused bubbler, a mechanical agitation system, a packed tower, or a venture mixer. Off-gas in the contactor is collected and sent to a heat catalyst or activated carbon unit, which reduces the ozone to oxygen and discharges it to the atmosphere (Chang et al., 2008).

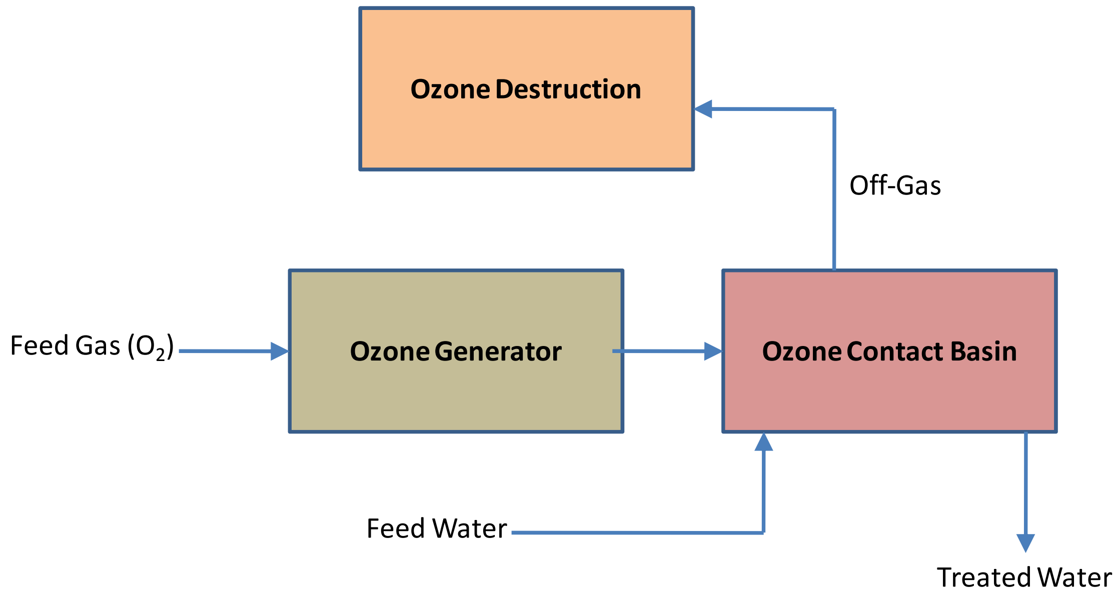

Figure B.9. General process schematic of ozonation water treatment system.

B.5 Overview of Process Energy

B.5.1 Energy Consumption of Desalination Processes

Though several technologies are currently available for desalination, the use of reverse osmosis membranes is predominant in many regions of the world. In the United States, more than 69% of the desalination capacity utilizes RO membranes for desalination (Greenlee et al., 2009). Both MSF and VC processes have significantly higher energy consumption than the RO process. Although the energy consumption of MED processes can be comparable to that of RO, the capital costs can be substantially higher for the MED process (Veerapaneni et al., 2007). Hence, desalination using RO membranes is gaining acceptance as the predominant desalination process. Moreover, improvements to RO membrane material and energy-recovery devices in the past decade have significantly improved the energy efficiency of RO desalination. For these reasons, the use of RO is gaining importance in treating high-salinity feed water. As discussed previously, the largest component of power usage is due to the high-pressure pumps required to feed the water for the first pass of the RO process. More than 33% of the cost of seawater desalination is attributed to electric power requirements. Higher recovery increases feed pressure requirements and hence the energy consumption. The optimum recovery based on energy consumption is between 35 and 45%. The optimum recovery based on life-cycle cost is between 42 and 45% (Long, 2008). Hence, reducing energy consumption is critical in lowering the cost of desalination.

B.5.2 Energy Consumption of Advanced Water Treatment Processes

B.5.2.1 Low-Pressure Membranes

When low-pressure membranes are used for pretreatment for RO, the components that consume the largest fraction of energy include the feed/vacuum pump, backwash pump, air scour blower, and recirculation pump (Chang et al., 2008). Use of heaters for temperature control of chemical cleaning solutions can also consume significant amounts of energy. Thus, membrane fouling is a significant determinant of energy consumption in MF and UF processes. As membrane permeability decreases because of fouling, higher pressure is required to maintain a constant permeate flow. Energy consumption by the backwash and air scour systems will depend on the frequency of backwash/air scouring and the volume of backwash water that is used (Chang et al., 2008).

Energy consumption in MBRs is largely determined by the pressure required to transport water across the membrane, which is typically done using vacuum pumps, and the aeration systems (Cheng et al., 2008). Energy in MBR systems is also consumed by support processes, such as the backwashing and clean-in-place (CIP) systems. The process air blowers and air scour blowers consume the largest fraction of the total MBR energy requirement (Chang et al., 2008). The process pumps comprise the vacuum pumps, the backflushing pumps, and the foam pumping system. The aeration sequence used in MBR systems has been reported to dramatically impact the energy usage. For continuous aeration systems, up to 50% of the total energy can be attributed to aeration. Cyclic aeration has been reported to reduce the aeration power requirement by up to 70% (Chang et al., 2008). Energy consumption of MBR processes has been estimated to be on average 0.44 kWh/m^3 (1.7 kWh per 1000 gal) of water treated (Pellegrin and Kinnear, 2010).

B.5.2.2 Ultraviolet Disinfection

When UV systems are used for post-treatment, the principal energy consumer is the lamps that generate the UV light (Chang et al., 2008). NYSERDA investigated the use of three UV technologies for wastewater treatment (NYSERDA, 2004). The technologies tested were low pressure–low intensity, low pressure–high intensity, and medium pressure–high intensity. These technologies were investigated at pilot scale under a variety of UV doses and flow rates. To meet a fecal coliform effluent limit of 200 MPN (most probable number)/100 ml, a fecal log inactivation of 2.7–2.9 was required. The inactivation level required UV doses of 26, 30, and 32 mW-s/cm^2 for low pressure–low intensity, low pressure–high intensity, and medium pressure–high intensity, respectively. It has been reported that UV disinfection increases energy consumption by 70 to 100 kWh/MG relative to that needed by conventional chlorination processes (EPRI, 1997). The NYSERDA study also compared the power requirements for the three pilot plants with the amount of power needed by a chlorination/dechlorination facility using hypochlorite and sodium bisulfate to treat the same quantity of water.

The energy consumption of low- and medium- pressure lamps used to disinfect biologically treated wastewater to comply with an effluent limit of 200 fecal coliform per 100 mL is summarized in Table B.2. Compared to a chlorination/dechlorination facility, which uses 6 kW, the UV systems have power usage of 60 kW (low pressure–low intensity), 45 kW (low pressure–high intensity), and 190 kW (medium pressure–high intensity) (NYSERDA, 2004). The study concluded that low pressure–low intensity UV lamps would not be cost-effective for an application with high flow rates.

Table B.2. Energy Consumption of UV Lamps (NYSERDA, 2004)

Variable	Low Pressure–Low Intensity	Low Pressure–High Intensity	Medium Pressure–High Intensity
Emission wavelength	254 nm	Broad spectrum	Broad spectrum
Power draw (W)	88	250	1000–15,000
Power use (kWh/MG)	3.2–4.8	—	6.8–15
Typical cost ($/lamp)	45	185	225

B.5.2.3 Ozonation

The major energy consumption components for ozonation systems are feed-gas treatment, ozone generator, cooling water pumps for the ozone generator, and ozone destruction unit (Chang et al., 2008). The primary energy consumption is due to the ozone generator. The ozone generator consumes energy by the production of voltage and the pumping of cooling water through the generator. The ozone diffuser requires energy for pumping the ozone-rich gas into the contact basin. Energy consumption associated with the ozone generator tends to increase with increasing ozone generation rate, but the energy required for the auxiliary systems remains relatively fixed regardless of the ozone generation rate. The energy consumption of ozonation systems used for disinfection can range from 0.005 to 0.013 kWh/m^3 (0.02 to 0.05 kWh per 1000 gal), 0.015 to 0.021 kWh/m^3 (0.06 to 0.08 kWh per 1000 gal), and 0.028 to 0.04 kWh/m^3 (0.11 to 0.16 kWh per 1000 gal) when liquid oxygen, vacuum pressure swing adsorption, and ambient air are used as feed (Chang et al., 2008).

B.5.3 Energy Minimization for Membrane Desalination Systems

Because the use of RO membranes is the predominant method of desalination, especially in the United States, energy minimization for desalination systems will be focused on membrane processes. Operating methods or process components used to reduce the overall energy requirements in RO desalination processes are described in this section. The cost of desalinating high-salinity water has decreased from about \$1.94/m^3 of water in 1998 to about \$0.5/m^3 of water currently. The key factor in economic improvement is due to advances in the process and membrane technology (Wilf and Bartels, 2005). In addition to the utilization of renewable energy resources, other factors influential in energy minimization and costs can be classified as:

- Enhanced RO system design
- High-efficiency pumping
- Energy recovery
- Advanced membrane material
- Application of innovative technologies

Each of these factors will be described in detail in the following sub-sections.

B.5.3.1 Enhanced Reverse Osmosis System Design

Design and configuration of the membrane unit can have a significant effect on the performance and economics of the RO plant (Wilf and Bartels, 2005). In the past, membrane units for feed water with high salinity were usually configured as two stages, with six elements per pressure vessel. A two-stage system results in a high feed and concentrate flow, reducing concentration polarization. Because of the higher feed flow, greater feed pressure is required to compensate for the increased pressure drop across the RO train. Design efforts to reduce power consumption have resulted in the use of single-stage configurations for high-salinity feed water applications. In some cases, seven (or eight) elements per pressure vessel are currently being used (Wilf and Bartels, 2005). The reduction in pressure drop from using a single stage instead of a two-stage system can result in a 2.5% lower power requirement (Wilf and Bartels, 2005). The use of larger-diameter elements (16-in. and 18-in.) instead of the typical 8-in. element has also been reported to reduce the capital cost by as much as 10% by minimizing footprint requirements. The use of 18-in. elements has been reported to produce seven times as much permeate as the use of 8-in. elements (van Gottberg et al., 2005).

Employing seven (or eight) elements per pressure vessel can lead to an uneven flux distribution with the lead elements when compared to the tail elements. Flux is a critical design parameter that determines the membrane area required to produce a target permeate flow rate (Veerapaneni et al., 2007). A higher design flux can lower the capital cost because fewer membrane elements are required. However, higher flux can also lead to higher fouling rates and more frequent cleaning intervals, which ultimately result in increased operating costs. Because energy consumption contributes significantly to the cost of desalinated water, an optimum flux must be balanced between capital and operating costs. Studies have shown that reduced capital cost due to higher flux rates does not necessarily lower treated water costs (Veerapaneni et al., 2007).

Another innovative design to reduce the pressure drop involved the use of a pressure vessel with a center port design (van Paassen et al., 2005). In this configuration, feed water enters the pressure vessel through two feed ports on each end of the pressure vessel in the first stage. The concentrate is collected through a middle port and flows to the middle port of a pressure vessel in the second stage. Thus, the flow path is reduced by half. In the center port design configuration, although the membrane unit has eight elements per pressure vessel, the flow path length is reduced to four elements per stage. Utilization of the center port pressure vessel results in lower feed pressure because of a lower pressure drop. A 15% reduction in the feed pressure has been reported from using the center port design rather than a conventional side port design (Wilf and Hudkins, 2010). The disadvantage of the center port design is the concern of scaling due to excessive concentration polarization. Thus, pilot testing is required before the implementation of the center port design to determine the influence of varying water quality on feed water recovery.

Optimization of energy consumption for RO treating high-salinity feed water has also been performed using a two-stage hybrid system with concentrate staging (Veerapaneni et al., 2005). The first stage consists of high-rejection brackish water membrane elements or high-permeability seawater membrane elements. The second stage consists of standard seawater elements. Using a two-stage system with brackish/low-pressure seawater membranes in the first stage requires lower feed pressure requirements because of lower membrane resistance (Veerapaneni, 2007). As most of the permeate is produced in the first stage by the use of high-permeability membranes, the pressure of only a small fraction of the remaining flow is boosted, resulting in significant energy savings. To reduce energy consumption, a two-pass nanofiltration system has been used by the Long Beach Water Department. Energy consumption was reduced by more than 5% when brackish water RO elements were used in combination with seawater RO elements. More than a 2% reduction in energy consumption was reported when two-pass nanofiltration was used (Long, 2008).

B.5.3.2 High-Efficiency Pumping

As discussed earlier, a major part of energy consumption is due to feed water pumping requirements. Because it is difficult to scale up all the process components from pilot-scale to full-scale applications, scale-up of pumps across a range of flows is a challenge. To achieve the highest possible efficiency, a typical pump would require the specific speed to be within a specified range for optimal efficiency (Veerapaneni, 2007). The use of high-speed and high-flow pumps at lower total dynamic head would result in optimal speed for highest efficiency. For large RO plants, the flow can be increased by centralized feed pumps that feed either larger skids or several smaller skids (Wilf and Bartels, 2005). Models of water-lubricated axial-piston pumps

(APP) are claimed to have high mechanical reliability and high efficiency in delivering pressures in the range needed for high-salinity feed water RO applications (MWH, 2007). To accommodate variability of feed pressure with time (due to salinity and temperature fluctuations), without the necessity to throttle high-pressure pumps or energy recovery devices, a VFD is incorporated into the electric motor unit that drives the high-pressure pump (Wilf and Bartels, 2005).

Numerous factors contribute to inefficient pumping. Performing a pump test and analyzing the test curves will help in determining the course of actions that can be taken to improve efficiency (Brandt et al., 2010; Kaya et al., 2008). Some common improvements include development of an optimum pump operational plan based on pump performance characteristics and system head requirements, replacement of pumps with energy-efficient pumps, drives, and motors, replacement of worn-out pump components, replacement of worn-out valves, trimming pump impellers, and adding VFDs.

The pump manufacturer's O&M manual provides maintenance intervals, guidelines, and procedures for pumping equipment. Pump components such as bearings, wearing rings, impellers, and mechanical seals must be checked and replaced as recommended in the O&M manual. Factory-preset clearances and tolerances must be observed and maintained. Worn-out or misaligned components affect pump performance and efficiency. Restoring pump clearances, repairing worn impeller and casing water passages, and applying new coatings to pump casing volutes and impellers has been proven to reduce water frictional losses (Brandt et al., 2010; Kaya et al., 2008). Coatings, such as Fluiglide, have recently been developed to reduce energy consumption of pumps (Corrocoat, 2011). Fluiglide is an advanced coating system that increases the overall efficiency levels of pumps and provides an effective corrosion barrier, preventing early fall-off in performance due to nodular growth and surface corrosion. The application of Fluiglide coatings to surfaces reduces the roughness amplitude, thereby reducing frictional losses.

For motors, by increasing the cross section of the copper conductors that are used in the motor winding, the primary I^2R losses can be decreased (Kaya et al., 2008). Iron core loss with the decrease of flux density can be limited by increasing the neck of the stator core (Kaya et al., 2008). These losses can also be further decreased by decreasing the thickness of the panels and using good-quality alloys (Kaya et al., 2008). In one study at a plant, existing pump efficiencies were 46–55%. After low–efficiency pumps were replaced with high-efficiency pumps, the pump efficiency was 60–71% (Kaya et al., 2008).

Pumping efficiency can also be improved by selection of the correct motor, which would include matching the horsepower output rating to the load, matching the motor utilization voltage to the provided systems voltage, matching the speed and torque rating of the motor and drive to the requirements of load speed and torque, and matching motor and drive requirements, including using inverter-rated motors with VFDs (Kaya et al., 2008). For applications involving variable flow, where the frictional pipe and valve losses are significant compared to the static head requirement, VFDs should be considered, especially if throttle valves, pressure control valves, or bypass valves are used in the system.

Electrical distribution and power quality issues should be looked at, including voltage problems (outages, sags, swells, overvoltage, undervoltage, phase voltage unbalance, transients, and harmonics), power factor, and electromagnetic interference (Kaya et al., 2008). These items may reduce motor efficiency and damage equipment in some severe cases. There are many potential solutions to these problems, including reduced-voltage starters (soft starters), surge arresters and surge protective devices (previously identified as transient voltage surge suppressors), VFDs, line reactors (input and output), filters, isolation transformers, and uninterruptable power supplies (Kaya et al., 2008).

B.5.3.3 Energy Recovery

Recovery of energy is crucial in making desalination of high salinity water economically feasible. Energy consumption for RO desalination processes can be reduced by using ERDs. The energy of the RO concentrate can be recovered by passing the concentrate stream through ERDs. The fraction of power recovered by the ERD depends on the type and efficiency of the equipment used. Four broad categories of ERDs are available, as follows:

- Pelton wheel turbine (PWT)
- reverse-running turbine pump (RRTP)
- turbo-booster pump (TBP)
- pressure or work exchanger (PWE) systems

The PWT, RRTP, and TBP are centrifugal types, whereas the PWE systems are isobaric. The centrifugal ERDs are limited in capacity and are usually optimized for narrow flow and pressure operating conditions (Stover, 2007). Isobaric ERDs achieve higher efficiency than centrifugal ERDs. Descriptions of each system are presented in the following.

Pelton Wheel Turbine (PWT): In a PWT, the RO concentrate stream is guided through a nozzle and made to impinge on turbine blades, which are of bucket shape (Stover, 2004). Pressurized water ejected through one or more nozzles is directed against a series of spoon-shaped buckets mounted around the edge of a wheel. Each bucket reverses the flow of water, leaving it with diminished energy, and the resulting impulse spins the turbine. The buckets are mounted in pairs to keep the forces on the wheel balanced as well as to ensure smooth, efficient momentum transfer from the fluid jet to the wheel. The wheel is mounted on the high-pressure pump shaft, which together with a motor drives the pump that pressurizes the RO system. Thus, the energy content of the high-pressure concentrate stream is usefully utilized to recover the energy. A Pelton wheel can be mechanically coupled directly to the RO feed water pump's shaft to reduce the work needed by the pump's motor. Pelton wheel turbines have few moving parts, are easy to maintain, and generally have high reliability (MWH, 2007). Efficiency of commercial Pelton wheels can reach 90%. The concentrate stream exiting the Pelton wheel is at atmospheric pressure and has to be able to freely flow to the discharge, or has to be pumped.

Reverse-Running Turbine Pump (RRTP): Two basic categories of the RRTP exist. The first category is a mechanically coupled type and the second is a hydroelectric submersible generator (MWH, 2007). A RRTP can be mechanically connected to the RO feed pressure pump and motor's shaft to allow unlading of the motor's work, with a resulting reduction in the horsepower required to drive the membrane pump. The submersible generator is a small-scale version of a hydroelectric plant. Induction generator and turbine pump impeller stages are installed inside a section of pipe, where a high-pressure RO concentrate stream flows through and rotates the RRTP and generator to produce electricity. Electricity produced by the submersible generator is then fed to a generator control and protection panel. The electricity generated can be used for operation of the RO plant or can be exported to a local electricity grid. The RRTP is not suitable for low flow range because of poor efficiency (Mirza, 2008).

The overall efficiency of the mechanically coupled RRTP is in the 75% to 85% range. For the submersible generator type, the overall efficiency is in the 62% to 75% range. The RRTP devices can operate with a liquid backpressure and do not need the discharge from the device to free-fall to a sump or chamber. The RRTP device can consume more power when system conditions are changed. These devices were found to be difficult to use and quickly fell out of favor (Mirza, 2008).

Turbo-Booster Pump (TBP): The turbo-booster has a Francis wheel turbine coupled to a single-stage pump by a shaft. The TBP is a free-running pump and turbine combination. A high-pressure RO concentrate stream is passed through the turbine end of the device, which rotates the pump shaft and provides energy needed for the pump to boost the pressure of the feed water RO stream (Lozier et al., 1989). Thus, the energy required for the high-pressure RO feed pump is reduced. The TBP is a rotary machine with only a few moving parts and does not require external lubrication. It has no electrical or pneumatic components. Hence, the TBP requires low maintenance. It is free to operate over a wide range of speeds and is not limited to the pump speed (Oklejas et al., 2005).

The device is relatively compact in size and has low weight compared to other ERDs. Because the TBP can operate with back pressure, the discharge stream from the device can be pressurized and transferred without repumping. The efficiency of the TBP ranges from 55% to 60%. The TBP's recovery of energy is affected by changes in the RO process flow rates caused by water temperature and feed water recovery changes. The TBP is typically used in smaller-capacity RO installations (MWH, 2007).

Pressure or Work Exchanger (PWE) Systems: The pressure or work exchanger (PWE) is a positive-displacement-type ERD. The PWE transfers the hydraulic energy of the pressurized RO concentrate stream to the RO feed water stream (Stover, 2007; Geisler et al., 1999). PWE systems can be categorized into two types; those that provide a physical barrier (piston) between the RO concentrate stream and feed side of the system, such as dual work exchanger energy recovery (DWEER), and those without a physical barrier, such as the pressure exchanger (PX) (Cameron and Clemente, 2008). A schematic of the DWEER installation is available from Flowserve Inc. (Flowserve, 2011). A typical process flow train of DWEER pressure exchangers installed in a seawater desalination plant is shown in Figure B.10. The system is based on moving pistons in cylinders. The high-pressure RO concentrate stream is directed to a work exchanger filled with low-pressure RO feed water. The system pressurizes the feed water to brine pressure. Critical elements of the system include moving parts and valves. Although the piston and cylinder arrangement is well suited for a wide range of water viscosities and densities, the system requires a large footprint (Mirza, 2008).

The working principle of a pressure exchanger (PX) is provided by ERI Inc. (ERI, 2011). The PX device is a positive displacement isobaric energy recovery device. The device consists of a ceramic cartridge with a feed water end cover, a rotor, a sleeve, and a concentrate end cover (Cameron and Clemente, 2008). The rotor contains axial ducts arranged in a circle around a center tension rod. The PX device directly pressurizes the feed water. Therefore, no transformational losses occur in the device and hence it has higher efficiency. The feed water and concentrate stream come into direct contact in the rotor, but mixing between the streams is limited by a water barrier that exists in the duct.

Although individual PXs have limited flow rates, higher capacity can be achieved by arranging several devices in series. Recently, the world's largest rotary isobaric energy recovery device for high-salinity RO applications was installed in Maspalomas, Spain (Stover, 2007). The device

(Titan 1200) can handle five times the flow of a standard PX (PX-180 and PX-220 from ERI Inc). The PX device has also been proven to lower costs for brackish water applications (MacHarg and McClellan, 2004). The PX device has been associated with very high noise levels requiring a sound abatement enclosure (Mirza, 2008). Another disadvantage of the PX device is the degree of mixing between the feed water and the concentrate stream. A mixing feed salinity between 1.5% and 3.0% results in an increase of required feed pressure for the RO system (Stover, 2004).

A comparison of the various energy recovery devices described is shown in Table B.3. Although all the described devices are proven technologies, certain devices (such as PWE) have higher efficiency than the other devices mentioned. Because PWE has the highest efficiency among the other ERDs, numerous RO desalination plants use this technology for energy recovery. Pressure exchangers from ERI alone have been installed in more than 400 RO installations worldwide (Cameron and Clemente, 2008). The Ghalilah SWRO plant utilizes a PX device from ERI to save energy and reduce power consumption (Stover et al., 2005). The PX device efficiency exceeds 95% at this location, with low mixing and low noise. Some of the other PX installations are in the Caribbean, China, Middle East, and Singapore (Cameron and Clemente, 2008; Veerapaneni et al., 2007). The 5,678 m^3/h (36 MGD) SWRO plant in Tuas, Singapore is regarded as the world's most efficient full-scale plant (Kiang et al., 2005).

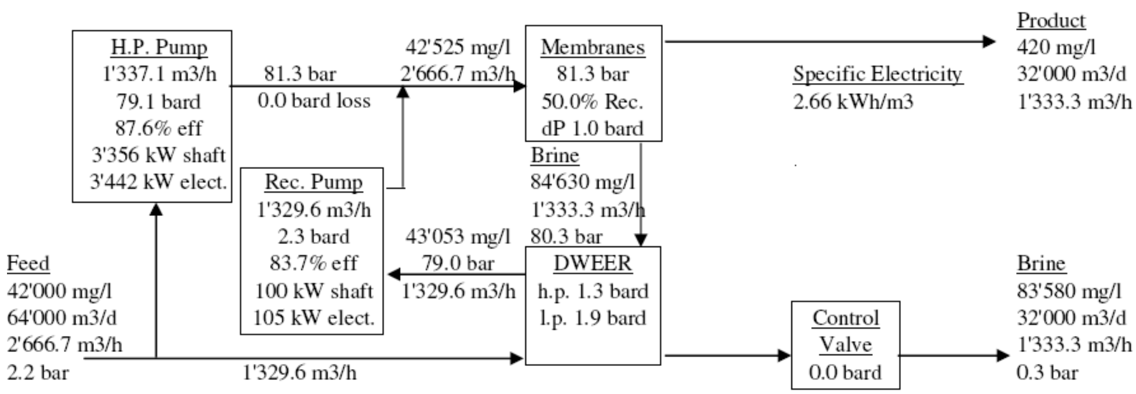

Figure B.10. Typical process schematic of Calder DWEER pressure exchanger installed for seawater desalination.

Table B.3. Comparison of Energy Recovery Devices

Criterion/Device	Pelton Wheel Turbine (PWT)	Reverse-Running Turbine Pump (RRTP)	Turbo-Booster Pump (TBP)	Pressure or Work Exchanger (PWE)
Commercial availability	Yes	Yes	Yes	Yes
Proven technology for high-salinity applications	Yes	Yes	Yes	Yes
Potential energy savings (relative to each other)	Medium	Low to medium	Low	High
Capital cost (relative to each other)	Low to medium	Low to medium	Low	High
O&M cost (relative to each other)	Low	Low	Low	High for multiple valve systems Medium for multiported single-valve systems Low to medium for valveless multiport rotating cylinder system.
Efficiency (relative to each other)	Medium (84% to 90%)	Mechanically coupled RRTP = low to medium (75% to 85%) Submersible generator = low to medium (62% to 75%)	Low (55% to 60%)	High (95% to 97%)
Efficiency curve	Varies	Varies	Slopes downward at low flows	Flat
Efficiency under changing process conditions (effect of deviation from design point)	Efficiency decreases when flow rate changes from design point	Efficiency decreases when flow rate changes from design point	Efficiency decreases when flow rate changes from design point.	Moderate impact on performance, efficiency maintained over a broad operating range

Source: **MWH, 2007**

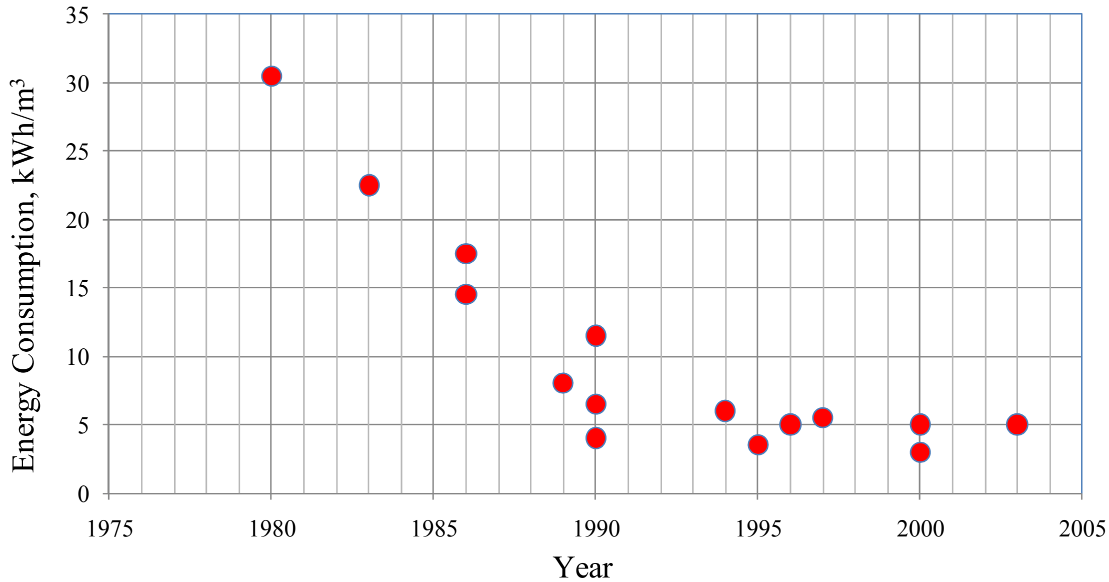

Figure B.11. Energy requirement for seawater RO processes (Chang et al., 2008).

B.5.3.4 Advanced Membrane Material

Significant improvements in the salt rejection capacity and permeability of the RO membranes for treating high-salinity feed waters have been achieved in recent years. The specific energy consumption for seawater RO membranes since the early 1980s is plotted in Figure B.11. In 1980, seawater RO systems consumed more than 30 kWh/m^3 (113 kWh per 1000 gal) of water produced. Today, seawater RO systems consume on average only 3.5 kWh/m^3 (13 kWh per 1000 gal) (Chang et al., 2008). New-generation RO membranes offer reduced feed pressure requirements while maintaining rejection. Research is also being performed to minimize energy losses and improve flow distribution within the membrane element to maximize the use of membrane area. Today's high-productivity membrane elements are designed with two features that result in more fresh water per membrane element: higher surface area and denser membrane packing (Voutchkov, 2007).

Nanocomposite membranes: New focus is also on developing new-generation RO membranes (Hoek and Ghosh, 2009). New-generation thin film composite RO membranes are made by combining zeolite nanoparticles dispersed within a traditional polyamide thin film (Jeong et al., 2007). An illustration of the nanocomposite membrane structure is available t NanoH2O's website (NanoH20, 2011). The zeolite nanoparticles are dispersed in one or more of the monomer solutions used to create the membrane by an interfacial polymerization process. Incorporation of zeolite nanoparticles into the polymer matrix of seawater RO membranes has resulted in enhanced flux more than double that of a commercial product with 99.7% salt rejection. Incorporation of nanocomposite-based RO membranes has been reported to result in 20% lower energy consumption.

Nanotube membranes: The use of carbon nanotubes has also been shown to consume lower energy when compared to conventional seawater water RO desalination (Holt and Park, 2006; Sholl and Johnson, 2006; Truskett, 2003). Water and ions are transported through membranes formed from carbon nanotubes that range in diameter from 6 to 11 Å. Membranes incorporating carbon nanotubes have been found to be promising candidates for water desalination using RO, as the size and uniformity of the tubes can achieve the desired salt rejection (Corry, 2008). A 10-fold permeability increase is expected using a carbon nanotube RO membrane, resulting in 30–50% energy savings. Simulations have shown that boron nitride nanotubes have superior water flow properties compared to carbon nanotubes and also achieve 100% salt rejection (Hilder et al., 2009). The use of a nanotube radius of 4.14 Å can functionalize the membrane to become cation-selective. When a nanotube radius of 5.52 Å is used, the membrane can be functionalized to become anion-selective (Hilder et al., 2009).

Biomimetic membranes: New developments have also occurred in the use of biomimetic membranes for desalination (Bowen, 2006). Biomimetic membranes are designed to mimic the highly selective transport of water across cell membranes. Natural proteins known as aquaporins are used to regulate the flow of water, providing increased permeability and high solute rejection. An illustration of aquaporins used in making desalination membranes is available at AquaZ Inc.'s Web site (AquaZ, 2011). Aquaporins act as water channels that selectively allow water molecules to pass through, whereas the transport of ions is restricted by an electrostatic tuning mechanism in the channel interior. The result leads to only water molecules being transported through the aquaporin channels and charged ions being rejected (Sui et al., 2001). Aquaporin membranes are considered to be 100 times more permeable than commercial RO membranes. Highly permeable and selective membranes based on the incorporation of the functional water channel protein Aquaporin Z into a novel triblock copolymer have been shown to have significantly higher water transport than existing RO membranes (Kumar et al., 2007). A particular difficulty to be overcome with biomimetic membranes is that they need to withstand high operating pressures, similarly to polymeric membranes.

The development of novel membrane materials with enhanced water passage and salt rejection can lead to the development of RO membranes with substantially lower feed pressure requirements and lower energy consumption. The nanocomposite membranes based on the incorporation of zeolite nanoparticles into the polyamide matrix have been tested at the pilot scale. Both nanocomposite and aquaporin membranes have been manufactured as spiral-wound elements. Commercial availability of nanocomposite membranes is expected by 2010. The development of nanotube membranes is still at the fundamental level and it will take several years before the product is feasible for commercialization.

B.5.3.5 Application of Innovative Technologies

New technologies utilizing the principles of separation with membranes and electric fields have been introduced in recent years. These technologies have the potential to offer a substantial reduction in energy consumption for desalination. Some of these technologies are discussed below.

Forward osmosis: In the forward osmosis (FO) process, instead of using hydraulic pressure, as in conventional RO desalination processes, a concentrated draw solution is used to generate high osmotic pressure, which pulls the water across a semipermeable membrane from the feed solution (McCutcheon et al., 2005). The draw solutes are then separated from the diluted draw solution to recycle the solutes and to produce clean product water. A schematic of the FO process is shown in Figure B.12. A mixture of ammonia and carbon dioxide gas has been used as the predominant draw solution (McCutcheon et al., 2006). When ammonia and carbon dioxide are mixed in the right proportion, a solution with high osmotic pressure can be formed. This solution has been used for drawing water saline feeds. The advantage of using such a mixture for a draw solution is that it has been shown to have the ability to be regenerated, when heated, and reused for the forward osmosis process. Thus, the FO process can be considered as a combination of membrane and thermal processes.

The energy utilized by the FO process has been reported to be approximately 25 to 45% of the thermal energy needed for multieffect distillation. FO has the added capability for using heat at a much lower or higher temperature than multieffect distillation processes. The FO process can use heat as low as 40 °C and as high as 200 to 250 °C. It has been reported that the electrical consumption of the FO process is substantially lower than that of existing desalination technologies. Specific energy consumption of less than 0.25 kWh/m^3 has been reported for the membrane part of FO (Cath et al., 2009). The process also has the advantage of lesser fouling propensity than for the reverse osmosis process. The lesser fouling and scaling propensity is attributed to the absence of hydraulic pressure and application of novel thin film composite membranes (Mi and Elimelech, 2010).

In an innovative approach to reducing energy consumption, FO has been used in combination with RO to form a hybrid process (Cath et al., 2009). A schematic of the hybrid process is shown in Figure B.13. In this novel approach, recycled water (tertiary treated effluent) is passed through a FO system, with seawater being used as the draw solution. The seawater is diluted by the recycled water within the FO process. The diluted seawater is then passed through a RO system where the feed pressure requirement is lowered by dilution of the seawater; hence lower energy consumption is obtained for the seawater desalination process. The concentrate (brine) from the RO process is further treated through a second stage FO process and the final seawater brine is discharged to the ocean. By using a combination of FO and RO, seawater desalination is performed with lower energy consumption and the recycled water is simultaneously treated through two physical barriers (FO and RO) (Cath et al., 2009).

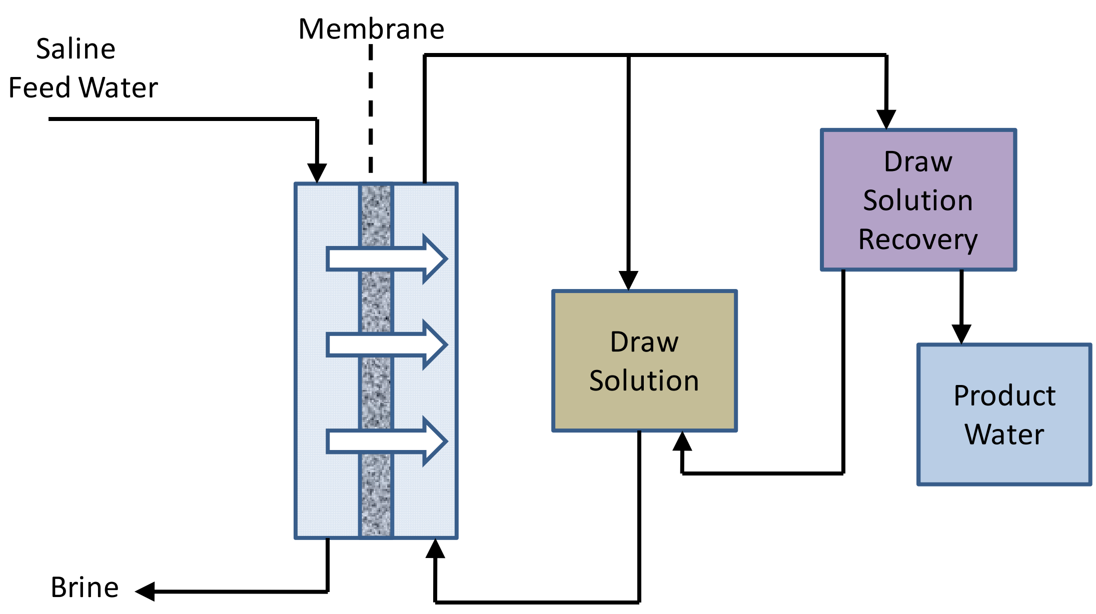

Figure B.12. Illustration of FO process.

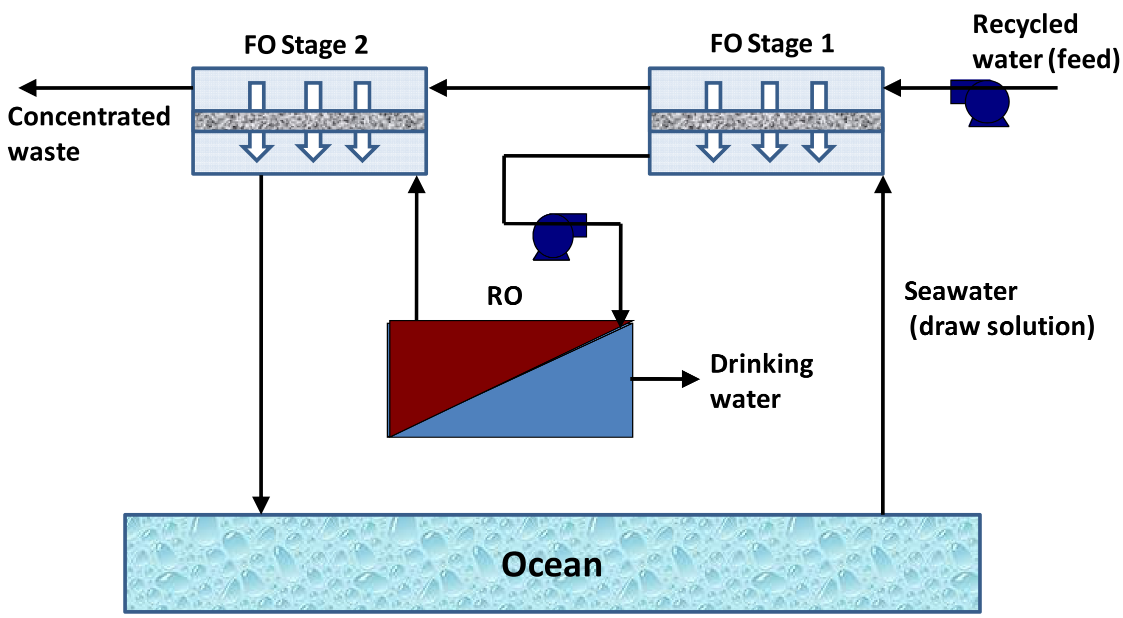

Figure B.13. Schematic of novel hybrid FO-RO process for water augmentation.

Ion concentration polarization: Ion concentration polarization has been utilized to desalinate seawater using an energy-efficient process (Kim et al., 2010). A schematic of ion concentration polarization is available from MIT (MIT, 2011). In this process, micro- and nanofluidics in combination with ion concentration polarization are used to desalinate seawater. Ion concentration polarization is a fundamental transport mechanism that occurs when an ionic current is passed through an ion-selective membrane. But, in the newly developed process, no membranes are utilized. An electrical potential is used to create a repulsion zone that acts a membrane separating charged ions, bacteria, viruses, and microbes from seawater flowing through a 500 × 100 µm microchannel. Water flows through the microchannel tangential to a nanochannel where the voltage is applied. The resulting force creates a repulsion zone and the stream splits into two smaller channels at a nanojunction. The two streams created are the treated water and concentrate. More than 99% salt rejection and 50% recovery have been reported using this process. The ion concentration polarization process has been reported to consume approximately 3.5 kWh/m^3 of energy (Kim et al., 2010). The process is best suited for small- to medium-scale systems, with the possibility of battery-powered operation.

Capacitive deionization: Although capacitive deionization (CDI) technology is not a recent discovery, several challenges exist for the identification of an optimum material for electrode manufacture (Farmar et al., 1997). The CDI technology was developed as a nonpolluting, energy-efficient, and cost-effective alternative to desalination technologies such as reverse osmosis and electrodialysis (Welgemoed, 2005). A schematic of CDI is shown in Figure B.14. In this technology, a saline solution flows through an unrestricted capacitor-type module consisting of numerous pairs of high-surface-area electrodes. The electrode material, typically carbon aerogel, has a high specific surface area (400–1100 m^2/g) and a very low electrical resistivity (less than 40 mΩ.cm). Anions and cations in solution are electrosorbed by the electric field upon polarization of each electrode pair by a DC power source. After the adsorption of ions, the saturated electrode undergoes regeneration by desorption of the adsorbed ions under zero electrical potential or reverse electric field (Seo et al., 2010). Thus, the adsorption ability of the electrode is the key parameter for the performance of CDI technology.

When a potential is applied to CDI electrodes, counterions are attracted onto the electrode surface; simultaneously co-ions are expelled from the counterelectrode (Kim and Choi, 2010). This leads to a higher energy consumption and a lower operation efficiency because of the mobility of unwanted ions. Recently, modification of capacitive deionization has resulted in higher recovery and efficiency in a membrane–CDI (MCDI) technology (Kim and Choi, 2010; Biesheuvel and van der Wal, 2010). In the MCDI technology, ion-exchange membranes are used for selective transport of ions to the electrodes. This has resulted in higher efficiency and better energy consumption.

Energy consumption as low as 0.1 kWh/m^3 has been reported in using this technology for brackish water treatment (Welgemoed, 2005). For seawater desalination, energy consumption of 1.8 kWh/m^3 using a combination of ED and continuous electrodeionization (CEDI) was recently reported (Siemens, 2011). In the hybrid approach, an electric field is used to draw sodium and chloride ions across ion-exchange membranes. As the water itself does not pass through the membranes, the process can be operated at lower pressure and lower energy consumption. Seawater is pretreated with a self-cleaning disk filter, followed by UF modules. The ED–CEDI system consists of ED units arranged in series to remove high concentrations of salt, followed by CEDI units arranged in parallel to remove smaller amounts of salt. Besides energy savings, other advantages of the ED–CEDI technology include lower vibration and noise levels, improved safety, and minimal pre- and post-treatment (Siemens, 2011).

Voltea process: The Voltea process combines ED and CDI (Voltea, 2011). An illustration of the process is available from Voltea Inc. (Voltea, 2011). A three-step process is utilized, with the water flowing in a cell containing positively and negatively charged electrodes. The electrode surfaces are covered with ion-selective membranes, so ions in the feed water are attracted to the oppositely charged electrodes, pass through the membrane, and finally accumulate within the porous electrode structure. Up to 99% salt rejection has been reported using the process. When the electrodes become saturated, their polarity is reversed. The process is estimated to use less than 1.0 kWh/m^3 when removing 3,000 mg/L of salt from water. The system can operate at 90% recovery and can be equipped with an energy recovery system to reuse the energy stored in ions on the electrodes.

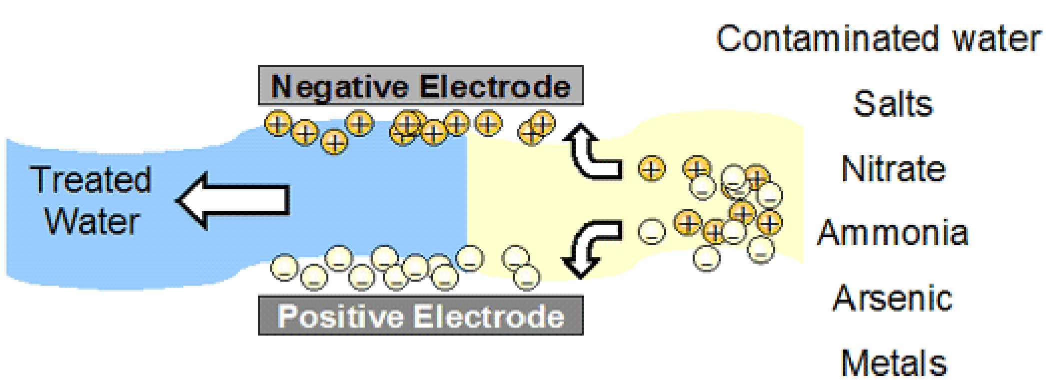

Figure B.14. Illustration of CDI process (NETL, 2011).

Table B.4. Specific Energy Consumption of CCD System While Desalinating Seawater with 35,000 mg/L of TDS (Desalitech, 2011)

Flux	kWh/m^3 at indicated recovery			
GFD	40%	45%	50%	55%
14.5	1.91	1.97	2.02	2.09
13.5	1.86	1.92	1.98	2.05
12.3	1.80	1.86	1.91	1.99
11.1	1.75	1.80	1.86	1.93
9.8	1.70	1.75	1.80	1.88
8.6	1.65	1.70	1.75	1.82

Saltworks process: The Saltworks process involves a thermo-ionic system that can operate on waters with feed water TDS range of 20,000 to 80,000 mg/L (Saltworks, 2011). A schematic of the thermo-ionic system is available from Saltworks Inc. (Saltworks, 2011). The thermo-ionic process uses ion-exchange membranes in an arrangement resembling an EDR system. However, in the thermo-ionic system, energy contained within a concentrated salt solution, rather than external power, is used for the desalination process. The hypersaline solution is produced in a special evaporative unit that operates at a temperature 10 °C warmer than the ambient wet bulb temperature (Saltworks, 2011). The system utilizes a proprietary ion-exchange membrane. Besides solar heat or other low-grade heat sources for the evaporative unit, the only external energy requirement is the electricity needed to operate the circulation pumps and fans. The remaining energy for the desalination process is produced by the hypersaline solution. A commercial unit for operation and testing is expected in 2012 (Saltworks, 2011).

Closed-circuit desalination: Closed-circuit desalination (CCD) is another proprietary technology based on a hydrostatic process at the core of the water treatment system that reduces desalination costs by more than 20% (Desalitech, 2011). The CCD process lowers the feed pressure required for desalination and hence reduces energy consumption. Its performance is being proven in several currently operating commercial installations using the same membranes and pumps as in conventional RO, but configured in a new way. The CCD process recycles concentrate until a desired recovery level is achieved, replacing brine with fresh feed without disrupting continuous permeate production and with practically no energy loss. The process has the advantage of 30–40% reduced energy consumption, reduction of equipment costs, and maximum feed water recovery (Desalitech, 2011). Energy consumption of the CCD process at various recoveries and flux is shown in Table B.4. Compared to a RO system with the same number of elements, a permeate flux of 8 GFD and a recovery rate of 45% while consuming over 2.5 kWh/m^3, the CCD system has an energy consumption of 1.7 kWh/m^3.

B.5.4 Energy Minimization for Advanced Water Treatment Processes

When RO is used for AWT and reuse, the same strategy for energy minimization as described in the previous section can be used. When low-pressure membranes are used for pretreatment, the energy efficiency is determined largely by the membrane permeability and the backwashing frequency (Chang et al., 2008). More frequent backwashing decreases the energy efficiency of the membrane system. Backwashing frequency and duration are optimized through careful selection of pretreatment practices and proper membrane selection (Crozes et al., 2003; Jacangelo et al., 1992).

When MBR systems are used, the submerged configuration reduces energy consumption as well as vacuum pressure (Chang et al., 2008). When a MBR system was operated with vacuum at negative 1 to negative 10 psi, the energy consumption was estimated to be 327,000 kWh per year (NYSERDA, 2004). In another study (Zhang et al., 2003), a transverse flow of water was used instead of a cross-flow mode to enhance filtration capacity and reduce fouling. A two-loop connection between the bioreactor and the membrane module was used to allow for low recirculating flow between the membrane and bioreactor. Additionally, the design required no cooling device. The investigators found that the membrane module consumed the majority of the energy.

For ozonation systems, understanding the electricity rate structure, installing energy monitoring devices, analyzing loads and energy consumption, and assessing process modifications can optimize energy consumption (Chang et al., 2008). Energy optimization opportunities can be classified into three categories (DeMers et al., 1996): Type 1—operations and maintenance activities; Type 2—operation and maintenance evaluation prior to implementing process changes; and Type 3—design change or system modifications. Examples of Type 1 include calibrating gas flow meters, ozone residual monitors, and power meters; inspecting and cleaning ozone generator dielectrics; and adjusting ozone dosage to match diurnal changes in ozone demand. Examples of Type 2 include extending a desiccant dryer cycle, decreasing system operating pressure, and utilizing an existing refrigerant dryer bypass. Examples of Type 3 include installing smaller compressors, bypassing/modifying a refrigerant dryer or chiller, modifying ozone residual sampling, and monitoring to accurately detect residual inside contactor.

Although UV is considered post-treatment, a dose control strategy is considered to be the most effective way to reduce energy consumption (Chang et al., 2008). This type of strategy alters the number of lamps in use or the lamp power based on the flow rate, level of disinfection required (dose), and water quality (such as UV transmittance) (USEPA, 2003). Settings on the transformer can be made to allow the lamps to be dimmed to 60% of the high-intensity setting to adjust for low flow or good influent water quality (EPRI, 1994). Low-pressure–low-intensity lamps operate optimally at 40 °C and a variation from this temperature can reduce lamp intensity by 1-3% per degree (NYSERDA, 2004). Lamp energy efficiency will also be affected by fouling of the lamp housing. Fouling reduces the amount of UV light, requiring that the lamps be operated at a higher intensity to maintain the same dose (Chang et al., 2008). Fouling is a function of the influent water quality, lamp configuration, and system hydraulic characteristics (Job et al., 1995; Mackey et al., 2001; NYSERDA, 2004). Hydraulic conditions and UV lamp configuration can also affect energy efficiency. Different possible UV lamp configurations are shown in Figure B.15. A linear configuration is considered to be the most energy-efficient for UV lamps to avoid UV emission losses that are due to self-absorption, reflection, or refraction (NYSERDA, 2004).

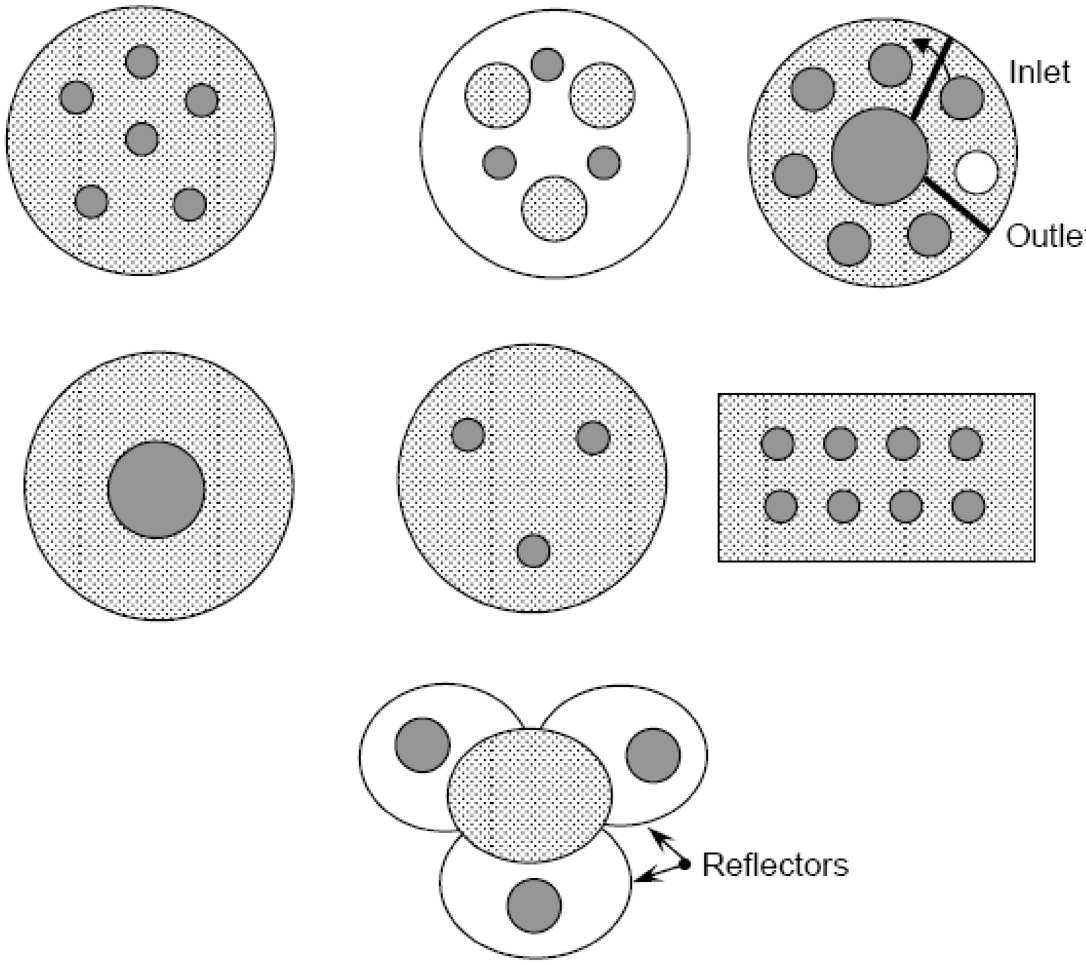

Figure B.15. Possible lamp configuration in flow-through UV disinfection systems (NYSERDA, 2004).
Note: **The solid gray circles represent the UV lamps. Dotted circles represent the water-filled areas.**

Appendix C

Renewable Energy Resources and Greenhouse Gas Emissions

C.1 History of Renewable Energy Sources

Solar radiation is considered to be one of the oldest forms of energy. The oldest large-scale application of solar energy was the burning of the Roman fleet in the bay of Syracuse by Archimedes, the Greek mathematician and philosopher, who used flat mirrors to focus the sun's rays to a common point on the ships (Belessiotis and Delyannis, 2000). The first solar collector was reported to be a solar bonfire in Europe in 1876. In Western Europe, many scientists experimented with natural forces to convert their potential energy into a usable form for direct utilization. The first solar pump was invented by Solomon de Cauz in 1615 A.D. During the 18th century, G. L. L. Buffon, a French naturalist, experimented with various reflecting devices to utilize solar energy. The French chemist L. Lavoisier constructed the first solar furnace in 1774. The basis of solar cells was discovered in France by A.C. Becqerel in 1839. He explained the photoelectric effect from his experiments. In the middle of the 19th century, the real solar energy revolution had begun. In Europe and the United States, many inventors experimented with solar machines, which were used to concentrate solar radiation. Their use was mainly to pump water for irrigation. From 1866 to 1956, small solar installations were constructed and put into operation. In recent years, solar electricity generating stations have been constructed continuously. Their primary purpose is the production of electricity and/or processing water for industrial use.

C.1.2 Wind Energy

Wind energy was used more than 5,000 years ago in the Mediterranean region (Belessiotis and Delyannis, 2000). In the beginning, wind propulsion was used by sailing ships. Wind-powered ships were in operation until 100 years ago, when diesel engines replaced sails. Wind kinetic power was used to drive various windmills. Around 2000 B.C., windmills were in operation in the Aegean Archipelago and Crete. In Crete, windmills were mainly used for pumping water. In England, windmills were in operation from 1200 A.D. The vertical axis windmill originates from Persia during the first millennium B.C. The horizontal axis windmill has been reported to originate in France during 1105 A.D. During the 19th century, the American multiblade windmill came into widespread use. About 6 million multiblade windmills were in operation in the United States alone at the beginning of the 20th century. Wind energy development rapidly expanded around 1975, when wind turbines were commercialized. The new generation of wind turbines range from 500 kW to 2.0 MW for onshore applications and up to 6 MW for offshore applications.

C.1.3 Geothermal Energy

Geothermal energy has been used in places with water geysers for centuries. Around 1300 A.D., geothermal heat was employed for heating purposes in Iceland (Belessiotis and Delyannis, 2000). The Etruscans have been reported to have extracted boric acid from geothermal brines and other minerals to prepare enamels, with which they decorated their vases. Modern large-scale extraction of boric acid started around 1800 A.D. when the French scientist Francesco de Larderele used geothermal brine to extract large amounts of boric acid. Heat was generated in the plant by burning wood. By 1927 about eight commercial plants were built in the region of Monte Ceboli, extracting boric acid and other minerals from geothermal brines using geothermal steam. Geothermal steam was used in 1897 to fire a boiler to produce steam for a steam engine. Electricity was produced from geothermal steam for the first time in 1904. The first condensing turbine based on geothermal steam, with a capacity of 250 kW, was installed in 1912. In 1923, a 250-kW generator was installed to utilize the geothermal energy from geysers in California. By 1958, the first large-scale commercial power plant was put into operation in New Zealand with a capacity of 192 MW. During the first few decades of the 20th century, the capacity of installed geothermal energy power plants increased by 7% per year, and over the last few decades by 20% per year (Belessiotis and Delyannis, 2000).

C.2 Renewable Energy Technologies for Desalination and Water Reuse

C.2.1 Solar Thermal Energy

Thermal solar energy is considered to be one of the most promising sources of renewable energy. The intensity of solar radiation in various parts of the world depends on the season. The highest quantity of incoming solar energy is during the summer months. Out of the total incoming solar energy, 30% is reflected from the atmosphere, clouds, and the ground. The remaining 70% of incident energy is absorbed (Kiehl and Trenberth, 1997) and available for use as an energy supply. The annual average solar energy received in the United States is shown in . The highest solar radiation received is in the southwestern states of California, Arizona, Nevada, New Mexico, and Texas. Solar thermal energy can be used for the production of electricity or mechanical energy.

Solar thermal desalination processes are characterized as either direct or indirect processes. Direct processes have all parts integrated into one system, whereas indirect processes have heat coming from a separate solar collecting device, such as solar collectors or solar ponds. Examples of direct solar desalination processes are solar stills. Examples of indirect solar desalination processes are MED and MSF processes.

A new study has estimated that 25% of the world's electricity could come from CSP by the year 2050 (Landry, 2010). It is estimated that the United States will add nearly 12,000 MW of solar thermal energy by 2020. The majority of these solar plants are proposed for the southwestern United States where heat, sun, and flat landscapes are plentiful (Landry, 2010). The National Renewable Energy Laboratory has estimated that the majority of CSP electric generation capacity by 2050 will be located in the desert southwest of the United States. Most commercial CSP facilities use a system of curved mirrors to collect the sun's energy to heat a fluid flowing through tubes. The hot fluid is then used to boil water in a conventional steam-turbine generator to produce electricity. Similarly to conventional thermal power plants, CSPs use water cooling towers to release the heat into the atmosphere through an evaporation process (Landry, 2010). A detailed description of CSP using dish/Stirling systems is provided in the later sections. Technologies using solar thermal energy are described in the following subsections.

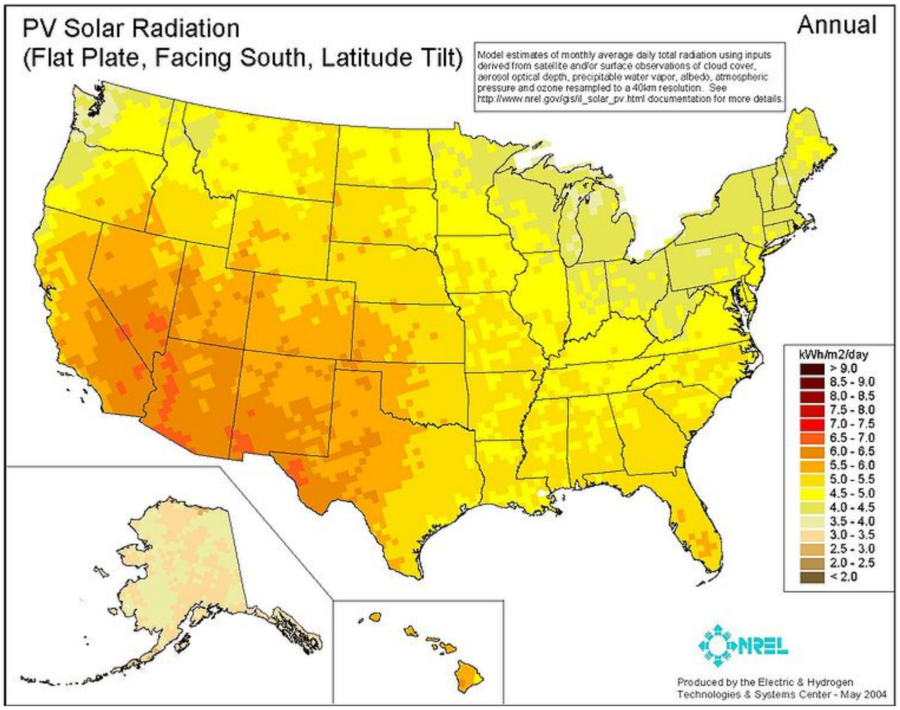

Figure C.1. U.S. annual average solar energy received by a latitude tilt photovoltaic cell (modeled) (NREL, 2004).

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C.2.1.1 Solar Stills

A solar still is a simple device that can be used to convert saline, brackish water into drinking water (Qiblawey and Banat, 2008). Solar stills are used for direct solar desalination, which is mainly suited for small production systems and regions where the freshwater demand is less than 7.9 m^3/h (0.05 MGD) (Rodriguez, 2002). The solar still consists of a transparent cover (glass or plastic) that encloses saline water. The principle of operation is evaporation and condensation. The solar still cover traps solar energy within the enclosure. The trapped solar energy heats up the saline water, causing evaporation and condensation on the inner surface of the sloped transparent cover. As the saline water is heated, its vapor pressure increases. The resultant water vapor is condensed on the underside of the roof cover and runs down into troughs, which collect the distillate. The distillate obtained is of high quality without any salts or organic and inorganic components.

The solar still requires frequent flushing. Flushing is performed to prevent salt precipitation. Design problems encountered with solar stills are brine depth, vapor tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape, and material (Eibling and Talbert, 1971). In practice, heat losses will occur through a still. Currently available state-of-the-art single-effect solar stills have an efficiency of approximately 30–40% (Qiblawey, 2008). The solar still of the basin type is the oldest method, and improvements in its design have been made to increase its efficiency (Naim et al., 2003). Modifications using passive methods include basin stills, wick stills, diffusion stills, stills integrated with greenhouses, and other configurations (Fath, 1998; Graeter et al., 2001; Malik et al., 1996).

C.2.1.2 Humidification–Dehumidification

A major drawback of the solar still is energy loss in the form of latent heat of condensation. To solve this problem, a humidification–dehumidification (HD) approach has been developed. Solar desalination based on the HD principle results in an increase in the overall efficiency of the desalination plant. The HD desalination process is considered a promising technique for small-capacity solar-driven desalination plants (Mathioulakis et al., 2007). The basic principle of the HD process is the evaporation of high-salinity water and condensation of water vapor from the humid air at ambient pressure. When circulating air comes in contact with hot saline water in the evaporator, a certain quantity of vapor is extracted by the air. Part of the vapor mixed with air may be recovered as a condensate by bringing the humid air in contact with a cooling surface in another exchanger, in which saline feed water is preheated by the latent heat of condensation. The HD process is based on the fact that air can be mixed with significant quantities of vapor. The vapor-carrying capability of air increases with temperature. Fresh water is produced by condensing out the water vapor, which results in dehumidification of the air. A significant advantage of the HD technology is that it provides a means of low-pressure, low-temperature desalination that can operate off of waste heat and is potentially very cost-competitive (Parekh et al., 2004).

To improve the performance of a HD unit, a multieffect humidification (MEH) system has also been developed (Muller-Holst et al., 1999). The MEH process is driven by solar energy, and fresh water production varies with seasonal changes. The principle of the MEH process is distillation under atmospheric conditions by an air loop saturated with water vapor. The air is circulated by natural or forced convection using fans.

C.2.1.3 Solar Thermal Membrane Distillation

As discussed earlier, MD is a thermally driven membrane process. It constitutes the most recent development in the field of thermal desalination processes. Solar energy can be used as the heat source for the MD process. The MD process takes place at atmospheric pressure and temperatures not exceeding 80 °C. For this reason, MD is a process with several advantages regarding integration into a thermally driven solar desalination system. Several studies have reported the use of MD with input heat supplied by solar energy and stand-alone MD systems powered by solar collectors (Bier and Plantikow, 1995; Hanemaaijer, 2004; Koschikowski et al., 2003). The MD process is promising, especially where low-temperature solar heat is available. When operating between the same top and bottom temperatures as MSF plants, MD with heat recovery can operate at performance ratios about the same as for commercial MSF plants, but with lower pumping power consumption. Also, MD systems are at least 40-fold more compact than other distillation desalination systems such as MSF (Mathioulakis et al., 2007).

C.2.1.4 Solar Ponds

Solar ponds conserve heat by reducing the heat losses that would occur if the less dense heated water were allowed to rise to the surface of the pond and lose energy to the atmosphere by convection and radiation (Kalogirou, 1997; Kalogirou, 2005). An illustration of a salinity gradient solar pond is shown in Figure C.2. The objective of the solar pond is to create a stagnant insulating zone in the upper part of the pond to contain the hot fluid in the lower section of the pond. In a solar pond there are three distinct zones. The upper zone is the surface zone and is a convecting zone (UCZ); it is of low salinity and is close to ambient temperature. The UCZ is typically 0.3 m thick, which is a result of wind-induced mixing and surface flushing. This zone is kept as thin as possible by using wave-suppressing surface meshes and placing windbreaks near the pond. The middle zone is the insulation zone and is a nonconvecting zone (NCZ). In the NCS, both salinity and temperature increase with depth. The vertical salt gradient in the NCZ inhibits convection and provides thermal insulation. The lower section of the pond is the storage zone and is the lower convecting zone (LCZ). In the LCZ, the salinity is high (typically 20% by weight) and the temperature is high (70–80 °C). Heat stored in the LCZ can be utilized to supply heat energy throughout the year.

In evaluation of solar ponds, several factors need to be considered. Because solar ponds are horizontal solar collectors, site location should be at low to moderate northern and southern latitudes (±40°). Another criterion for consideration of solar ponds is that the water table should be at least a few meters below the bottom of the pond to minimize heat losses, because the thermal conductivity of the soil increases greatly with moisture content. Other considerations are the selection of a liner and ensuring that the pond does not pollute the aquifers underneath it. Most solar ponds constructed today consist of a reinforced polymer material 0.75–1.25 mm in thickness. Continuous draining of hot water from the pond will lower the pond's storage capacity and effectiveness.

Solar ponds can be used to provide energy for various types of applications. Smaller ponds can be used for water heating, whereas larger ponds can be used to provide heat for various processes, electric power generation, and desalination. Solar ponds produce relatively low-grade, less than 100 °C, thermal energy and are considered well suited for supplying direct heat for thermal distillation processes (Qiblawey, 2008). Waste brine from membrane desalination plants can also be used as the salt source for the solar pond density gradient. Using desalination brine for solar ponds provides not only a preferable alternative to environmental disposal, but also a convenient and inexpensive source of solar pond salinity.

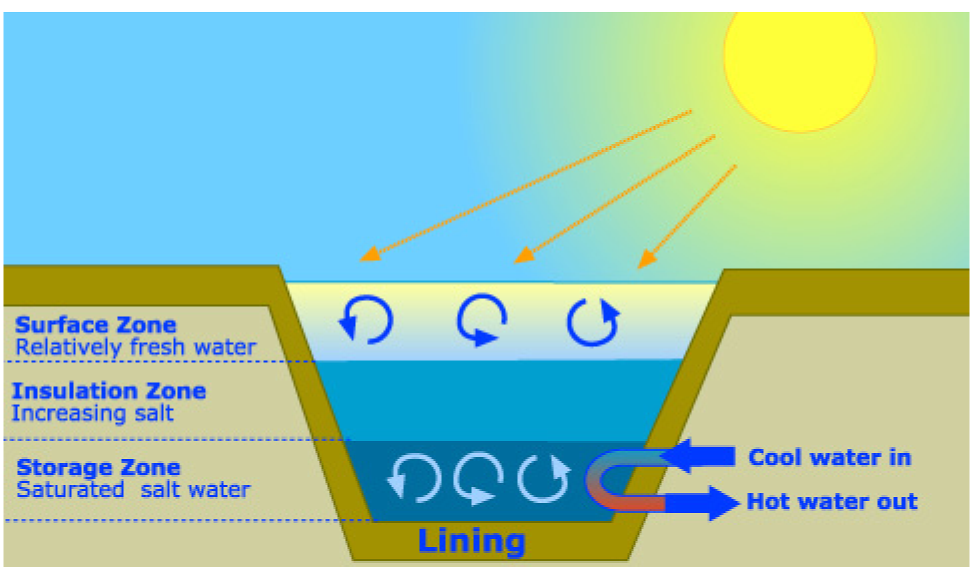
- 

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Figure C.2. Schematic of solar pond (Energy Education of Texas, 2011).

Electric power generation from solar ponds has been evaluated in Israel (Tabor, 1981). The analysis included a 1500-m^2 solar pond used to operate a 6-kW Rankine-cycle turbine–generator and a 7000-m^2 solar pond for producing 150 kW of peak power. Both the solar ponds were operated at about 90 °C. Solar ponds can also be coupled with desalination systems. The hot brine from the ponds can use a thermal source to evaporate the water to be desalted at low pressure in a MED evaporator (Kalagirou, 2005). Salinity gradient solar ponds have also been used in seawater and brackish water RO desalination (Lu et al., 2000) and used as a solution for brine disposal at inland ED plants (Matz and Feist, 1967), and with a multieffect multistage distillation system, a membrane distillation unit, and a brine concentrator and recovery system at El Paso, Texas for zero liquid discharge purposes (Lu et al., 2001). Solar-pond-powered desalination has been studied since 1987 at the El Paso Solar Pond Project, El Paso, TX. From 1987 to 1992, the search mainly focused on the technical feasibility of thermal desalination coupled with solar ponds. Since 1999, the research has focused on long-term reliability, improvement of thermodynamic efficiency, and economics. During this period, a small multieffect, multistage flash distillation (MEMS) unit, a MD unit, and a brine concentration and recovery system (BCRS) were tested over a broad range of operating conditions. The most important variables for the MEMS operation were flash range, concentration level of reject brine, and circulation rate of the first effect. The brine concentration and recovery system was part of the goal of developing a systems approach combining salinity-gradient solar pond technology with multiple-process desalination and brine concentration. The thermal energy from the ponds can be used to heat the feed water of ED plants and thus increase their performance.

C.2.2 Photovoltaics

The PV process converts sunlight directly into electricity. A PV cell consists of two or more thin layers of semiconducting material (mostly silicon). When the semiconducting material is exposed to sunlight, electrical charges are generated and this can be conducted away by metal contacts as DC. The PV sector has been growing at 20% per annum or more for several years and is now a multi-billion-dollar business in Europe (Infield, 2009). In 2008, a total of around 5.95 GW of capacity was installed worldwide. The majority of the market was in Spain and Germany, which accounted for more than 70% of the demand—see Figure C.3.

Photovoltaic cells can be either monocrystalline silicon cells, multicrystalline silicon cells, or amorphous cells. Monocrystalline cells are made of very pure monocrystalline silicon, whereas multicrystalline cells are produced using numerous grains of monocrystalline cells. Amorphous cells are composed of silicon atoms in a thin homogeneous layer (Kalogirou, 2005). The electrical output from a single cell is small. Hence, multiple cells are connected together and encapsulated in glass to form a module or panel. The PV panel is the principal building block of a PV system, and any number of panels can be connected together to give the desired electrical output. PV modules are designed for outdoor use. The choice of active photovoltaic material can have important effects on system design and performance. Both the composition and the atomic structure of the cell are important considerations for assessing performance. PV cells can be fragile and susceptible to corrosion by humidity. Stand-alone PV systems are used in areas that are not easily accessible to electricity. A stand-alone system is independent of the electricity grid, with the energy produced being stored in batteries (Kalagirou, 2005). Typically, a stand-alone PV system will consist of a module, batteries, and a charge controller. An inverter may also be included to convert the DC generated by the PV module to AC form.

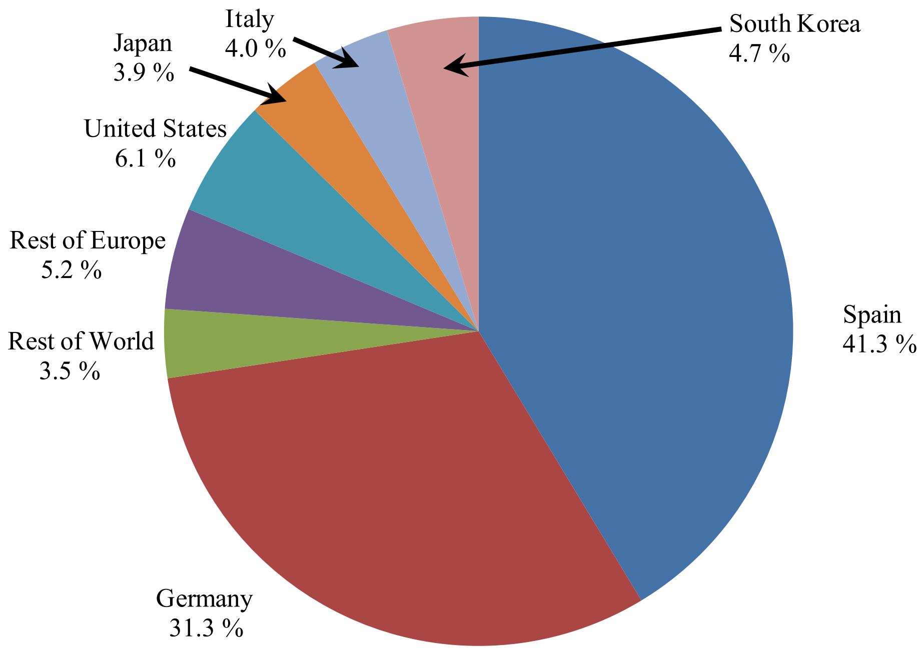

Figure C.3. Photovoltaic installation market demand in 2008 (Solarbuzz, 2008).

A PV system combined to a RO or ED system is considered a good combination for small stand-alone systems (Bayod-Rujula and Martinez-Garcia, 2009; Mohamed et al., 2008). An example of a PV used to power a RO system is shown in Figure C.4. Several PV–RO systems have been operational in the past for both brackish and seawater applications. Examples are given in Table C.1. Small stand-alone systems are used in areas that are not easily accessible or have no access to main electricity. It is typical practice to connect PV systems to the local electricity grid. Thus, during the day, energy generated from the PV systems can be used directly by the grid. During the night, when the solar system is unable to provide the electricity required, power can be utilized from the electricity grid. Thus, the grid acts as an energy storage system.

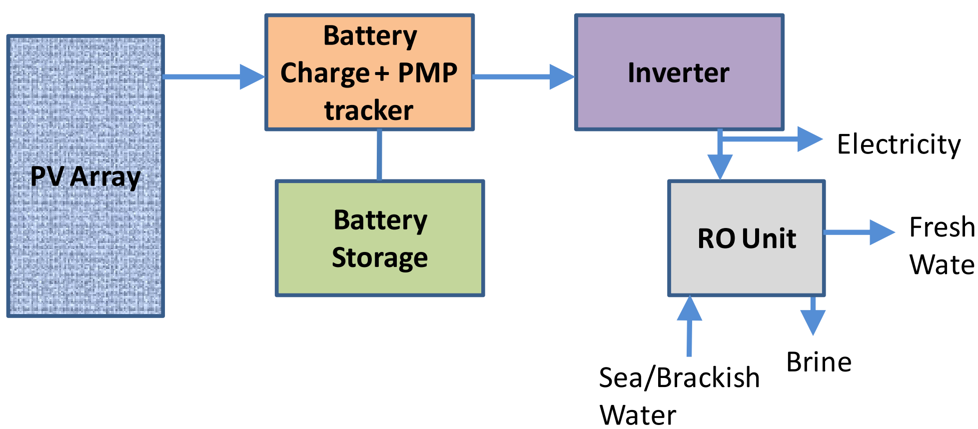

Figure C.4. Typical schematic of solar photovoltaic reverse osmosis system.

Table C.1 Reverse Osmosis Plants Powered by Photovoltaic Cells (Garcia-Rodriguez, 2002)

Plant Location	Type of Water	Plant Capacity	Photovoltaic System
North of Jawa	Brackish	0.5 m^3/h (0.003 MGD)	25.5 kW
Red Sea, Egypt	Brackish	1.5 m^3/h (0.01 MGD)	19.84 kW
Perth, Australia	Brackish	0.94 m^3/h (0.006 MGD)	25 kW
Almerla, Spain	Brackish	2.36 m^3/h (0.015 MGD)	23.5 kW
Doha, Qatar	Seawater	0.15 m^3/h (0.001 MGD)	11.2 kW
Florida, U.S.	Seawater	< 0.15 m^3/h (< 0.001 MGD)	2.7 kW + diesel generator
Vancouver, Canada	Seawater	< 0.15 m^3/h (< 0.001 MGD)	4.8 kW
Lampedusa Island, Italy	Seawater	4.73 m^3/h (0.03 MGD)	100 kW

C.2.3 Dish/Stirling Systems

Dish/Stirling systems are small power sets that generate electricity by using direct solar radiation. The system involves the concentration of solar radiation and its use as a heat source in operating a Stirling engine, which serves as an electricity generator (Zejli et al., 2002). The Dish/Stirling systems consist of a parabolic solar concentrator, a solar heat exchanger (receiver), a Stirling engine with a generator, and a tracking system. An illustration of the Dish/Stirling system with the major components is provided by Energy Direction (Energy Direction, 2011). In contrast to the Otto and Diesel engines, which run on internal combustion, the Stirling engine depends only on external heat supply, with no preference for the type of heat source being utilized.

C.2.4 Wind Energy

Wind has reemerged as one of the most important and fastest-growing sustainable energy resources since wind turbines were first commercialized in the 1970s (Ackermann and Soder, 2002). Wind power generated from wind turbines can be classified depending on their nominal power (Pn) as very low power (Pn < 10 kW), low power (Pn < 100 kW), medium power (100 kW < Pn < 0.5 MW), and high power (Pn > 0.5 MW) turbines (Garcia-Rodriguez, 2002). Wind turbines are considered to be a mature technology and are commercially available. Wind power is becoming cost-competitive with coal, gas, and nuclear power in many countries when the external and social costs are included. Wind-powered desalination represents one of the most promising renewable-energy desalination options, especially for coastal areas presenting a high availability of wind energy resources (de la Nuez Pestana et al., 2004; Forstmeier et al., 2007; Zejili et al., 2004). A wind resource map for the United States is shown in Figure C.5. Estimates of the wind resource are expressed in wind power classes ranging from Class 1 (the lowest) to Class 7 (the highest). Each class represents a range of mean wind power density or equivalent mean wind speed at specified heights above the ground. Modern utility-scale wind turbines typically require Class 4 or stronger winds, whereas some smaller turbines (below about 100 kW in capacity) can operate economically in areas with Class 2–3 wind resources, allowing them to provide power to more remote sites where the cost of electricity is higher. Areas designated as Class 1 are generally unsuitable for wind energy development. Thus, in the United States, wind resources are high in the Midwest, the Northeast, and the coastal regions of the West. The southern states have a very low potential for utilizing wind energy. The installed wind power capacity is shown in Figure C.5. The highest installed capacity is in the state of Texas, followed by Iowa and then California.

After solar energy, wind energy is the most widely used renewable energy source for small-capacity desalination plants. The two common approaches to wind-powered desalination systems are connecting both the wind turbines and the desalination system to a grid system, and direct coupling of the wind turbines with the desalination system (Ackermann and Soder, 2002). The latter option is likely to be a stand-alone system at remote locations that have no electricity grid. In this case, the desalination system may be affected by power variations and interruptions caused by the power source (wind). Hence, stand-alone wind desalination systems are often hybrid systems, combined with another type of renewable energy source (for instance solar), or utilizing a backup system such as batteries or diesel generators (Mathioulakis et al., 2007).

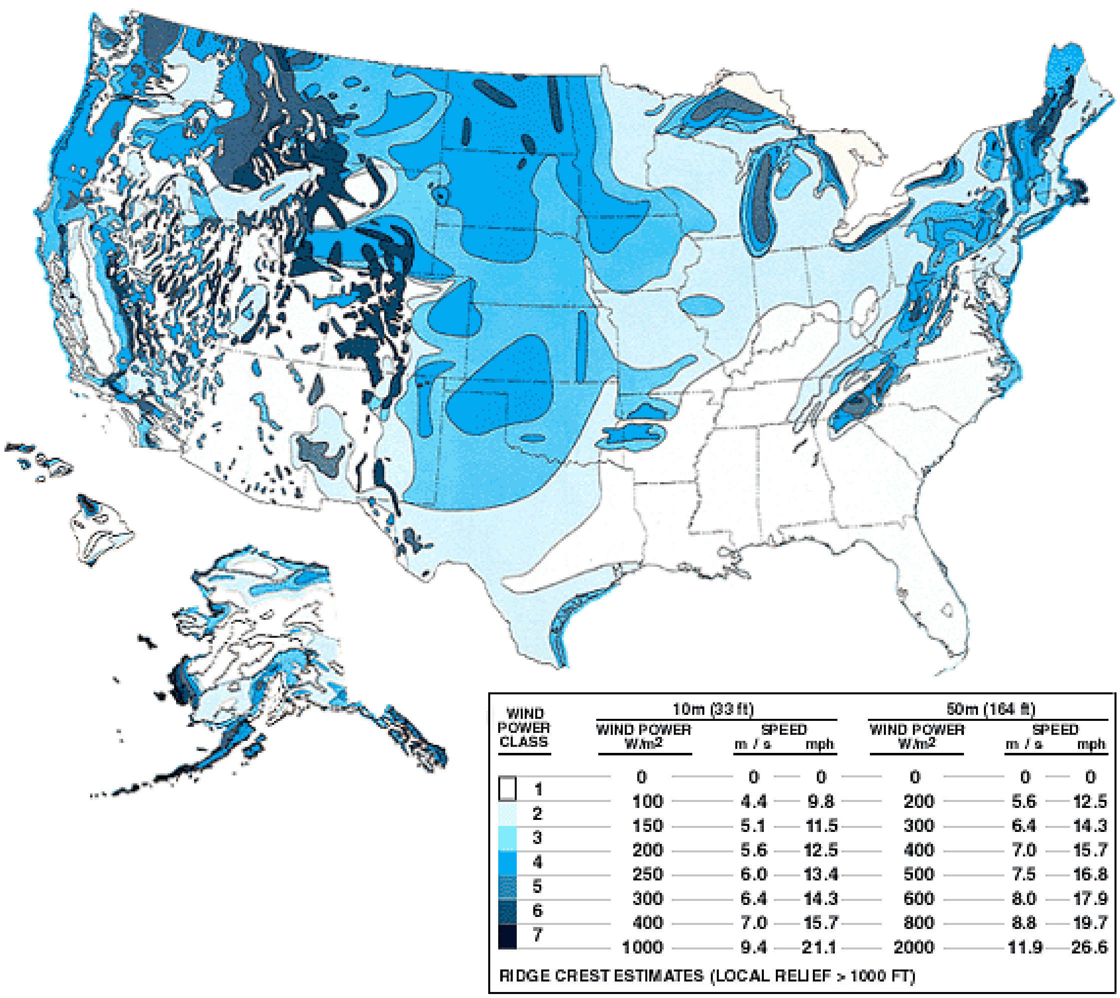

Figure C.5. Wind resource map for the United States (DOE, 2011d).

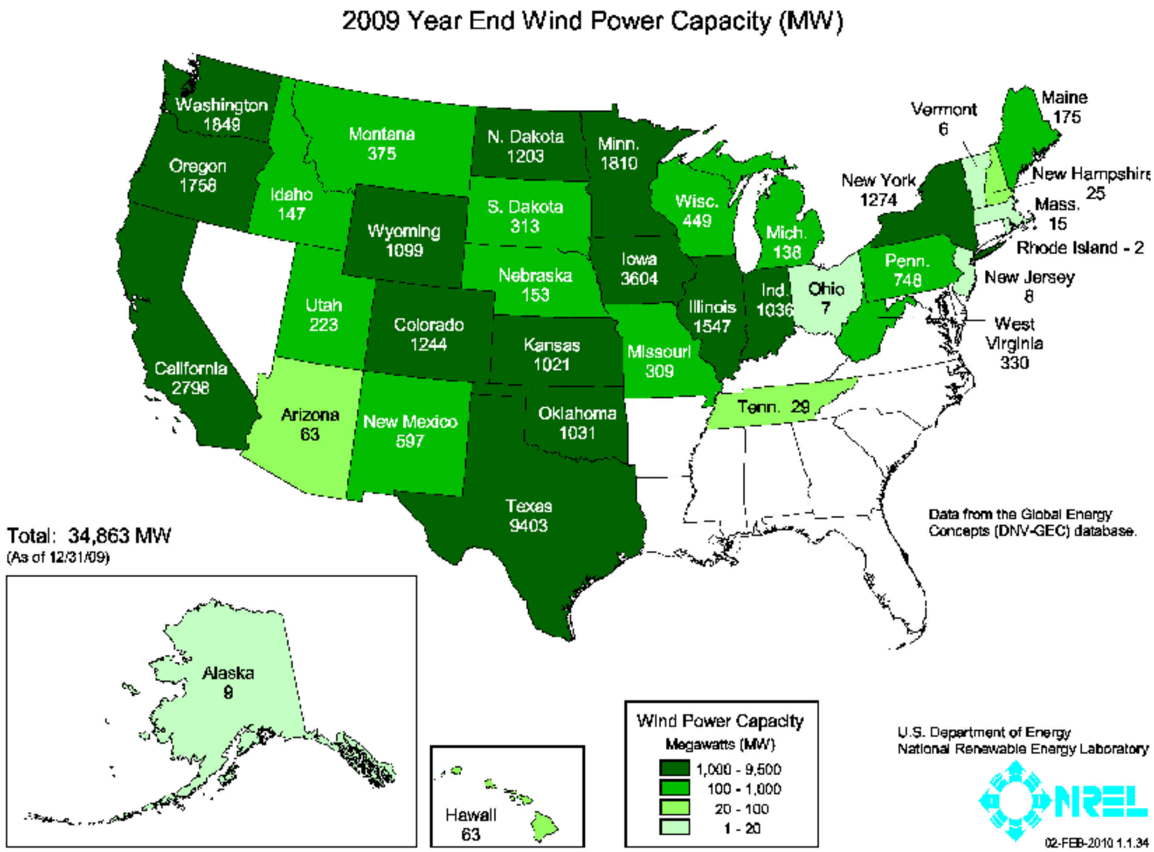

Figure C.6. Installed wind power capacity in the United States as of December, 2009 (Wind Powering America, 2009).

Wind energy systems provide electricity or direct shaft power, which can be used to power RO, ED, or mechanical VC desalination systems. The most popular combination is the use of wind energy with RO. Wind-powered RO plants have been implemented at a number of locations around the world. Below are a few examples:

Among the earliest wind–RO systems, a brackish water desalination plant with fresh water production of < 0.15 m^3/h (< 0.001 MGD) was designed for small remote communities in Australia (Robinson et al., 1992). A feedback control system was not included and a small diesel or portable gasoline pump was used when the available wind power was low.

A RO plant treating seawater using wind energy was operated in Gran Canaria, Spain (Rybar et al., 2005). Wind energy is obtained from a farm with four wind generators for the 205 m^3/h (1.3 MGD) RO permeate production. At times, excess wind power that was not consumed by the SWRO plant is sold to the grid, and sometimes, supplementary power is obtained from the grid to operate the SWRO. Energy use at the plant is less than 2.9 kWh/m^3 (10.9 kWh per 1000 gal) of produced water.

A stand-alone wind desalination system, known as AEROGEDESA, was developed by Canary Islands Technological Institute (ITC) with capacities between < 0.15 m^3/h (< 0.001 MGD) (Canary Islands Technological Institute, 2002).

Several prototypes of variable-load RO systems adapted to wind energy were installed in Europe. Ehmann and Cendagorta (1996) reported a RO system with variable load connected to a wind turbine installed at the ITC, located at Pozo Izquierdo, Gran Canaria, Spain. Miranda and Infield (2002) developed a wind-powered RO system without batteries. A 2.2-kW wind turbine generator was used to power a variable-flow RO desalination facility; the water production was dependent on the instantaneous wind speed.

A wind-powered brackish desalination system was installed on Coconut Island off the northern coast of Oahu, Hawaii, for brackish water desalination (Liu et al., 2002). The system directly connected the shaft power production of a windmill to the high-pressure pump for the RO. A constant fresh water production of 13 L/min was maintained with a wind speed of 5 m/s. The energy efficiency of 35% was comparable to the typical energy efficiency of well-operated multivaned windmills.

A wind-powered RO plant was implemented on the islands of the county of Split and Dalmatia, Croatia (Vujčić and Krneta, 2000). A RO desalination plant employing a new energy recovery system optimized for use in combination with wind energy (ENERCON project) was implemented on the island Utsira in Norway (Paulsen and Hensel, 2005l, 2007).

Water Corporation of Western Australia operates the Perth 38-mgd SWRO plant using 185 GW-h/yr of energy produced in part from a wind farm (Veerapaneni et al., 2007). At this plant it was reported that every kWh of energy produced by wind generators reduced the emissions by 0.6 kg of CO_2, 1.33 kg of SO_2, and 1.67 kg of NO_x. GHG emission reductions are site-specific because they depend on local factors such as the national energy mix and power plant efficiency levels.

The use of wind power with an ED or MVC system has also been investigated. Zejli et al. (2004) conducted an economic analysis of the wind–MVC system and showed that the energy consumption still remained high but could be lowered with more research. MVC is more robust than RO and presents fewer problems because of the fluctuations of the energy resource (Garcia-Rodriguez, 2002). A couple of MVC pilot plants powered by wind energy have been installed (Plantikow, 1999) and the influence of the main operating parameters has been studied (Karameldin et al., 2003). Finally, modeling and experimental tests of a wind–ED system has been conducted by the ITC, Gran Canaria, Spain (Veza et al., 2001).

The cost evaluation of wind-powered desalination systems was summarized in a review paper by Karagiannis and Soldatos (2008). For stand-alone wind-energy-driven desalination units, the reported cost of fresh water produced ranged from $1.35/m^3 to $6.7/m^3. Garcia-Rodriguez et al. (2001) analyzed the influence of the main parameters, including climatic conditions and plant capacity, on the product cost for SWRO driven by wind power. Several studies have reported that wind-powered RO is cost-competitive with conventional desalination plants, especially in areas with good wind resources that have high costs of conventional energy (Forstmeier et al., 2007; Kiranoudis et al., 1997; Voivontas et al., 2003). The disadvantage of using wind energy for power generation is its unpredictability. Thus, wind turbines are mostly installed in coastal regions with weaker grid supplies. In Germany, wind turbines in the North are prohibited from feeding electricity into the grid for some periods, due to grid overloading (BINE, 2007).

Technological developments in wind turbines have significantly reduced the cost and extended the market potential for wind energy. During the last decade of the 20th century, worldwide wind capacity doubled approximately every three years. At the same time, wind energy technology has moved very fast toward new dimensions. Currently, wind turbines are commercially available in a wide range of power from 40 W to 5 MW. A valuable review of wind technology was presented by Ackermann and Soder (2002).

Horizontal-axis, medium- to large-size grid-connected wind turbines (>100 kW) currently have the largest market share and are expected to dominate the development of wind turbines in the near future. Smaller turbines from tens of W to hundreds of kW can still be useful, particularly in the context of stand-alone power systems in remote regions where fuel is limited (Infield, 2009).

Three-blade wind turbines currently dominate the market for grid-connected, horizontal-axis wind turbines. Two-blade wind turbines have been constructed to reduce the costs and prolong the life of machines with lighter tower top weight and light supporting structure. The three-blade wind turbines have "better" visual aesthetics and a lower noise level than two-blade wind turbines; further, the rotor moment of inertia is easier to handle. All these aspects are important considerations for wind turbine utilization in highly populated areas.

C.2.5 Geothermal Energy

By the year 2000, the capacity of geothermal power plants was approximately 6,000 MW of electricity, and 0.3% of the world's total electrical energy was generated from geothermal resources (Baldacci et al., 1998). A complete overview of geothermal energy technology was presented by Barbier (2002). The geothermal energy sources are classified in terms of the measured temperature as low (<100 °C), medium (100–150 °C), and high temperature (>150 °C) (USDOE, 2011b). Geothermal energy is usually extracted with ground heat exchangers (Kalogirou, 2005). The primary advantage of geothermal energy compared to solar and wind is that it is both continuous and predictable, and therefore thermal storage is unnecessary. A geothermal resource map for the United States is shown in Figure C.7. The highest subterranean temperatures exist in the western states. As California exists on tectonic plate conjunctions, it has the largest geothermal energy generating capacity in the United States (California Energy Commission, 2009).

Geothermal energy is a mature technology that can be used to provide energy for desalination systems. High-temperature geothermal fluids can generate electricity to power RO or ED plants directly as shaft power on mechanically driven desalination. A well-studied option is the use of high-temperature geothermal fluid for thermal desalination technologies. The main advantage of using geothermal energy for desalination is that it is a stable and reliable heat supply 24 hours a day, 365 days a year. Also, desalination using geothermal energy sources is environmentally friendly, with no emission of GHGs (EGEC, 2010).

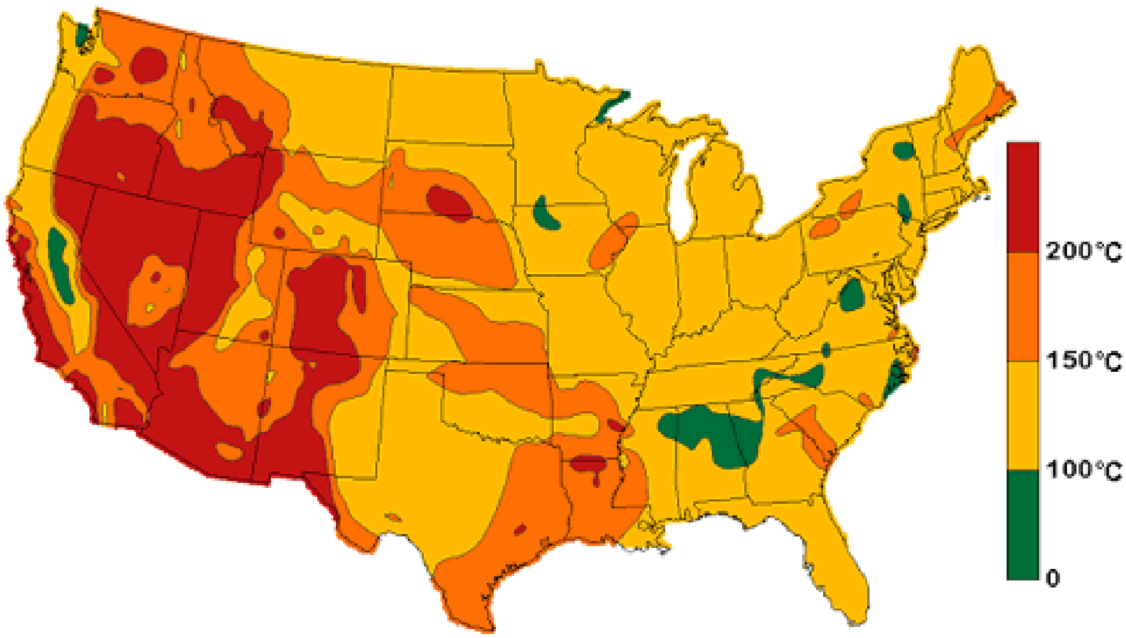

Figure C.7. Geothermal resource map for the United States. Estimated subterranean temperatures at a depth of 3.7 miles are shown on the map (NREL, 2011).

In the United States, eight geothermal projects are under development, located in the states of Utah, New Mexico, Nevada, and Oregon. Raser's geothermal power plant (the Hatch Plant) is selling clean, green electricity to the City of Anaheim, CA as part of a 20-year power purchase agreement. Geothermal energy is also being looked into for desalination in Queensland, Australia (Queensland Geothermal Energy Center of Excellence, 2010). This energy center has estimated that a geothermal plant in the 1000–100,000 m^3/d range can easily provide the entire fresh water needs for an outback city at the cost of around \$0.73–1.46/m^3. The first installation of geothermal-energy-powered desalination plants was reported by the Bureau of Reclamation of the U.S. Department of the Interior in the 1970s (Awerbuch et al., 1976; Boegli et al., 1977). They reported a geothermal-powered desalination pilot plant near Holtville, California, in 1972, and the testing of various potential options for the desalination technology, including MSF distillation and high temperature ED. Other application of geothermal energy include the following:

- An economic analysis by Ophir (1982) showed that geothermal desalination with sources at 110–130 °C could be a feasible option. Karytsas (1998, 2002) proposed a technical and economic analysis of a MED plant powered by a low-temperature geothermal source, installed on Kimolos Island, Greece. This 3.15m^3/H (0.02-MGD) brackish water desalting system costs \$2.7/m^3 of fresh water produced with the use of geothermal energy.
- Bourouni et al., (1999, 2001) presented results from the investigation of two geothermal-powered distillation plants, one installed in France and one in the south of Tunisia.
- More recently, Bouchekima (2003) analyzed the performance of a hybrid system in arid areas of South Algeria, consisting of a solar still in which the feed water is brackish underground geothermal water.
- Desalination of seawater has been evaluated in the Baja California Peninsula (Hiriart,

2008). Over 84 °C has been measured at a meter depth in the beach of Los Cabos, and more than a hundred hot springs have been identified, some of them a few meters into the sea and others several miles into the land. The potential of a binary plant of 1 MW capacity could be used to operate a RO plant that produces 252 m^3/H (1.6 MGD) of water. The hot seawater was found to have the potential to preheat the intake water, gaining 3% efficiency of the RO process with every °C of increase in water inlet temperature.

- A pilot study was performed at Kimolos Island in Greece (EGEC, 2010). A geothermal water flow rate of 0.4 MGD at a wellhead temperature of 61–62 °C was utilized from a borehole 188 m deep. The desalination method used was MED with distillation under vacuum in vertical tubes, and a two-stage desalination system was installed. The desalination system produced excellent water quality with a salinity level close to 10 mg/L. It was determined that fewer stages/effects were needed in this installation than in a MSF system, resulting in lower costs per m^3 of produced fresh water. The produced water cost was estimated to be about \$2.16/m^3.

- Geothermal energy is planned for desalination at Milos Island in Greece (EGEC, 2010). The MED seawater desalination system will provide 75–80 m^3/h (< 0.5 MGD) of desalinated water. The installation will use the low-enthalpy geothermal energy for electricity generation and seawater desalination simultaneously. A total of 10 wells (70–185 m deep) are to be utilized, with wellhead temperatures ranging between 55 and 100 °C.

C.2.6 Fuel Cells

Fuel cells convert the chemical energy contained in a fuel into electrical energy electrochemically. A schematic of a fuel cell is shown in Figure C.8. The building block of a fuel cell is an electrolyte layer in contact with an anode and a cathode on either side. In a typical fuel cell, fuel is fed continuously to the anode and an oxidant is fed continuously to the cathode (DOE, 2004). The electrochemical reactions take place at the electrodes to produce an electric current through the electrolyte, while driving a complementary electric current that performs work on the load. The fuel cell produces power as long as fuel is supplied.

The major components of a fuel cell consist of the fuel cell module, electrical balance of plant (EBOP) and mechanical balance of plant (MBOP) (USDOE, 2004). Fuel cell systems consist of the following (USDOE, 2004):

- Fuel preparation: Except during the use of pure fuels (such as pure hydrogen), fuel preparation is required. Preparation involves the removal of impurities, thermal conditioning, and fuel processing (such as reforming).
- Air supply: Air compressors or blowers are used to supply oxidant to the fuel cell.
- Thermal management: All fuel cell systems require careful management of the fuel cell stack temperature.
- Water management: Water might be needed in some parts of the fuel cell, and water is a byproduct of the reaction and needs to be managed to ensure smooth operation of the system.
- Electric power conditioning: Fuel cell stacks provide DC voltage output, and electric power condition is typically required before it can be used.

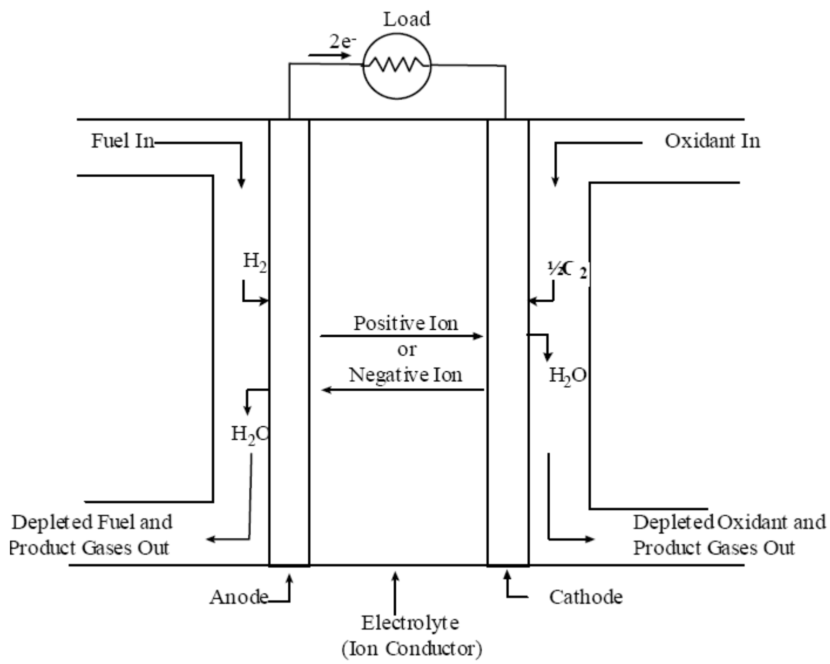

Figure C.8. Schematic of an individual fuel cell (USDOE, 2004).

An illustration of major processes occurring in a fuel cell is shown in Figure C.9. The feed gas is cleaned in the fuel processor, and then converted into a gas containing hydrogen. Energy conversion occurs when DC is generated by individual fuel cells combined in stacks or bundles. A varying number of cells or stacks can be matched to a particular power application. In the stage, power conditioning converts the electric power from DC into regulated DC or AC for use (USDOE, 2004).

Most fuel cells use gaseous hydrogen or a synthesis gas rich in hydrogen as fuel (USDOE, 2004). In wastewater treatment plants, methane produced from the anaerobic digester is used as a fuel to generate ultraclean electricity that powers the treatment plant or parts of the treatment plant. The byproduct of the fuel cell can be used to heat the sludge to facilitate anaerobic digestion. The combined heat and power application results in 90% efficiency. When the digester gas production is variable, the fuel cell plant can be designed to operate with automatic blending with natural gas.

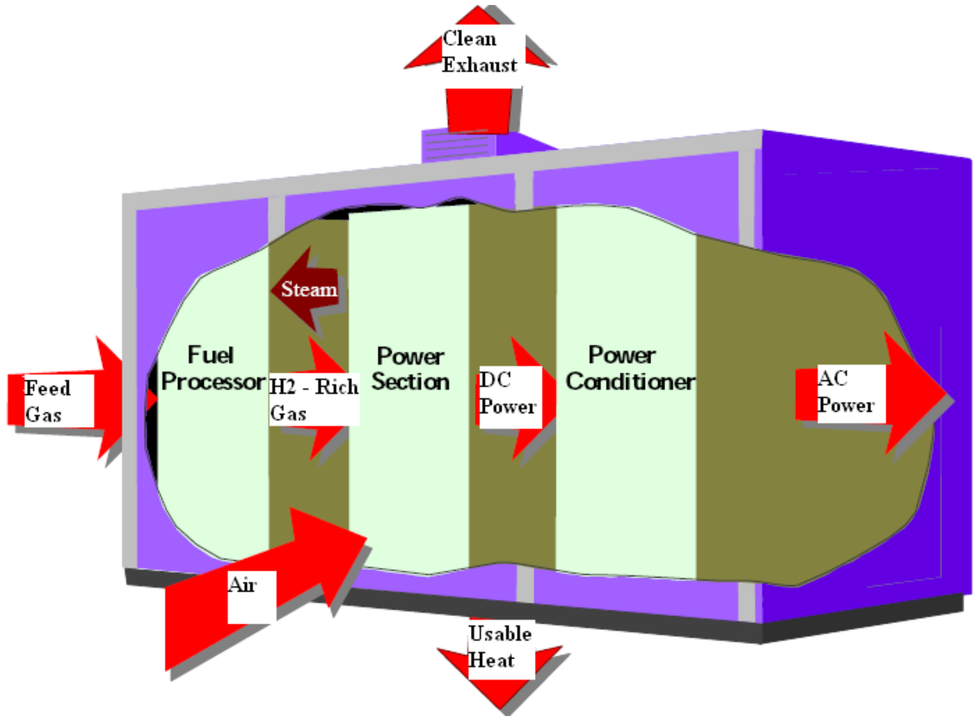

Figure C.9. Major processes in a fuel cell power plant (USDOE, 2004).

Various types of fuel cells exist. The most common classification of fuel cells is by the type of electrolyte used in the cell. The common types include (1) polymer electrolyte fuel cells (PEFCs), (2) alkaline fuel cells (AFCs), (3) phosphoric acid fuel cells (PAFCs), (4) molten carbonate fuel cells (MCFCs), and (5) solid oxide fuel cells (SOFCs) (USDOE, 2004). A comparison of the fuel cell types is provided in Table C.2. The choice of electrolyte dictates the operating temperature range of the fuel cell, which in turn dictates the physicochemical and thermomechanical properties of materials used in the cell components (USDOE, 2004). Aqueous electrolytes are limited to temperatures below 200 °C by their high vapor pressure and rapid degradation at higher temperatures. MCFC are designed to operate at higher temperatures than PAFCs or PEMCs and can achieve higher fuel-to-electricity and overall energy use efficiencies than low-temperature cells (USDOE, 2011c). When MCFC technology is used in a wastewater treatment plant, methane is converted into a hydrogen-rich gas inside the fuel cell stack by internal reforming (USDOE, 2011c). The hydrogen reacts with carbonate ions at the anode to produce water, carbon dioxide, and electrons. The electrons travel through an external circuit, creating electricity, and return to the cathode. At the cathode, electrons react with oxygen from air and carbon dioxide (recycled from anode) to form carbonate ions that replenish the electrolyte and provide ionic conduction through the electrolyte, completing the circuit (USDOE, 2011c). Fuel cells have been installed in several wastewater treatment plants in the United States. For example, at the Columbia Boulevard Wastewater Treatment Plant, City of Portland, a fuel cell system was installed to produce 200 kW of power. The capital cost was $1.3 million and the facility received a $200,000 Department of Defense grant, a $247,000 green power credit from Portland General Electric, and a $10,000 grant from the Oregon Department of Environmental Quality. The fuel cell provides about $60,000 per year in net operational cost savings (USDOE, 2011a).

Table C.2. Comparison of Major Fuel Cell Types (USDOE, 2004)

	PEFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Hydrated polymeric ion exchange membranes	Mobilized or immobilized potassium hydroxide in asbestos matrix	Immobilized liquid phosphoric acid in SiC	Immobilized liquid molten carbonate in LiAlO2	Perovskites (ceramics)
Electrodes	Carbon	Transition metals	Carbon	Nickel and nickel oxide	Perovskite and perovskite/metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carbon or metal	Metal	Graphite	Stainless steel or nickel	Nickel, ceramic, or steel
Prime cell components	Carbon-based	Carbon-based	Graphite-based	Stainless steel-based	Ceramic
Operating temperature	40–80 °C	65–220 °C	205 °C	650 °C	600–1000 °C
Charge carrier	H^+	OH^-	H^+	CO_3^{2-}	O^-
External reformer for hydrocarbon fuels	Yes	Yes	Yes	No, for some fuels	No, for some fuels and cell designs
External shift conversion of CO to hydrogen	Yes, plus purification to remove trace CO	Yes, plus purification to remove CO and CO2	Yes	No	No
Product water management	Evaporative	Evaporative	Evaporative	Gaseous product	Gaseous product
Product heat management	Process gas + liquid cooling medium	Process gas + electrolyte circulation	Process gas + liquid cooling medium or steam generation	Internal reforming + process gas	Internal reforming + process gas

C.2.7 Internal Combustion Engines

Using internal combustion engines is another method of producing electricity using biogas. When an anaerobic digester is used on wastewater sludge, biogas is produced. Biogas consists of approximately 60% methane and 40% carbon dioxide. Biogas from wastewater treatment plants has been successfully utilized to provide both heat and electricity. Methane from the biogas is used to heat the digesters and keep them at the appropriate temperature. In addition to fuel cells, microturbines and internal combustion engines are the other technologies typically used for generation of electricity from biogas (Massachusetts DEP, 2007). The appropriate technology is largely determined by the size of the wastewater treatment plant. Microturbine technology is more applicable to wastewater treatment plants with low flow (< 1,072 m^3/h). Minimum flows required for fuel cells and internal combustion engines are 1,687 m^3/h (10.7 MGD) and 6,530 m^3/h (41.4 MGD), respectively (Massachusetts DEP, 2007). Internal combustion engines for a 1060-kW capacity cost approximately $2,161,425 with a cost per kW of $2,039 (Massachusetts DEP, 2007).

C.2.8 Hybrid Systems

Hybrid renewable energy systems for desalination have been utilized in the recent past. Combinations of wind and solar energy have been used for driving desalination systems. The purpose of using hybrid wind–solar systems for desalination is based on the fact that in certain locations, wind and solar time profiles do not coincide (Mathioulakis et al., 2007). The complementary features of wind and solar resources make the use of hybrid wind–solar systems an attractive means by which to drive desalination systems (Charcosset, 2009). Hybrid wind–solar PV systems have been implemented in the Sultanate of Oman, Israel, Mexico, Germany, and Italy (Al Malki et al., 1998; Petersen et al., 1981; Pretner and Iannelli, 2002; Weiner et al., 2001). Two RO desalination plants supplied by a 6-kW wind energy converter and a 2.5 kW solar generator have been designed for remote areas (Petersen et al., 1979). Stand-alone systems for seawater desalination using hybrid wind–PV systems have also been designed (Mohamed et al., 2006). Using wind and solar conditions in Eritrea, East Africa, the hourly water production was determined to be 2.5 m^3/h with a specific energy consumption of about 2.31 kWh/m^3 (8.8 kWh per 1000 gal) of water (2.33 kWh/m^3) (Gilau and Small, 2008). Although several studies have been performed using hybrid renewable-energy desalination systems, none of them represent large-scale applications. The opportunity to install a hybrid system has to be carefully investigated by means of simulation using typical meteorological data (Mathioulakis et al., 2007).

C.2.9 Design of Renewable Energy Systems

While designing a renewable-energy-powered desalination system, the designer needs to select a process suitable for a particular application. The factors that need to be considered are as follows (Kalogirou, 1997):

- Suitability of the process for renewable energy application
- Effectiveness of the process with respect to energy consumption
- Quantity of fresh water required in a particular application, in combination with the range of applicability of the various desalination processes
- Water treatment requirements
- Capital cost of the equipment
- Land area required for the equipment installation
- Variation in water demand and energy generation
- Economies of scale of facility sizing to accommodate variable (nondispatchable) energy generation
- Energy cost structure (including both capital and operational energy costs)

Design of a renewable energy–desalination system needs to be performed with an iterative approach (Voivontas et al., 2001). The iterative approach should involve a careful assessment of available options in meeting the water demand and the economic viability of the selected solution. An overall algorithm for designing renewable energy–desalination systems is shown in Figure C.10. The first step of the approach involves the definition of a list of alternative technologies that satisfy the water demand. In the next step, a detailed design analysis of each candidate option is made to determine the plant capacity, the structure of the power unit and the operation characteristics. The final step involves a financial analysis of the investment associated with the selected renewable energy–desalination combination.

The most challenging issue associated with the implementation of renewable energy–desalination technology is the optimum matching of the intermittent renewable energy power output with the steady energy demand of the desalination process. Power management and demand-side management are regarded as the two options available to address this problem (Voivontas et al., 2001). In the first case, an appropriately controlled hybrid renewable energy resource unit that is capable of providing a steady energy output is used. This unit is sized at the nominal power demand of the desalination process. In the demand-side management option, the desalination process would operate only when the energy output of the renewable energy resource unit was able to cover the energy demand. Other options available to address the issue of intermittent renewable energy power output are different types of energy storage, such as electromechanical, virtual (through process modification), and grid energy (Kalogirou, 1997). Compressed-air energy storage plants can also be used when energy produced from wind turbines exceeds grid load capacity (BINE, 2007). For limited periods, the compressed-air stores cover the short-term reserve requirement, which is needed because of the unpredictable forecasts of wind power feeding the grid. In this case, wind turbines do not have to deactivate in the event of a grid overload, and if there is an excess supply of electrical energy, the storage technology refines base-load electricity, converting it to peak-load electricity (BINE, 2007). An energy balance between energy production from the renewable energy resource and the energy demand of the desalination process can be used for determining the capacity of the energy unit and a complete cost analysis and comparison among alternative renewable energy resource–desalination combinations, used to determine the optimum solution for a specific case.

C.2.10 Renewable Energy Technology Selection

Renewable energy resource selection for desalination should consist of an iterative approach. The factors that need to be considered in designing are the suitability of the process for a renewable energy application, the effectiveness of the process with respect to energy consumption, the amount of fresh water required in a particular application in combination with the range of applicability of the various desalination processes, the water treatment requirements, the capital cost of the equipment, and the land area required for the equipment installation. An evaluation of renewable energy technologies, shown in Table C.3, indicates that all renewable energy resources are equally appropriate for powering desalination plants. In terms of resource availability, solar thermal energy and photovoltaics are considered to be a better choice than wind and geothermal energy, which are location-dependant. In terms of the continuity and predictability of power output, geothermal energy is the most reliable resource, as the output for solar thermal, photovoltaic, and wind energy is intermittent and less predictable.

Recommended renewable energy and desalination combinations are listed in Table C.4. A majority of these applications consist of different types of solar energy for small plants with a capacity of < 1.57 m^3/h (< 0.01 MGD) of water production capacity. Wind energy is applied predominantly in medium-sized plants with a capacity of 2.08–10.4 m^3/h of water production capacity. Geothermal energy is applied mostly to large plants with a water production capacity exceeding 9.4 m^3/h (> 0.06 MGD). The current installed capacity of renewable energy resources used for desalination is only 0.02% of the total desalination capacity (Delyannis and Belessiotis, 1996). The reasons for this low percentage of installation are availability, costs, technology, and sustainability. Availability is an important contributor to the implementation of renewable energy resources for desalination because the geographical distribution of the energy sources does not always comply with the water stress intensity at a local level. Costs play an important role as well. The initial capital installation cost and various system components are still expensive compared with the use of traditional fossil fuel energy supplies. Although prices are decreasing continuously, they are still considered high for commercialization. The technology of integrating a renewable energy source with a desalination system is still developing. Finally, in many cases the maturity of the technology does not match the level of infrastructure and technical support.

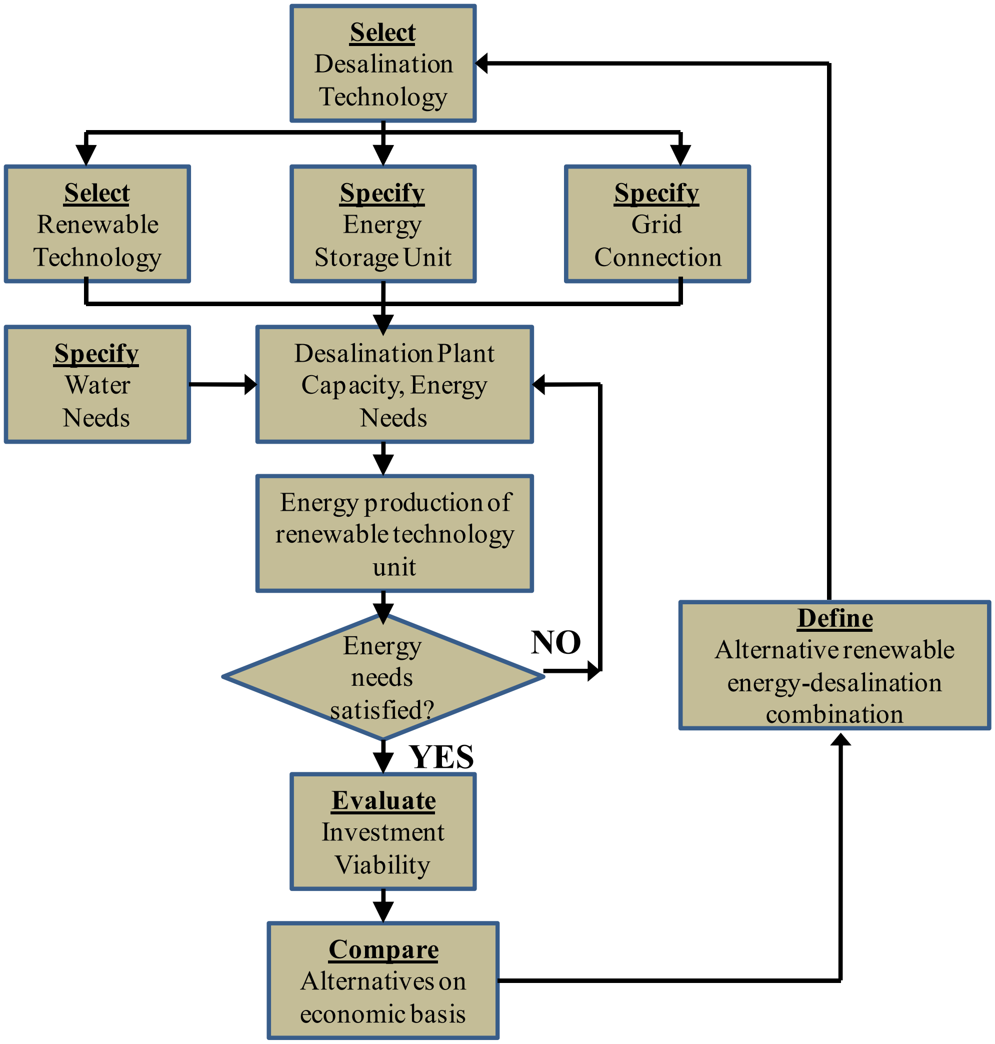

Figure C.10. Renewable energy resource–desalination design algorithm (Voivontas et al., 2001).

Table C.3. Evaluation of Renewable Energy Technologies (Delyannis and Belessiotis, 1996; Eltawil et al., 2009)

Criterion	Solar Thermal Energy	Photovoltaic	Wind Energy	Geothermal Energy
Suitability for powering desalination plants	Score 3—Well suited for desalination plants requiring thermal power	Score 3—Well suited for desalination plants requiring electrical power	Score 3—Well suited for desalination plants requiring electrical power	Score 3—Well suited for desalination plants requiring thermal power
Site requirement and resources availability	Score 3—Good match with need for desalination	Score 3—Good match for need for desalination	Score 2—Resources are location-dependent	Score 1—Resources is limited to certain location
Continuity of power output	Score 1—Output is intermittent (energy storage required)	Score 1—Output is intermittent (energy storage required)	Score 1—Output is intermittent(energy storage required)	Score 3—Continuous power output
Predictability of power output	Score 2—Output is relatively unpredictable	Score 2—Output is relatively unpredictable	Score 1—Output is very unpredictable	Score 3—Output is predictable

Note: Score 3 = excellent compliance with criterion; score 2 = good compliance with criterion; score 1 = poor compliance with criterion.

Table C.4. Recommended Renewable Energy–Desalination Combinations

Feed Water Type	Product Water	Renewable Energy Resource	System Size: Small, < 2.0 m^3/h	System Size: Medium, 2–10 m^3/h	System Size: Large, >10 m^3/h	Suitable Renewable Energy–Desalination Combination
Brackish water	Distillate	Solar	X			Solar distillation
	Potable	Solar	X			PV-RO
	Potable	Solar	X			PV-ED
	Potable	Wind	X	X		Wind-RO
	Potable	Wind	X	X		Wind-ED
Seawater	Distillate	Solar	X			Solar distillation
	Distillate	Solar		X	X	Solar thermal - MED
	Distillate	Solar			X	Solar thermal - MSF
	Potable	Solar	X			PV-RO
	Potable	Solar	X			PV-ED
	Potable	Wind	X	X		Wind-RO
	Potable	Wind	X	X		Wind-ED
	Potable	Wind		X	X	Wind-VC
	Potable	Geothermal		X	X	Geothermal-MED
	Potable	Geothermal			X	Geothermal-MSF

Source: Matioulakis et al., 2007; Delyannis and Belessiotis, 1996
Note: Distillate represents treated water with TDS < 50mg/L; Potable represents treated water with TDS < 500 mg/L.

Table C.5. Cost of Water Produced Based on the Type of Energy Supply System

Feed Water Type	Type of Energy	Cost ($/m^3)	Source of Information
Brackish	Conventional	0.26–1.33	Afonso et al., 2004; Al-Wazzan et al., 2002; Avlonitis, 2002; Chaudhry, 2003; Jaber and Ahmed, 2004; Rico and Arias, 2001; Sambrailo et al., 2005
	Photovoltaics	5.57–12.77	Tzen, 2006
	Geothermal	2.47	Tzen, 2006
Seawater	Conventional	0.43–3.34	Atikol and Aybar, 2005; Avlonitis, 2002; Chaudhry, 2003; Leitner 1991
	Wind	1.24–6.19	Kershman et al., 2005; Tzen, 2006; Voivontas et al., 2001; Zejli et al., 2004
	Photovoltaics	3.88–11.14	Mohamed and Papadakis, 2004; Voivontas et al., 2001
	Solar Collectors	4.33–9.90	Tzen, 2006; Tzen and Morris, 2003

C.2.11 Cost of Renewable Energy Resources

A detailed cost analysis is necessary for important investment decisions. In the literature, the calculation of desalination costs is based on different assumptions by various authors. For example, there could be significant variations in the interest rates and life expectancy of the equipment. In some cases, the estimation of fresh water cost does not include the investment cost, labor, or other operational costs (Karagiannis and Soldatos, 2008). Cost estimates for brackish and seawater desalination using conventional and renewable energy resources are listed in Table C.5. The cost of water produced from desalination systems using a conventional source of energy, such as gas, oil, or electricity, can be lower than the cost of water produced from desalination systems using a renewable energy resource, depending on the cost of electricity, intergrid connection, and the availability and variability of the renewable energy resource. For systems treating brackish water using a conventional source of energy, the total cost of water produced ranges between $0.26/m^3 ($1 per 1000 gal) and $1.33/m^3 ($5 per 1000 gal), with the higher cost representing plants that are small in size. Seawater desalination plants have a total cost that varies between $0.43/m^3 ($1.6 per 1000 gal) and $3.34/m^3 ($12.6 per 1000 gal), with the higher cost representing small plants with 2–3 m^3 daily production. The capital cost of desalination using renewable energy resources is high now because of lack of infrastructure and the need for capital-intensive installations. Desalination with renewable energy resources, as opposed to desalination with conventional energy sources, can be an attractive solution when reduced environmental impact and lower gas emissions are required. A detailed analysis of greenhouse gas emissions for various processes is presented in the next section.

Several tools have been developed for the estimation of costs when renewable energy resources are used (Karagiannis and Soldatos, 2008). Software tools such as IPSEpro and RESYSpro are capable of performing technical, economic, and ecological analysis. Recently, the Agricultural University of Athens developed a decision support tool (DST) called AUDESSY. This software can estimate the water desalination cost for systems using renewable energy sources. AUDESSY has been specifically designed to study RO–PV, RO–wind, and hybrid RO–wind–PV desalination systems. Other software tools available are listed in Table C.6. Software tools can be used to identify technical information that may lead to the selection of an optimized desalination system, administer a database, and provide enhanced documentation for financial and engineering calculations.

Table C.6. List of Potential Modeling Software Available for Energy Optimization and Utilization of Renewable Energy

Name	Developer	Scope	Platform	Methodology	Cost (U.S.$)/ Licensing	Web Site/ Contact
EnergyPLAN	Aalborg University, Denmark	Simulates and optimizes the operation of an entire national energy system for every hour in a particular year.	Windows	Simulation/	Free	energy.plan.aau.dk. Last accessed: July 21, 2011.
Energy Costing Tool	UNDP	Estimates the amounts and types of energy investments required to meet the Millennium Development Goals (MDGs)	Excel	Accounting	Free	www.undp.org. Last accessed: July 21, 2011.
ENPEP	Argonne National Laboratory, USA	Suite of Models for Integrated Energy/Environment Analysis	Windows	Various	Depends on modules used and type of institution.	www.dis.anl.gov. Last accessed: July 21, 2011.
GEMIS	Oeko-Institut, Germany	Lifecycle analysis of energy chains	Windows	Physical Accounting	Free	http://www.oeko.de. Last accessed: July 21, 2011.
HOMER	National Renewable Energy Laboratory, USA	Design of off- and on-grid electrification options	Windows	Optimization	Free	- www.nrel.gov/homer. Last accessed: July 21, 2011.
LEAP	SEI	Integrated Energy/Environment Analysis	Windows	Physical Accounting, Simulation	Free to qualified users from developing countries. Click here for licensing for other institutions	www.energycommunity.org. Last accessed: July 21, 2011.
MAED	International Atomic Energy Agency	Integrated Energy / Environment Analysis	Windows & Linux	Physical Accounting, Simulation	Free to public sector nonprofit and research organizations	www.iaea.org. Last accessed: July 21, 2011.

Name	Developer	Scope	Platform	Methodology	Cost (U.S.$)/ Licensing	Web Site/ Contact
MESSAGE	International Atomic Energy Agency	Final and Useful Energy Demand	Windows	Optimization	Free to public sector, nonprofit, and research	www.iaea.org. Last accessed: July 21, 2011.
RETSCREEN	Natural Resource Canada	Energy production, life-cycle costs, and GHG emission reductions for various energy-efficient and renewable energy technologies	Excel	Physical Accounting	Free	www.retscreen.net. Last accessed: July 21, 2011.
SUPER	OLADE	Energy demand and conservation, hydrology, planning under uncertainty, hydro-thermal dispatch, financial, and environmental analysis	Windows	Optimization and Simulation	$4000–$10,000 depending on institution	http://www.olade.org.ec. Last accessed: July 21, 2011.

Source: Energy Community, 2011

A comparison of current and future costs of potential renewable energy technologies with those of fossil fuels is made in Table C.7. The cost of renewable energy technologies, especially photovoltaics, is expected to decrease substantially by the year 2020 because of improvements and maturity of the technology. Declining costs and stronger tax and investment incentives are making solar power more cost-competitive with the fuels that America's utilities have traditionally used to generate electricity.

A recent report by the Lawrence Berkeley National Laboratory found that the installed costs before tax incentives for residential and commercial photovoltaic systems had fallen to $7.60 per watt from $10.50 per watt in 2007 (Venkataraman, 2010). The incentives that lower the costs of PV include state cash incentives, the federal investment tax credit, and accelerated depreciation. Solar incentives by state are listed in Table C.8. There is a wide difference in the incentives that various states offer for solar power, suggesting that the growth of solar power will vary substantially by state (Venkataraman, 2010). The costs of silicon PV panels had stalled in 2005 and varied widely from state to state, and economies of scale improved for systems larger than 750 kW (Venkataraman, 2010). As far as wind energy is concerned, utility studies have shown that it represents a certain capacity credit, though a factor of 2–3 lower than the value for nuclear and fossil-fuel-fired plants (Kalogirou, 2005). Thus, wind energy can replace fossil fuels and save capacity of other generating plants. Although the cost of conventional energy sources could decrease in the future, most of the technologies have matured (REN21, 2005).

Table C.7. Cost Comparison of Renewable and Conventional Energy Sources

Technology	Current Cost (U.S. cents/kWh)	Projected future costs beyond 2020 as the technology matures (U.S. cents/kWh)
Solar thermal electricity	12–18	4–10
(insolation of 2500 kWh/m^2 per year) Grid-connected photovoltaics, according to incident solar energy (insolation):		
1000 kWh/m^2 per year (e.g., U.K.)	50–80	About 8
1500 kWh/m^2 per year (e.g. southern Europe)	30–50	About 5
2500 kWh/m^2 per year (most developing countries)	20–40	About 4
Stand-alone systems (including batteries), 2500 kWh/m^2 per year	40–60	About 10
Wind electricity:		
Onshore	3–5	2–3
Offshore	6–10	2–5
Geothermal energy:		
Electricity	2–10	1–8
Heat	0.5–5	0.5–5
Electricity grid supplies from fossil fuels:		
Off-peak	2–3	Capital costs will come down with
Peak	15–25	technical progress, but many
Average	8–10	technologies largely have matured
Rural electrification	25–80	and may be offset by rising fuel costs.
Costs of central grid supplies, excluding transmission and distribution:		Capital costs will come down with
Natural gas	2–4	technical progress, but many
Coal	3–5	technologies largely have matured
		and may be offset by rising fuel costs.

Source: REN21, 2005

Table C.8. Solar Incentives by State ($/watt) for Commercial Facilities

State	Less than 100 kW	More than 100 kW
Arizona	3.3	4
California:		
California Energy Commission	2.3	0
Self-Generation Incentive Program	2.5	2.5
California Solar Initiative	2	2.2
Connecticut	4.1	4.1
Illinois	0.8	0
Massachusetts	6.6	2.4
Maryland	0.4	0
Minnesota	2	0
New Jersey	4.7	3.4
New York	4	0
Oregon	1.3	0
Pennsylvania	0	0
Wisconsin	2.1	0

Source: Venkataraman, 2007

C.2.12 Economics and Policy Supporting Renewable Energy Development

The geopolitical commitment to develop carbon-neutral renewable energy is driven by the Intergovernmental Panel on Climate Change (IPCC)'s assessment that carbon emissions must peak before 2020 in order to mitigate climate change. Stabilizing the energy sector GHG emissions, which represent approximately 65% of the world's emissions, to a CO_2 equivalent in the atmosphere of 445–490 mg/L is considered essential to limiting the global temperature rise to a safe limit of 2 °C (IPCC, 2010). According to the International Energy Agency's World Energy Outlook 2007, this translates to a scenario where the renewable energy sector comprises 40% of total generated global electricity or 12,000 TWh. Excluding large hydropower, renewable energy power generation capacity increased 25% in 2008 (by 40 GW), but this increase still only composed 6.2% of global power capacity and 4.4% of actual. An additional 25–30 GW of large hydropower capacity also occurred in 2008, with 12–15 GW added in China and more than 5 GW added in India.

Elevated oil prices, together with the political will to control climate change ,have enabled the clean energy sector to resist the global financial crisis better than many other sectors. The year 2008 was the first year in which new power generation investment was greater in renewable than in fossil-fueled technologies (UNEP and New Energy Finance, 2009). New global investment in sustainable energy companies and projects reached $155 billion, and an estimated $180 billion of support was made available from major government fiscal stimulus packages. The economic crisis resulted in slowed sector growth in late 2008 and early 2009, as global reduction in liquidity impacted the flow of investment dollars. There is also the question of whether funds can be invested in a sufficiently accelerated timeframe to meet the 2020 emissions peak requirement. New Energy Finance Global Futures (UNEP and New Energy Finance, 2009) shows that in the Peak Scenario, CO_2 emissions from the world's energy infrastructure must peak at 30.8 gigatonnes in 2019, which will require annual investments in sustainable energy to rise from $155 billion to $500 billion by 2020.

Therefore, government stimulus funding must be heavily augmented through private sector investment, and carbon markets will be a vital component driving the pace of renewable energy development and implementation by decoupling GHG emissions from economic growth (UNEP and New Energy Finance, 2009).

Sustainable energy financing covers a continuum of activities that range from technology research and technology development to manufacturing scale-up and construction of generating facilities. Wind is the most mature and best-funded renewable technology, driven largely by asset finance, as new generation capacity is added both on shore and off shore worldwide, particularly in China and the United States. Solar is the second most invested-in sustainable technology and the fastest-growing sector for new investment (UNEP and New Energy Finance, 2009).

Regionally, financial new investment in renewable energy technologies is greatest in Europe (49.7%) followed by North America (30.1%), Asia and Oceania (24.2%), South America (12.3%), and finally the Middle East and Africa (2.6%), with all regions showing steady growth from 2002 through 2009 and some stagnation from the global economic crisis manifesting in 2008 (UNEP and New Energy Finance, 2009).

Australia, in particular, has set up an A$500M Renewable Energy Fund to utilize in an 18-month roll-out alongside private sector money in developing renewable energy projects and new technology (UNEP and New Energy Finance, 2009). Geothermal is expected to provide around 7% of the country's base load power by 2030 and is earmarked to receive 10% of the Renewable Energy Fund through a Geothermal Drilling Fund being implemented in 2009. Wind is expected to provide 20% of renewable energy by the 2020 peak carbon target; 1.3 GW of capacity became installed at the end of 2008 and a further 9 GW is being installed, primarily in Australia's southern states of Victoria, New South Wales, and South Australia. Solar and marine power also have large growth potential, but it might not be realized due to lack of government support for solar and the precommercial status of marine technology.

The untapped potential of wind and solar sources is very apparent when one considers that only 0.02 TW of wind power is generated from an estimated accessible worldwide capability of 40–85 TW, and only 0.008 TW of solar power is generated from an accessible potential 580 TW (UNEP and New Energy Finance, 2009). The difficulty in relying upon wind and solar supplies arises from the intermittency of these sources and the lack of technologically developed storage capabilities and transmission grids. Intermittency problems can be addressed by utilizing a base supply generated from a steady renewable source such as geothermal or tidal power, relying upon wind at night and solar by day, and augmenting this mix with a reliable renewable source such as hydropower to smooth out supply or meet peak demands. A case study has shown the ability of this mix to generate 100% of California's electricity around the clock for a typical July day in the year 2020 (Jacobson and Delucchi, 2009).

Technologies advances are important, but economic and political factors are also critical to large-scale deployment of renewable energy. In the United States, generation of electricity from renewable sources increased during the restructuring of domestic electricity markets because of such state-based policies as the renewables portfolio standard (RPS). An RPS typically requires eligible renewable energy sources to compose a certain minimum percentage of the electricity produced (or sold) in a state, and as of 2008, 27 states and the District of Columbia had RPSs and another 6 states had voluntary programs. Compliance with these RPSs is estimated to result in another 60 GW of new renewable electricity by

2025. Installing wind technology to generate 8 GW per year and solar technology to generate 0.2 GW per year would result in full compliance with the RPSs in less than 10 years. A federal production tax credit (PTC) also contributes to the growth of renewable energy by offering a 2.1-cent tax credit (in 2009) for every kilowatt-hour of electricity generated in the first 10 years of the life of a private or investor-owned renewable electricity project. The PTC has been extended and other incentives expanded in the Emergency Economic Stabilization Act of 2008 and the American Recovery and Reinvestment Act (ARRA) of 2009. The ARRA includes $2.5 billion for applied research, development, and deployment activities of the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). The bill also includes $6 billion to support loan guarantees for renewable energy and electric transmission technologies and $11 billion to modernize the nation's electricity grid and study the transmission issues facing renewable energy. Future incentives that might be legislated in the United States to hasten growth in development of renewable energy include a federal RPS, a carbon tax, a cap-and-trade scheme, or a carbon portfolio standard.

C.2.13 Greenhouse Gases and Global Warming Potentials

A large amount of scientific evidence has established that changes in the atmospheric abundance of GHG can alter the energy balance of the earth's climate system through absorption of infrared radiation, which traps heat within the surface–troposphere system. This global warning concern led to the development of the Kyoto Protocol by the United Nations Framework Convention on Climate Change (UN, 1998). The protocol indicates that an entity should assess its operations for sources that emit, utilize, or produce materials that contain the following six GHGs (UN, 1998): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Typically, the global warming potential (GWP) of GHG emissions is calculated by the heat-trapping ability of each GHG relative to CO_2. The Intergovernmental Panel on Climate Change (IPCC) has been periodically updating the GWP conversion factors listed in Table C.9 in response to changes in the global concentrations and atmospheric residence times of these gases. Therefore, prior to reporting, emission of each gas is typically converted to carbon dioxide equivalent (CO_2-e) using the 100-year GWP values. For instance, one ton of CH_4 is equivalent to approximately 25 tons of CO_2-e based on the 2007 GWP data.

Table C.9. GWP Estimates of GHG

GHG	1995	2001	2007
Carbon dioxide	1	1	1
Methane	21	23	25
Nitrous oxide	310	296	298
Sulfur hexafluoride	23,900	22,200	22,800
Hydrofluorocarbons*	140–11,700	120–12,000	124–14,800
Perfluorocarbons*	7000–9200	5700–11,900	8830–12,200

*The actual value is relevant to a specific compound.
Source: IPCC, 2010

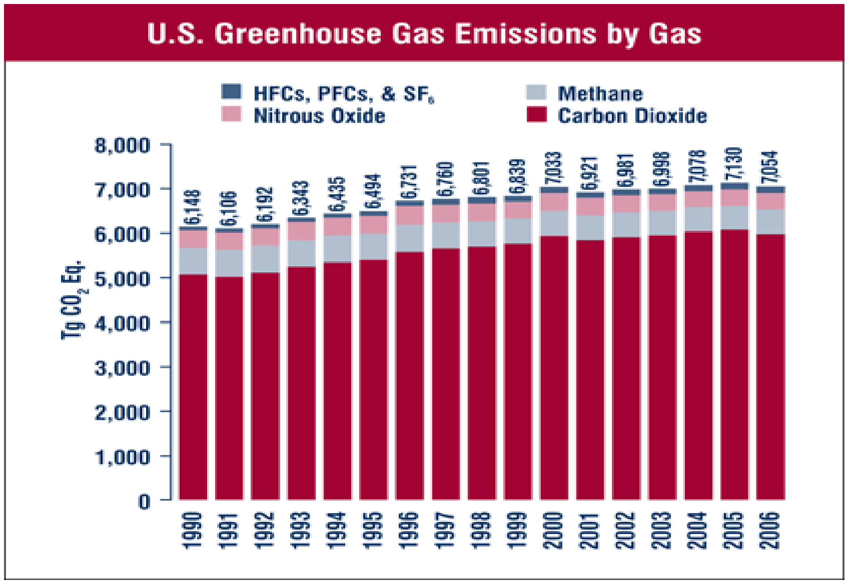

Figure C.11. GHG emission inventory of the United States (USEPA, 2010).

Figure C.11 illustrates the relative contributions of the direct greenhouse gases to total U.S. emissions for the period 1990–2006 (USEPA, 2010). The primary greenhouse gas emitted by anthropogenic activities in the United States was carbon dioxide (CO_2), representing approximately 85% of total GHG emissions. Carbon dioxide can be removed from the atmosphere through activities such as planting trees, improving existing forests, and soil management. Carbon sequestration in the United States in 2006 removed approximately 13% of total U.S. emissions (USEPA, 2010; USEPA, 2011).

C.2.13.1 Typical Greenhouse Gas Sources in Desalination and Reuse Facilities

Desalination and reuse facilities contribute to GHG emissions primarily through the use of stationary combustions, mobile combustions, and treatment processes. The following categories of sources emit GHGs from a water/wastewater treatment facility:

Scope 1 (Direct) Emission Sources. These emission sources include all direct GHG emissions, except for direct CO_2 emissions from biogenic (that is, recently biologically fixed) sources. Typical sources of Scope 1 emissions are provided in Table C.10.

Scope 2 (Indirect) Emission Sources. These emissions occur outside of the boundary of the entity (e.g., electric utility) from the production of electricity, steam, or hot/chilled water for use within the entity's organizational boundary.

Scope 3 (Other Indirect) Emission Sources. These indirect emissions occur within organizational boundaries, and the organization can exert significant influence over these emissions. Examples of such emissions are supply-chain GHG emissions such as upstream production and upstream/downstream transport of chemicals, materials, and fuels, landscaping, biosolids reuse including land application or other methods that are outside the organizational boundary, landfilling of biosolids, emissions from services contracted with outside vendors, and emissions from commuting and business travel of employees.

Table C.10. Description and Example of Direct Emission Sources

Subcategories	Description	Examples
Stationary	Nonmoving equipment that combusts fuels to produce steam, heat, power, or electricity	Boilers, heat drying, turbines, compressors, thermal oxidizers
Mobile	Movable equipment and/or transportation vehicles that combust fuel	Fleet vehicles and maintenance vehicles
Process-related	The results of physical and/or chemical processes	N_2O release nitrification/denitrification, any by-product
Fugitive	Intentional/unintentional release of emissions, primarily methane	Incomplete digester gas combustion, anaerobic and facultative treatment lagoons,

Source: Huxley et al., 2009

C.2.13.2 Regulatory Perspective on Greenhouse Gas Monitoring

There has been extensive interest in the United States in adopting the necessary policies to reduce anthropogenic releases of GHGs to the environment. Beginning in September 2009, the U.S. EPA adopted a mandatory GHG reporting rule for utilities with operations emitting 25,000 Mt CO_2 eq or higher per year (USEPA, 2010). It is estimated that about 10,000 facilities will have to comply with this regulation, although most domestic water and wastewater industries should fall below the emissions criterion that triggers compliance with this regulation. Various programs that govern GHG monitoring requirements for stationary combustion sources are listed in Table C.11.

Table C.11. GHG Monitoring Requirement for Stationary Combustion

Program	Type of Participation
California ARB GHG Reporting Rule—Proposed	Mandatory
US EPA Climate Leaders	Voluntary
US DOE 1605 (b) Voluntary Reporting of GHGs Program, 10 CFR 300	Voluntary
The Climate Registry (TCR)	Voluntary
California Climate Action Registry (CCAR)	Voluntary
US EPA Acid Rain Program	Mandatory
Regional Greenhouse Gas Initiative (RGGI)	Mandatory
European Union Emission Trading Scheme (EU ETS)	Mandatory
Australian National GHG Reporting System—Proposed	Mandatory
Canadian GHG National Reporting Program	Mandatory

Source: Huxley et al., 2009

Table C.12. List of GHG Tools Currently Available or Under Development

Organization	Type	Water or Wastewater
The Climate Registry	Registry & methodology	No
The California Climate Action Registry (CCAR)	Registry & methodology	No
USEPA Mandatory GHG Reporting Rule	Registry & methodology	No
USEPA Climate Leaders	Registry & methodology	No
International Council for Local Environmental Initiatives (ICLEI)—Local Governments for Sustainability	Methodology	No
Chicago Climate Exchange (CCX)	Methodology and GHG sales platform	No
US Department of Energy—Voluntary Reporting of Greenhouse Gases Program [1605(b)]	Methodology & registry	No
International Organization for Standardization (ISO) 140064/65	Framework methodology	N/A
UKWIR—Workbook for Quantifying Greenhouse Gas Emissions	Methodology	Yes
USEPA—National Greenhouse Gas Inventory	Top-down national GHG estimation methodology	Yes
Global Reporting Initiative	Framework methodology	N/A
UN Framework Convention on Climate Change, Clean Development Mechanism (CDM) and Joint Implementation	Methodology & registry of CDM projects	Yes
Regional Greenhouse Gas Initiative (Northeastern U.S. States)	Reporting framework for power sector & GHG trading platform	No
California Assembly Bill 32	Reporting framework and methodology	Yes, to be phased in

Source: Huxley et al., 2009

C.2.13.3 Calculation of Baseline Emissions from Desalination and Reuse Facilities

The baseline estimation of GHG emissions from desalination and reuse facilities is dependent on the assessment approaches currently utilized by water and wastewater facilities. GHG accounting methodologies have been well established under globally recognized frameworks. These include two principal sources: the IPCC and the World Research Institute/World Business Council for Sustainable Development (WRI/WBSCD). The IPCC is considered the source of all of the equations for calculating GHG emissions from all significant sectors, including treatment of wastewater from both municipal and industrial sources. The WRI is considered the source of the methodology for GHG accounting. Secondary to the IPCC, to which all signatories to the Kyoto protocol file annual report, are national regulatory entities that may have established specific equations governing GHG emissions inventory reporting the water sector. Emissions reporting practices have also been established by several organizations and a list of such registries, programs, and protocols is presented in Table C.12.

Some of the tools listed assist in quantifying emissions from business activities in general, but they are not specifically tailored to the water sector. A number of water utilities have developed their own Excel-based spreadsheet models for estimating emissions. These calculated results are valid for regulatory agency reporting purposes provided that all of the assumptions and emission factors utilized in the calculations are properly identified. It is important to note that the science of stationary and mobile combustion sources and the associated GHG emissions calculations have become well established and standardized within the protocols developed by the agencies.

C.2.13.4 Greenhouse Gas Emissions by Desalination Technologies

This section provides a comparative evaluation of GHG emissions from the three most commonly used desalination technologies, namely, MSF, MED, and RO. Table C.13 shows CO_2 and NO_x emissions reported by Raluy et al. (2006) for these three desalination technologies. The assessment was conducted by applying life-cycle analysis to examine cradle-to-grave consequences of making and using products and services, energy and material usage, and waste discharges. The results suggest that the emissions from the RO system are an order of magnitude less than those from thermal processes. The primary sources of electricity used for this analysis were, in terms of origin, 43% thermal, 40% nuclear, and 17% hydropower. The energy consumption of RO desalination technology has progressively declined in recent years due to the installation of energy recovery systems, utilization of more energy-efficient membranes, and better system designs. An analysis was conducted by Raluy et al. (2005) to show how utilization of less energy reduces the life-cycle emissions of the primary GHGs. The results indicate that both CO_2 and NO_x emissions drop as less energy is consumed, but the rate of emission reduction is higher for NO_x, which has about 300 times more global warming potential than CO_2 emission (Raluy et al., 2006).

Table C.13. GHG Emissions Produced by Desalination System

Technologies	Emissions/m^3 Desalted Water		Design Assumptions
	CO_2 (Kg)	NO_x (g)	
MSF	23.41	28.3	• Brine recycle flow with high-temperature anti-scale treatment and cross-tube configuration • Average 45,000 m^3/day of desalted water • Thermal energy consumption is 333 MJ/m^3 of desalted water • Mechanical energy consumption is 4kWh/ m^3 of desalted water
MED	18.05	21.41	• Horizontal falling film and high-temperature anti-scale treatment • Average 45,000 m^3/day of desalted water • Thermal energy consumption is 263 MJ/m^3 desalted water • Mechanical energy consumption 2 kWh/m^3 of desalted water
RO	1.78	3.87	• Consists of eight trains • Average 46,000 m^3/day of desalted water with 8000 h of operation per year • Mechanical energy consumption is 4 kWh/m^3 of desalted water

Source: Raluy et al., 2006

C.2.13.5 Greenhouse Gas Emissions from Traditional and Renewable Energy Sources

To understand the benefit of integrating renewable energy sources for desalination and reuse plants, comparative evaluation of GHG emissions from traditional and renewable energy sources and the factors impacting GHG emissions estimations is necessary. Weisser (2007) reviewed and compared GHG emission life-cycle analyses of fossil fuel and renewable energy technologies. The life-cycle assessment of energy sources of that study accounted for GHG emissions in the following stages:

- Energy resource exploration, extraction, and processing
- Raw materials extraction for technology and infrastructure
- Production of infrastructure and fuels
- Transport of fuel and related transport activity (e.g., construction, decommissioning)
- Conversion to electricity or heat or mechanical energy
- Waste management and associated infrastructure

Table C.14. Parameters Impacting GHG Emission Estimation Associated with Different Energy Sources

Energy Source	Factors
Fossil fuels	• Carbon content and calorific value • Mine type and location • Fuel extraction practices • Transmission losses • Conversion efficiency • Installation rate and efficiency of emission control devices • Life time and load factor
Solar	• Grade and quantity of silicon used • Technology type • Installation type (e.g., slanted and flat rooftop, façade) • Lifetime • Module efficiency • Balance of system (bos) material and efficiency
Wind	• Tower and nacelle for onshore systems • Tower and system foundation for off-shore system • Capacity factor • Life time • Scale up and associated efficiency issues

- *Source*: Weisser, 2007

Consideration of the upstream and downstream processes of the power plant (i.e., the electricity generation stage) and associated GHG emissions is important to avoid any sort of underestimation during the life-cycle GHG emission assessment. For instance, upstream GHG emission rates can be up to 25% of the direct emissions from the power plant for fossil fuel, whereas more than 90% of cumulative emissions can account for the upstream and downstream emissions of renewable energy technologies. According to a study conducted by the Department of Energy, about 10% of natural gas (e.g., methane) is lost before reaching the power plant, creating significant GHG emissions from this traditional power source, because the GWP of methane is roughly 23 times higher than the GWP of carbon dioxide. A large number of factors impact the estimation and interpretation of GHG emissions associated with energy production. A list of important factors is presented in Table C.14.

Lignite power plant emissions ranged from 800 to 1700 g CO_2eq/kWh. In coal-fired and natural gas power plants, the emissions values ranged from 800 to 1000 g CO_2eq/kWh and 360 to 575 g CO_2eq/kWh, respectively (Weisser, 2007). For wind energy sources, the emissions ranges for onshore and offshore turbines were 8–30 and 9–19 g CO_2eq/kWh. Theemissions of four different types of photovoltaic systems, monocrystalline, multicrystalline, amorphous, and CIGS (copper indium gallium diselenide), ranged between 43 and 73 g CO_2eq/kWh.

C.2.13.6 Greenhouse Gas Emissions by Desalination Technologies Integrated with Renewable Energy Resources

The GHG emissions from renewable energy sources are significantly lower than the emissions from traditional energy sources. Therefore, utilization of renewable energy for the desalination process should significantly reduce GHG emissions from desalination facilities. Raluy et al. (2005) conducted a comparative assessment of the life-cycle GHG emissions of an RO plant operated with traditional energy and renewable energy sources. The findings, along with some important design assumptions, are presented in Table C.15. The analysis suggests that CO_2 and NO_x emissions from an RO plant operated with a traditional energy source are twice those emitted from a plant operated with solar energy and an order of magnitude higher than those emitted from a plant operated with wind energy. The study also evaluated the impact of plant size on GHG emissions from renewable energy sources. The data show that an increase in the wind or solar plant production capacity should substantially decrease GHG emissions.

Table C.15. GHG Emissions of RO System Integrated with Renewable Energy

Technologies	Location	Emissions/m^3 Desalted Water		Design Assumptions
		CO_2 (Kg)	NO_x (g)	
RO with traditional energy source	Europe	1.78	4.05	• Energy requirement was about 4 kWh/m^3 desalted water • 43.3% thermal, 40.3% nuclear ,and 16.4% hydroelectric
RO with WE (150 KW)	Switzerland	0.17	0.412	• Lifetime of moving parts was 20 years and nonmoving parts was 40–50 years
RO with WE (2 MW)	Denmark	0.117	0.429	• The plant generating 2MW was an offshore plant with a capacity factory of 30% • The efficiency of wind plants was assumed to be 25%
RO with SE (100 kWp, polycrystalline Si)	Switzerland	0.9	2.105	• Flat plate collectors with a gas natural boiler (producing about 40% of total energy) to compensate when solar was insufficient in bad weather
RO with SE (500 kWp, monocrystalline Si)	Switzerland	0.626	1.816	• Plant lifetime was 30 years • The photovoltaic plants in operation in Switzerland show an average electricity production of 860 kWh/kWp

Note: KWp refers to kilowatt-peak for solar panel installations.

Source: Raluy et al., 2005

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