Investigation of the Water-Renewable Energy-Nexus in Transition Plans Towards Sustainability in Iran
(イランにおける持続可能な社会に向けた移行計画のための水・再生可能エネルギーネクサスの研究)

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Abstract

This work deals with two interconnected transitions happening due to climate change in the in the regions facing water scarcity and having access to water sources to be desalinated: First, the transition towards energy systems with a high share of variable renewable resources; Second, the transition towards water systems with a share of its supply coming from desalination. The first aims to cut greenhouse gas emissions, while the latter provides an alternative water supply.

Different sources and their associated technologies can be combined into a range of diverse systems which meet transition targets, and result in an array of different sociotechnical regimes. This research aims at investigating the role of the water-energy-nexus in transition plans towards a higher share of renewable energy, and desalination as a share of the water supply. It further probes the impacts of these transition plans on the economy, environment and society.

A novel nonlinear methodology, which represents the characteristic of the nexus concept, is applied to design transition pathways for interconnected energy and water sectors. First, as two Separated Systems, in which each sector is considered as an exogenous factor for the other sector, without any control on each other. Secondly, this research investigates the water and energy sectors in an Integrated System, in which both are studied together, as endogenous parts of one single system. Plans and solutions towards aforementioned transitions are designed for both system types in the southern coast of Iran, which has ready-access to seawater but faces severe potable water scarcity. These outcomes are benchmarks for trade-offs between system integration on one hand, which increases complexity to the point where the decision making is delayed or incapacitated; and on the other hand separated systems, which are less complex, but potentially less efficient. Moreover, different system configurations, namely centralized versus decentralized systems in combination with various technology mixes, could influence the extent of these synergies, inefficiencies, conflicts of interests, and their complexity.

In short, the key contributions, conclusions of the research and the important findings obtained are as follows:

1. Applying a novel nexus approach, an interactive multi-period model is developed to design renewable energy and water supply with consideration of Iran's particularities and situation:
    - The nexus approach reveals the capacity of an integrated planning of the energy and water sectors, which considers the operational aspects in long-run planning, in order to achieve synergies and avoid conflicts or inefficiencies that arise from separated planning.
    - Furthermore, it shows that a water supply with a share of desalination operates efficiently as a flexible electric load, compensating for fluctuating variable renewable power generation, thereby addressing to some extent one of the main challenges of a future energy sector with a high share of variable renewables.
2. Applying the proposed nexus model, this research demonstrates and assesses different configurations of centralized versus decentralized water sectors powered by on-grid renewables for an integrated water-energy supply planning:
    - The decentralized solutions give rural areas, prioritized in the SDGs strategies in Iran, an opportunity to fully engage in the transition plans, thereby enhancing the overall sustainability of the future system.
    - While the energy sector benefitted greatly from an integrated design in all the proposed scenarios for the case study, the water sector experienced synergistic results only in the scenario using multiple effect distillation desalination technology, in a decentralized configuration.
3. The research establishes social equity as a key factor in design and quantitative nexus evaluation of water and energy transition plans:
    - The comparative distributive justice analysis demonstrates that scenarios with decentralized desalination distribute benefits and burdens of the transition between urban and rural areas, while enhancing the overall system equity level.

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Abbreviations and Acronyms

Abbreviations and acronyms used throughout the work are reported here. Further specific nomenclature is reported in the Appendices.

VRE	Variable renewable energy
ESS	Energy storage systems
MSF	Multi-stage flash
MED	Multiple-effect distillation
VC	Vapor compression
RO	Reverse osmosis
ED	Electrodialysis
MD	Membrane distillation
MVC	Mechanical vapor compression
TVC	Thermal vapor compression
H/HD	Humidification/dehumidification
PV	Photovoltaic
RE	Renewable energy
LCOE	Levelized cost of energy
LCOW	Levelized cost of water
TDS	Total dissolved solids
NPC	Net present cost
O&M	Operation and maintenance
GDP	Gross domestic product
SDGs	Sustainable development goals
LDR	Learning-by-doing ratio

LSR	Learning-by-searching
FYDPs	The Iranian Five-Year Economic, Cultural and Social Development Plans
R&D	Research and development
CDF	Cumulative distribution functions
PDF	Probability density function
GHG	Greenhouse gas

Chapter 1

Introduction and Background

1.1 Background

Over 2 billion people live in countries under high water stress in 2019 (UN Water, 2018). A United Nations study predicted that, by 2050, under the current average economic growth rate and without improvement in the water sector's efficiency, the global freshwater demand could increase by 20% to 30% (UN, 2019). The ongoing pace of improvement in water sector efficiency is not sufficient to close this freshwater supply-demand gap (UN Water, 2018). Moreover, the potential of remaining freshwater resources that can be harnessed sustainably is limited, and due to steep marginal costs, the water prices are expected to rise (World Bank, 2019).

There are non-conventional options, such as desalination and reuse of wastewater, which are the ultimate solution to meet water demand in specific regions. Rapidly progressing desalination technologies and market maturation have led to a significant drop in desalination costs, and the environmental impacts of the desalination process are progressively being mitigated. Even though desalination costs are likely to remain more expensive than other traditional water options, it will increasingly be considered as an option in specific areas due to climate change, natural and physical water scarcity, freshwater resource security, and the need to improve access to clean water and address health concerns.

Climate change is likely to impose a greater incidence of drought due to decreasing and unpredictable rainfall, as well as a higher rate of evaporation arising from higher temperatures. The rising temperature could also cause an increase in water demand, exacerbating competition among agriculture, municipal, and industrial users. Desalination constitutes a viable solution to enhance climate change resilience.

Additionally, desalination is economically and politically important to achieve self-reliance in specific areas. Israel and Singapore are examples where investments in desalination have been made to reduce their dependency on imported water due to their geopolitical situation. Furthermore, with population growth, providing quality water for cities becomes a challenge for policy-makers. Supplying water to dynamic sectors of the economy, namely commercial and industrial users, is an economic priority. Any failure in providing water to these sectors leads to high economic, social, and political costs. Desalination is considered a secure supply with high reliability for these water demands.

As a result, desalination is becoming an economical and practical option to meet water demand in an increasing number of locations. A multi-criteria analysis in Kuwait (Aliewi et al., 2017) showed that among management options and strategic policies to meet future water demand, desalination powered by renewable resources and wastewater reuse ranked the highest. Based on Figure 1-1, municipal and industrial sectors account for the main share of desalinated water production worldwide.

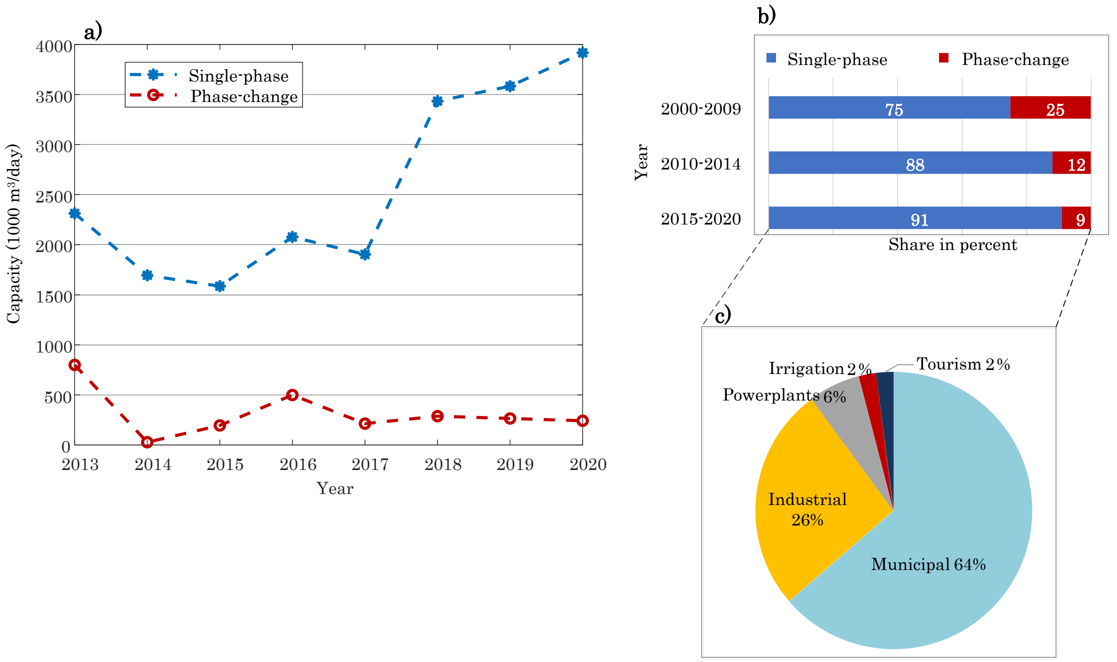


Figure 1-1. Total worldwide installed desalination: **(a)** capacity by technology; **(b)** technology share; and **(c)** share of each user from worldwide desalinated water (ALMAR Water Solution, 2017).

On the other hand, the total world energy consumption has been forecasted to increase by 44% from 2006 to 2030, according to a report by the US Department of Energy (Khan and Arsalan, 2016). Desalination is an energy-intensive process. Energy requirement in commercial desalination processes ranges from a minimum of 1.8 KWh/m^3 for reverse osmosis technology to a maximum of 12.5 KWh/m^3 for multi-stage flash technology (Gude, 2016a; World Bank, 2019). On average, desalinating 1000 m^3 of saline water by conventional technologies consumes about 37 barrels of crude oil, utilizing combined cycle power plant and reverse osmosis desalination technology, which causes around 10 tons of CO_2 emissions (Alkaisi et al., 2017). According to the World Energy Outlook 2016 IEA, in the Middle East, the water sector's share of total electricity consumption is expected to increase from 9% in 2015 to 16% by 2040, because of a rise in desalination capacity. Furthermore, the energy sector is also set to become thirstier over the next decades, with energy-related water consumption increasing by nearly 60% between 2014 and 2040. In the meantime, many countries have targets to reduce dependency on fossil fuels and move towards energy systems with higher shares of variable renewable resources (VRE), which can cause problems such as instability in electricity systems due to the inherent fluctuation of renewable energy resources. There are solutions to overcome this instability, including the installation of energy storage systems (ESS), to increase the flexibility of demand (demand response), and exchanging renewable electricity with neighboring countries or regions.

There are two types of fluctuation which need to be dealt with. First, fluctuations for short periods (minutes to hours) which are studied in this research and second, fluctuations for long periods (days to weeks). The security and resilience of energy systems with a high share of variable renewable resources highly hinge on designing and planning solutions to these two types of fluctuations in order to avoid instability in energy systems. Moreover, solutions that provide long-term storage, hydrogen among others, play a chief role in mitigating risks associated with reliance on the exchange of renewable energy with neighboring countries, such as potential political conflicts or technical failures. It is considered that the integration of water systems and their share of desalination supplies, with the energy systems and their share of variable renewable resources, could offer potential solutions to solve this instability to some extent through the provision of flexible demand.

Although desalination costs have dropped significantly because of technological progress, market maturation, the sustainability of these systems are still under question because of the environmental impacts of the desalination process, such as high carbon footprint and effluent-associated pollution, which are only partially mitigated. Contributions that meaningfully address the technical, economic, environmental, and social issues of desalination are required in this era of water stress in order to achieve sustainable desalination in the future.

1.2 Aim of the work

Due to climate change and overutilization, a growing number of countries face stress on freshwater resources. Desalination technologies provide a viable alternative solution, and a number of these countries have plans to increase the share of desalination in their water supply. Currently, more than 150 countries in the world are already using desalination technologies. However, since desalination is an energy-intensive technology, energy consumption for water provision is expected to increase. Fossil fuel resources are the main supply for powering desalination facilities in the world. The energy sector, as the focal target for decarbonization, plays a chief role in achieving net greenhouse gas emissions neutrality through a transition towards a high share of renewables. The renewable energy resources with steady and stable power generation such as hydropower and biofuels are limited in the regions facing water scarcity. Due to fluctuating power generation from variable renewable energy resources (VRE) — arising from their intermittent nature — energy systems with a high share of VRE, namely wind and solar resources, may fall short on a vital feature: stability. Ensuring system stability requires flexibility, which is defined as the system ability to cope with events, causing imbalances between supply and demand at different time scales. The water sector with desalination facilities — as flexible electric load — can reduce the fluctuation in VRE power output. The Middle East is suffering from severe water scarcity and its energy sector heavily depends on fossil fuel available in its rich local reserves. In short, this research deals with two transitions happening in the Middle East: first, the transition towards energy systems with a high share of variable renewable resources; second, the transition towards water systems with a share of its supply coming from desalination.

Traditionally, energy and water transitions have been largely understood in terms of sources and associated technologies, such as the transition from oil to renewables. Combinations of these sources and technologies are highly flexible to be shaped into a range of diverse systems with different forms of social, economic, and political arrangements that need to also be factored into planning of the transitions.

This study aims to investigate the role of the water-energy-nexus in transition plans towards a higher share of renewable energy and using desalination as a share of the water supply. It further probes the impacts of these transition plans on the economy, environment and society in the regions facing water scarcity. It attempts to clarify the extent to which the nexus between interconnected sectors would lead to different plans, solutions and results for a transition towards sustainability, in comparison with the outcomes of separated systems. Finally, it investigates how the nexus approach could influence or reform the future characteristic shape and structure of the system, stakeholders, as well as economic and social transformations inevitably happening when transitioning from one system to another.

1.3 Literature review

This literature review seeks to identify the state-of-art of desalination-based water provision, considered from a wide variety of perspectives beyond just the techno-economic analysis and address the interlinks between water sector and energy sector. It aims to identify the promising advantages of desalination technologies, particularly in connection with renewables, and to clarify the identified disadvantages as shown through a critical review of recent studies. In addition to extracting the technical and economic trends and emerging environmental and social issues of desalination technologies, it highlights the role of renewable energy technologies in the sustainability of the future water sector with an increasing share of desalination.

1.3.1 Technical Aspect

Desalination Technologies

The desalination technologies are divided into two categories: desalination with phase-change or thermal processes and desalination with single-phase or membrane processes. These technologies are summarized in Table 1-1. The phase-change desalination technologies include multi-stage flash (MSF), multiple-effect distillation (MED), vapor compression (VC), and freezing. Reverse osmosis (RO), electrodialysis

(ED), and membrane distillation (MD) are examples of the single-phase desalination technologies. Reverse osmosis, multi-stage flash, multiple-effect distillation, electrodialysis, and hybrid technologies are commercially viable and commonly use desalination technologies with a share of 63%, 23%, 8%, 3%, and 3%, respectively (Li et al., 2018).

Table 1-1. Desalination technologies.

Phase-change processes	**Membrane-based processes**
Multi-stage flash (MSF)	Reverse osmosis (RO)
Multiple effect distillation (MED)	Electrodialysis (ED)
Vapor compression (VC)	Membrane Distillation (MD)
Freezing	
Humidification/dehumidification	
Solar stills	

Currently, multi-stage flash distillation (MSF) and multi-effect distillation (MED), reverse osmosis, and a combination of these technologies (hybrid desalination) are the dominant technologies for seawater desalination.

Phase-Change Desalination

The primary energy required for phase change technologies is thermal energy. MSF, MED, and vapor compression (VC), which could be mechanical (MVC) or thermal (TVC), are the most commercially available technologies in this category (Kalogirou, 2005). In the MSF process, vapor is generated by a sudden pressure reduction of seawater or brine when saline water enters an evacuated chamber stage by stage. MED is based on vapor generation using the absorption of thermal energy by saline water. In the VC process, after the generation of vapor from saline water, this vapor is converted into freshwater by thermal or mechanical compression.

The separation process in the desalination of water by freezing follows the solid–liquid phase-change phenomenon. In this process, the temperature of saline water is reduced to the freezing point, which ice crystals of pure water are formed within the salt solution. Refrigeration systems are used in this process to reduce the temperature. In the next step, these crystals can be separated and washed. A humidification/dehumidification (H/DH) process captures the water vapor, which is mixed with air. In this method, brine is used to increase the humidity in an air stream. In the next stage, freshwater is collected by condensing this humid air on the surface of cool coils. H/DH technologies have not matured industrially due to technical barriers (Kalogirou, 2005).

Single-Phase Desalination

The primary types of energy needed for membrane-based desalination are electricity and hydraulic pressure. Reverse osmosis, electrodialysis and membrane distillation (MD) technologies are the most commonly utilized in this category. In the RO processes, electricity or shaft power is required to drive high-pressure pumps. For the RO process, mechanical pressure is applied to overcome osmotic pressure and separate salt of saline water. In the ED process, electricity is used for the ionization of salts contained in the seawater. The membrane distillation process consists of two streams: one hot saline stream and a cool freshwater stream. Water vapor is transported between these two streams because of a temperature difference of streams. With a 80 percent water recovery rate, ED technology has better performance compared to RO technology, which has about a 40 to 50 percent recovery rate.

Hybrid Desalination

Hybrid desalination plants are typically co-located with power plants so as to use waste heat for a thermal desalination facility (MSF or MED) and a combination of a RO desalination plant. Combined thermal and RO plants are usually suitable for situations with wide diurnal or seasonal variation in power or water demand. In such countries, peak power demand during summer is 30 to 40 percent higher than the maximum power demand in winter. In the Middle East, this difference reaches up to 50 percent, while the demand for desalinated water is almost constant. Switching between the RO and thermal plants allows benefiting from cheap available energy, thus leading to the cheapest desalination process.

Renewable Energy and Desalination

Among renewable resources, hydropower and biomass sources are not suitable in combination with desalination technologies due to the requirement for water resources, which is limited in regions facing water scarcity. A study (Tokui et al., 2014) considered biomass resources in order to reduce the CO_2 footprint of desalination plants in Saudi Arabia but did not mentioned the source or type of biomass. In areas with abundant solar irradiance, the main focus has been on integrating the desalination process and solar energy since water scarcity is more likely to occur in these regions (Vakilifard et al., 2018). Solar energy, with 51 percent of worldwide renewable desalination capacity, has the highest share, followed by wind energy, which accounts for 30 percent (Kharraz et al., 2017). Due to affordability, availability and zero water consumption for power production compared to other renewable resources, wind and photovoltaic (PV) resources have been recommended by several studies to operate RO plants (Astariz and Iglesias, 2015; Eltawil et al., 2009; Gude et al., 2010; Manju and Sagar, 2017). Figure 1-2 shows the integration of desalination technologies with renewable energy resources and the share of each renewable technology in desalination worldwide. Geothermal as well as wave and tidal resources are the other options to couple with renewable resources, which are still in the research phase and are not yet economically feasible (Alkaisi et al., 2017).

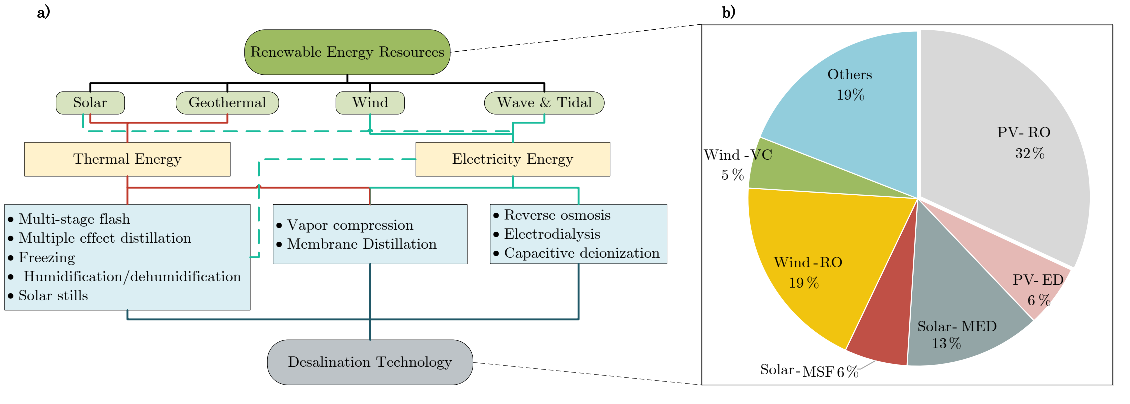


Figure 1-2. (a) The integration of desalination technologies with RE. **(b)** The share of renewable energy technologies in worldwide renewable-powered desalination processes in 2017.

Previous studies (Slocum et al., 2016) investigated co-locating pumped hydro storage systems with reverse osmosis desalination plants based on geographical and economic benchmarks in several cities in the USA, Iran, China, and Chile. The results indicated that pumped hydro systems can compensate for the intermittent nature of power generation from photovoltaic panels and wind turbines and decrease the energy intensity needed for reverse osmosis plants. Average daily historical data were used for calculating the renewable energy (RE) generation for a whole year, which did not describe the renewable production with sufficient accuracy to calculate the fluctuations resulting due to the intermittent nature of renewable power production. Another study (Aminfard et al., 2019) proposed a spatial model to assess potential technical and economical viable site locations for desalination facilities powered by renewables, namely wind and solar. Depth of water resource, distance to current water facilities, salinity degree, the magnitude of local RE resources, and local water price were considered as criteria in the model. Among 1,445 site locations, 193 site locations were recognized as economically viable for RO desalination facilities, 145 of which were wind-powered desalination units. Solar-powered units were preferable at the remaining 48 sites.

There are three categories of technologies to harness ocean energy: thermal, mechanical, and chemical or salt gradient. The ocean mechanical, namely tidal and wave energy, and the thermal energy technologies are more advanced than ocean chemical energy technology. Integrating the thermal energy technologies with phase-change desalination processes and using direct ocean mechanical energy, namely tidal, wave, and current energy, without transforming to electricity in desalination methods needing hydraulic pressure, could improve the efficiency and economic feasibility of the integrated systems. Ocean salt gradient technology is still far away from being a reality. However, in the future, ocean salinity gradient energy is a promising ocean energy source, since the forward osmosis, pressure retarded osmosis, and reverse electrodialysis devices can be readily integrated into current desalination technologies as a recovery energy system without major reconstruction in plants. There are several limitations for developing ocean-based power generation, including technological and economic limitations of energy harvesting and transport, as well as device maintenance underwater. Having said that, using ocean energy in desalination applications could solve the ocean energy technological defects relating to economic limitations by co-location in the future (Li et al., 2018).

Solar thermal and geothermal resources are water-consuming resources. Water availability is an essential factor that must be considered to assess the potential of these resources in each region, which has not been considered in the majority of studies such as (Kang and Cho, 2018; Ramos et al., 2017). A study (Tarroja et al., 2018) examined the extent to which physical water scarcity can limit the deployment of geothermal and solar thermal energy resources to produce electricity in California. The study first calculated the sustainable amount of extraction from the water resources and then determined the supportable capacity of these power plants from the available water supply based on technology and cooling type by 2050. For several areas in California, the estimated capacity of geothermal and solar thermal resources was found to be limited due to insufficient water availability, and without considering water limitations the assessment would not be realistic.

Table 1-2 indicates the renewable energy resources used for desalination purposes. This table shows that solar and wind electricity are the most common sources of renewable energy for desalination among studies. RO desalination technology is the dominant technology that has been studied the most (51 studies). MSF desalination technology, which requires high temperatures for the process, is not popular among studies, two studies in the Middle East and another one in the American region, compared to MED technology (8 studies), which operates at low temperatures.

Table 1-2. Renewable energy resources used for desalination purpose. RO: reverse osmosis; MED: multiple-effect distillation; MVC: mechanical vapor compression; MSF: multi-stage flash; ED: electrodialysis.

Model type									Desalination technology	Ref.
	Solar electricity	Solar thermal	Wind turbine	Geothermal	Ocean energy	Hydropower	Diesel generator	Hydrogen		
On-grid	✓								RO	(Al-Kaabi and Mackey, 2019)
	✓	-	-	-	-	-	-	-	RO	(Birge and Berger, 2019)
	✓	-	-	-	-	-	-	-	RO	(Ghorbani et al., 2017)
	✓	-	✓	-	-	-	-	-	RO, MED	(Caldera et al., 2018)
	✓	-	-	-	-	-	-	-	RO	(Caldera and Breyer, 2017)
	✓	-	✓	-	-	-	✓	✓	RO	(Abdelshafy et al., 2018)
	✓	-	-	-	-	-	-	-	RO	(Salama and Abdalla, 2019)
	✓	-	✓	-	-	-	-	-	RO	(Li et al., 2019)
	✓	-	✓	-	-	-	-	-	RO	(Jaime Sadhwani and Sagaseta de Ilurdoz, 2019)
	✓	-	✓	-	-	-	-	-	RO, MVC	(Marini et al., 2017)
	✓	✓	-	-	-	-	-	-	RO	(Katz and Shafran, 2019)
	-	-	-	-	✓	-	-	-	RO	(Corsini et al., 2015)
	✓	-	✓	-	-	-	-	-	RO	(Mentis et al., 2016)
	✓	-	✓	-	-	-	-	-	RO	(Fornarelli et al., 2018)
	✓	-	✓	-	-	-	-	-	RO	(Shahabi et al., 2014)
	✓	-	✓	✓	-	✓	-	-	RO	(Nagaraj et al., 2019)
	✓	-	-	-	-	-	-	-	RO	(Sadiqa et al., 2018)
	✓	-	✓	-	-	-	-	-	RO	(Hamilton et al., 2019)
	✓	-	-	-	-	-	-	-	RO	(Cavalcante et al., 2019)
	✓	✓	-	-	-	-	-	-	RO	(Stokes and Horvath, 2009)
	✓	✓	-	-	-	-	-	✓	MSF	(Gençer and Agrawal, 2018)
	✓	-	✓	-	-	-	-	✓	RO	(Aminfard et al., 2019)
	✓	✓	✓	-	-	-	-	-	RO	(Gold and Webber, 2015)
	✓	-	✓	-	-	-	-	-	RO	(Kim et al., 2016)
	✓	-	✓	-	-	✓	-	-	RO	(De Barbosa et al., 2017)

	-	✓		-	-	-	-	-	MED	(Mata-Torres et al., 2017)
	✓	-	✓	✓	-	✓	-	-	MED	(Aghahosseini et al., 2019)
	✓	-	-	-	-	-	-	-	RO	(Vakilifard et al., 2019)
Total number	26	5	15	2	1	3	1	3		30
Off-grid	✓	-	-	-	-	-	-	-	RO, Solar-still	(Jijakli et al., 2012)
	-	-	-	-	✓	-	-	-	MED	(Ng and Shahzad, 2018)
	✓	✓	✓	-	-	-	-	-	RO, MSF	(Heidary et al., 2018)
	✓	-	✓	-	-	-	-	✓	RO	(Maleki, 2018)
	✓	-	✓	-	-	-	-	-	RO	(Peng et al., 2018)
	-	✓	-	-	-	-	-	-	MSF	(Darawsheh et al., 2019)
	✓	-	-	-	-	-	-	-	RO	(Mostafaeipour et al., 2019)
	✓	-	-	-	-	-	-	✓	RO	(Rezk et al., 2019)
	✓	✓	-	-	-	-	✓	-	RO, MED	(Astolfi et al., 2017)
	✓	-	-	-	-	-	-	-	ED	(Fernandez-Gonzalez et al., 2015)
	-	-	-	-	✓	-	-	-	RO	(Fernández Prieto et al., 2019)
	✓	-	-	-	-	-	-	-	RO	(Karavas et al., 2019)
	-	✓	-	✓	-	-	-	-	MED	(Calise et al., 2017)
	✓	-	-	-	-	-	-	-	RO	(Kyriakarakos et al., 2017)
	✓	-	✓	-	-	-	-	-	RO	(Li et al., 2017)
	✓	-	-	-	-	-	✓	✓	RO	(Kofinas et al., 2018)
	✓	-	✓	-	-	-	-	-	RO	(Giudici et al., 2019)
	✓	-	✓	-	-	-	-	-	RO	(Meschede, 2019)
	✓	-	✓	-	-	-	-	-	RO	(Padrón et al., 2019)
	✓	-	✓	-	-	-	-	-	RO, MD	(Uche et al., 2019)
	✓	-	✓	-	✓	-	-	-	RO	(Trapanese and Frazitta, 2019)
	-	-	-	-	-	-	-	-	Solar-still	(El-Kady and El-Shibini, 2001)
	✓	-	✓	-	-	-	-	-	RO	(Gulagi et al., 2018)
	✓	-	-	-	-	-	-	-	RO	(Alghoul et al., 2016)
	-	✓	-	-	-	-	✓	-	MED, Solar-still	(Park et al., 2016)
	✓	-	-	-	-	-	-	-	RO	(Thompson et al., 2016)
	✓	-	✓	-	-	-	✓	-	RO	(Gökçek, 2018)
	✓	-	✓	-	-	-	-	-	RO	(Liu et al., 2019)

	✓	-	✓	-	-	-	-	-	RO	(Ye et al., 2019)
	-	✓	-	-	-	-	-	-	MED	(Stuber, 2016)
Total number	23	6	13	1	3	-	4	3		30
	On-grid	**Off-grid**	**RO**	**MED**	**MSF**	**Solar-still**	**ED**			
Number of studies/ Total studies	30/60	30/60	51/60	8/60	3/60	3/60	1/60			

System Configuration

Configuration of a system is defined as the characteristic shape and structure of the system, as well as the technologies composing it. Conventional thermal desalination technologies are now well-proven and mature. Therefore, a further improvement in these technologies is relatively limited. Continuous innovation in RO desalination technology in the last twenty years has reduced the energy consumption per unit of product water to 1.8 KWh/m^3 compared to the historic energy consumption range of 3 to 5.5 KWh/m^3, which is close to the theoretical minimum required energy for seawater desalination (Elimelech and Phillip, 2011). This means that a further significant reduction in energy consumption is not expected for RO technology. However, further significant advances in membrane technology are predicted, which increases in water productivity per area (World Bank, 2019).

Decentralization

The variety of existing definitions and concepts of decentralization within the literature clearly indicates that different perspectives and incentive systems have been applied to political science, economics, technology, etc.

Political decentralization is mainly concerned with a redistribution of the authority and responsibility of a central entity over policymaking and decision-making. As an example of political decentralization, administrative decentralization is the transfer of responsibility for the planning, financing and managing of certain public functions from the central government and its agencies to field units of government agencies.

The economic decentralization is concerned with market types, participation, competencies (expenditure side) and fiscal instruments (revenue side). One example of economic decentralization is privatization of public owned functions and businesses. Market decentralization can also be done through deregulation, the abolition of restrictions on businesses competing with government services.

The current study refers decentralization as a transfer from concentrated to distributed mode production and consumption of goods or services (Eggimann, 2016). A centralized water system refers to systems in which desalinated water is produced in one unit and distributed among all target users, while a decentralized water system includes more than one desalination unit that is providing water demands. These decentralized desalination plants, mostly small-scale, have a great potential to solve the intermittent power generation problem of variable renewable resources, namely, wind and solar. These desalination plants can effectively operate without energy storage systems, mostly batteries, as water can be desalinated based on energy availability and stored as the final product (Freire-Gormaly and Bilton, 2018). This direct consumption of renewable energy increases the efficiency of the whole system because storage systems such as battery systems have a typical charge-cycle efficiency of 75 to 98% (Kharraz et al., 2017; Tomaszewska et al., 2019). Furthermore, high ambiance temperatures, which are common in regions facing water scarcity, increase the self-discharge rate and performance of batteries. A small-scale RO desalination unit coupled with a PV system with battery storage in Malaysia was tested for six months (Alghoul et al., 2016). The experiment aimed to examine the system performance and find the optimal condition to operate an RO desalination unit. The results indicated that climatic conditions, such as high ambiance temperatures, significantly reduced the performance of the battery and PV system.

Although desalination units with larger capacity face technical limitations to operate as variable units, it is still possible to integrate them with renewable resources to a certain extent. For instance, one of the main problems with an intermittent RO desalination unit is the biological fouling when the unit is not in operation. The pretreatment of intake feed-water can significantly decrease the fouling (Kharraz et al., 2017). This membrane fouling needs to be considered in the desalination system design in order to avoid an under-sized system and unmet water demand (Freire-Gormaly and Bilton, 2018). By providing flexibility of RO units and decreasing the required battery capacity, a study (Caldera et al., 2018) showed that the levelized cost of energy could be decreased by 3 percent in a 100-percent renewable-supply scenario for Saudi Arabia. The authors in another study (Gençer and Agrawal, 2018) introduced an integrated process of MSF desalination, hydrogen production, and solar power production. The study considered solar hydrogen production as an energy storage and a hydrogen-fired power plant to overcome issues related to the intermittency of solar power generation.

Furthermore, a centralized water system typically requires more energy for the water transfer and distribution than a decentralized water system. Water distribution pumps, with 70–80% of the energy consumed in a surface-water-based supply, are the highest energy-intensive components of conventional water supply systems (Vakilifard et al., 2018).

Other authors (Vakilifard et al., 2019) introduced an alternative water supply for a region in Australia. After calculating the surplus electricity production from roof-top PV systems for the region, this excess electricity production was considered as an energy source for RO units. This alternative system could provide a reduction of 20 percent levelized cost of energy (LCOE) for the PV system and 10 percent levelized cost of water (LCOW) compared to a system with no control on the water system. It should be noted that the surplus electricity production from the roof-top PV systems was assumed as waste energy with zero cost and zero benefit in the study.

1.3.2 Major Impacts on Desalination Cost

Removing the salts from saline water is a high-cost and high energy-consuming process compared to other freshwater supply and treatment alternatives. This section discusses the prospects of the current desalination costs and expected future costs of desalination for different technologies. Desalination technology, feed-water, energy use, intake–outlet system, and target water quality are the main factors affecting the desalinated water costs. Table 1-4 summarizes the cost of desalination for current commercially viable desalination technologies. Authors (Caldera et al., 2016) developed a model to estimate the cost of providing municipal, industrial, and agricultural water demand using RO desalination plants powered by a combination of PV, wind energy, battery and power-to-gas plants for regions facing water scarcity, regions where more than 40 percent of the renewable water resources are being withdrawn, in 2030. The levelized cost of water (LCOW) for the described system was found to be 0.65 to 3.10 USD/m^3.

Table 1-3 gives an overview on amount and type of required energy for desalination technologies.

Table 1-3. Energy consumption of desalination technologies (Giwa et al., 2016; Gopi et al., 2019; Gude, 2016a, 2016b, 2015; Li et al., 2018; Voutchkov, 2018; World Bank, 2019).

Technology	H/DH	MSF	MED	VC	RO	FD	ED	MD
Thermal energy (KWh/m^3)	45-100	7.5-11	4-7	0 (MVC) 51.9-63 (TVC)	-	8-24	-	30-240
Electricity (KWh/m^3)	-	2.5-3.5	1.5-2.5	7-15 (MVC) 1.6-1.8 (TVC)	1.8-6	-	2.5-5.5	0.6-1.8

Feed-Water

Salinity, temperature and biofouling elements of feed-water are important factors for RO desalination efficiency, performance, and costs, while the thermal desalination process is mostly insensitive to these factors. For low salinity, RO units desalinate water with lower cost comparing to the thermal desalination technologies, mainly because of energy-saving and lower energy requirements. As an example, a Red Sea RO seawater desalination plant with an average salinity of TDS (total dissolved solids) 44 ppt requires 30 percent more energy comparing to plants desalinating Pacific Ocean or Atlantic Ocean seawater, which have a salinity of TDS 35 ppt, with all other conditions being the same (World Bank, 2019).

Changes in feed-water quality and temperature affect the efficiency of RO plants because the membrane performance is sensitive to these changes during the thermal desalination process. A study (Voutchkov, 2018) found that RO plants in the Persian Gulf require 16 percent more capital costs and 14 percent more recurrent costs compared to ones in the Mediterranean region because of the different source of water. This is mostly because of the higher salinity and biofouling potential of seawater in the Persian Gulf, which requires costly pretreatment and intake systems and a more frequent need to change or clean the membranes.

Target Product Water Quality

Target water demands are categorized into three groups, namely potable demand, industrial demand, and agriculture demand. Studies in this field have mostly targeted potable water, and there are few studies which investigated the agricultural or industrial sectors as the target water user.

The product water of the thermal desalination process has lower salt (TDS of 50 milligrams per liter), boron, and bromide levels compared to water desalinated through the RO process. The high level of salt and boron of desalinated RO water needs to pass through an additional RO stage to achieve good-quality water. The second-pass stage can increase by 10 to 25 percent in the total cost of the first-pass desalination process (Voutchkov, 2018). Furthermore, calcium-based compounds and chlorine, for disinfection, are added to desalinated water which is typically soft before distribution. For most of the industrial and agricultural applications, it is not necessary to design this second-pass stage. The current costs of RO product water of desalination include the second-pass stage, which can reach up to 25 percent of the total RO water desalination costs. Studies which evaluate RO units without this second-pass stage are lacking.

Energy

Energy is one of the chief factors affecting the sustainability and feasibility of desalination projects. From 30% to more than 50% of desalination costs are spent on energy, as can be seen in Table 1-4 (Li et al., 2018). Energy affects not only the desalination cost, but also technology adoption. The largest desalination plants located in the Middle East are adopting thermal-process-based desalination technologies, making use of their rich fossil fuel reserves (Li et al., 2018). Currently, fossil fuel resources are the main supply for powering desalination facilities in the world (World Bank, 2019). Renewable-powered desalination is a promising solution to mitigate the carbon footprint and eliminate the dependency of desalinated water costs on fuel prices (IRENA, IEA-ETSAP, 2013).

Total recurrent costs for each unit product of RO desalination plants are about twice those of MSF desalination plants and three times more than the MED per unit of water production. The main share of these recurrent costs goes to energy.

Table 1-4. Cost components of the dominated desalination technologies (Gude, 2016a; World Bank, 2019).

Technology	Total Cost ($\$/m^3$)	Amortised capital (%)	Electrical energy (%)	Thermal energy (%)	Membranes (%)	Labor (%)	Chemicals (%)	Miscellaneous (%)
RO	0.6-2.86	36.2	37.2	-	3.5	11.2	8.2	3.8
MED	1.12-1.5	34.9	7.2	37.3	-	9.6	9.6	1.2
MSF	1.02-1.74	39.3	18.7	29	-	7.5	4.7	0.9

A study (Fornarelli et al., 2018) designed an energy supply for an RO plant to desalinate brackish water in a rural area in Australia. The RO desalination unit with variable capacity operation has been assumed to treat brackish water of a river as a water supply. The optimization results for a 25-year period showed that the hybrid system with a combination of wind turbines, rooftop solar photovoltaic and electricity grid had the minimum levelized cost of energy (COE) and minimum overall net present cost (NPC). Another study (Solomon et al., 2018) investigated several scenarios to achieve a net zero-emissions electricity supply system by 2050. In two scenarios, the future electricity demand for seawater desalination was forecast and considered. Although desalination demand was approximately 3 percent of the total electricity demand in 2050, the comparison among scenarios showed that sector coupling between the desalination and electricity sector does not cause a significant change to the future electricity supply. The reason is that the desalination electricity demand was constant in the study, causing the electricity system not to benefit from using desalination plants as flexible electric loads to compensate for the fluctuation of variable renewable power generation. Authors in another study (Molinos-Senante and González, 2019) evaluated the overall costs of RO water desalination by considering several scenarios for energy supplies in Chile. The study divided these costs into two categories, internal costs and external costs. Internal costs refer to investment costs as well as operation and maintenance costs, while the external costs cover a carbon tax on energy resources. The evaluation showed that by considering this carbon tax, the unit cost of desalinated water for scenarios with renewable energy resources is lower than the scenarios powered by conventional energy resources.

Water distribution pumps are also energy-intensive components, which should be considered for site selection, size of desalination plants, and type of water system, namely, decentralized water configurations with several small-size desalination units or centralized water systems with a large-size desalination unit. Figure 1-3 depicts the current state of development, potential capacity and estimated cost of water production for the integration of renewable energy resources with desalination technologies. For details, see the list of the reference studies to outline the development state of renewable-powered desalination technologies in Appendix A.

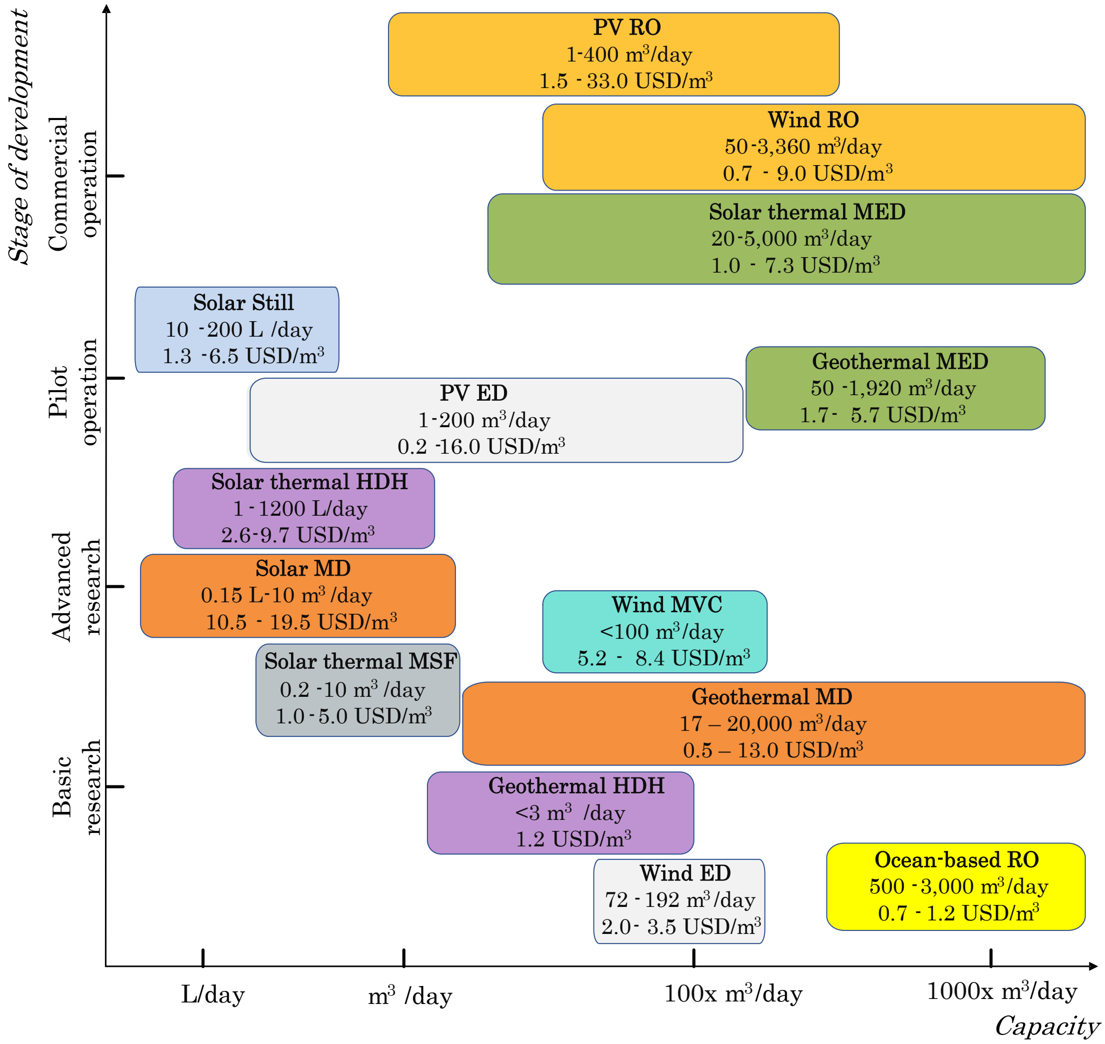


Figure 1-3. The status of the renewable-powered desalination technologies.

The current share of renewable desalination is less than 1 percent of global desalination capacity (Gude, 2018a). The cost of renewable desalination is still higher than the cost of conventional desalination powered by fossil fuels. However, renewable technologies are experiencing a rapid cost reduction, making the renewable desalination already cost-competitive with the conventional desalination in remote regions, where the cost of electricity transmission and distribution is higher than the cost of decentralized electricity generation. With this rapid cost reduction of renewable technologies, technical advances, and an improvement in the knowledge and experience by increasing the number of installations, the costs of renewable-powered desalination are likely to reduce significantly in the near future.

As discussed, each desalination technology has its advantages and disadvantages. As shown in Table 1-2, RO is the most utilized desalination technology among previous studies indicating the potential of this technology for integration with renewables as a future sustainable solution for water-scarce regions. As an advantage, RO plants are scalable, typically consisting of several dozen units, and thereby its size can be expanded to meet the growing demand by adding more units as needed. The costs of RO desalination significantly decrease in treating lower salinity or brackish water due to lower energy requirements. By contrast, thermal distillation processes, namely MED and MSF technologies, need the same amount of energy regardless of salinity. As a result, thermal distillation processes are more competitive than RO desalination technology for high salinity waters when there is also high biofouling potential. MED technology is more competitive at a smaller scale compared to MSF technology, making this technology a better option for integration with renewables. Furthermore, MED operates at lower temperatures than MSF; as a result, its process is more compatible for integrating with renewable thermal power generation.

Solar and wind resources have been widely used for powering desalination among previous studies, as can be seen in Table 1-2. Power generation from wind and photovoltaic requires zero or little water use (Gude, 2018a). Wind power is likely to be cheaper than photovoltaic power wherever it is available. Coastal areas usually benefit from a high availability of wind power resources. On the other hand, water-scarce regions or drylands are characterized by abundant solar radiation, which increases the capacity factor of solar resources and makes them more competitive compared to wind resources (Parrillo, 2008).

To sum up, the most promising combination of technologies is RO desalination technology with photovoltaic and MED desalination technology with solar thermal collectors. For large-scale units, wind power is more attractive wherever it is available, as it does not need a large area for installation, such as islands where often limited flat ground is available.

1.3.3 Environmental Issues

Studies repeatedly addressed the two major environmental impacts of the desalination process, the indirect impact, namely, the carbon footprint due to energy consumption, and the direct impact, intake seawater and effluent-associated pollution. Thermal, chemical and saline pollution caused by the disposal from the desalination process, which is most commonly discharged in the ocean, are the main environmental impacts of desalination. Evidently, the magnitude of these environmental impacts depends on the choice of desalination technology and site.

One study (Jijakli et al., 2012) compared three systems to provide potable water for a rural area in the UAE based on environmental impacts. These water systems included a solar still unit, a PV system coupled with an RO unit, and water delivery by truck from a central RO plant. The environmental impacts in the study were categorized as eco-toxicity, minerals, fossil fuels, carcinogens, respiratory inorganics, radiation, ozone layer depletion, acidification/eutrophication, respiratory organics, climate change, and land use. The result of a life cycle assessment indicated that the PV system, coupled with the RO unit, had the smallest environmental impact among these three proposed options.

Intake-Related Environmental Impacts

The main impact of intake facilities is on aquatic organisms. Subsurface intake wells, instead of direct saline or brackish water intake from the surface water, and constructed wetlands are commonly used to mitigate the environmental impacts of seawater intake for desalination. Adding an intake impact mitigation stage to desalination units can increase the capital cost by 5.3 percent and the annual operation and maintenance (O&M) costs by 4.5 percent (Rodriquez, 2015). A study (Al-Kaabi and Mackey, 2019) assessed the environmental impacts of the open-intake pretreatment and subsurface intake pretreatment of two RO desalination plants in the Persian Gulf. A life cycle assessment highlighted that the subsurface intake method had fewer environmental impacts compared to open intake pretreatment.

As discussed, renewable-powered desalination is suitable for the decentralized water configuration because of its size compatibility. The decentralized system increases the options of site locations for desalination units. Such multiple options enable the policymakers to choose site locations with a lower density of aquatic organisms.

Effluent-Related Environmental Impacts

Brine is a sub-product of the desalination process causing two environmental impacts including the effects of highly concentrated saline and metal components, namely, copper, nickel, iron, chromium, zinc, etc., which are discharged with the brine during pre- and post-treatment processes (Von Medeazza, 2005), that may heavily affect marine ecosystems. Besides, the outlet brine of the thermal desalination process could have a higher temperature than the ambient seawater and the amount of brine volume is much greater than the volume from RO process. Thermal desalination technologies use almost twice as much saline water comparing to RO technology to produce the same amount of freshwater. On the other hand, the outlet from the RO process is more concentrated, which requires treatment prior to discharge.

To decrease the impacts of brine on marine ecosystems, first, the discharging of brine into sensitive ecosystems must be avoided through process design and the assessment of site location, and its ecological value, its hydro-geological and hydrodynamic conditions; Second, the salinity must be reduced through active dilution processes, such as artificial diffusers or through natural local hydrodynamic conditions. Another study (Grubert et al., 2014) introduced a geographic information systems multi-criteria framework to identify regions that where suitable for the deployment of RO units coupled with solar energy supplies. The study chose solar irradiance, ocean salinity, ocean temperature water stress, prevailing water prices, and population as factors for evaluation. Another study (Fernández Prieto et al., 2019) examined the potential of wave energy resources to provide the power demand of current desalination plants for an island in Spain. The study assessed the selected location based on the environmental lens to ensure that there is no vulnerable or sensitive area, such as reserves or marine and land habitats, with some environmental protection, which are leading to restrictions for the deployment of wave energy converters. The technical aspect and the compatibility of the desalination technologies with the proposed alternative energy resource were not considered in the research.

Another study (Li et al., 2018) found that adding ocean salinity gradient energy devices to existing desalination plants can decrease these environmental and social risks without a major change to current desalination infrastructures. Another study (Slocum et al., 2016) introduced a hydro storage system with a reverse osmosis desalination plant that can help the problems related to brine disposal of reverse osmosis plants by diluting with seawater before its release to the sea. However, the study did not consider environmental issues caused by an artificial lake of brine water, which would have vast consequences for exposed ecologies. For instance, the area proposed for usage as a lake for pumped hydro storage around the capital of Iran, Tehran, is located around agricultural lands.

Another study (Van der Merwe et al., 2013) investigated the current status of regulations on discharge from desalination plants in Saudi Arabia. The results indicated that studies regarding the discharge from desalination plants are facing deficient statistics and a lack of supporting data. The study showed the necessity to impose more strict regulations on effluent water quality monitoring systems in desalination plants.

GHG Emissions of the Desalination Process

Powering desalination processes with renewable energy resources is considered the main solution to decrease the GHG emissions of desalination plants. It is noteworthy to mention that different renewable resources also have different levels of GHG emissions that need to be considered in studies. The authors in one study (Raluy et al., 2004) provided an estimation about the potential reduction of life cycle GHG emissions of RO, MED, and MSF technologies when renewable energy supplies were utilized instead of conventional energy systems. The study showed that hydro-power has the best performance in decreasing GHG emissions compared to wind and solar supplies. In the study, desalination units were considered as fixed loads and the fluctuation of renewable power resources was neglected, which is not realistic.

Cities are aiming to increase the share of local water resources for enhancing water security, but the GHG footprint of these local sources should be compared to imported sources to reach solutions that are more effective. Upstream or non-combustion emissions of energy resources are another aspect that should be considered in models to achieve more holistic results. By excluding upstream emissions in a study

(Fang et al., 2015), the carbon footprint of water supplies in Southern California were shown to be underestimated by up to 30 percent. The results of the study indicated that with current energy supplies in Southern California, importing water resulted in a lower carbon footprint than expanding local recycled water.

Another study (Chhipi-Shrestha et al., 2017) proposed an urban water system to apply several scenarios for the water sector for a city in Canada. The difference between scenarios included considering wastewater as a water resource and demand-side water management. The study calculated the amount of energy consumption related to the water sector, the water consumption of the energy sector and the CO_2 emissions related to the water sector due to energy usage for each scenario. The study concluded that designing these policies, scenarios, and plans, such as carbon mitigation, should not discourage economic or population growth. For reaching this aim, the most important step is the baseline measurements, which should be calculated based on alternative metrics, for example, emissions per gross domestic product (GDP) or per jobs.

1.3.4 Social Perspective

Palestine and Israel have access to the Mediterranean Sea, facing land limitations for developing large-scale renewable energy projects. Meanwhile, Jordan, a neighbor country, has an abundance of available land suitable for solar electricity production but has no access to the Mediterranean Sea, which is close to population areas facing water scarcity in Jordan. Authors in a study (Katz and Shafran, 2019) examined the technical and economic feasibility of exchanging desalinated water with renewable electricity among countries. The study considered the exchange of desalinated water and RE as a potential solution to ease relationships among these countries, which are facing critical political issues. Social acceptance has a vital role in the failure or success of such projects. For instance, according to a study (Fornarelli et al., 2018), an RO desalination project was opposed and halted in Australia as a result of the lack of community engagement during the planning and the common perception of the RO as an environmentally unsustainable and energy-intensive solution. The study showed that increasing renewable energy resources in this region could improve the social acceptance of the desalination project.

Another study (Marini et al., 2017) assessed two approaches to choose desalination technology and source of energy for a desalination unit in an island in Italy. In the first approach, just the technical and economic feasibility were investigated, as a result of which the combination of RO technology with wind energy had the best performance. The list of considered criteria in the second approach were economic, environmental, social, legislation, policies, and technical aspects, as well as the specific location characteristics. Through a multi-criteria analysis with the participation of stakeholders, the combination of RO technology and PV ranked highest using the second approach. A survey with 333 respondents was conducted in Australia (Gude, 2016a), with around 55 percent of respondents having very low to low levels of trust in the desalination water corporation, while 23 percent of them neither trusted nor distrusted the company. Social issues of desalination also depend on the size of the community. Another study (Werner and Schäfer, 2007) focused on the social acceptance of small-scale RO plants with solar electricity supply in remote areas in Central Australia. The study evaluated the unit's capacity to meet water demands, whether potable or non-potable for domestic or agriculture use, as well as the availability of human resources to operate and maintain these units, and the attitudes of community members to prototype RO units. The results of interviews, questionnaires, and site visits indicated that these units were generally perceived positively, showing great potential for acceptance by communities. One of the best examples to depict the role of public acceptance is the case of Ngare Nanyuki in Northern Tanzania. Volcanoes in nearby mountains provide the potable water supply for this area, which was considered as a symbol of pure water by their society. These natural water resources contain high levels of fluoride, which is toxic. Although a membrane-based desalination unit is producing high quality and healthy water for this region, people are still drinking directly from the toxic water sources (Kharraz et al., 2017).

Role of Culture

The massive deployment of desalination technologies in a society can trigger a cultural change in water consumption. Although water scarcity has accelerated recently, it is not a new phenomenon and in arid parts of the world watering techniques have been adapted to this resource-scarce condition for centuries. A study (Von Medeazza,

2004) refers to the fact that the rise of water consumption in Lanzarote, Morocco, after the introduction of desalination technologies was a result of falling costs of supply and water availability rather than an increase in actual water demand. Hence, countries considering desalination units as their future water supply also need to consider the demand side to conserve traditional, water-saving consciousness developed by the local population and increase the awareness of society regarding the amount of energy and materials that are consumed in the desalination processes. As another example, a community in Greece destroyed donated solar stills (Kharraz et al., 2017). This example reveals that society needs to pay for a share of service costs, even if partially, to increase society's responsibility towards that service.

Another study (Giwa and Dindi, 2017) discussed the sustainable solutions to meeting future water demand in the UAE, including increasing the efficiency of the water sector and diversifying the water supplies, applying wastewater treatment and solar RO plants. Based on the article, treated wastewater is not a viable source for the domestic sector in Islamic countries due to religious beliefs.

Policy-Making

Decision-makers should consider both the demand side and the supply side to reach more effective roadmaps in the water sector. A study (Lam et al., 2016) compared the results of different water trajectories for two regions in Australia including South East Queensland and Perth between 2002 and 2014. Both areas encountered a water crisis for some time during this period. The decisions in Perth have been focused on the supply-side, while in South East Queensland, in addition to the supply side, demand-side management was also taken into consideration. Another study (Brent et al., 2011) proposed a framework to evaluate the policies in the water and energy sectors to develop concentrated solar thermal technologies coupled with desalination technologies in South Africa. The study aimed to assist policy-makers in truly understanding the nexus and complexity of the water and energy systems they are attempting to influence. The size of the community also affects the social issues of desalination technologies. Small communities in remote locations usually rely on transported water and water supply infrastructure does not exist; in consequence, desalination projects face less social issues compared to locations with large communities, and in addition, these projects might seem attractive for them. Authors in another study (Gibbons et al., 2008) studied policies and legislation within the European Union in the Mediterranean region for developing autonomous desalination units powered by renewables. Policy barriers to decentralized desalination implementation generally stemmed from ignorance regarding these systems when desalination regulations were enacted. These decentralized systems were viewed as large fossil-fuel-based desalination systems with outright opposition in the regulations. As an example, small-scale water abstractions in the region were exempt from both the Water Framework Directive and the Drinking Water Standards Directive, while the decentralized autonomous desalination systems had to comply with strict regulations that apply to all drinking water supplies. Another study done in Turkey (Sözen et al., 2008) also indicated that framework conditions in this country do not pose unnecessary barriers for the implementation of autonomous desalination units.

Another study (Siddiqi et al., 2013) first investigated the current and future status of the Jordanian water and energy sectors and then focused on linkages between these sectors. In the next step, the study addressed the stakeholders of both sectors and the solutions to enforce the links between these two sectors in Jordan's future policy-making. The study classified the stakeholders based on power, legitimacy, and urgency and provided solutions to increase the inter-linkages between key actors and groups for achieving sustainable integrated water and energy policy-making. According to Jordan's future energy plan, oil shale and nuclear energy are expected to increase from zero to 21% of total energy supply by 2022. The required water intensity of oil shale extraction is significantly larger than that for conventional oil extraction. Due to insufficient groundwater and surface water resources in the country, seawater desalination and reuse of municipal sewage are the only alternatives.

Lastly, water pricing policies need to consider the social and environmental elements above the technical aspect. Heavily subsidized prices can induce changes in user behavior and cause an unexpected increase in irresponsible utilization and inefficient resource use by ignoring the demand-side behavior in policy-making (Gude, 2016a).

Social Equity

Our definition of sustainability is a widely used overarching representation defining sustainability as the interdependent concepts of economic growth, social equity, and environmental protection (Chapman et al., 2016). Although a growing literature is available on energy equity (Szulecki and Overland, 2020) there is a gap in the scope of studies in assessing the social equity aspects of water sectors that include desalination facilities.

Studies (Heffron and McCauley, 2018; Jenkins, 2018) have argued that the influence of environmental and climate justice on decision-making is insufficient. Environmental justice illustrates a right for all citizens to be protected from environmental pollution and to live in and enjoy a clean and healthful environment. Heffron and McCauley (Heffron and McCauley, 2018) argued that climate and environmental justice focus on adaptation, discussing solutions to reduce the damage from bad 'events' that have already occurred. While energy justice, beyond considerations of adaptation, also covers inequality before the 'event' happens.

There are three key elements of energy justice: firstly distributive justice, which is concerned with spatial allocation of benefits, costs, opportunities and risks, secondly justice as recognition, namely who or which affected sections of society are ignored, and thirdly procedural justice, which processes, mechanisms, and strategies can avoid, remediate or reduce injustice (Jenkins et al., 2016). In essence, addressing "where, who and how". Distributive justice is concerned with the benefits, costs and burden of energy production and consumption across society, including poverty, pollution, investments and, wealth (Chapman et al., 2016). The current research is concerned foremost with distributive justice.

Justice as recognition inspires researchers to ensure that none of affected sections of society are misrepresented, disrespected, degraded or devalued in comparison to others. A lack of recognition can therefore occur as various forms of social, cultural, ethnic, racial and gender differences. Moreau et al. (Moreau et al., 2017) studied procedural equity in the circular economy concept. They suggested shifting the tax burden from labor to energy flows and allocating costs among economic agents instead of transferring them onto the environment, as leverage for institutions, in order to improve equity in the economy.

Finally, procedural justice moves researchers to explore the ways in which all stakeholders and communities meaningfully engage in the policy decision-making process. One relevant study (Cole, 2012) investigated the impacts of unsustainable water distribution and overuse of underground water by the tourism industry on water inequity in Bali, Indonesia. The study mapped the stakeholders and examined the awareness and tendency of these stakeholders to participate in conservation programs. Farmers were recognised as vulnerable residents impacted by water resource depletion and cost increases of potable water. Another study (Dearing et al., 2014) focused on the link between social wellbeing and sustainable resource management. Two low-income communities were studied in China to evaluate a regional framework investigating environmental costs of agricultural intensification. Other research (Cai, 2008) has investigated the social impacts of water transfer from agriculture to municipal and industrial sectors in northern China. Policy reforms were introduced to mitigate the influence of this water transfer on the livelihood and income of farmers in this area.

Some studies (McCauley et al., 2019) suggested cosmopolitan justice as another tenet of energy justice, implying that principles must apply universally to all human beings in all nations. Healy et al. (Healy et al., 2019) assessed the energy injustices connected to decommissioning a coal-fired power plant in the US and its replacement with a natural-gas power plant. The social impacts on a region in Colombia, from where the coal power plant was importing coal, were examined by exploring fossil-fuel supply chains and their interconnected chains of energy injustice. Since cosmopolitan justice calls for mandatory transboundary impact assessments of large-scale energy-related projects, principles, and regulations, we recognize it as procedural justice in the current study. Other studies (Pellegrini-Masini et al., 2020) considered intergenerational justice as another tenet of energy justice addressing *A Theory of Justice* by John Rawls (Rawls, 1971), arguing that the difference principle cannot be applied to different generations.

Studies (Miller et al., 2013) have also argued that energy justice is an overlooked dimension in the field of energy transitions. Citizens and communities often have different perspectives on whether and how energy systems will change, when compared with industry executives or policy-makers. Rather than seeing communities as barriers to energy development, the study demonstrated communities as valuable partners in renewable energy deployment and planning. Such outcomes can be achieved by an active engagement of social actors in how, when, whether, and where to build energy systems. Studies have (Miller et al., 2013) indicated that by focusing on the design stage, many benefits can be achieved without greatly increasing the cost of new energy systems while retrofitting existing energy infrastructures. Scholars (Jenkins, 2018; Sovacool and Dworkin, 2015; Szulecki, 2018) introduced energy justice as a practical analytical tool to assist policy-makers and consumers in making more informed energy decisions.

1.3.5 Summary

As described, two transitions are happening simultaneously in the regions facing water scarcity and having access to water sources to be desalinated, the transition towards energy systems with a high share of VRE resources; and the transition towards water systems with a large share of supply coming from desalination. Sustainability is seen as the ultimate goal of these transitions. The literature review sheds light on the potential of renewable energy resources to integrate with desalination technologies for making the whole system more sustainable.

Since desalination is an energy-intensive technology, energy consumption for water provision is expected to increase. As an example, the production of desalinated seawater in the Middle East is predicted to rise almost fourteen-fold by 2040 based on IEA report. The renewable energy resources with steady and stable power generation such as hydropower and biomass are limited in the regions facing water scarcity. The fluctuating power generation from VRE, arising from their intermittent nature, constitutes one the main challenges of energy systems with a high share of VRE, stability. The water sector offers opportunities through desalination facilities — as flexible electric load — to reduce the variance in VRE power output.

Currently, desalination facilities are mainly centralized and fossil-fuel-based, causing environmental concerns. Conventional thermal desalination technologies are now well-proven and mature. Thus, further improvement in these technologies is relatively limited and a further large reduction in energy consumption is not expected for desalination technologies. However, further significant advances in renewable energy technologies in the future are highly likely to decrease the water cost of renewable-powered desalination. Powering desalination plants with renewable resources has positive impacts on the social acceptance of these systems and also reduces GHG emissions from desalination facilities, which are currently one of the main environmental impacts of these systems. Figure 1-3 showed that direct renewable-powered desalination systems are suitable for a small capacity of water production, while studies are mostly focusing on large desalination capacities with on-grid renewable supply. It is possible to operate large membrane-based desalination facilities powering by the fluctuating electricity generation from variable renewables, but studies are limited and the techno-economic performance is still uncertain. The compatibility of other small- to large-scale desalination technologies requires further investigation.

Centralized and large-scale desalination are the most frequent systems investigated among the studies in planning water supply with a share of renewable energy. Currently, the poor energy infrastructure is one of the impediments in the consideration of decentralized desalination systems suitable for deployment in rural areas due to size combability. This is particularly the case in developing regions such as the Middle East. Promoting renewable resources in such rural areas could address this issue, while ensuring rural areas have an opportunity to benefit from a secure water supply and heavy national investments through desalination and renewable projects. In other words, the transformation into an energy system with a high share of renewables brings decentralized desalination as an alternative solution for the water system transformation in both rural and urban areas. It avoids both high marginal cost of grid reinforcement/extension and fuel transfer for generating thermal energy, and increases efficiency by decreasing electricity transmission loss.

Energy savings from water distribution and transfer are also considerable in the decentralized water systems, which cause further cost reductions. Moreover, energy storage systems are responsible for a significant share of renewable energy cost, which is avoidable with the application of desalination units as flexible loads in the regions facing water scarcity and having access to water sources to be desalinated. Besides, the freedom to choose site locations for decentralized desalination configurations is larger than that for centralized systems. Selecting locations in which the feed-water suits the desalination technology better not only results in cost reduction, as discussed in previous sections, but could also mitigate environmental impacts, namely intake-related and effluent-related impacts. Furthermore, presenting such multiple location alternatives allows the policy-makers to allocate desalination to other target users apart from potable water, the main target product among studies. As an example, water containing high levels of salt and boron, even after first-pass RO water production, needs to pass through an additional RO stage to achieve good-quality water that is suitable for drinking. The second-pass stage can increase the total cost of the first-pass desalination process by 10 to 25 percent. For most industrial and agricultural applications, it is unnecessary to design this second stage pass. The current cost of desalinated water includes the second-pass stage, which is responsible for up to 25 percent of total RO water desalination costs.

Considering all of these cost reductions and developments, desalination is an expensive water supply compared to other conventional fresh-water resources and needs heavy national investments and subsidies from governments for the next few decades. Table 1-5 shows that technical, economic, and environmental aspects have received considerable attention compared to social aspects. Above technical and environmental aspects, different potential target users and system configurations will result in different sociotechnical regimes. Considering the impacts of these sociotechnical regimes on the society in the decision-making process makes the transition plans towards sustainability more realistic and effective.

Table 1-5. Summary of focal factors in desalination systems powered by renewable resources.

Horizon	Description of the System	Nexus	Approach	Analysis	Uncertainty Level	Geographical Scale	Ref.
Review/ Understanding	• Sustainable solutions to meet future water demand in the UAE.	Social	Discussion	Qualitative	-	National	(Giwa and Dindi, 2017)
	• Investigation the policies regarding to autonomous desalination in the EU.	Social	Discussion	Qualitative	-	Regional	(Gibbons et al., 2008)
	• Investigation the policies regarding to autonomous desalination in Turkey.	Social	Discussion	Qualitative	-	National	(Sözen et al., 2008)
	• Evaluating the social acceptance of RO units powering by solar electricity using surveys.	Social	Discussion	Qualitative	-	Rural	(Werner and Schäfer, 2007)
	• Proposing a framework to evaluate water-energy polices.	Policy	Discussion	Qualitative	-	Regional	(Brent et al., 2011)
	• Studying decentralized solar-powered desalination systems in remote regions.	Sustainability	Review	Qualitative	-	-	(Kharraz et al., 2017)
	• Integrating wave energy converters with desalination technologies for commercialization of wave energy.	Technical and Economic	Review	Qualitative	-	Island (remote)	(Foteinis and Tsoutsos, 2017)
	• Investigating the potential and development of ocean-based power generation for desalination systems.	Sustainability	Review	Qualitative	-	-	(Li et al., 2018)
Short-Term/ Operation	• Integration of MSF desalination, solar thermal power, and hydrogen production processes to achieve synergy.	Technical	Process simulation	Quantitative	Deterministic	City	(Gençer and Agrawal, 2018)
	• Co-locating pumped hydro storage with reverse osmosis desalination plants.	Technical and Environmental	Optimization	Quantitative	Deterministic	City	(Slocum et al., 2016)
	• Operating an MED desalination process by ocean energy (thermal energy which is harnessed from seawater temperature gradient).	Technical	Process simulation	Quantitative	Deterministic	Stand-alone	(Ng and Shahzad, 2018)
	• Proposing a tool for operating a reverse electrodialysis system to produce power (salinity gradient power).	Technical	Process simulation	Quantitative	Deterministic	Laboratory scale	(Nagaraj et al., 2019)
	• Studying optimal climate conditions for operating small-scaled RO desalination units coupled with PV systems.	Technical	Experimental	Quantitative	Deterministic	Laboratory scale	(Alghoul et al., 2016)
	• Studying the capability of an RO desalination plant to manage the variability of renewable energy production.	Technical	Process simulation	Quantitative	Deterministic	City	(Kim et al., 2016)
	• Studying the performance of a combination of the MED process with solar still desalination powered by solar thermal and waste heat.	Technical	Experimental	Quantitative	Deterministic	Laboratory scale	(Park et al., 2016)

Short-Term/ Operation	• Operating an MSF desalination unit powered with a hybrid energy system including solar, geothermal, and ocean thermal energy.	Technical	Process design	Quantitative	Deterministic	-	(Azhar et al., 2017)
	• Introducing an energy management and control system for an RO desalination connected to a DC micro-grid (PV-Battery).	Technical and Economic	Fuzzy optimization	Quantitative	Deterministic	Island	(Kyriakarakos et al., 2017)
	• Using concentrating solar power for a MED process and electricity production as a hybrid system.	Technical and Economic	Process design	Quantitative	Deterministic	City	(Mata-Torres et al., 2017)
	• Evaluating the optimal operation of an MSF desalination system powered by solar thermal energy.	Technical and Economic	Experimental	Quantitative	Deterministic	Laboratory scale	(Darawsheh et al., 2019)
	• Considering membrane fouling during intermittent operation in designing PV powered RO installations.	Technical and Economic	Process simulation	Quantitative	Deterministic	Laboratory scale	(Alghoul et al., 2016)
	• Shifting load using desalination demand as a flexible load for increasing the share of renewable resources in the energy system.	Technical and Economic	Optimization	Quantitative	Deterministic	Island	(Hamilton et al., 2019)
	• Evaluating the potential of water desalination and distribution for load shifting in an off-grid remote energy system.	Technical	Linear optimization	Quantitative	Monte-Carlo	Island	(Meschede, 2019)
Long-Term Planning	• Design a cost-effective energy system for small desalination plant.	Economic	Optimization	Quantitative	Deterministic	Rural	(Fornarelli et al., 2018)
	• Coupling PV and CSP with RO and MED plants to minimize the cost and to maximize the RE penetration in an island.	Economic	Optimization	Quantitative	Deterministic	Island	(Astolfi et al., 2017)
	• Investigating the potential of RO plants to meet future water demand.	Economic-Environmental	System dynamics	Quantitative	Deterministic	State	(Sahin et al., 2017)
	• Proposing scenarios to achieve an electricity system with net-zero emission.	Economic	LP Optimization	Quantitative	Deterministic	National	(Solomon et al., 2018)
	• Minimizing the total cost and GHG emissions of a hybrid energy system coupled with an RO plant.	Economic and Environmental	Multi-object Optimization	Quantitative	Stochastic	-	(Li et al., 2019)
	• Evaluating life cycle GHG emissions of different desalination technologies coupling with renewables.	Environmental	LCA	Quantitative	Deterministic	-	(Raluy et al., 2004)
	• Evaluating the environmental impacts of different desalination technologies coupling with solar resources.	Environmental	LCA	Quantitative	Deterministic	Rural	(Jijakli et al., 2012)
	• Considering carbon tax as an external cost of desalination process.	Economic	-	Quantitative	Deterministic	National	(Molinos-Senante and González, 2019)
	• Identifying regions that are suitable for deployment of RO units coupled with solar energy supplies.	Economic and Technical	GIS	Quantitative	Deterministic	Global	(Grubert et al., 2014)
	• Evaluating the potential of wave energy resources to provide the power demand of desalination plants.	Environmental and Technical	-	Quantitative	Deterministic	Island	(Fernández Prieto et al., 2019)

Long-Term/	• Evaluating the environmental impacts for open-intake pretreatment and subsurface intake pretreatment of RO desalination plants.	Environmental	LCA	Quantitative	Deterministic	City	(Al-Kaabi and Mackey, 2019)
Planning	• Evaluating the environmental impacts RO desalination plants powered by hybrid renewable energy resources and the grid electricity.	Environmental	LCA	Quantitative	Deterministic	City	(Shahabi et al., 2014)
	• Studying the scenarios to achieve 100% RE in Iran by considering electricity demand of RO desalination by 2050.	Economic	LP Optimization	Quantitative	Deterministic	National	(Ghorbani et al., 2017)
	• Designing a sustainable desalination system powered with renewable energy resources.	Sustainability	AHP	Quantitative	Deterministic	Island	(Marini et al., 2017)
	• Evaluating the feasibility of exchanging desalinated water with renewable electricity.	Technical and Economic	Optimization	Quantitative	Deterministic	Multi-national	(Katz and Shafran, 2019)
	• Evaluating the GHG emissions of different water sources.	Environmental	LCA	Quantitative	Deterministic	City	(Stokes and Horvath, 2009)
	• Investigation on the economic impacts and CO_2 footprint of desalination units.	Environmental and Economic	Triple-I light	Quantitative	Deterministic	City	(Tokui et al., 2014)
	• Investigating the role of the desalination sector to achieve a 100 percent renewable energy system in Saudi Arabia.	Technical and Economic	linear optimization	Quantitative	Deterministic	National	(Caldera et al., 2018; Caldera and Breyer, 2017)
	• Achieving 100 percent renewable energy in India by considering desalination energy demand.	Technical and Economic	linear optimization	Quantitative	Deterministic	National	(Gulagi et al., 2018)
	• Proposing a spatial model to assess potential technical and economically viable site locations for RO desalination facilities powered by renewables.	Technical and Economic	Multi-criteria	Quantitative	Deterministic	Regional	(Aminfard et al., 2019)
	• Finding the optimal size and configuration of a small-scaled RO desalination unit coupled with a PV system (including battery storage and water storage).	Technical and Economic	Fuzzy Optimization	Quantitative	Deterministic	Island	(Karavas et al., 2019)
	• Technical feasibility of using RO desalination units powered by wave energy as an alternative for imported water.	Technical	Optimization	Quantitative	Deterministic	Island	(Corsini et al., 2015)
	• Calculating the optimal size of renewable energy supply (wind turbine and PV) for RO desalination units with a solar preheating water system.	Technical and Economic	Optimization	Quantitative	Deterministic	Regional	(Gold and Webber, 2015)
	• Estimating the cost of providing water demand using renewable-powered RO desalination plants for regions facing water scarcity in 2030.	Economic	Linear Optimization	Quantitative	Deterministic	Global	(Caldera et al., 2016)
	• Developing a tool for sizing RO desalination plants powered by renewables units.	Economic	Optimization	Quantitative	Deterministic	Island	(Mentis et al., 2016)

Long-Term/ Planning	• Investigating the economic feasibility of desalinating agriculture drainage water using the MED process powered by solar thermal.	Economic	Optimization	Quantitative	Deterministic	Region	(Stuber, 2016)
	• Evaluating the technical and economic feasibility of RO desalination units powered by distributed PV-battery systems in Myanmar.	Technical and Economic	Optimization	Quantitative	Deterministic	National	(Thompson et al., 2016)
	• Considering desalination energy demand in the transition to a 100 percent renewable system in South and Central America.	Technical and Economic	Optimization	Quantitative	Deterministic	Multi-National	(De Barbosa et al., 2017)
	• Studying the benefits of the integration of RO desalination energy demand in the transition to a 100 percent renewable energy system for India and the South Asian Association for Regional Cooperation.	Technical and Economic	Optimization	Quantitative	Deterministic	Multi-National	(Gulagi et al., 2017)
	• Minimizing the cost and CO_2 emissions of an energy system including PV, wind turbine, hydrogen electrolyzer, battery, and hydrogen storage coupled with an RO desalination unit.	Economic and Environmental	Heuristic optimization	Quantitative	Deterministic	City	(Abdelshafy et al., 2018)
	• Investigating the role of RO desalination demand in the transition to a 100 percent solar electricity system in Pakistan by 2050.	Economic	Linear optimization	Quantitative	Deterministic	National	(Sadiqa et al., 2018)
	• Proposing a dynamic approach to consider the operation of an RO plant in sizing the PV and wind turbine energy system.	Technical and Economic	Multi-objective optimization	Quantitative	Deterministic	Island	(Giudici et al., 2019)
	• Forecasting CO_2 emissions from different energy systems providing desalination power demand for an Island by 2020.	Environmental	Scenario-based	Quantitative	Deterministic	Island	(Jaime Sadhwani and Sagaseta de Ilurdoz, 2019)
	• Estimating the potential amount of desalination water powering with solar and wind electricity in Iran.	Technical and Economic	Scenario-based	Quantitative	Deterministic	National	(Mollahosseini et al., 2019)
	• Investigating the technical and economic feasibility of RO units powered by off-grid PV systems in remote case studies in Iran.	Technical and Economic	Fuzzy optimization	Quantitative	Deterministic	Rural	(Mostafaeipour et al., 2019)
	• Planning a water desalination system powered by excess solar electricity generation in Australia.	Technical and Economic	Optimization	Quantitative	Deterministic	National	(Vakilifard et al., 2019)
		Technical	**Environmental**	**Economic**	**Social**	**Qualitative**	**Quantitative**
Number of studies/ Total studies		33/59	14/59	36/59	3/59	8/59	51/59

1.4 Contributions of the Study

A nexus approach designs two or more inherently interconnected systems as an integrated system simultaneously. This study reveals the capacity of the nexus approach for renewable energy and water supply planning in a holistic manner in order to achieve synergies and avoid conflicts or inefficiencies in regions facing water scarcity and having access to water sources to be desalinated. There are three main contributions to knowledge from this study:

(i) In this study, the nexus approach is applied to design the future configuration of both the water supply (with a share of desalination) and the energy supply (with high share of variable renewable resources) together in the southern coast of Iran, which has ready-access to seawater but faces severe potable water scarcity. This nexus approach includes characteristics and particularities of policy-making in combination with various technology mixes, by considering economic, demographic and geographical conditions in the region of study. In addition to oil-overdependent economy, unemployment and highly subsidized water and energy sectors, Iran is facing water scarcity due to droughts, population growth, and water resource mismanagement. The methodology presented is general and can be applied to any case which faces water scarcity and has access to water sources to be desalinated. It quantitatively evaluates the effect of the developed nexus approach on renewable energy and water supply planning. Moreover, most studies on synergies in designing jointly energy and water systems, share a common approach in which they model technology cost just as a function of time. This poses difficulties because it does not allow the consideration of synergistic effects but maintains a separation of the systems due to the assumption of learning based on time. Furthermore, operational flexibility of the desalination units, water transfer and water storage are key factors that need to be considered in long-run planning of interconnected water and energy sectors. It can compensate for fluctuating renewable power generation due to the compatibility of the water sector as a flexible electric load with inherent intermittency of VRE. To achieve a realistic understanding in this regard, considering just a few hours/days of operation is not adequate to study the influence of the renewable power fluctuations on planning and designing interconnected water and energy sectors.

(ii) In the current study, the transformation of the energy sector towards a high share of renewables highlights decentralized desalination as an alternative solution for the transformation of the water sector in both rural and urban areas. Applying the proposed nexus model, this research demonstrates and assesses different configurations of centralized versus decentralized water sectors powered by on-grid renewables for an integrated water-energy supply planning with a share of desalination. The climate of Iran is one of great extremes due to its geographic location and varied topography, resulting in very uneven distribution of population across the country. Geographic distribution of water resources of the country has not been consistent with geographic distribution of population. As transferring water is an extremely sensitive political and social issue in Iran, the proposed decentralized solutions play a chief role in achieving sustainable water-energy supply in the region of study. Although renewable-powered desalination systems are typically considered to be suitable small-volume desalination, studies in this field have mostly focused on large-capacity desalination facilities and centralized water systems.

(iii) Lastly, ignoring the social aspect is the major defect in designing previous transition plans with a renewable-powered desalination water supply, particularly social equity, which is a crucial pillar in achieving sustainability. Although a growing literature is available on energy equity, there is a gap in the scope of studies in quantitative assessing the social equity aspect of the water sector with a share of renewable-powered desalination supply. This study establishes social equity as a key factor in the design and quantitative nexus evaluation of water and energy transition plans, in order to distribute benefits and burdens of the transitions between urban and rural areas. Based on Iran's culture, the current and original pre-Islamic religious practices and climatic condition, providing fair opportunity for communities to benefit from a secure water supply has an imperative role in achieving equity in the region of study.

1.5 Overview of the Work

A nexus approach is applied to design the future configuration of both water and energy systems together. The nexus concept is deemed necessary to design future inherently interconnected sectors in a holistic manner from the start of the design process (Hoff, 2011). This approach is different from concepts such as the integrated management approach which is suitable for existing systems. In the nexus approach, one of the targets is to identify which sectors will be inherently interconnected in the future. The outcomes of the nexus approach elaborate two focal points, first, highlighting potential synergies and second, identifying inefficiencies or critical conflicts to be dealt with (Allan et al., 2015).

This study first investigates water and energy sectors in a Separated System, in which each sector is considered as an exogenous factor for the other sector, without any control on each other. Secondly, this research investigates them in an Integrated System, in which both energy and water sectors are studied together, as endogenous parts of one single system. Plans and solutions towards aforementioned transitions are designed for both system types in the southern coast of Iran, which has ready-access to seawater but faces severe water scarcity. The outcomes of both system designs constitute benchmarks for trade-offs between interconnected sectors. While integrating both sectors in one system could potentially reach higher efficiency, it also increases complexity to the point where decision making is delayed or incapacitated.

Furthermore, different system configurations could influence the extent of these synergies, inefficiencies, conflicts of interests, and complexity. The sustainability of the water sector and the energy sector is expected to improve in the case of the integrated supply planning. This is considered to be a synergy effect of the water sector and energy sector in this study.

This research is built in five Chapters:

First, Chapter 1 provides an assessment of state-of-the-art desalination-based water provision, considered from a wide variety of perspectives beyond just the techno-economic analysis, and addresses the interlinks between the water and energy sectors. It further highlights the role of renewable energy technologies in the sustainability of the future water sector with an increasing share of desalination supply. Furthermore, this chapter clarifies the characteristics and particularities of the water and energy sectors, as well as policy-making, economic, climatic and demographic conditions in the chosen case study of Iran.

Considering Iran's particularities and situation, Chapter 2 develops a nexus approach in order to plan both renewable energy and water supply planning simultaneously in a holistic manner in the southern coast of Iran, which has ready-access to seawater but faces severe potable water scarcity. This chapter quantitatively examines the effect of this nexus approach on renewable energy and supply planning, thereby elaborating potential economic and technical synergies. Model development and validation are conducted in this chapter. It further assesses the flexibility of the water sector with a share of desalination as an electric load, compensating for fluctuating variable renewable power generation (wind and solar).

With consideration of climatic condition, varied topography, and demographic distribution of Iran, Chapter 3 investigates the technical, economic, and environmental impacts of different system configurations, namely centralized vs decentralized systems in combination with various technology mixes, on the transition plans using the nexus model developed in Chapter 2. If planned together, the studied transitions can offer significant synergies and avoid inefficiencies, making desalinated water cheaper and more environmentally friendly, while creating a considerable amount of flexibility available to the grid.

In order to achieve more realistic and sustainable water-energy supply planning, Chapter 4 focuses on the social aspect of aforementioned transitions. It considers social equity as a key factor in the design and nexus evaluation of transition plans with a share of variable renewable resources and desalination supply in the regions facing water scarcity. A quantitative distributive justice analysis is introduced in order to evaluate the equity level of the proposed transition plans and results of Chapter 3. The proposed integrated system with decentralized desalination leads to a balance between rural and urban households in the distribution of benefits and burdens of the transitions, while improving the overall social equity level of the system.

Lastly, Chapter 5 reports on the conclusions of the overall research and possible directions to be followed in future research.

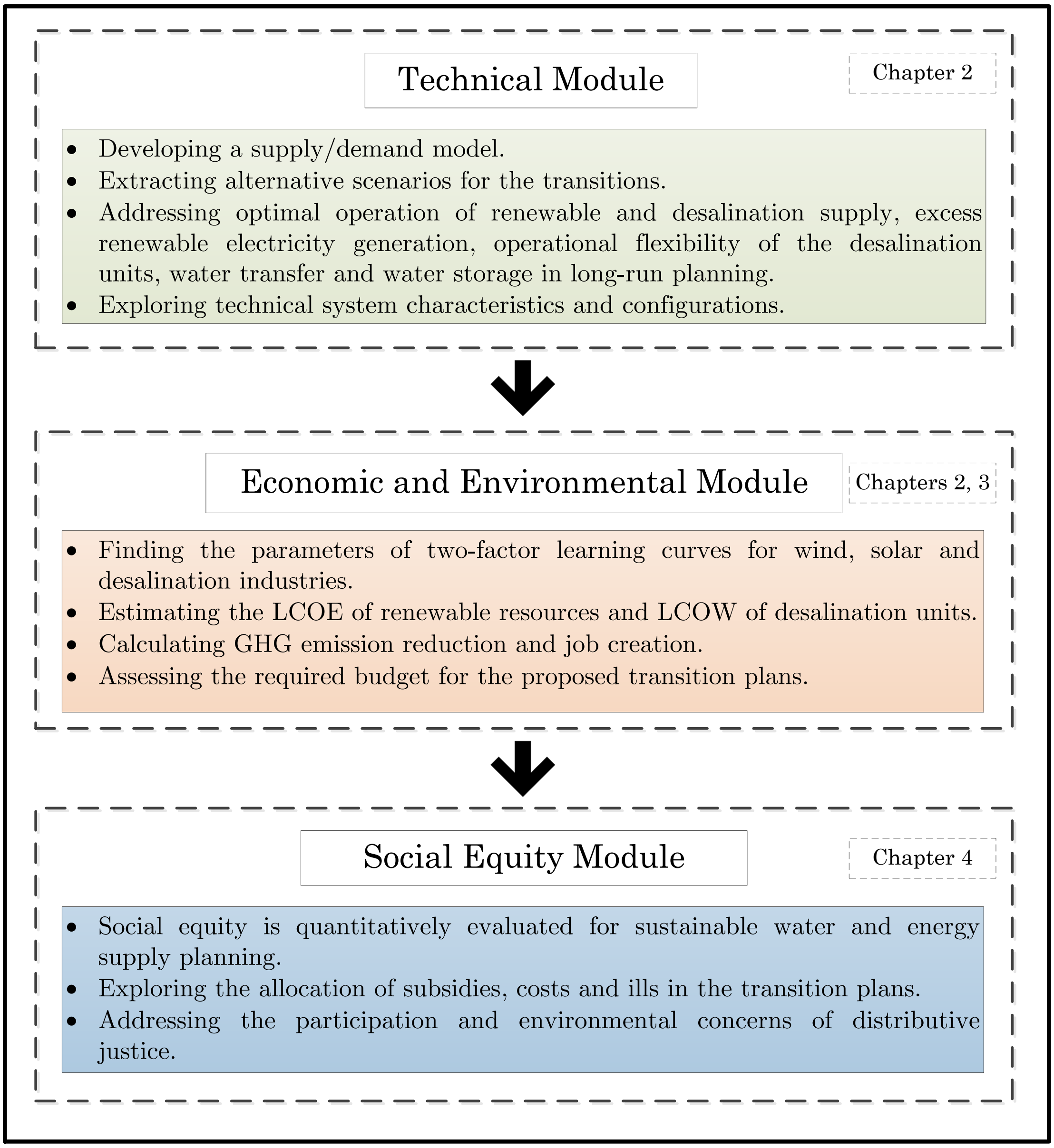


Figure 1-4. Thesis flow diagram.

The future energy systems with a high share of VRE requires solutions to overcome fluctuations in power generation and avoid instability caused by an imbalance between the supply side and demand side. The presented model in this work only considers the water sector as a flexible electric load and compares it with battery storage. However, there are also other solutions to overcome this instability, such as exchanging renewable electricity with neighboring countries or regions, as well as electrification of transportation sector operating as an energy storage. The characteristic of water sector as a flexible load is that the water load can be extracted, desalinated and transferred in advance and be stored in the reservoirs to meet the water demand.

Case Study

The Islamic Republic of Iran covers a total area of about 1.65 million square kilometers — the 17th largest country in the world — located in the Middle East. Currently, Iran possesses the second richest oil and gas reserves in the world (Sabetghadam, 2006). About 99.27% of the country is covered by land and 0.73% by water, accounting for 2,700 kilometers of water borders (Madani, 2005).

The United Nations addressed water resource management and deployment of renewable energy among focal targets to achieve sustainable development goals (SDGs) in Iran (UN, 2015).

Water plays an imperative role in improving life quality and socioeconomic development in the Middle East (Saatsaz, 2019). According to national law, all water bodies are public property and the government is responsible for their management. Oil and gas are also regarded as national resources and controlled by the government according to Iranian law, resulting in the large public sector involvement in the oil and gas sector. The energy market in Iran is a monopoly. As a result, the government sets the price of energy carriers. The government's predominance in the energy sector and the water sector means that the government shoulders the majority of the investment burden.

During the second development plan formed after the Nationalization of Oil Industry in 1953 until the Islamic Revolution of 1978, income from the export of oil has been the primary source of government funds for investment in industrial development and infrastructure. The result was moderate economic growth over two decades. The role of planning and budgeting became more critical, especially after the

1960s, as government became more centralized and political and administrative institutions expanded. After the Islamic Revolution of 1979, related social and political changes revealed the need for reform in political and social systems through supporting parliament, encouraging public participation, and privatizing and liberalizing the economy. The Five-Year Economic, Cultural and Social Development Plans (FYDPs) are the key development strategy and planning instrument of the government since 1989. These development plans encompass the national development policies. The Management and Planning Organization is responsible for preparing the FYDPs which operates under the auspices of the President. The FYDPs require the approval of the Cabinet and the parliament (the Islamic Consultation Assembly). The Annual General Government Budgets are also developed by the Management and Planning Organization in the context of the FYDPs. The Budget documents also require the approval of both the Cabinet and the parliament. It is noteworthy that in the parliament, different committees on water, energy, natural resources, budgeting, and development, supervise management activities all across Iran.

The primary energy consumption has almost doubled since 2004 in Iran, mostly because of the growth of energy-consuming industries, expanding demand for transportation and electrification. Natural gas and oil are the main primary energy consumption, with marginal contributions from hydropower, nuclear, and other renewables.

In the energy sector, the Ministry of Petroleum is responsible for the oil and gas sector. The Ministry of Energy is the main organ of the government responsible for regulating and implementing of policies applicable to the generation, transmission and distribution of electricity. For the aforementioned responsibilities, the Ministry of Energy consists of three levels:

1. At the highest level is the headquarters, where policymaking and governance activities in the power sector are performed.
2. At the middle level are specialized holding companies, such as the following:
   - TAVANIR (Generation, Transmission and Distribution of Electricity Company) is in charge of planning, supervision and evaluation of its subsidiary companies. It also manages electricity transmission and distribution in the country through its regional and distribution companies.
   - Thermal Power Plant Holding is responsible for organizing government activities and plans related to thermal power plants. It also manages its subsidiaries' plants.
3. At the operational level are subsidiary companies, including regional electric companies, power distribution companies, power generation management companies, Iran Grid Management Company, Iran Power Plant Project Management Company and Renewable Energy and Energy Efficiency Organization. These companies are responsible for the implementation of the plans, programs and macro-policies adopted in the power sector.

The energy policy of Iran is outlined in the National Energy Strategy Plan, which sets out policies through 2041. Approved by the Cabinet of Ministers on July 2017, the document outlines a comprehensive set of long-term goals and strategies in the country's energy sector aligned with the sixth FYDP.

Given the challenges concerning fossil fuels on the one hand and increased annual consumption of energy, on the other hand, alternative energy sources and approaches have been considered in policymaking to manage energy demand effectively and to reduce dependence on fossil resources. Accordingly, the government plans to develop clean and renewable energy capacity in the country according to Article 50 of the sixth FYDP. By 2003, almost 100 percent of urban households and 92 percent of rural population have access to electricity. 99.7 percent of the villages with over 20 families and 34.8 percent of villages with less than 20 families have been electrified (Sabetghadam, 2006). These remaining off-grid areas are geographically distant and on-grid centralized electrification is costly and slow. The adoption of small-scale renewable technologies to help electrify remote villages is anticipated to have a higher success rate. Due to abundant sources of oil and gas, the opportunities offered by renewable energy has been neglected.

In the 2015 Paris Climate Agreement, COP21, Iran pledged to meet a target of 7.5 GW of renewable electricity generation capacity by 2030 (Noorollahi et al., 2019). According to the Iranian Sixth FYDP, the Ministry of Energy is assigned a target of supplying 5% of total electricity demand from renewables by 2021 (The Iranian Parliament, 2017). Moreover, according to the Iranian National Strategic Energy Plan, Iran aims to reach competitive costs for renewable power production by 2041 and increase the current renewable deployment rate, which is around 1% yearly. The Iranian Ministry of Energy has proposed comprehensive plans to hit the aforementioned targets, such as a feed-in tariff mechanism and long-term contracts at guaranteed prices, extended from five-year contracts to 20-year contracts from 2015 (Omid Shokri Kalehsar, 2019).

During the fundamental changes in the country's economic system, investment in the development of water resources (after Nationalization of Oil Industry in 1953) has considerably increased, and the system of water resources utilization has undergone drastic changes. Between 1960 and 1996, about 37 million people (about 50 percent of the existing population) were added to the country's population. The direct impact of population growth on the Iran's water resources management was an increase need for potable water in population centers. Indirect impacts were increased demand for agricultural products, development of irrigated lands, and the need for job opportunities. In total, these changes have resulted in an increase of water exploitation around 2.25 times from 1960 to 1996 (Ardakanian, 2005). At present, in the water sector, the leading institutions for water resources management are as follows:

1. Iran Water Resources Management Organization (Deputy Minister for Water Affair) is responsible for planning, development, and conservation of the country's water resources management and supervision on its implementation. It also provides and compiles suggestions for water resources management strategies, policies, and programs.
2. National Water and Wastewater Engineering Company provides oversight and assistance to service providers in areas such as investment planning, human resources development, and the establishment of standardized systems and procedures.
3. Regional water companies are responsible for the management of water resources, sustainable development, optimal use of water resources and quantitative and qualitative conservation of water resources within the region.
4. Provincial Water and Wastewater companies and their subsidiaries are in charge of the operation and clean water distribution as well as the hygienic disposal of sewage.

Population distribution in Iran is very uneven due to enormous natural and climatic conditions and economic potentials. The climate of Iran is one of the extremes due to its geographic location and varied topography. Annual rainfall ranges from less than 50 mm in the southeast and central parts to more than 1,600 mm in some coastal regions near the Caspian Sea. The average annual rainfall is 228 mm. About 65 percent of the country receives less than 100 mm of annual precipitation, resulting in approximately 90% of the country as arid or semi-arid. (Saatsaz, 2019). Transmission systems and technology expanded considerably and in complex ways because of the water resources development and an increased distance between water supply centers and demand locations. In urban water supply systems, transmission pipelines, tunnels, pumping stations, and physical treatment have become more important.

Although Iran has a long history in the management and development of water resources, it is presently facing major problems in the water sector. Water shortages manifest these problems, water quality deterioration, groundwater over-abstraction, lake and river drying up, soil–water salinity, dust storming, agricultural losses, and ecological degradation. Since 1999, Iran has faced a water crisis so severe that in response, the Iranian government began accepting foreign aid for only the second time since the revolution in 1979. By 2005, droughts have adversely affected drinking water supply systems for 37 million people in Iran. Almost 80% of potable water wells are influenced, namely, low water yield, a drop-in water table, intrusion of saltwater, or complete dryness (UN, 2000). Integrating such challenges into health, environmental, economic, political and social issues has greatly focused public attention on the water problem consequences. The water crisis in Iran is partly drought-related; the academics and experts claim that the water resource mismanagement is more significant cause of the current crisis (Madani, 2005). Investigating the water and energy policy decisions in Iran reveals that the policymaking and planning for these sectors have been conducted separately. The construction of conventional power plants in extreme water-scarce regions — such as Shazand Thermal Power Plant with 1.3 GW capacity which impose further stress on the water supply — is an obvious example.

The energy sector and the water sector are highly subsidized in Iran. According to an IEA report in 2019 (IEA, 2019a), Iran ranked first among the world's top countries in terms of the subsidies allocated to energy consumption, which accounts for 18.8 percent of its total GDP. Oil revenues mainly fund these subsidies in Iran, which provide cheap energy and water for consumers. The government has started a gradual price reform on energy carriers since 1996. This reform aimed at correcting the relative prices of oil products and their relationship to the general consumer price index. However, because of the gradual and insufficient increase in energy price, the policy has not been effective.

Iran has six main and 31 secondary drainage basins which can be seen in Figure 1-5 (Statistical Center of Iran, 2013). The six major basins are the Central Plateau in the middle of the country, the Lake Urmia basin in the north-west, the Persian Gulf and Gulf of Oman basin in the west and south, Lake Hamoon basin in the east, the Kara-Kum basin in the north-east, and the Caspian Sea basin in the north (Statistical Center of Iran, 2013). To the south, Iran borders the Persian Gulf and the Oman Sea with a long coastline of 2,440 kilometers. The Gulf of Oman and Persian Gulf basin has access to seawater, which gives this basin the opportunity to use desalination plants as a source of water. Four provinces inside this water basin are chosen as the region of the present case study.

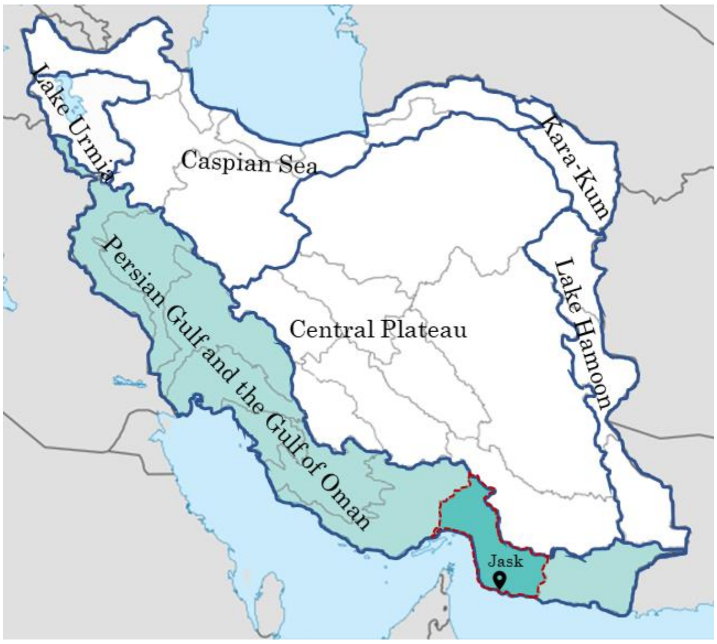


Figure 1-5. Iran's main drainage basins. Adapted from Iran Water Statistical Yearbook (2011-2012).

Iran is facing severe water scarcity in the mentioned area of the country (Statistical Center of Iran, 2013), which also has ready-access to seawater for desalination. According to the sixth FDYPs, the Ministry of Energy is assigned to propose a plan for transferring required knowledge and providing sufficient financial support toward supplying 70% of the urban water demand on the shoreline of the Persian Gulf and the Gulf of Oman by 2021 from desalination (The Iranian Parliament, 2017).

The overview of the future plans which focuses on large-scale centralized desalination in the region of the case study, only considers urban areas for deployment of desalination facilities, while rural areas in Iran are given priority for development in strategies for achieving the SDGs (UN, 2009). In the region of the case study, rural households spend 4.7 percent of their yearly income on energy and water bills. By contrast, utility bills account for only around 3.6 percent of the urban households' income in this region (Statistical Center of Iran, 2018). It is apparent that the rural households must spend a higher proportion of their income on water and energy services even though they use less energy (Goldthau and Sovacool, 2012).

The chosen area as a case study, in the south of Iran, has a great potential for solar and wind power production, based on which solar and wind electricity resources are considered as the variable renewable energy (VRE) supplies in this study. Based on hourly data, the daily average solar radiation is equal to 5.63$KWh/m^2/day$, and the hourly average wind speed is 3.26m/s for this area (SATBA, 2014). Jask is a port town, situated on the Gulf of Oman and is chosen as the sample urban area for this study. Jask has a hot desert climate with very hot summers and little precipitation. In the 2017 census, Jask county's population was 58,884 (Statistical Center of Iran, 2018).

Chapter 2

Assessing a Novel Nexus Approach for Integrated Planning of Water and Energy Supply

2.1 Introduction

Current large-scale reverse osmosis units coupled with renewable resources are grid-connected, such as an RO unit in Saudi Arabia with 60,000 m^3/day capacity powered by PV supply and the national grid to ensure stable electricity supply to the facility and constant water production (Ahmed et al., 2019). The economic feasibility of such plants depends on the availability of renewable resources and typically some form of financial support such as a feed-in tariff (Ahmed et al., 2019; Alsayegh et al., 2010). However, large-scale RO plants are energy-intensive units, for instance, the share of desalination electricity consumption is estimated to be 4 to 12 percent of total electricity consumption in the Persian Gulf Cooperation Council countries (Shafiullah et al., 2013; Siddiqi and Anadon, 2011).

With regards to short-term fluctuations of variable renewable power generation, desalination can be considered as a potential flexible load. There are several key features to determine the adequacy of desalination loads as flexible load resources to overcome short-run fluctuations, in other words, to support ancillary services in electric grids, including (Kim et al., 2016):

- Initial-response time: the time lag to change a power set-point.
- Ramp-rate: the change rate in the amount of power consumption.
- Settling-time: the settle-time period after changing an operating power set-point.

- Duration: the period of time after settling-time at which it is possible to maintain the new power set-point.
- Power-capacity: the rated operation power.
- Minimum turn-down: the lowest operation power point for the plant, below which the plant must turn off.

According to the above factors, reverse osmosis desalination units are considered an attractive solution to operate as a flexible load to compensate for the fluctuation due to variable renewable resources. RO desalination units are able to operate with unlimited minimum turn–down. Authors (Kim et al., 2016) examined the operation capability of an RO plant to integrate with an energy system with variable renewable resources. The results of the study indicate that RO units are capable of responding quickly, settle to the desired power set point in a reasonable time, and operate continuously for long enough, duration, in the meantime, maintaining the quantity and quality of required water demand. This means that such RO units can be effectively powered by energy systems with renewable fluctuating power production without ESS, as water is desalinated based on energy availability and stored as a final product (Freire-Gormaly and Bilton, 2018). This direct consumption of renewable power production improves the efficiency of the energy systems, due to the avoidance of energy loss of ESSs in each charge-discharge-cycle. Authors (Gude, 2015) showed that applying large-scale energy storage systems for renewable-powered desalination units is impractical, because they increase the capital cost and make the system more complicated due to additional required equipment, such as charge controllers. Specifically, applying battery units negatively influences the economic feasibility of desalination projects powered by renewables because of the high capital cost and relevantly short life-time (Ali et al., 2018; Gude, 2015).

While many studies have been done to date, there is a gap in the scope of studies regarding the design and planning of energy systems with a share of variable renewables while having water desalination as a source of water systems. Studies have typically followed a sequenced approach for planning such systems; one sector is considered as an existing system with a fixed shape, based on which the other system is designed, planned or optimized. Moreover, operational flexibility of the desalination units, water transfer and water storage are key factors that needs to be considered in long-run planning of such systems. To achieve a realistic understanding in this regard, considering just a few days of operation, is not adequate to study the influence of the renewable power fluctuations on planning and designing such a system. This operational flexibility has only been considered in studies focusing on the operational aspect of the desalination systems powered by VRE (Al-Nory and El-Beltagy, 2014; Hickman et al., 2017; Smaoui and Krichen, 2016). On the other hand, the time horizon of months to years is required to study a realistic roadmap towards the transition to energy systems with a share of renewables and water systems with a share of desalination. This chapter aims to develop a nexus approach elaborating potential synergies in designing both energy systems and water systems together.

2.2 Methodology

Optimization modeling has been increasingly used for long-run planning of the water supply. One study (Tayfur, 2017) reviewed the optimization methods used in water resource planning. Another study (Adeyemo and Stretch, 2018) presented a review on the application of hybrid evolutionary algorithms in designing optimal water reservoirs. Studies (Ghelichi et al., 2018; Marques et al., 2018) have also developed multi-objective optimization problems for water distribution planning. Others (Ghelichi et al., 2018) applied a two-stage stochastic programming to capture demand uncertainties. Another study (Al-Nory et al., 2014) addressed various aspects of long-term desalination supply planning by developing a supply chain approach. Other studies developed multi-period construction and capacity expansion planning of desalination water supplies at city scale (Shahabi et al., 2017) and regional scale (Saif and Almansoori, 2014; Vakilifard et al., 2019).

In the energy sector, four key categories of models are standard in planning transitions to expand the share of variable renewable resources. They include network analysis models, production cost models, geo-spatial planning models, and long-term energy planning models (IRENA, 2017). Advanced modeling tools tend to cover multiple planning features, as a result distinction among these modeling categories are not typically not stringent.

Network analysis models are dedicated to assessing the stability and reliability of power systems and operational aspects, typically spanning a period of weeks to several years. Capacity mix, network infrastructure and its topography and dispatch scenario are all inputs in order to evaluate a network at a particular given point of time. Examples of network analysis tools include DIgSILENT GmbH and Simens PTI (Zare Oskouei and Mohammadi-Ivatloo, 2020).

Production cost models simulate power system operations typically on a one-year timescale, during which the mix of VRE capacity is assumed constant. These models investigate the techno-economic impacts of alternative energy policies and market configurations such as capacity markets and ancillary markets. Generally, investment costs are out of scope of these models. Therefore, production cost models are not designed to be the sole basis for long-run investment decision-making. Examples of production cost modeling software are EnergyPlan and PLEXO (Kiwan and Al-Gharibeh, 2020).

Geo-spatial planning models provide network topography analysis as a starting basis for the described detailed technical network models. These models assist to achieve an economic trade-off between location-specific variable renewable power productivity and transmission investment requirements for expansion of the VRE. Examples of GIS software used in the renewable energy planning are ArcGIS, ILWIS and Global Mapper (Vakilifard et al., 2019).

Long-term energy planning models are increasingly used to determine the optimal long-run mix of renewable technologies and investment paths to meet the national and regional targets during a time horizon typically ranging from 20 to 40 years (IRENA, 2017), or even longer. Examples of such modeling include MARKAL and OSeMOSYS, and WASP. The proposed model in the current study, fits in this modeling category. Long-term planning models employ reduced-form dispatch and simplified approaches to avoid the model becoming computationally unwieldy (Diakov et al., 2015; IRENA, 2017). As explained in the introduction, the integration of VRE into power grids is challenging due to fluctuating power production. Therefore, considering these fluctuations is essential in long-term energy supply planning. There are mainly four method classification for solar radiation and wind speed prediction (Ahmad et al., 2020) including (1) artificial intelligence and statistical techniques, (2) remote-sensing techniques, (3) numerical climate forecasting approaches, and (4) the hybrid forecasting approaches. A statistical approach has been used to validate the results in this study.

A novel nexus methodology is proposed to model the synergies of integrated planning of interlinked sectors. Two system types are assumed for investigation in this study including:

1. **Separated System**: The water sector is considered as an exogenous factor for the energy system, in which there is no control over it.

2. **Integrated System**: Both energy and water systems are studied as an integrated system, which are endogenous parts of one integrated system.

There are four modules within the model developed in this Chapter, as shown in Figure 2-1: (1) developing a supply-demand module, (2) proposing an energy storage module, (3) obtaining the two-factor learning curves for the case study in Iran and, (4) conducting a cost analysis.

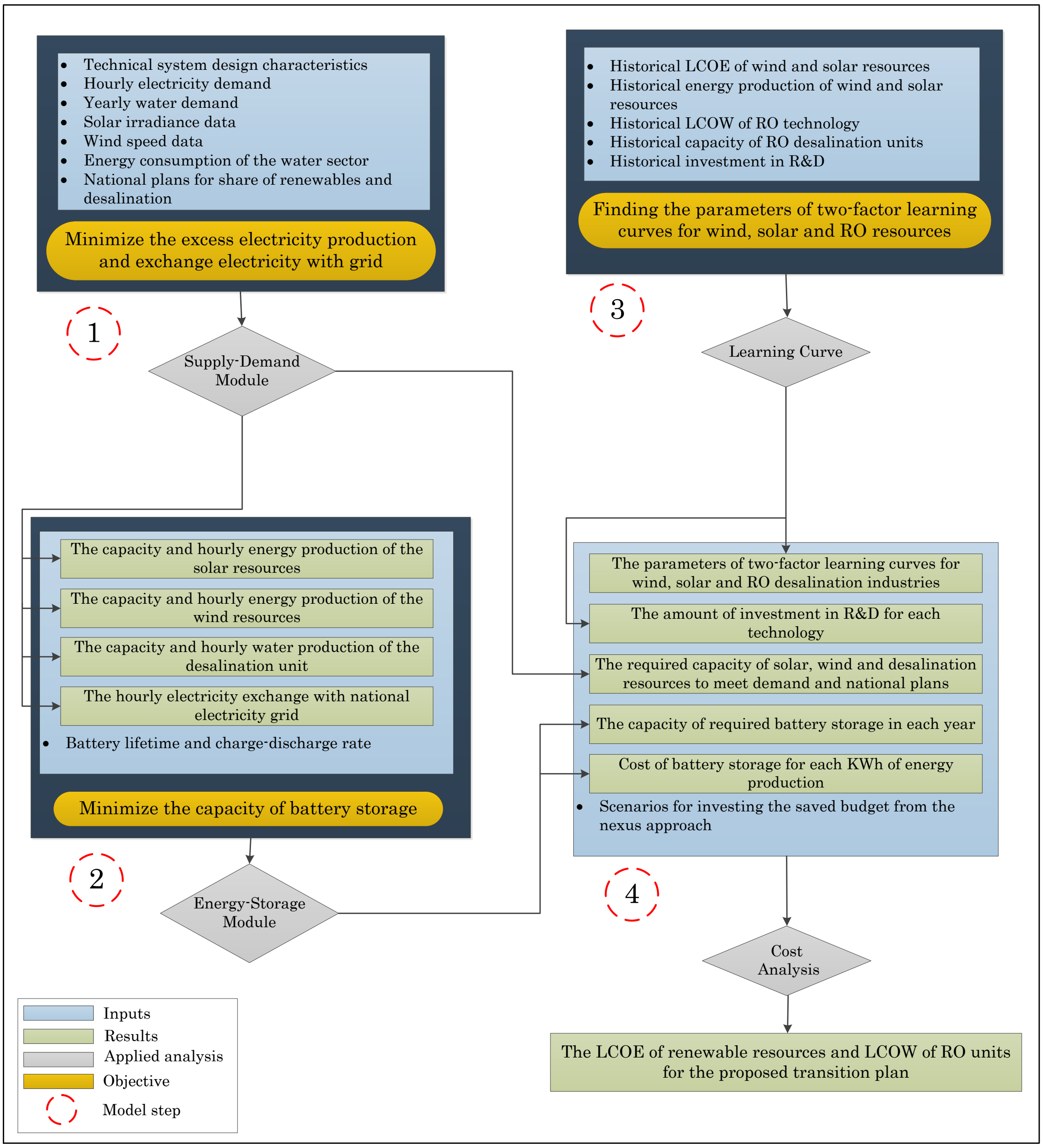


Figure 2-1. The proposed Methodology in Chapter 2.

The following describes the details of the modules and their decision procedures in Figure 2-1.

2.2.1 Supply-demand Module

In the first step, a supply-demand module is developed to investigate the technical aspects of these systems. In this module, the energy demand curves are estimated based on demographic trends, historical data and resource limitations. Technology trends, system configurations, and national plans and goals are considered in these optimization models.

Water Model

Integrated system

To meet the water demand, the amount of water in the city's water revisor at the end of each day need to be more than the water demand for the next day.

$$w_d(d, y) \geq w_{r,city}(d-1, y) \quad (2\text{-}1)$$

Where w_d is the daily water demand and $w_{r,city}$ is the amount of water in the water reservoir.

The hourly amount of stored water in the water reservoir is calculated as Equation (2-2).

$$w_{r,city}(t, y) = w_{r,city}(t-1, y) + w_{conv}(t, y) + w_{pmp,des}(t, y) \quad (2\text{-}2)$$

Where w_{conv} is the amount of water extraction from conventional water resources, underground and surface water, and $w_{pmp,des}$ depicts the amount of pumped water from the desalination plant's reservoir. The amount of water in the desalination reservoir is obtained from Equation (2-3).

$$w_{r,des}(t, y) = w_{r,des}(t-1, y) + w_{des}(t, y) - w_{pmp,des}(t, y) \quad (2\text{-}3)$$

Where w_{des} is the hourly amount of water production from the desalination plant. The amount of stored water in the reservoirs cannot exceed the capacity of them which can be defined as (2-4), and (2-5).

$$w_{r,city}(t,y) \le Cap_{r,city}(y) \tag{2-4}$$

$$w_{r,des}(t,y) \le Cap_{r,des}(y) \tag{2-5}$$

The amounts of water production from the desalination plant, conventional resources and pumped water are limited based on **Error! Reference source not found.**), **Error! Reference source not found.**), and **Error! Reference source not found.**).

$$w_{conv}(t,y) \le Cap_{conv}(y) \tag{2-6}$$

$$w_{des}(t,y) \le Cap_{des}(y) \tag{2-7}$$

$$w_{pmp,des}(t,y) \le Cap_{pmp,des}(y) \quad \text{(2-8)} \quad \text{(2-9)}$$

The amount of water demand is provided by the desalination plant needs to meet to target in each year which is considered as Equation (2-10).

$$\sum_t w_{des}(t,y) = RO_{share}(y) \times \sum_d w_d(d,y) \tag{2-10}$$

Desalination plants need to operate more than 80 percent of their capacity during a year, to become economically and technically feasible (Alonso et al., 2020). This limitation is imposed on the model based on (2-11).

$$\sum_t w_{des}(t,y) \ge Cap_{des}(y) \times 365 \times 0.8 \tag{2-11}$$

The hourly electricity consumption of the water sector for the integrated system is obtained from Equation (2-12) for each year.

$$p_w(t,y) = \sum_t p_{conv} \times w_{conv}(t,y) + p_{pmp} \times w_{pmp,des}(t,y) + p_{des} \times w_{des}(t,y) \tag{2-12}$$

Where p_w is the hourly electricity consumption of water sector, p_{des} is the required energy for producing unit of desalinated water, p_{pmp} is the required electricity for pumping unit of water from the desalination plant to the city's reservoir, and p_{conv} is the amount of energy needed to extract and transfer unit of water from conventional water resources.

Separated system

The amount of hourly electricity which the water sector consumes is constant for the separated system and obtained from Equation (2-13).

$$p_w(t,y) = \left[RO_{share}(y) \times (p_{pmp} + p_{des}) + (1 - RO_{share}(y)) \times p_{conv} \right] \times w_d(d,y)/24 \quad (2\text{-}13)$$

Energy Model

In the proposed model, the amount of hourly wind power production is calculated as Equation **Error! Reference source not found.**).

$$p_{wind}(t,y) = Cap_{wind}(y)v(t)^3 \quad (2\text{-}14)$$

Where p_{wind} is the hourly wind electricity production, Cap_{wind} is the wind energy capacity, and v describes the hourly wind speed which is normalized.

The amount of solar electricity production is obtained from Equation (2-15).

$$p_{pv}(t,y) = Cap_{pv}(y)I(t) \quad (2\text{-}15)$$

Which p_{pv} depicts the hourly electricity production from photovoltaic panels, Cap_{pv} is the capacity of the photovoltaic panels, and I is the hourly solar radiation during the year which is normalized.

As a result, the hourly renewable electricity production is obtained from (2-16).

$$p_{RE}(t,y) = p_{pv}(t,y) + p_{wind}(t,y) \quad (2\text{-}16)$$

Where, p_{RE} is the hourly renewable energy production.

Inequation (2-17) ensures to meet the share of renewable energy production which is targeted to reach in each year in percent of the whole electricity demand during each year.

$$\sum_t p_{RE}(t,y) = RE_{share}(y) \times \sum_t \left[p_d(t,y) + p_w(t,y) \right] \tag{2-17}$$

Where RE_{share} is the target share of renewable energy production in each year and $p_d(t,y)$ depicts the hourly electricity demand.

Equation (2-18) shows the electricity balance to meet hourly demand.

$$p_d(t,y) + p_w(t,y) = p_{grid}(t,y) + p_{RE}(t,y) \tag{2-18}$$

Where p_{grid} is the amount of hourly electricity exchange with the national grid getting both negative (fed electricity into the grid) and positive values (for injecting electricity from the grid).

The objective function is to minimize the exchange of electricity with the grid which is explained in Equation (2-19).

$$\text{Min} \sum_{t,y} \left| p_{grid}(t,y) \right| \tag{2-19}$$

For the separated system, the capacity of PV units and wind units and hourly electricity exchange with the grid are the variables of the optimization problem. For the integrated system, the capacity of PV units, wind units and desalination unit, hourly water production of desalination unit, hourly water extraction from the conventional water resources, hourly pumped water from the desalination unit's reservoir to the city's water reservoir and hourly electricity exchange with the grid are the variables of the optimization problem.

The following is examples showing how the supply-demand module performing. The monthly photovoltaic and wind electricity generation from 2027 to 2029 are depicted in Figure 2-2 and Figure 2-3 for the separated system. The maximum wind power generation accrues during June. Photovoltaic supply generates its maximum power in May. The database that has been used in this study is from a weather station at Jask (SATBA, 2014) providing hourly wind speed and solar irradiance data for two years. For further investigation, daily solar irradiance data from NASA database (NASA, 2020) through 01/01/2019 to 01/01/2020 for this case study (Jask, latitude: 25°38′N, longitude: 57°46′E) are depicted in Figure 2-4. As can be seen in Figure 2-4, the month of May has the maximum solar irradiance in 2019. These results revealed that the monthly variability of wind power is higher than the variability of photovoltaic power for the case study.

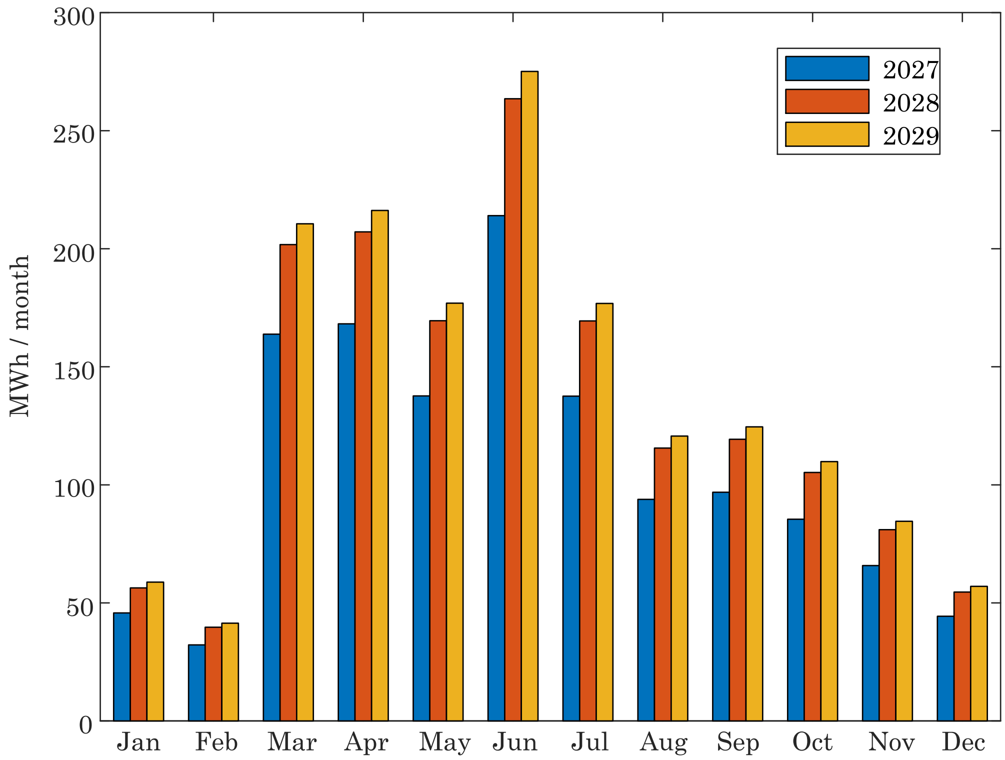


Figure 2-2. Monthly wind power generation between 2027-2029 for the separated system.

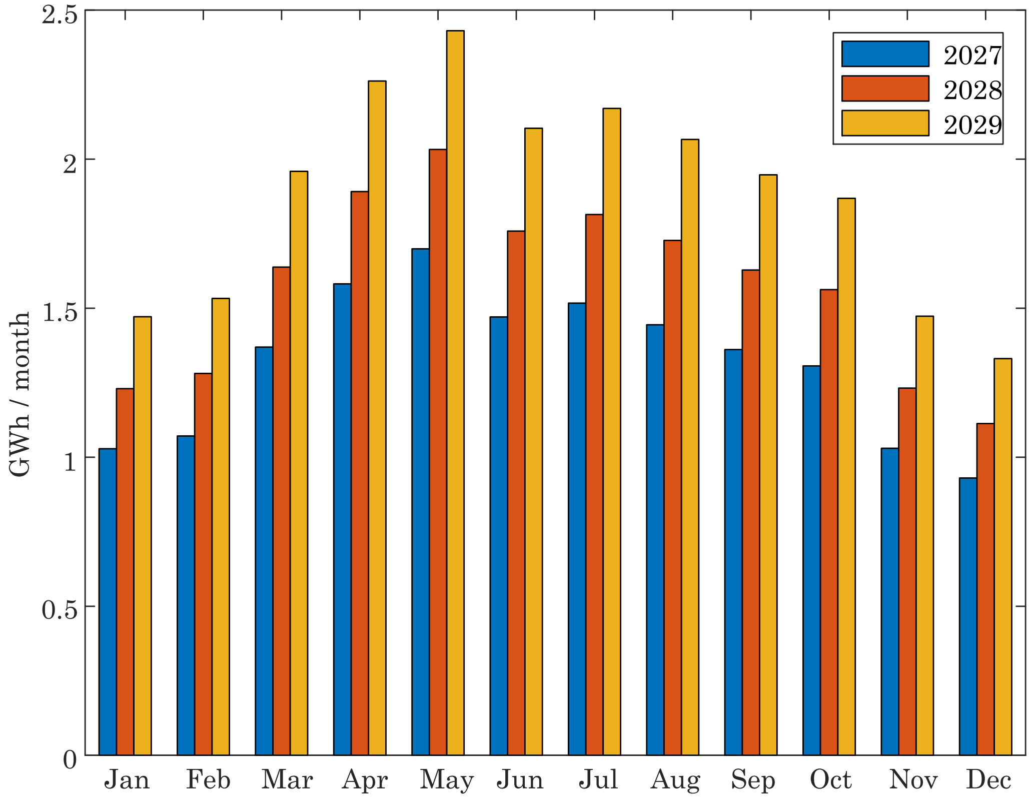


Figure 2-3. Monthly photovoltaic power generation between 2027-2029 for the separated system.

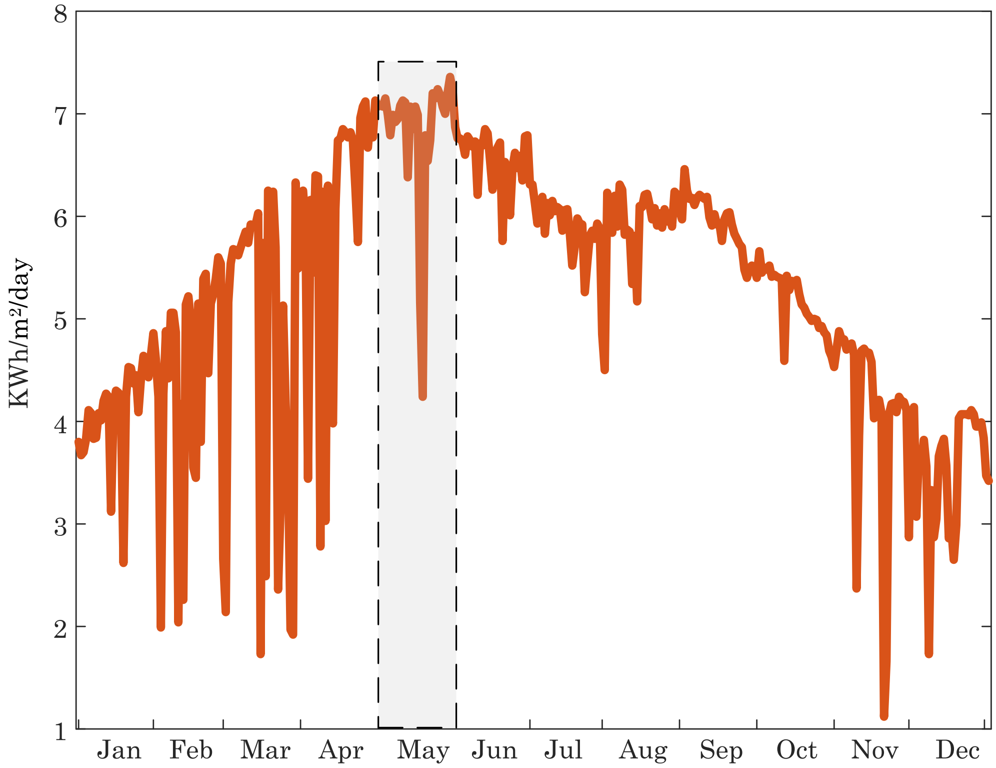


Figure 2-4. Daily solar irradiance in 2019 from NASA database.

The model is applied to a sample of hourly data for 5 days in July for the integrated system. The daily water demand is 9,389 m^3, 50 percent of which is planned to be provided by desalination supply. Figure 2-5 shows the hourly non-water electricity demand. The share of renewable resources from the total power generation is set at 20 percent.

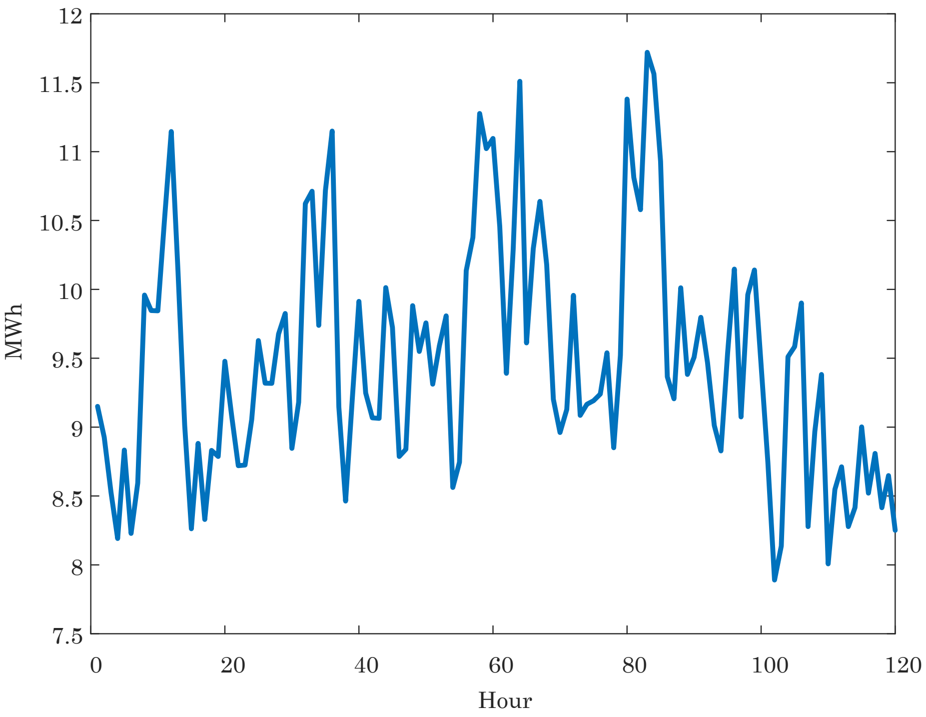


Figure 2-5. Non-water electricity demand for 5 sample days in July.

The optimization results for the sample data show that the minimum amount of exchanged electricity with the grid is 773.1 MWh for these sample days. The obtained wind capacity is 2.6 MW and photovoltaic capacity of 12.9 MW. Photovoltaic and wind electricity generation accounts for 83% (418.3 MWh) and 17% (86.6 MWh) of total renewable power generation, respectively. Figure 2-6 depicts a comparison between the optimal result and when the model is forced to have 50 percent wind generation from the total renewable power generation. For the 50% wind power share, the electricity exchange with the grid reaches 808.5 MWh for these 5 sample days.

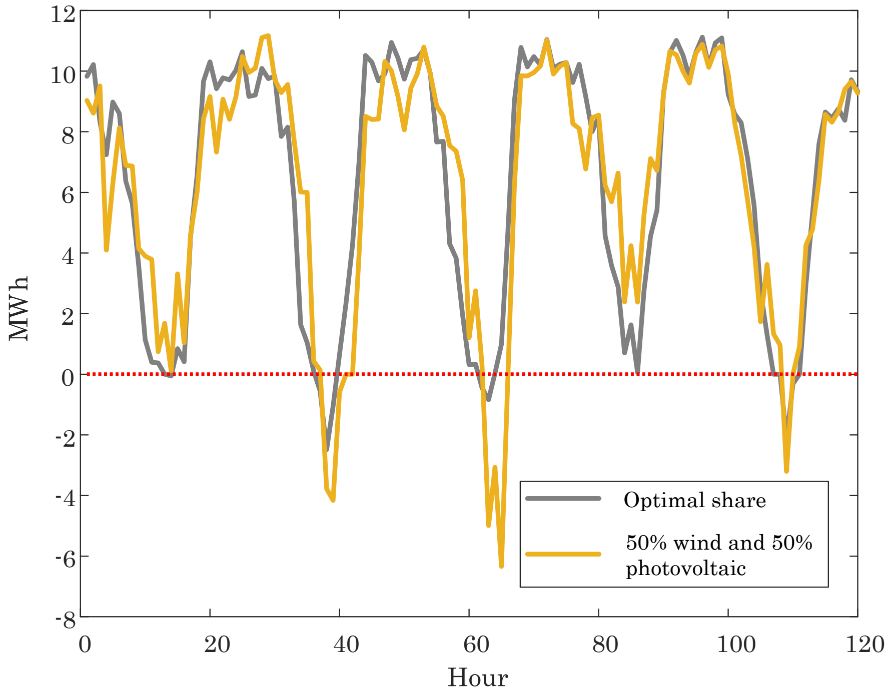


Figure 2-6. Electricity exchange with the grid for 5 sample days in July for the integrated system.

2.2.2 Energy Storage Module

The aim of this module is to find the required battery storage unit equivalent to the operational capacity of the flexible water sector. Based on the results of the supply-demand model the new required capacity of battery storage and cost of battery storage for a unit of energy production (MWh) are calculated. To this aim, the share of excess renewable electricity generation of the base scenario is required to be equal to the other proposed scenarios by installing new batteries, which is imposed on the model based on Equation (2-20).

$$\text{if } p_{grid}(t,y) < 0$$

$$\sum -p_{grid}(t,y) / (RE_{share}(y) \times \sum_t [p_d(t,y)]) = Ex_{sc}(y) \tag{2-20}$$

where Ex_{sc} depicts the share of excess renewable electricity generation for each scenario. This excess electricity generation refers to the portion of variable renewable power generation, which exceeds electric load.

Equation (2-21) describes the amount of stored energy in the battery storage.

$$E_{bat}(t,y) = E_{bat}(t-1,y) \times eff_{bat} + p_{ch}(t,y) - p_{dch}(t,y) \tag{2-21}$$

where E_{bat} depicts the amount of hourly stored energy, which cannot exceed the capacity of the battery storage, as can be seen in (2-22), p_{ch} is the amount of hourly electricity charge of the battery storage, and p_{dch} shows the amount of hourly discharged energy from the battery storage.

$$E_{bat}(t,y) \leq Cap_{bat}(y) \tag{2-22}$$

To limit the hourly amount of charged or discharged electricity based on charge and discharge rate limitation of battery storage, Equation (2-23) is considered in the model.

$$\begin{aligned} p_{ch}(t,y) &\leq Cap_{bat}(y) \times R_{bat} \\ p_{dch}(t,y) &\leq Cap_{bat}(y) \times R_{bat} \end{aligned} \tag{2-23}$$

In Equation (2-23), R_{bat} is the maximum charge/discharge rate of the battery storage, share of the total capacity.

Equation (2-24) ensures the electricity balance to meet hourly electricity demand in this model.

$$p_d(t,y) + p_w(t,y) + p_{ch}(t,y) = p_{grid}(t,y) + p_{RE}(t,y) + p_{dch}(t,y) \tag{2-24}$$

The objective function, which is depicted in (2-25), is to minimize the capacity of batteries ($Cap_{bat}(y)$) equivalent to the operational capacity of the flexible water sector.

$$\mathrm{Min}\sum_{y} Cap_{bat}(y) \tag{2-25}$$

The new required battery storage capacity, hourly electricity exchange with the national grid, and charge/discharge of the battery storage are the variables of this optimization problem.

Using the same 5 sample days in July, the supply-demand model results show that the electricity exchange for the separated scenario is 803.8 MWh, as can be seen in Figure 2-7. The optimization results of the storage model depict that 5.3 MWh battery capacity is required to reach the same performance as the integrated scenario with 773.1 MWh electricity exchange with the grid.

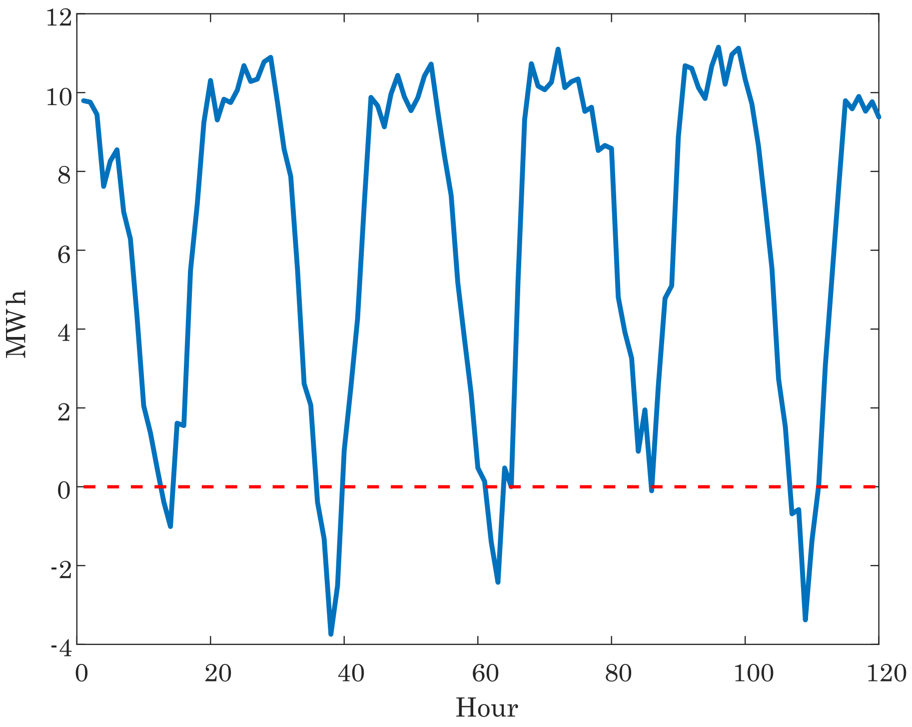


Figure 2-7. Electricity exchange with the grid for 5 sample days in July for the separated system.

2.2.3 Learning Curves

Learning curves have been used as an effective way of looking at technology cost reductions. The basic assumption of the learning curve is that experience, knowledge and other factors can improve technology performance, causing unit cost declines with the accumulation of aforementioned factors. The one-factor learning curve, which reached its popularity in the mid-1970s, is sensitive to the choice in certain cases and only considers the effects from the demand side. Studies have (Rubin et al., 2015) shown that the one-factor model overestimates the learning-by-doing ratio (LDR) because it does not consider the contribution of R&D investment. To overcome these issues, a two-factor learning curve was introduced in 2000 (Zhou and Gu, 2019). The one-factor learning curve only considers the cumulative production, experience, whereas the two-factor learning curve reflects both experience and knowledge mechanisms.

For studying synergies in designing both energy systems and water systems together, modeling technology cost just as a function of time ($f(time)$), which is the most common approach among the energy and water transition studies (Shahabi et al., 2017), is not practical because it does not allow the consideration of synergistic effects but maintains a separation of the systems due to the assumption of learning based on time. In this study, technology cost is assumed to be a function of experience and knowledge ($f(experience, knowledge)$) and modeled by the two-factor learning curve. The two-factor learning curve is chosen to estimate the future costs of different renewable energy production from the resources and desalinated water from RO units. Equation (2-26) describes the two-factor learning curve (Zhou and Gu, 2019).

$$C_t = C_0 \times CC^{-\alpha} \times KS^{-\beta} \tag{2-26}$$

Where C_t is the unit cost in year t, C_0 depicts the initial unit cost, CC is the cumulative production, α is the learning-by-doing elasticity, KS describes the knowledge stock, and β is the learning-by-searching elasticity.

Based on this curve, the unit cost decreases from the initial cost by increasing the research and development (R&D) investment as well as the cumulative production. The decreasing cost is illustrated by the learning-by-doing ratio and learning-by-searching (LSR) ratio which denotes the percentage of change in cost as a result of doubling the cumulative production and R&D budget, respectively. The learning-by-doing ratio is obtained as $1-2^{-\alpha}$ and the learning-by-searching ratio (LSR) is calculated as $1-2^{-\beta}$ where α is the learning-by-doing elasticity and β is the Learning-by-searching elasticity.

Because of a lack of data, a new methodology is applied to estimate the Learning-by-searching elasticity and the average research and development budget using particle swarm optimization in MATLAB software. The details of this approach and the two-factor learning curve are described in Appendix B.

2.2.4 Cost Analysis

To reveal the synergy effect, the results of the previous segments are used to estimate the future costs of renewable energy production and desalinated water for the region of the case study. This section focuses on the difference between the integrated system and the separated system. Two sensitivity analysis are conducted to elaborate the effect of R&D budget scenarios on the future costs and the influence of each learning rate on the systems.

2.3 Results & Discussion

In the current section, first, the results of the technical modules for one urban area as a sample of the case study, Jask, Iran, are explained. In the next step, the results were developed for the region of the case study, southern coastal line of Iran, the outcome of which was the baseline for further analysis.

2.3.1 Supply-Demand Model

In 2015 COP21, also known as the 2015 Paris Climate Agreement, Iran voluntarily agreed to reach 7,500 MW capacity of renewable electricity production by 2030 (Noorollahi et al., 2019). According to the Sixth Iranian National Development Plan, the Ministry of Energy, Iran's leading electric utility and subsidiaries, and the Renewable Energy Organization are committed to supply 5 percent of total electricity from renewables by 2021 (The Iranian Parliament, 2017). The Iranian Ministry of Energy has formulated a broad plan to meet these targets, such as feed-in tariffs and long-term contracts at guaranteed prices, which have been extended from 5 to 20 years in 2015 (Omid Shokri Kalehsar, 2019). Based on the Iranian National Strategic Energy Plan, Iran is planning to reach competitive renewable electricity costs in the electricity sector by 2040 and improve the renewable deployment rate which is currently about one percent yearly growth (SATBA, 2016). In the water sector, according to the Sixth Iranian National Development Plan, the Ministry of Energy is committed to plan for providing financial support and transferring knowledge to supply 70 percent of the urban water demand on the coast of the Persian Gulf and Gulf of Oman by 2021 (The Iranian Parliament, 2017). It is assumed that the share of VRE is increasing 2 percent each year, according to government plans, and reaches 42 percent in 2040 (Statistical Center of Iran, 2018). The assumption for expansion of desalination is a linear increase across the period to meet the 70 percent target, meaning a 3.5 percent yearly growth in its share of total water supply. All water, energy and battery related costs were converted to 2018 United States dollars ($).

A linear programming model is solved for 20 years with an hourly horizon between 2020 to 2040 in GAMS software for the sample urban area, Jask, Iran. The optimal capacity of wind, solar power and RO plant, the hourly operation of RO unit, the amount of water stored in the city's water reservoir, the amount of water stored in the desalination unit's reservoir, the water production from conventional water supplies to meet the target share of VRE, the amount of water pumped from the desalination's reservoir and desalination with minimum electricity exchange with the national grid are obtained by this model. Figure 2-8 illustrates the amount of renewable electricity production from PV and wind supplies from 2020 to 2040. As can be seen in Figure 2-8 and Figure 2-9 solar power performs better in following the load demand in this region and is the dominant renewable source with a share of about 80 percent of total renewable electricity production for both the integrated and separated systems.

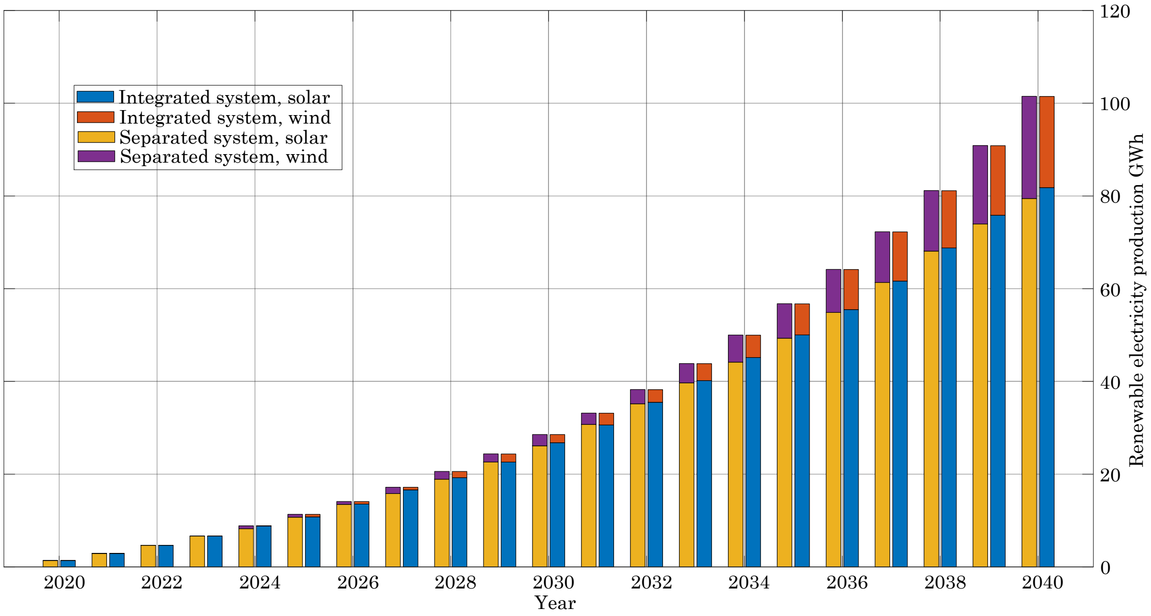


Figure 2-8. Renewable electricity production from the PV and wind supplies.

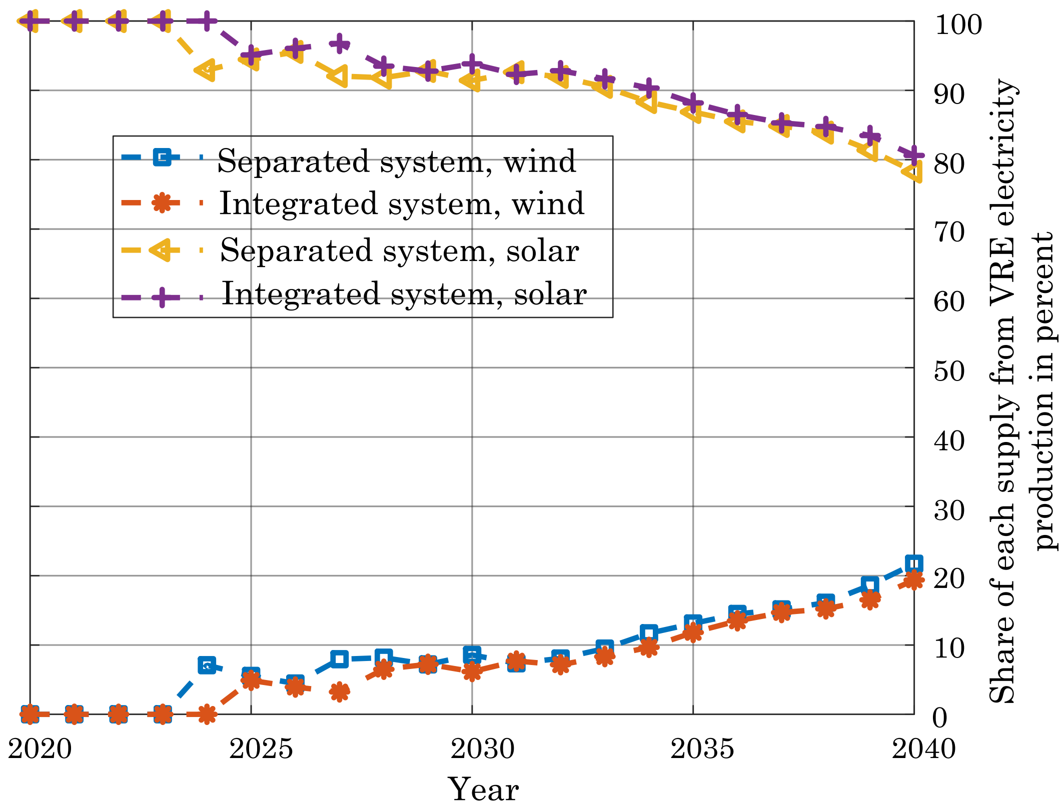


Figure 2-9. Share of PV and wind supplies in total VRE electricity production.

The amount of excess electricity production from renewable resources in 2040 reaches about 13 percent of total renewable power production for the separated system, while this excess energy production is around 11 percent for the integrated system. Variability of VRE power generation can cause mismatches between the temporal profiles of VRE electricity production and electric demand. In this study, the excess electricity production is defined as the portion of VRE power production which exceeds electric load. Figure 2-10 shows the amount of excess renewable electricity production and share of self-consumption from VRE electricity production in each year for both systems. The self-consumption of VRE refers to electricity that is produced from VRE, and is not fed-into the national grid but is consumed directly by the case study city.

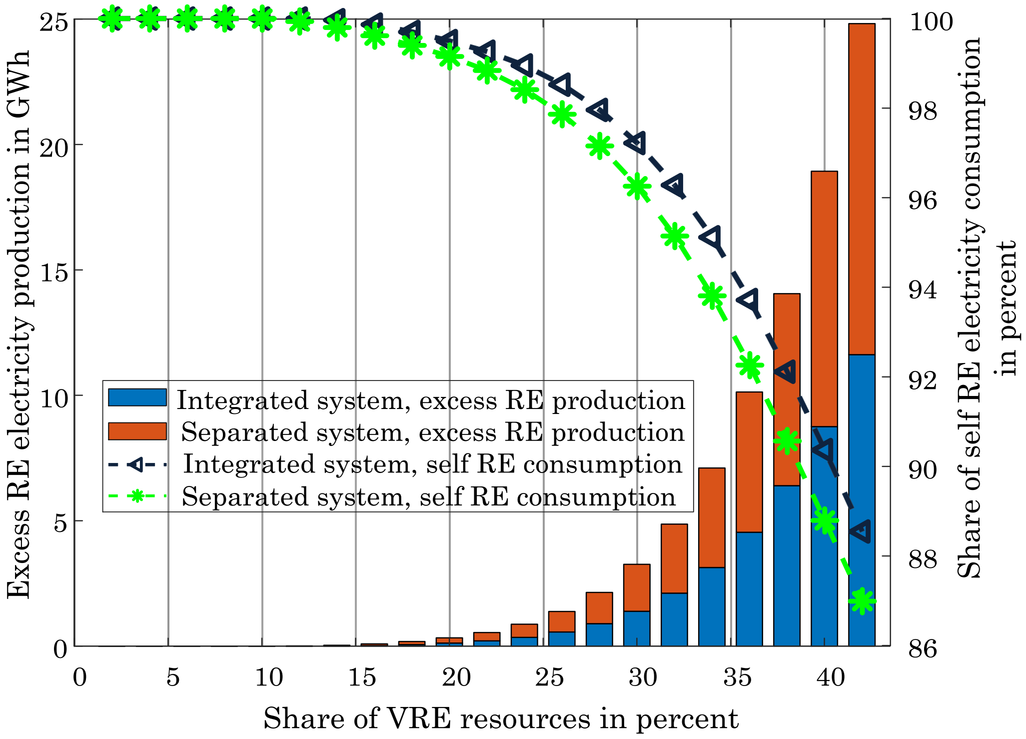


Figure 2-10. Share of self-consumption from VRE electricity generation and amount of excess renewable electricity production.

Figure 2-11 illustrates the share of the electricity consumption of the water sector of total electricity demand and the amount of electricity consumption in this sector each year. Although the water sector's electricity consumption is increasing due to higher share of desalination, 3.5 percent increase for each year and demand growth based on Iran's urban population growth (World Bank, 2020a), its share of total electricity demand increases from 5.7 percent in 2020 to 6.9 percent in 2030 and then decreases to 6.2 percent in 2040. It comes from the difference between the rate of population growth which directly influences the water demand in this model and the growth rate of electricity demand which is a constant rate based on national data predictions, 6.5 percent yearly (Statistical Center of Iran, 2018).

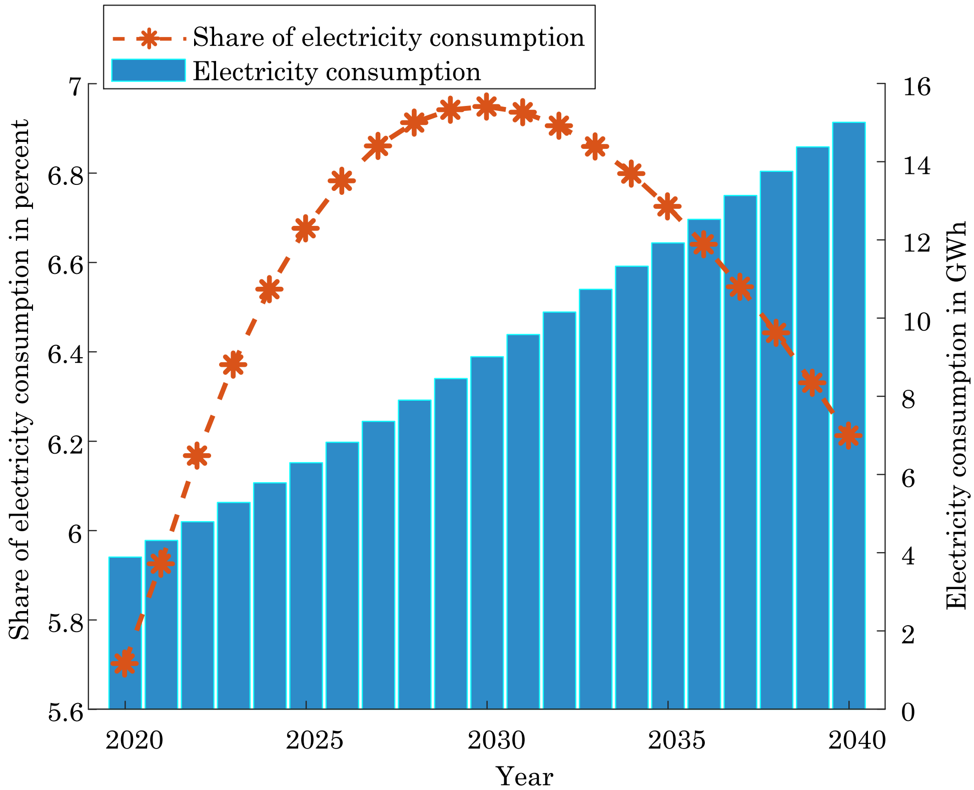


Figure 2-11. Electricity consumption of the water sector and its share from total electricity demand.

Statistical Model Validation

The cumulative distribution functions (CDF) for wind speed and solar irradiance are developed in order to validate renewable power generation in the proposed supply-demand module. It is assumed that wind speed is following two-parameter Weibull distribution as follows (Li and Zhi, 2016):

$$F_w(x) = 1 - \exp[-(\frac{x}{\sigma})^{\xi}] \quad \text{2-27)}$$

Weibull probability density function (PDF) is

$$P(x) = \frac{\xi}{\sigma}(\frac{x}{\sigma})^{\xi-1}\exp[-(\frac{x}{\sigma})^{\xi}] \quad (2\text{-}28)$$

Where ξ and σ are two parameters of Weibull distribution. ξ is the shape parameter and σ is the scale parameter.

Beta distribution is chosen to develop a distribution curve of solar irradiance in this study (Lv et al., 2016) as:

$$F_I(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \int_0^x (t)^{a-1}(1-t)^{b-1} dt \tag{2-29}$$

Beta probability density function follows:

$$P(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} (x)^{a-1}(1-x)^{b-1} \tag{2-30}$$

Where a and b are the parameters of Beta distribution and Γ refers Gamma function.

24 Weibull PDFs are obtained by fitting historical data representing PDF of wind speed for each hour of a day, as can be seen in Figure 2-12. Using historical data of solar irradiance, the parameters of 10 Beta probability distribution are estimated representing PDF of solar irradiance from 8 am to 5 pm, as depicted in Figure 2-13.

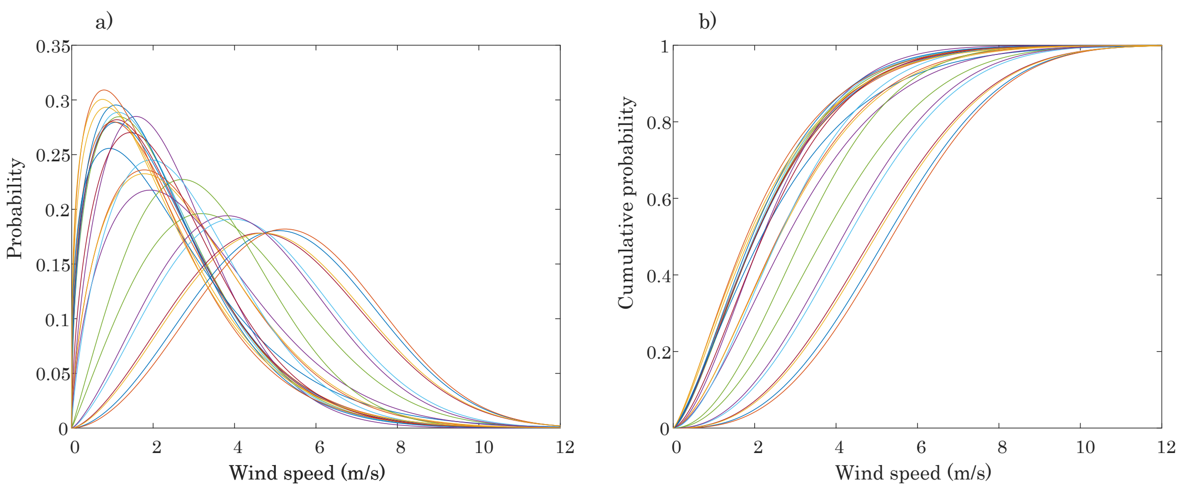


Figure 2-12. Wind speed distribution curves for the case study, **(a)** Weibull probability distribution; **(b)** Weibull cumulative probability distribution.

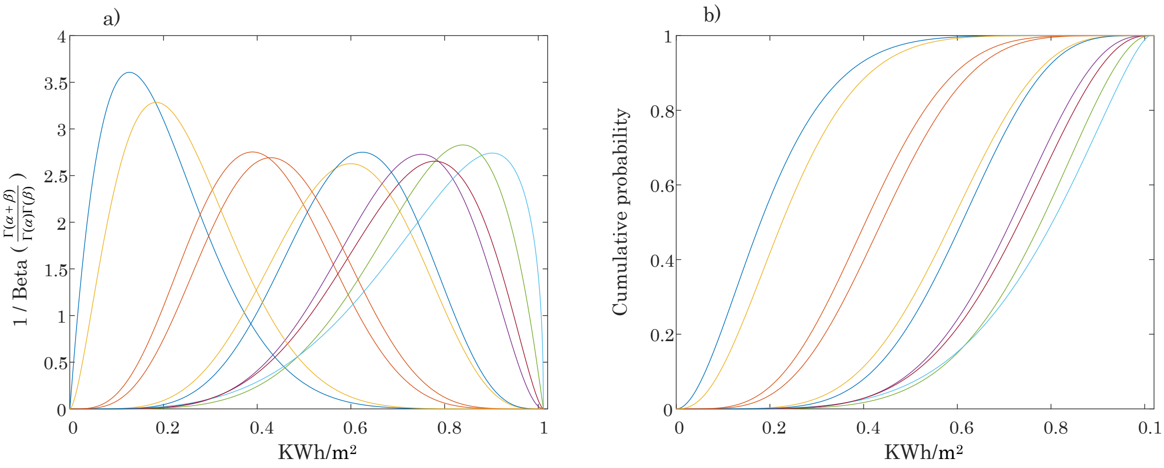


Figure 2-13. Solar irradiance distribution curves for the case study, **(a)** Beta probability distribution; **(b)** Beta cumulative probability distribution.

The following representative results are evaluated for the separated system. The obtained Weibull cumulative distribution curves show that the probability of wind power generation higher than 93.9 GWh — equal to 90 percent of the result of the proposed model — is 92%. The probability of wind power generation lower than 10.4 GWh — 10 percent of the wind power generation in the proposed model — is only 2 percent.

For photovoltaic electricity generation, the obtained Beta cumulative distribution functions estimate that the probability of higher than 601.4 GWh photovoltaic electricity generation — 90 percent of the photovoltaic power generation in the proposed model — is 75%. In the worst scenario possible, photovoltaic electricity generation is more than 26 percent, 167.1 GWh, of the photovoltaic electricity generation in the proposed model. As can be seen in Figure 2-13 (b), this comes from the fact that for 8 hours during the day, the probability of solar irradiance lower than 100 Wh/m^2 is zero.

2.3.2 Energy storage

In the next step, an optimization problem was solved using GAMS software to find the minimum required capacity of batteries to reach the same VRE self-consumption for both systems, namely, integrated and separated. The optimization results, depicted in Figure 2-14, indicate that a battery unit with a capacity of 17.4 MWh would be required in 2040. The annual equivalent of the lump sum unit investment cost of the battery unit is calculated to obtain the cost of energy storage for a unit of power production ($/MWh) which is described in Figure 2-14. The annual equivalent of the lump sum unit investment cost of each technology is obtained by calculating the lump sum by a stream of equal annual payments over the lifetime of the technology. The present value of the stream is exactly equal to the lump sum unit investment cost, for each technology. This cost is falling in several periods, from 2025 to 2026, from 2027 to 2033, and 2034 to 2037. This is due to the assumption that the cost of battery technology will decrease by 40 percent by 2040 (Battke and Schmidt, 2015; Cole and Frazier, 2019) causing a lowering of costs in these periods while the required capacity of the battery unit is constant or decreasing.

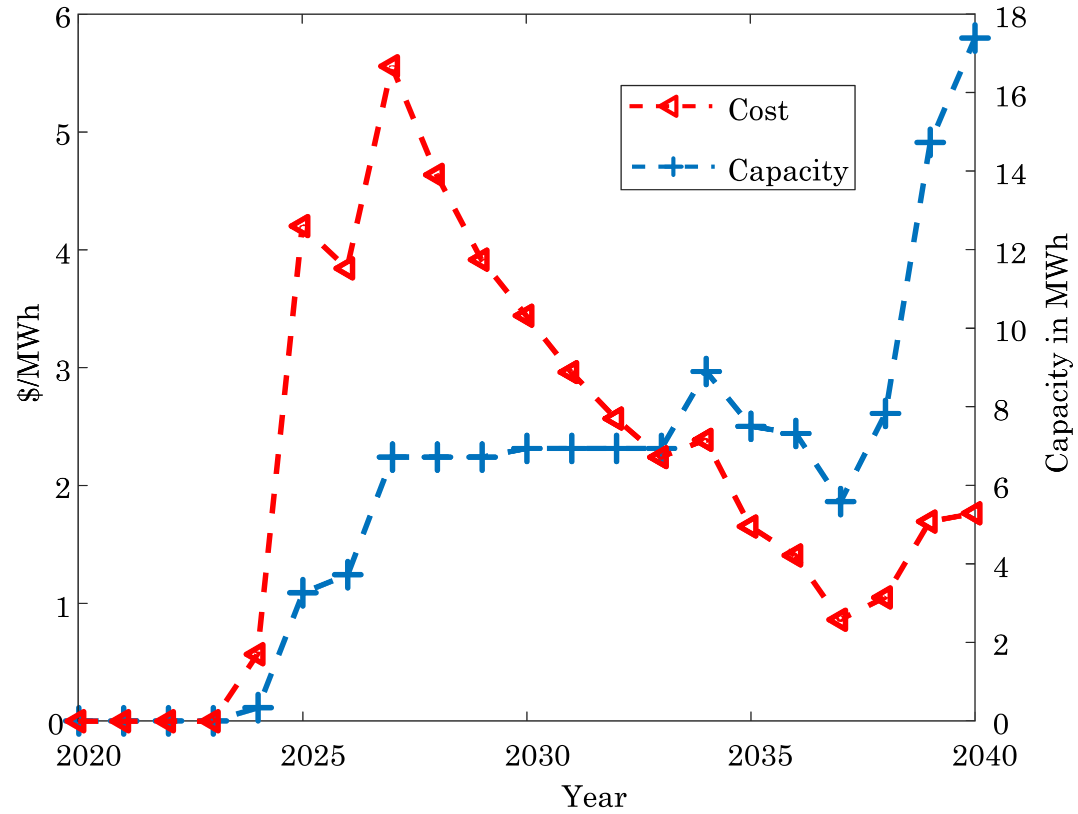


Figure 2-14. Capacity and cost of the battery storage to reach same VRE self-consumption.

2.3.3 Learning Curve

The parameters of the two-factor learning curve have been estimated for wind, solar technologies in the Middle East and for worldwide RO desalination technology. The results are depicted in Figure 2-15 and Figure 2-16. To calculate the LCOE of solar and wind energy, 49 PV projects and 32 wind projects were examined, as explained in detail in Appendix B.

For the Middle East's wind power between 2010 to 2018 the obtained LDR was 13.5% and LSR was 36.6% with a goodness of fit (R^2) of 90.0% based on the average levelized cost of energy and 67.4% based on overall data. Overall LDR rates span a very large range, from -11% to 35% among studies (Rubin et al., 2015). The predicted levelized cost of wind energy is equal to 34.6 $/MWh in 2020. Previous studies (Kobos et al., 2006; Zhou and Gu, 2019) adopting a similar two-factor learning curve to estimate wind power cost, obtained an LDR of 14.2 percent and an LSR of 18.0%, from 1991-2000, and LDR of 17% and LSR of 37%, from 2009 to 2016.

From 2013 to 2019, the LDR of 15.3% and LSR of 33.9% are the estimated parameters of the two-factor learning curve for solar power in the Middle East with a goodness of fit (R^2) equal to 96.9 percent based on the average and 86.9 percent based on the overall data. The estimation shows the levelized cost of solar energy will reach 55.2 $/MWh in 2020. LDR is calculated as 18% with the one-factor learning curve for 26 regions in North Africa, South America, and Australia (Köberle et al., 2015) to estimate the LCOE of PV technology. Authors in previous studies (Miketa and Schrattenholzer, 2004) found an LDR of 17% and an LSR of 10% by developing the two-factor learning curve for PV systems. Other studies (Kobos et al., 2006), using data from 1975 to 2000 using worldwide data, and (Zhou and Gu, 2019), using data from 2009 to 2016 for the US, also include a time lag between investment in R&D and subsequent declines in cost, and report rates of 18.4% and 6.7% for LDR and 14.3% and 75.2% for LSR, respectively.

The learning rates that have been obtained in this study, by applying the two-factor learning curve, were higher than the previous studies, indicating that, in the Middle East, with large-scale investments and commercialization, the learning ability of PV and wind power technologies have substantially improved. Furthermore, for these technologies, LSR was higher than LDR which indicates that wind and photovoltaic industries are both experiencing an explosion of knowledge-driven technology cost reductions, which is ensuring R&D investment can play an important role in the development of these industries.

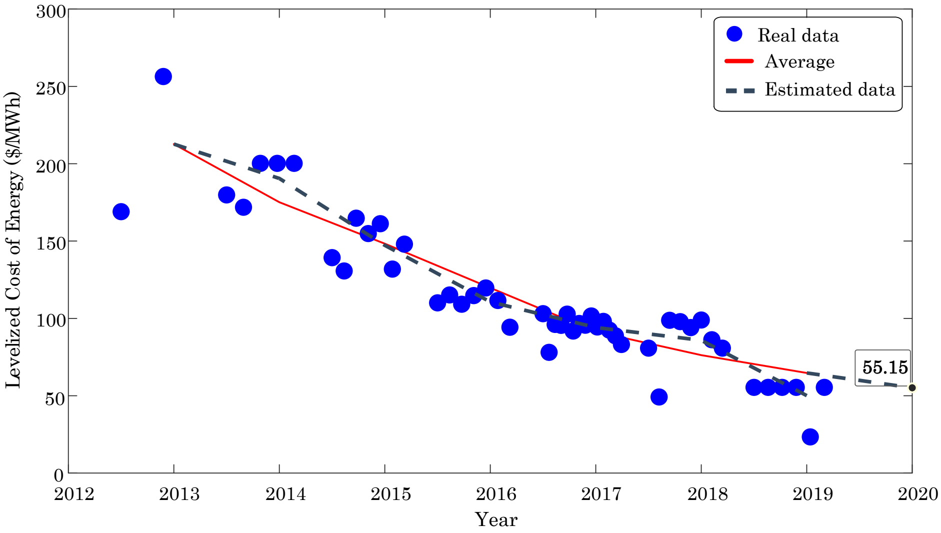


Figure 2-15. Learning-curve model fitting of photovoltaic (PV) investment cost.

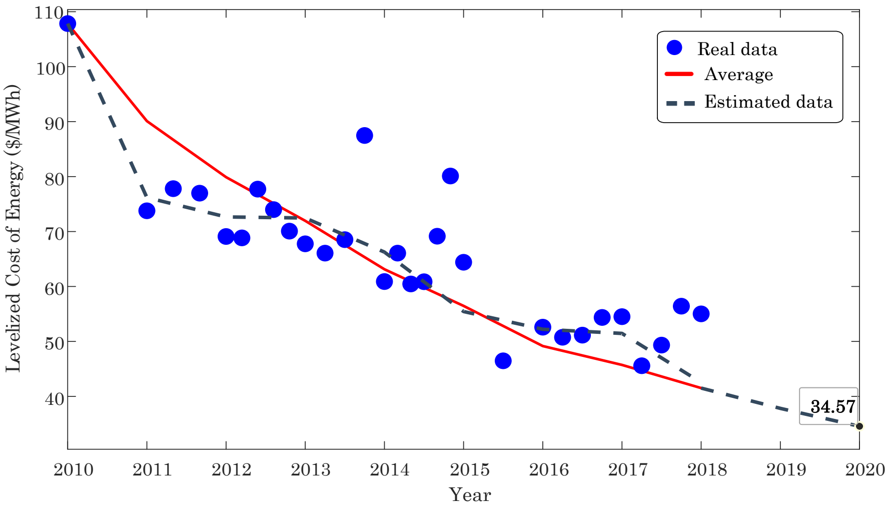


Figure 2-16. Learning-curve model fitting of wind-power investment-cost reduction.

For RO technology in 2012 to 2020 (ALMAR Water Solution, 2017), the obtained LDR is 9.1%, LSR is 49.6 percent with a goodness of fit (R^2) of 98.8%. The result for RO technology is illustrated in Figure 2-17. Previous studies, (Caldera, 2017) adopting a one-factor learning curve to estimate the learning rate for the CAPEX of RO technology, found an LDR of 15% for RO desalination technology using worldwide empirical data. Other studies (Mayor, Beatriz, 2018) proposed a range of 6 to 20, high learning scenario, percent for LDR of RO technology.

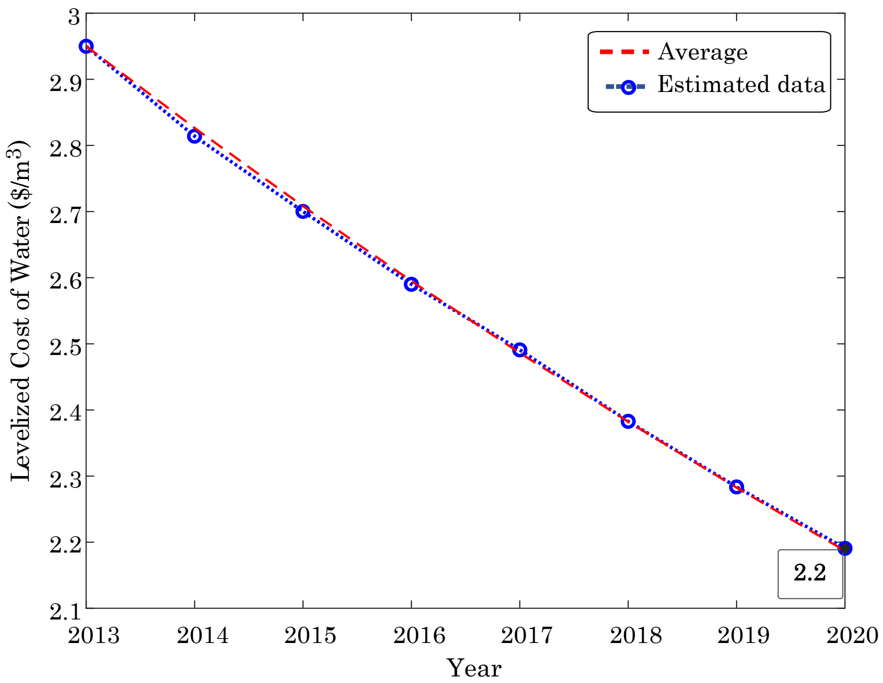


Figure 2-17. Learning-curve model fitting of RO desalination industry investment cost.

2.3.4 Cost Analysis

Based on the previous results, the future LCOE for wind and solar energy and the LCOW for RO technology are estimated for the coastal area in the southern part of Iran. The future electricity and water demand for this area have been obtained based on national predictions (Statistical Center of Iran, 2018) and the World Bank's population estimation (World Bank, 2020a).

Ten percent of the budget, saved from a lower capacity of batteries for the integrated system, is assumed to be invested in the R&D of wind and solar industries in proportion to the share of each technology in renewable electricity generation, as can be seen in Figure 2-9. The rest of the saved budget, 90 percent, is assumed to be invested in producing wind and solar power, also in proportion to the share of each technology in renewable electricity over 20 years. This means that the new installed capacity is producing energy for the next 20 years which is considered as the life-time of the wind, PV and RO units in this study.

Based on previous studies (Gude, 2016a; Sood and Smakhtin, 2014; World Bank, 2019) around 40 percent of the LCOW of RO technology goes to energy, causing a cost-saving in water desalination for the integrated system compared to the separated system, due to lower LCOE. Moreover, the difference between the LCOW of the integrated and the separated systems is another source of budget savings for the water sector. These savings are invested in RO industry R&D, 10 percent of the saved budgets, and RO water production, 90 percent of the saved budgets, over the period of 20 years to increase the share of desalination in the region of the case study. Table 2-1 summarizes the LCOE of renewable supplies and LCOW of RO technology for 20 years from 2020 to 2040 in Iran.

Table 2-1. Estimated future LCOE of VRE and LCOW of RO.

Year	Separated system, wind energy, $/MWh	Integrated system, wind energy, $/MWh	Separated system, solar energy, $/MWh	Integrated system, solar energy, $/MWh	Separated system, desalinated water, $/m3	Integrated system, desalinated water, $/m3
2020	34.6	34.6	55.2	55.2	2.19	2.19
2021	34.6	34.6	48.3	48.3	2.05	2.05
2022	34.6	34.6	43.9	43.9	1.94	1.94
2023	34.5	34.5	40.7	40.7	1.84	1.84
2024	30.5	34.5	38.8	38.2	1.75	1.75
2025	30.4	30.8	36.6	36.5	1.67	1.67
2026	30.4	30.7	34.7	34.3	1.60	1.60
2027	27.8	30.6	33.4	32.3	1.54	1.53
2028	27.0	27.7	32.0	30.6	1.48	1.47
2029	26.7	26.6	30.7	29.0	1.42	1.42
2030	25.4	26.5	29.7	27.4	1.37	1.36
2031	25.4	24.9	28.5	26.1	1.32	1.31
2032	24.4	24.6	27.6	24.8	1.28	1.27
2033	23.1	23.3	26.8	23.7	1.24	1.22
2034	21.7	22.1	26.1	22.7	1.20	1.18
2035	20.7	20.7	25.4	21.7	1.16	1.14
2036	19.8	19.7	24.7	20.9	1.13	1.10
2037	19.2	18.8	24.0	20.1	1.09	1.07
2038	18.5	18.2	23.4	19.4	1.06	1.03
2039	17.5	17.4	22.9	18.8	1.03	1.00
2040	16.6	16.4	22.5	18.1	1.01	0.97

Table 2-1 shows that the levelized cost of PV electricity will reach 22.5 $/MWh for the separated system and 18.1 $/MWh for the integrated system in 2040. The obtained LCOE for the integrated system is 20 percent lower than the LCOE for the separated system while the required budget is 13 percent lower than the separated system. It was calculated that 74% of the cost reduction of solar power in 2040 compared with 2020, is driven by the influence of cumulative production, and 26% is driven by the effect of the knowledge stock of the cumulative increase in R&D spending for the integrated system. These shares for the separated system are 96% of cost reduction by the experience effect of cumulative production, and 4% by the cumulative increase in R&D spending. Although LSR is higher than LDR, the main share of the cost reduction comes from the experience of cumulative production which shows the inadequate solar industry R&D budget. Wind industry is also facing this inadequate budget.

For the wind industry, the LCOE in 2040 is equal to 16.6 $/MWh for the separated system and 16.4 $/MWh for the integrated system. About 89% of this cost reduction in 2040 as compared with 2020 is caused by the experience of cumulative production, and 11% comes from the knowledge stock of the cumulative increase in R&D spending for the integrated system. The cost reduction for the separated system is caused by 94 percent due to the cumulative production experience and only 6 percent because of the R&D budget. The cost reduction of wind power is much lower than the cost reduction of solar power. There are several factors that cause this difference. First, the wind power production share of total VRE power production reaches around 20 to 22 percent in 2040, as can be seen in Figure 2-9, which affects the cost reduction by the experience of cumulative production. In the proposed model in this study, the technology with a higher share of power production gains more budget for R&D and new capacity because it's more attractive based on the technical model.

The LOCW for RO technology will reach 1.01 $\$/m^3$ for the separated system and 0.97 $\$/m^3$ for the integrated system. For RO technology in the integrated system, about 64% of the cost reduction caused by the effect of knowledge stock in 2040 as compared with 2020 and around 36 percent is driven by the experience effect of cumulative production which means the RO technology received more adequate R&D budget compared to wind and solar industry. The cost reduction for the separated system is about 62 percent due to the production experience and 38 percent of caused by the R&D knowledge stock.

Above the lower LCOE for wind and solar power and LCOW for RO technology, the share of renewable electricity production in 2040 will be 1.2 percent, 2,443 GWh, more than the VRE share for the separated system with 13 percent lower budget compared to the separated system. Furthermore, with one percent lower budget compared to the separated system, the integrated system desalinates 0.4 percent more water than the separated system in 2040 which is equal to 8.0 million m^3.

Sensitivity Analysis

Two sensitivity analyses are developed. First, a sensitivity analysis has been conducted to explore the role of R&D budget share in the future costs of wind, solar and RO technologies. To this end, the share of research and development investment from the saved budget is assumed to differ by up to 20 percent. The results in 2040 are summarized in Table 2-2. Because of the higher effect of cumulative production and receiving a higher share of the research and development budget, the LCOE for solar power has been affected the most, about 30 percent cost reduction, by increasing the share of R&D budget compared to the LCOE of wind power, around 6 percent cost reduction, and LCOW of RO technology, around 12 percent cost reduction. As expected, the share of VRE is decreased by increasing the share of R&D investment, because the budget for VRE production is decreased and invested in R&D. The share of desalinated water reaches 71.4% by raising the share of the R&D budget to 20 percent. Although the share of RO water production decreases to 80 percent, the total saved budget is increasing because of the high cost reduction of PV energy, around 30 percent. This shows the role of LCOE in the cost of water desalination which is considerable and with 5 percent lower budget compared to the budget for no share of R&D, as can be seen in Figure 2-18, the RO water production rises about 1.4 percent.

Table 2-2. Sensitivity analysis on the share of research & development from the budget savings.

Share of R&D in percent	Solar energy, $/MWh	Wind energy, $/MWh	Desalinated water, $/m3	VRE share in percent	Desalination share in %
0	22.2	16.9	1.01	43.3	70.0
2	21.2	16.8	1.00	43.3	70.1
4	20.3	16.7	1.00	43.3	70.1
6	19.5	16.6	0.99	43.2	70.2
8	18.8	16.5	0.98	43.2	70.4
10	18.1	16.4	0.97	43.2	70.5
12	17.5	16.3	0.96	43.2	70.7
14	17.0	16.2	0.94	43.1	70.8
16	16.5	16.1	0.93	43.1	71.0
18	16.0	16.0	0.91	43.1	71.2
20	15.6	15.9	0.89	43.1	71.4

In this study, it is assumed the share of the saved budgets goes into production, adding new capacity to the supply side. In other words, these shares of the budget are spent to cover the overall cost of production for the life-time of each technology, which is equal to 20 years. Figure 2-18 depicts the share of the total production of these new capacities during their lifetime. The results indicate that with just the new capacity from the saved budgets in the integrated system by 2040, these new capacities during their lifetime will produce 6 percent more VRE electricity and 5 percent more desalinated water, for 20 percent share of R&D, compared to the production of the separated system by 2040. Figure 2-18 also illustrates the role of R&D in the share of desalination in the integrated system. The obtained LSR of the RO technology, around 50 percent, in this study is higher than VRE technologies, around 34 to 37 percent, causing the rise in the share of R&D budget influences the RO water production much more than the VRE electricity production.

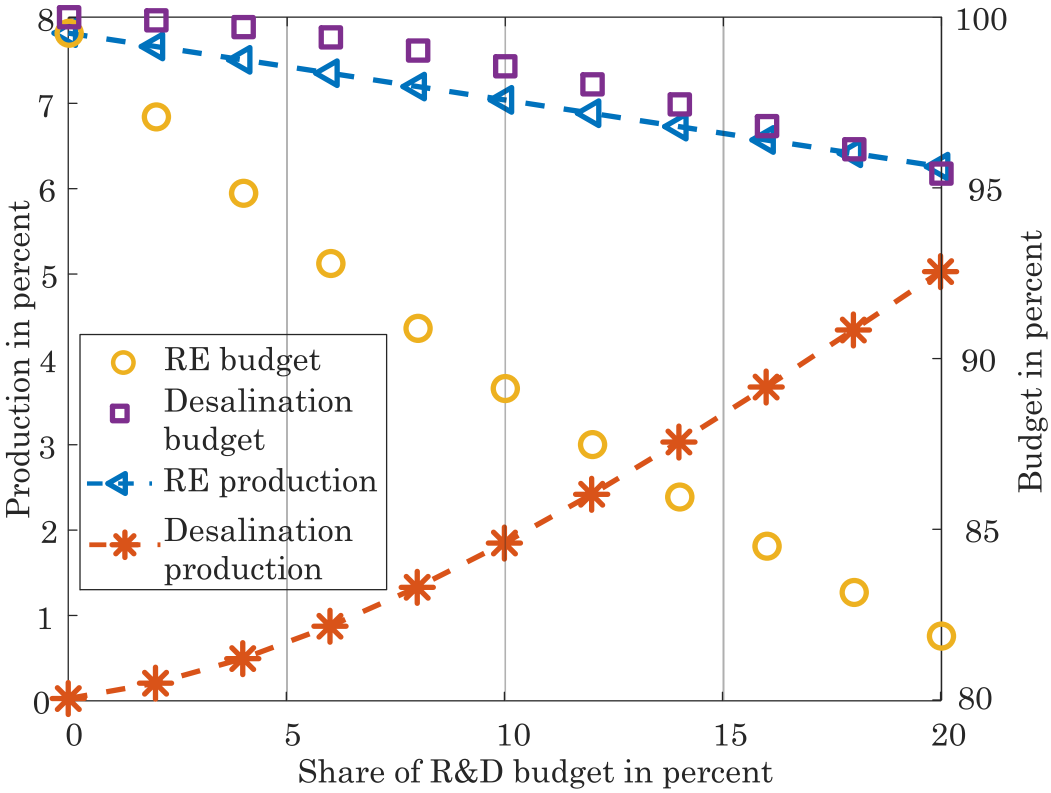


Figure 2-18. Share of lifetime VRE electricity generation from the saved budgets out of the total VRE electricity generation of the separated system and required budget compared to the separated system. Share of lifetime RO water generation from the saved budgets out of the total RO generation of the separated system and required budget compared to the separated system.

A further sensitivity analysis has been conducted to study the influence of learning rates of each technology on systems with a fixed 10 percent share of R&D. Figure 2-19 to Figure 2-21 illustrate the results of this sensitivity analysis. Despite the higher rate of LSR compared to LDR, the results indicate that wind and PV technologies are more sensitive to changes in LDR compared to LSR causing as an example, 45 percent rise in LCOE of PV, for the integrated system, by decreasing 0.1 of learning by doing elasticity (αPV) while reducing 0.1 of learning by searching elasticity (βPV) increase the LCOE only 4 percent in Figure 2-19(b). As mentioned, more investments on R&D in wind and PV industry must be spent to promote the stock of knowledge of these technologies.

Similar to the previous sensitivity analysis, RE share depicts the percentage of lifetime variable renewable electricity generation from the saved budgets out of the total VRE electricity generation of the separated system. As expected, this RE share surges by increasing the VRE learning elasticities because of lower LCOE of VRE causing higher VRE capacity, as can be seen Figure 2-19(e). With limited renewable financing being one of the challenges that renewable projects are facing (IRENA, 2016), especially in developing countries, these lower costs could accelerate the development and uptake of renewable energy.

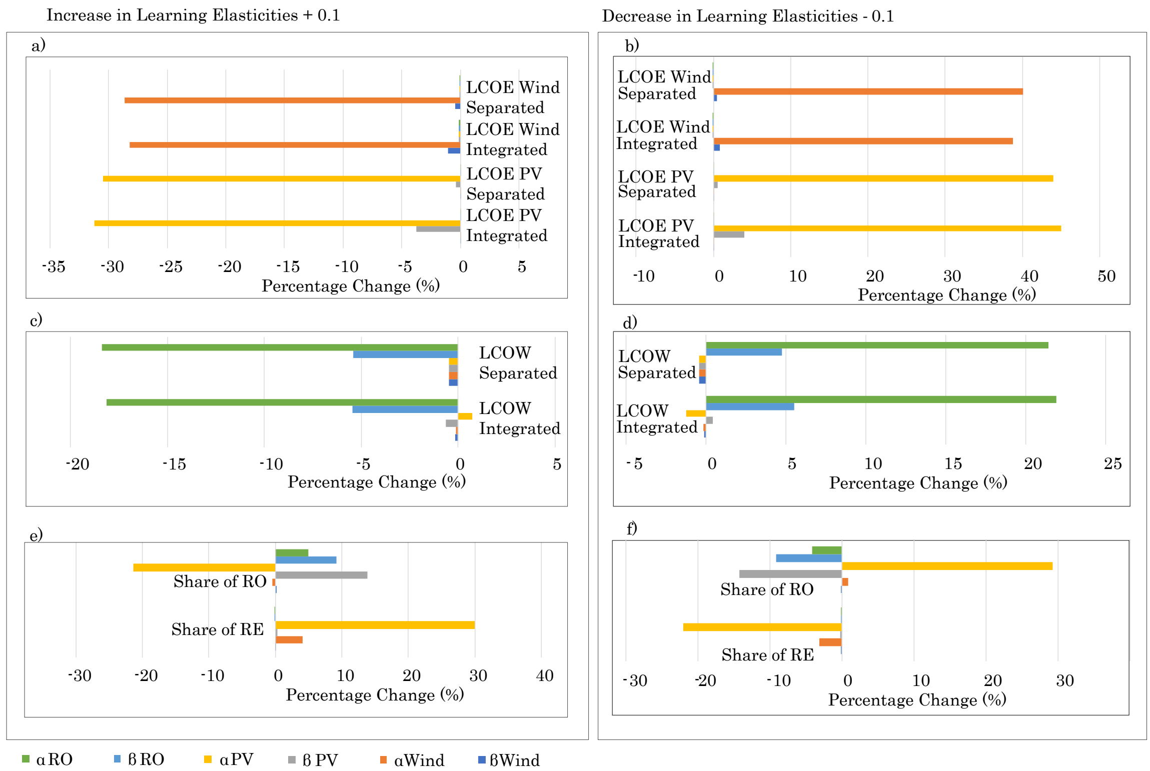


Figure 2-19. Sensitivity analysis on the influence of the learning elasticities (depicts the variations in percent) on: **(a)** increase **(b)** decrease in levelized cost of renewable energy; **(c)** increase **(d)** decrease in levelized cost of desalinated water; **(e)** increase **(f)** decrease in share of VRE and RO production for the integrated scenario.

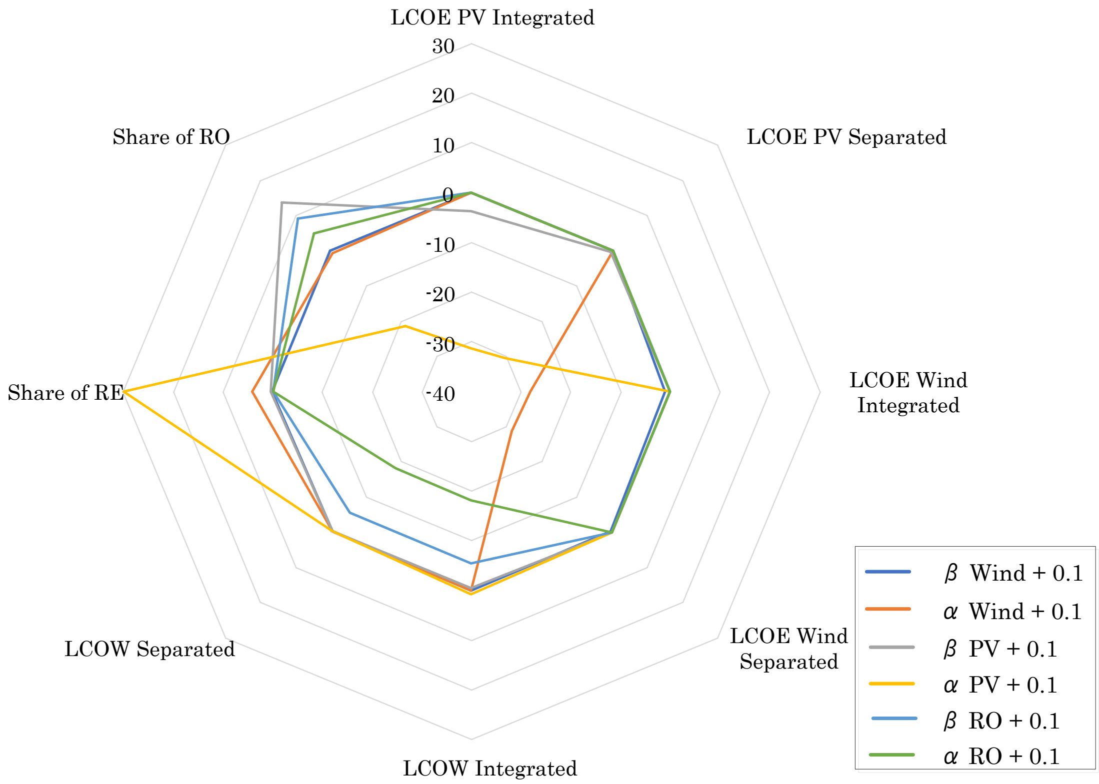


Figure 2-20. Sensitivity analysis on the influence of the learning elasticities, increase.

The share of RO illustrates the percentage of life-time RO water production from the saved budgets out of the total reverse osmosis water production of the separated system. In Figure 2-19(f), although the learning by doing elasticity of PV (α PV) diminishing 0.1 (lower LDR and higher LCOE), the RO share rises 29 percent and LCOW declines 1.3 percent, as depicted Figure 2-19(d). It comes from a higher saved budget due to a different growth in LCOE of PV between the separated system and the integrated system. For the integrated system, this cost rises from 18.1 $/MWh and reaches 26.2 $/MWh while for the separated system surges 44 percent from 22.5 $/MWh and reaches 32.4 $/MWh, as can be seen in Figure 2-19(b). This means the difference of cost increases from 4.4 to 6.2 $/MWh. Because of the same reason, the

RO share rises 0.8 percent and LCOW declines 0.2 percent by falling 0.1 the learning by doing elasticity of wind (α wind).

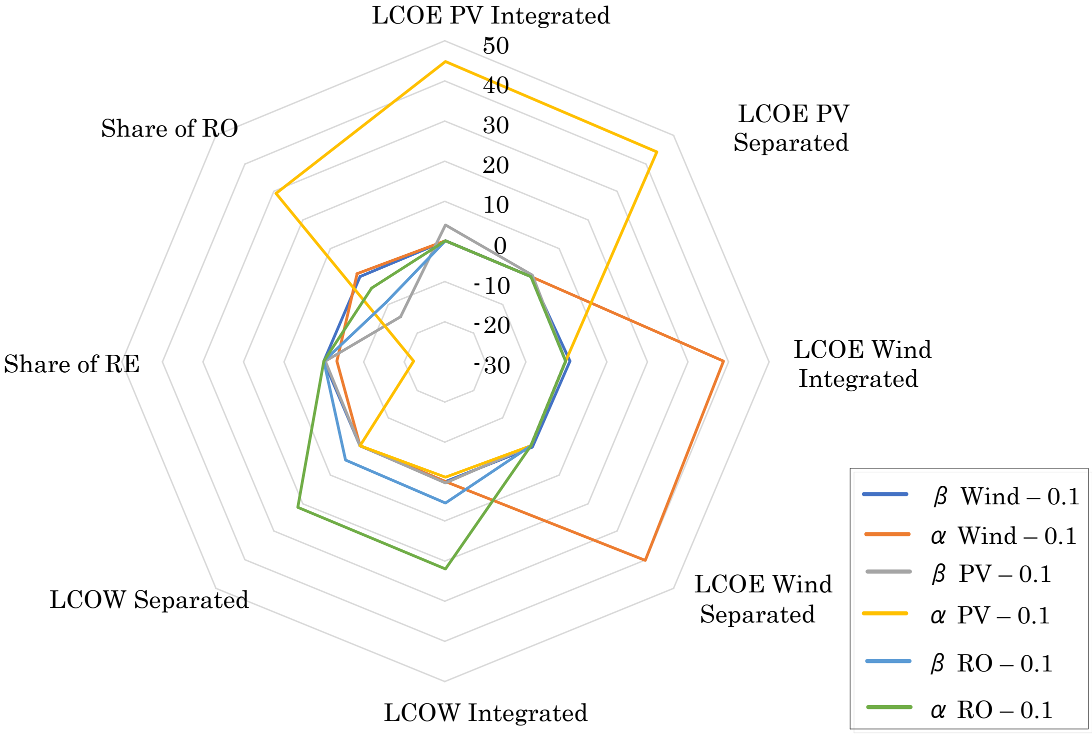


Figure 2-21. Sensitivity analysis on the influence of the learning elasticities, decrease.

Cost of Battery

The excess electricity production — as the portion of VRE power generation which exceeds electric load — impose further costs on energy systems. A cost minimization problem is developed to investigate the share of these costs from the overall cost of energy systems with a high share of VRE. It is assumed that battery is used to reach a balance between the supply and demand. The objective function is to minimize overall cost as follows:

$$\text{Min}\sum_{t,y} \begin{array}{l} p_{pv}(t,y)\times Cost_{pv}(y) + p_{wind}(t,y)\times Cost_{wind}(y) \\ + p_{ex}(t,y)\times Cost_{ex}(y) \end{array} \tag{2-31}$$

Where p_{ex} is the excess electricity generation and $Cost$ refers to overall cost including variable and fixed costs. Constraints (2-13) to (2-17) from the supply-demand module and constraints (2-21) to (2-24) from the energy storage module are considered in order to find required renewable capacity and ensure supply-demand balance. The levelized cost of wind and photovoltaic electricity in Table 3-2 are used for cost calculations. The imposed cost from the excess electricity generation is calculated using the energy storage module for the separated scenario.

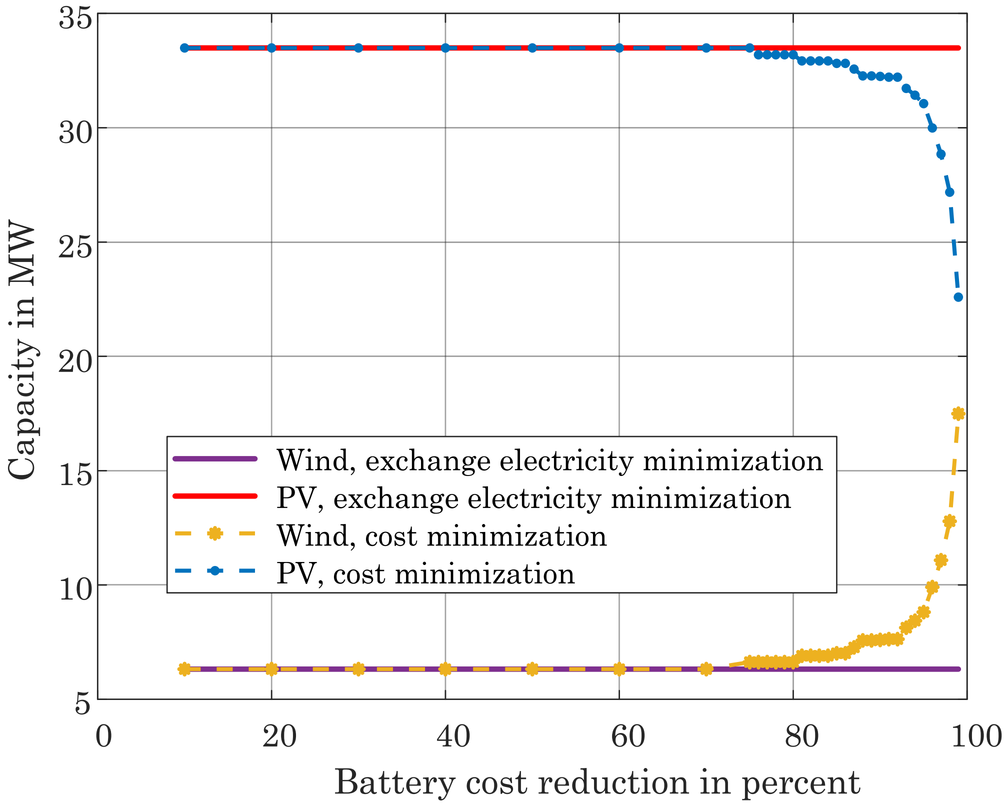


Figure 2-22. Required renewable capacity in 2040, 42 percent VRE penetration rate, with different battery cost reduction percentages.

The cost problem was solved for the separated system to reach 42 percent renewable share in 2040. The results indicate that up to 76 percent battery cost reduction, the excess electricity generation is the main factor influencing cost due to high cost of battery. Above 76 percent battery cost reduction, the share of wind resources is increasing, as can be seen in Figure 2-22. Although the capacity factor of wind supply is higher compare to photovoltaic supply, but as can be seen in Figure 2-2 and Figure 2-3, wind supply shows wide diurnal or seasonal variation in power generation causing higher required energy storage capacity. Average wind power generation in June is almost 6 times more than the average wind power generation in February. As a result, wind resources can compete with photovoltaic resources by decreasing battery cost, due to higher capacity factor and lower LCOE.

As discussed, the current study assumed that the cost of battery technology will decrease by 40 percent by 2040 (Battke and Schmidt, 2015; Cole and Frazier, 2019). Further investigation is conducted to elaborate the influence of renewable penetration rate on aforementioned outcomes, as in the proposed scenarios, synergistic effects bring the VRE penetration rate above 42%. To this aim, the VRE penetration rate is set at 63 percent, 42 percent is the base target rate, from total electricity generation in 2040. As expected, by increasing the VRE penetration rate the turning point moved from 76 percent battery cost reduction to 59 percent, at which point the share of wind resources started increasing, 19 percent more than assumed for the battery cost reduction in the current study.

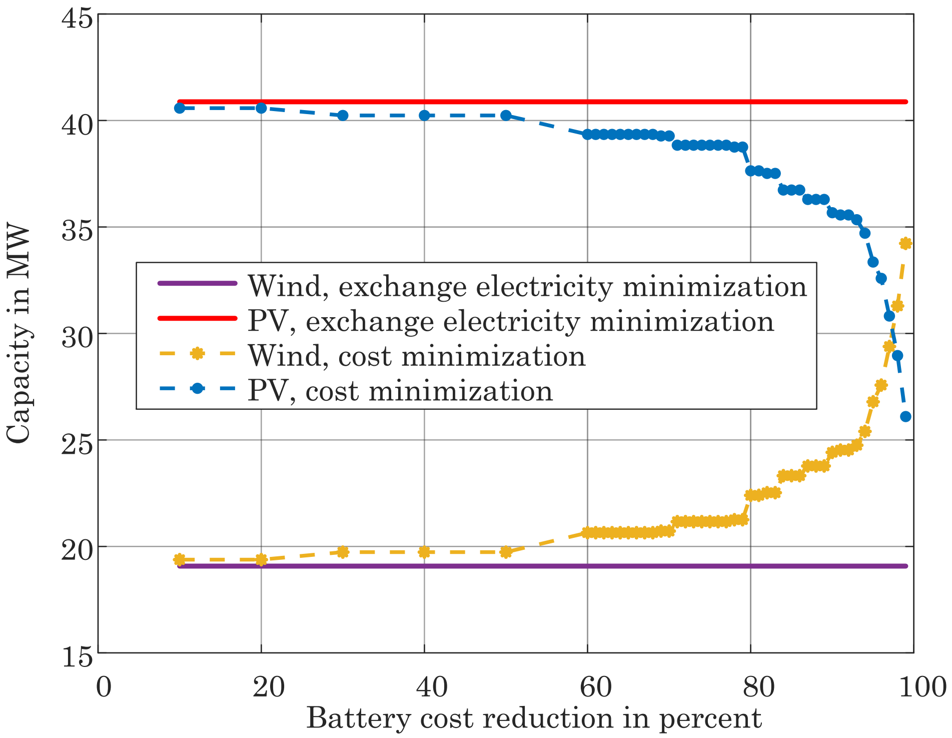


Figure 2-23. Required renewable capacity in 2040, 63 percent VRE penetration rate, with different battery cost reduction percentages.

2.4 Conclusions

The water and energy sectors are experiencing a transition to deploying desalination water supplies and renewable resources in the Middle East. Applying a novel nexus approach, an interactive multi-period model is proposed to study the synergies of integrated water and energy supply planning, taking into account operational flexibility of the water sector and its compatibility with inherent intermittency of variable renewable resources.

In this chapter, the results showed that storage service using battery technology — in order to compensate for fluctuating renewable electricity generation — has a much higher value than renewable electricity in the current markets. This shows that the electricity system is still far from the level of renewable energy penetration when the battery storage availability becomes a constraint. Designing the water and energy sectors as endogenous parts of one system has the potential to decrease the cost of mitigating the fluctuation of variable renewable power production, which is the main challenge to the deployment of renewable resources in regions facing water scarcity. This reflects the necessity of an integrated planning of the energy and water sectors, which considers also the operational aspects in long-run planning, especially the fluctuations of variable renewable power.

Furthermore, technology cost is assumed to be a function of experience and knowledge in order to capture the synergies of integrated planning of inter-connected sectors, instead of following the most common approach in the literature and modeling technology cost just as a function of time. Therefore, the two-factor learning curves are developed to estimate the path of technology deployment and the pace of cost reduction which showed a good fit for the decline in investment costs. The calculated learning rates showed that solar, wind and reverse osmosis technologies are rapidly developing technologies, with higher learning-by-searching rates comparing to learning-by-doing. In other words, the research and development investment has a significant role in deployment and cost reduction for these technologies in the future. A driver analysis found that by 2040 the experience effect of cumulative production accounts respectively for 74%, 89%, and 64% in the integrated system and 96%, 94% and 62% in the separated system of the total cost reduction for solar power, wind power, and reverse osmosis technologies. Despite learning-by-searching being higher than learning-by-doing for all industries, the main share of the cost reduction comes from the experience of cumulative production for wind and solar power which depicts the inadequate research and development budget. However, in the integrated system, investing a portion of the saved budgets on research and development solved this issue to some extent.

Additionally, we find that solar electricity resources is a better option, as it matches the electrical load pattern in the region of the case study. In comparison, the wind resources impose a higher level of seasonal fluctuations on the electricity system.

Chapter 3

Alternative Sector Configurations for Integrated Planning of Water and Energy Supply

3.1 Introduction

Variable renewable resources (VRE), including wind and solar power, impose fluctuations on energy systems. The future energy sector, with its high share of renewables, needs to ensure secure energy supply (Gyalai-Korpos et al., 2020) in the event of a crisis such as technical failures or potential political conflicts in the case of exchanging renewable electricity with neighboring countries or regions. Variable renewable energy resources are non-dispatchable, therefore they cannot be controlled by operators. This means the future energy sector needs flexible plans to deal with demand shifts or decline in the case of a crisis such as the COVID-19 outbreak. An IEA report showed that full lockdowns due to the coronavirus outbreak caused an average 25% decline in energy demand per week and this decline is equal to 18% for partial lockdowns (IEA, 2020). The resilience of energy systems with a high share of VRE hinges on exploring solutions to overcome these fluctuations in power generation to avoid instability caused by an imbalance between the supply side and demand side. Desalination units are capable of compensating for the fluctuating power production of VRE to some extent, as water is desalinated whenever energy is available and is stored as a final product (Kim et al., 2016).

Chapter 1 reveals that renewable-powered desalination systems are typically considered to be suitable small-volume desalination, while studies with on-grid energy systems focus on large-capacity desalination facilities. In this study, a centralized desalination system refers to a water system in which saline water is desalinated by one unit and distributed among all target users, while in a decentralized desalination configuration, there are more than one desalination unit providing for water demand, as depicted in Figure 3-1. As discussed in chapter 1, and to the best of the authors' knowledge, there is only one study (Vakilifard et al., 2019), which modeled a water system with more than one unit of desalination for the long-run planning of a water system with on-grid renewable energy resources. The study followed a sequenced approach (Vakilifard et al., 2019). After calculating the surplus electricity from roof-top photovoltaics in a region in Australia for only two days during a year through a spatial model, this excess electricity is considered as a yearly fixed energy resource for RO units at zero cost, assumed as waste energy. The proposed system led to the LCOE reduction by 20% for the photovoltaic electricity generation and reducing the levelized cost of desalinated water (LCOW) by 10% compared to the water sector as a fixed electric load.

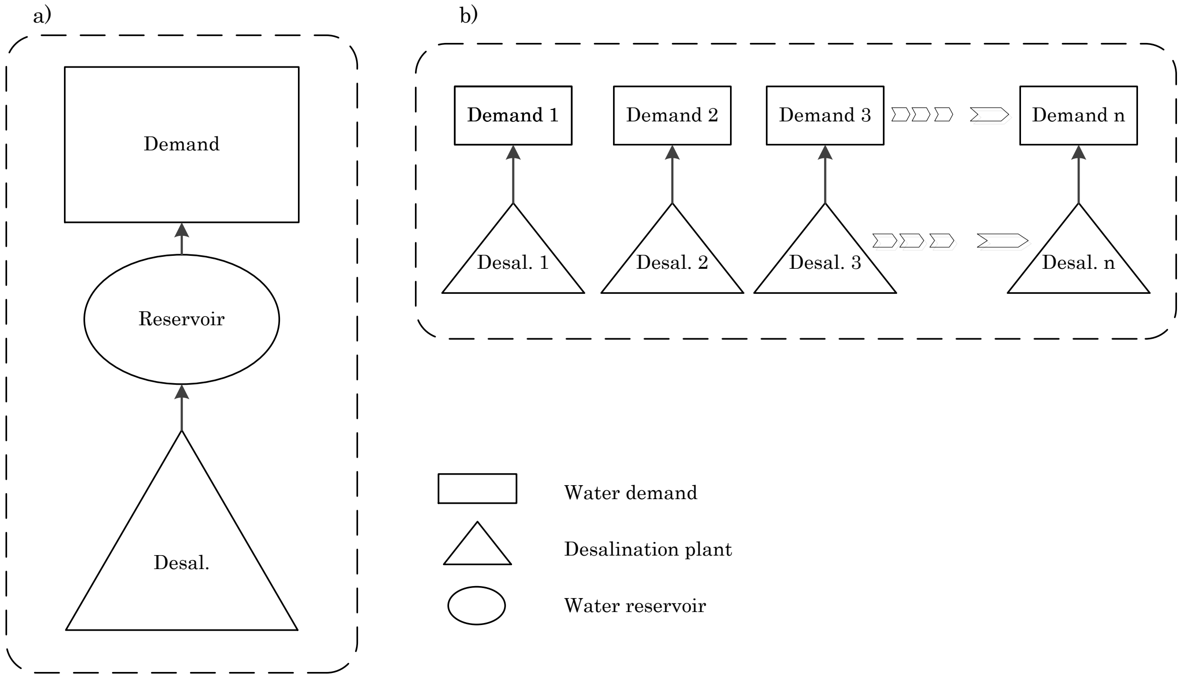


Figure 3-1. (a) Centralized water sector, base and C_RO scenarios. **(b)** Decentralized water sector, D_RO and D_MED scenarios.

Moreover, these decentralized desalination systems have the potential to save energy from water distribution by increasing the number of options for site locations of desalination units. Pumps for water distribution are energy-intensive components, which need to be considered for site selection, the location, size of desalination plants, and system configuration. Studies (Gude, 2016a; Zhou and Tol, 2005) estimated the cost of water transport from coastal desalination plants as summarized in Table 3-1. It can be seen that for several cases, the cost of water transfer is considerable, relative to the cost of water desalination.

Table 3-1. Transport costs of desalinated water.

City, country	Distance (km)	Elevation increase (m)	Transport cost (USD/m^3)
Beijing, China	135	100	1.13
New Delhi, India	1050	500	1.90
Yemen, Sana	135	2500	2.38
Riyadh, Saudi Arabia	350	750	1.60
Crateus, Brazil	240	350	1.33
Mexico City, Mexico	225	2500	2.44
Zaragoza, Spain	163	500	1.36
Mexico City, Mexico	280	320	2.44

There is a gap in the scope of studies to compare the long-term planning of centralized and decentralized desalination systems powered by on-grid VRE considering short-term (hourly) operational constraints. These systems have the potential to compensate for the fluctuating power production of variable renewables, to reduce GHG emissions, and to solve effluent-associated environmental issues by providing multiple options for site locations avoiding discharging brine into sensitive ecosystems and distributing the brine.

This chapter aims to shed light on potential synergies and conflicts of the transition to an energy sector with a share of renewables and a water sector with a share of desalination. More precisely, this chapter reveals the economic, technical, and environmental impacts of centralized and decentralized system configurations using alternative technology mixes, on transition plans to achieve a higher share of renewable energy and desalination supply for regions facing water scarcity.

3.2 Methodology

As discussed in Chapter 1, the outcomes of the nexus approach are benchmarks for trade-offs among system integration, increasing complexity to the point where the decision making is delayed or incapacitated; and designing these systems as separated systems with less complexity, but potentially lower efficiency. Moreover, different system configurations could influence the extent of these synergies, conflicts of interests, and complexity.

Two system types, integrated and separated, and two system configurations for the water sector (see Figure 3-1) are assumed, making a total of four scenarios for investigation in this chapter, including:

1. **Base Scenario:** The water sector is considered as a centralized system with MED desalination technology.
2. **C_RO Scenario:** The water sector is studied as a centralized system with RO desalination technology.
3. **D_RO Scenario:** The water sector is assumed as a decentralized system with RO desalination technology.
4. **D_MED Scenario:** The water sector is considered as a decentralized system with MED desalination technology.

In the base scenario, the water sector is studied as an exogenous factor for the energy system, in which there is no control over it. In C_RO, D_RO, and D_MED scenarios, both energy and water systems are studied as an integrated system, which are endogenous parts of one integrated system. The energy sector is considered as centralized in all of the above scenarios because of the data limitation for descaling learning curves for variable renewable resources to give sensible differentiation between a set of small-scaled systems and an equivalent large-scaled system.

As shown in Figure 3-2, there are four modules within the model proposed in this study: (1) Proposing a supply-demand module, (2) developing an energy storage module, (3) estimating the learning curves for the region of the case study, and (4) conducting economic analysis and calculating GHG emissions reduction.

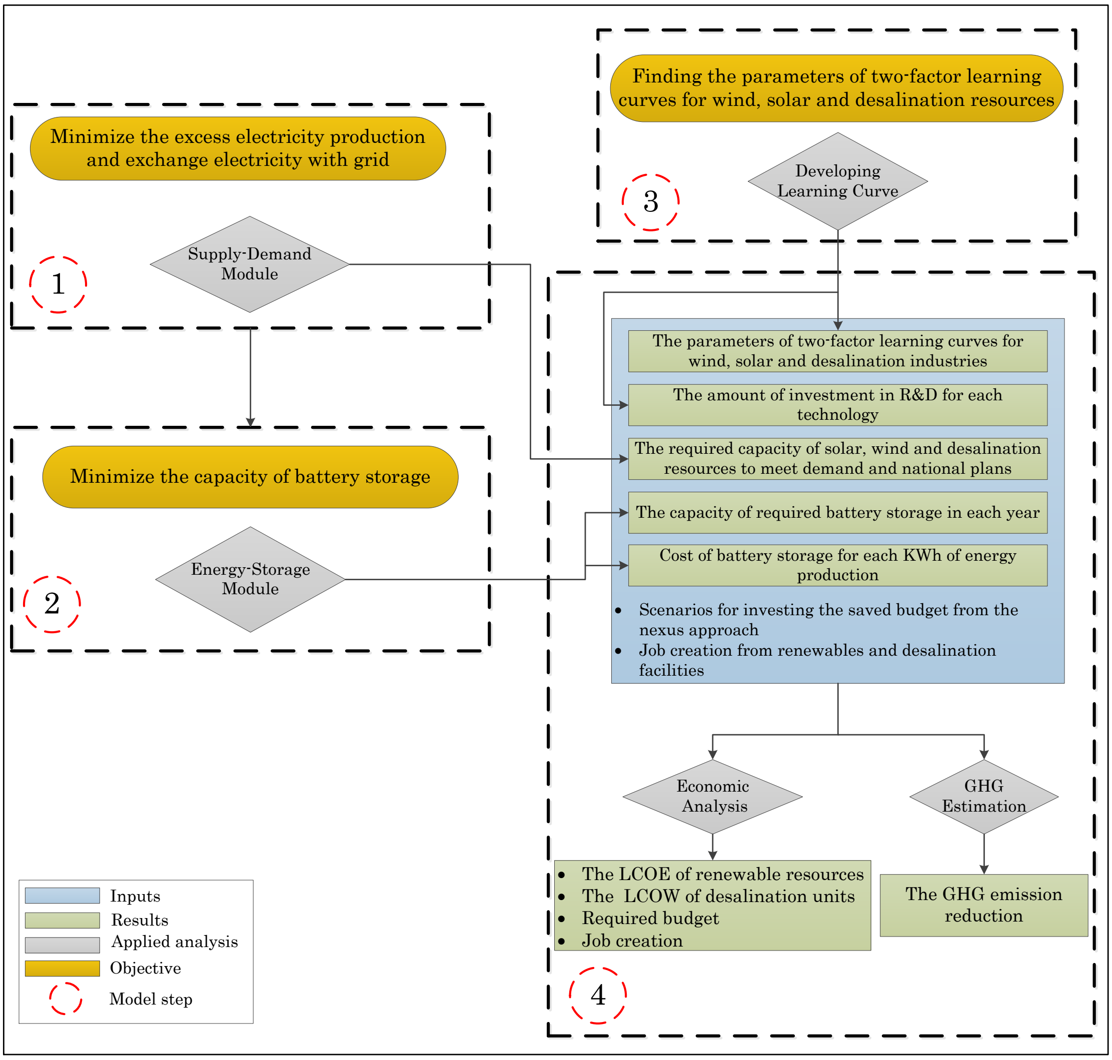


Figure 3-2. The proposed methodology in Chapter 3.

3.2.1 Supply-Demand Module

A supply-demand module is developed as the first step of the proposed model, to study the technical aspects of the proposed scenarios. The energy demand is estimated based on demographic trends and historical data. System configuration and national plans and targets are taken into account in this optimization module. Supply-demand module in Chapter 2 has been modified to model the decentralized water sector.

Water Module

Integrated System

The amount of water in the water reservoir in each location should be more than the water demand for the next day, which is described as:

$$w_d(l,d,y) \geq w_r(l,d-1,y) \tag{3-1}$$

where w_d is the daily water demand in each location and w_r is the amount of water in the water reservoirs. For the centralized water sector, there is only one location.

For the decentralized water sector, the hourly amount of water in the water reservoir for each location is obtained as Equation (3-2).

$$w_r(l,t,y) = w_r(l,t-1,y) + w_{conv}(l,t,y) + w_{des}(l,t,y) \tag{3-2}$$

where w_{conv} describes the amount of water extraction from conventional water supplies, which are underground and surface water resources, and w_{des} is the amount water production from the desalination supply.

For the centralized water sector, the hourly amount of water in the desalination reservoir follows Equation (3-3).

$$w_{r,des}(t,y) = w_{r,des}(t-1,y) + w_{des}(t,y) - w_{pmp,des}(t,y) \tag{3-3}$$

where $w_{pmp,des}$ is the amount of pumped water from the centralized desalination plant's reservoir.

The amount of stored water in each reservoir cannot exceed the capacity of the reservoir, which can be described as (3-4) and **Error! Reference source not found.**.

$$w_r(l,t,y) \leq Cap_r(l,y) \tag{3-4}$$

$$w_{r,des}(t,y) \leq Cap_{r,des}(y) \tag{3-5}$$

The capacity of water production from the desalination plant, conventional resources, and the amount of pumped water are limited based on (3-6), (3-7), and **Error! Reference source not found.**.

$$w_{conv}(l,t,y) \leq Cap_{conv}(l,y) \tag{3-6}$$

$$w_{des}(l,t,y) \leq Cap_{des}(l,y) \tag{3-7}$$

$$w_{pmp,des}(t,y) \leq Cap_{pmp,des}(y) \tag{3-8}$$

The share of desalination from the total water demand needs to meet the target for each year, which is imposed on the model as Equation (3-9).

$$\sum_{t,l} w_{des}(l,t,y) = Des_{share}(y) \times \sum_{l,d} w_d(l,d,y) \tag{3-9}$$

As discussed, to become economically and technically feasible, desalination facilities are required to operate more than 80% of their total capacity through a year (Alonso et al., 2020). This constraint is considered in the model as:

$$\sum_{t} w_{des}(l,t,y) \geq Cap_{des}(l,y) \times 365 \times 0.8 \tag{3-10}$$

The hourly electricity consumption of the centralized water sector for each year is calculated as Equation (3-11). It is assumed that for the decentralized water sector, the desalination is located exactly at the demand location; as a result, there is no need to transfer the desalinated water. The hourly electricity consumption of the decentralized water sector is obtained from Equation (3-12).

$$p_w(t,y) = \sum_{t} p_{conv} \times w_{conv}(t,y) + p_{pmp} \times w_{pmp,des}(t,y) + p_{des} \times w_{des}(t,y) \tag{3-11}$$

$$p_w(t,y) = \sum_{l,t} p_{conv} \times w_{conv}(l,t,y) + p_{des} \times w_{des}(l,t,y) \tag{3-12}$$

Where p_w depicts the electricity demand of water sector, p_{des} shows the required electricity to produce unit of desalinated water, p_{conv} is the amount of electricity required for extracting and transferring unit of water from conventional water supplies, and p_{pmp} is the required electricity for pumping unit of water from the desalination facility to the reservoir.

The remainder of this module, including the objective function, water model for the centralized water sector and the energy model are similar to Chapter 2, constraints (2-13) to (2-18). The objective function is to minimize the electricity exchange with the national grid, which is defined as:

$$\text{Min} \sum_{t,y} \left| p_{grid}(t,y) \right| \tag{3-13}$$

Where p_{grid} is the absolute value of hourly electricity exchange with the national grid including both negative, for selling electricity to the grid, and positive values, for purchasing electricity from the grid.

For the integrated system, the capacity of solar supply, wind supply and desalination facilities, hourly water extraction from the conventional water supplies, hourly water production of each desalination facility, hourly pumped water from the desalination unit's reservoir to the water reservoir, only for the integrated system with centralized water sector, and hourly electricity exchange with the national grid are the variables of the optimization problem. For the separated system, the capacity of solar supply, wind supply, and hourly electricity exchange with the national grid are considered as the variables of the optimization problem.

3.2.2 Energy Storage Module

The energy storage module is developed to find the required battery capacity equivalent to the operational capacity of the flexible water sector. This optimization model was described in detail in Chapter 2. The new required capacity of battery storage for each year and the cost of this battery storage for a unit of variable renewable energy generation (MWh) are calculated using the results of the supply-demand module.

3.2.3 Learning Curves

As explained in the previous Chapter, the path of cost reduction is modeled by the two-factor learning curve and is assumed to be a function of experience and knowledge ($f(experience, knowledge)$), which is explained in Chapter 2 and Appendix B.

3.2.4 Economic Analysis and GHG Emissions

To reveal the synergistic effects, conflicts, and the influence of the system type and shape, the results of the previous modules are used to assess the future cost of variable renewable energy and desalinated water for the proposed scenarios for the region of the case study. Furthermore, the potential of each scenario in decreasing GHG emissions is calculated. Finally, a sensitivity analysis is conducted to evaluate the effect of R&D investment on the technologies.

3.2.5 Case Study

The Persian Gulf and Gulf of Oman basin has ready access to seawater, giving four provinces inside this water basin, which are considered as the region of the present case study, to deploy desalination as a source of freshwater.

Figure 3-3. Iran's main drainage basins and the county of study.

Jask county has a hot desert climate with sweltering summers and little precipitation, situated on the Gulf of Oman. A port town as can be seen in Figure 3-3, the capital of the county, also named Jask, is the case study as an urban area, small town, with a population of 16,860 at the 2017 census (Statistical Center of Iran, 2018). To model a decentralized water sector for rural areas, 19 rural districts are selected as depicted in Figure 3-3, which are inside Jask county and have access to seawater for desalination. The total population of these districts is 16,855 (Statistical Center of Iran, 2018), in order to be readily comparable with the centralized case (see Appendix C for details). Due to a lack of data, it is assumed that the water demand of these 19 rural districts is equal to Jask port and distributed as a proportion of their population.

3.3 Results and Discussion

In this section, first the results of the supply-demand module and the energy storage module for the proposed scenarios the case study are explained. These outcomes are the baseline for technical, economic, and environmental analysis for the whole region in the southern coast of Iran.

All water, energy, and technology-related costs were converted to 2018 USD ($).

3.3.1 Supply-Demand Module

Ten days in each season, for a total of 40 days as representative of each year, are chosen, due to a software limitation, as the short-term operation horizon for each year between 2020 to 2040 as the long-run planning horizon to solve the linear supply-demand module. The module is coded into GAMS 26.3.5 and solved by CPLEX solver for the sample county, Jask, Iran. Similar to Chapter 2, the growth rate of VRE's share of total electricity supplies is assumed to be 2% per year by 2040 and a linear increase for the expansion of desalination across the period to meet the 70% target.

The total renewable electricity production for each scenario is the same, 68,371 MWh from 2020 to 2040, 40 days each year. The optimal yearly capacity of wind supply, photovoltaic (PV) supply, and desalination plants are obtained for the proposed scenarios. The hourly water production of each desalination plant, the amount of stored water in the city's reservoir, for the base and C_RO scenarios, the amount of water stored in the desalination unit's reservoir, the amount of water pumped from the desalination reservoir, for the base and C_RO scenario, and the amount of hourly water extraction from the conventional water sources are the other variables of this model to meet the mentioned target share of VRE and desalination production. The share of PV and wind in the total VRE electricity production is depicted in Figure 3-4 and Figure 3-6. For D_RO and D_MED scenarios, the share of solar electricity rises from 32% and 0% of total renewable electricity generation in 2020 to 86% and 85% in 2040, respectively, while for the base and C_RO scenarios, the share of solar electricity production from the total VRE electricity production declines from 100% in 2020 to 85% and 88% in 2040, respectively. As can be seen in Figure 3-4 to Figure 3-7, solar electricity performs better in following the electrical load pattern in this case study and with a share of more than 85% of total VRE, electricity production is the dominant renewable resource for all the scenarios.

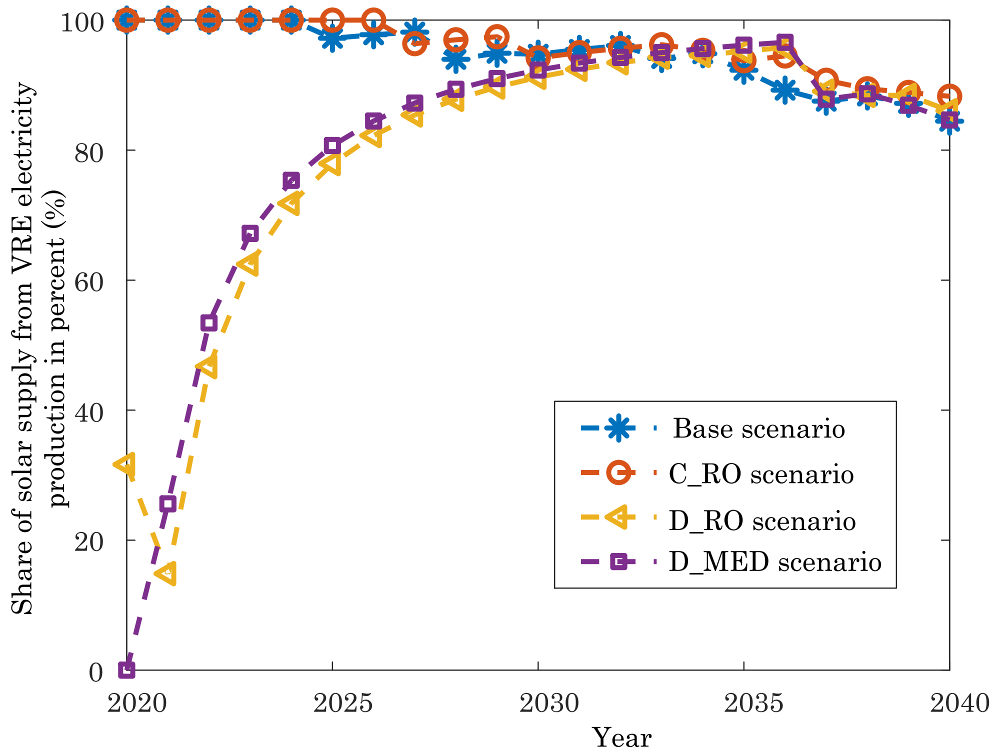


Figure 3-4. Share of photovoltaic (PV) in the total VRE electricity generation.

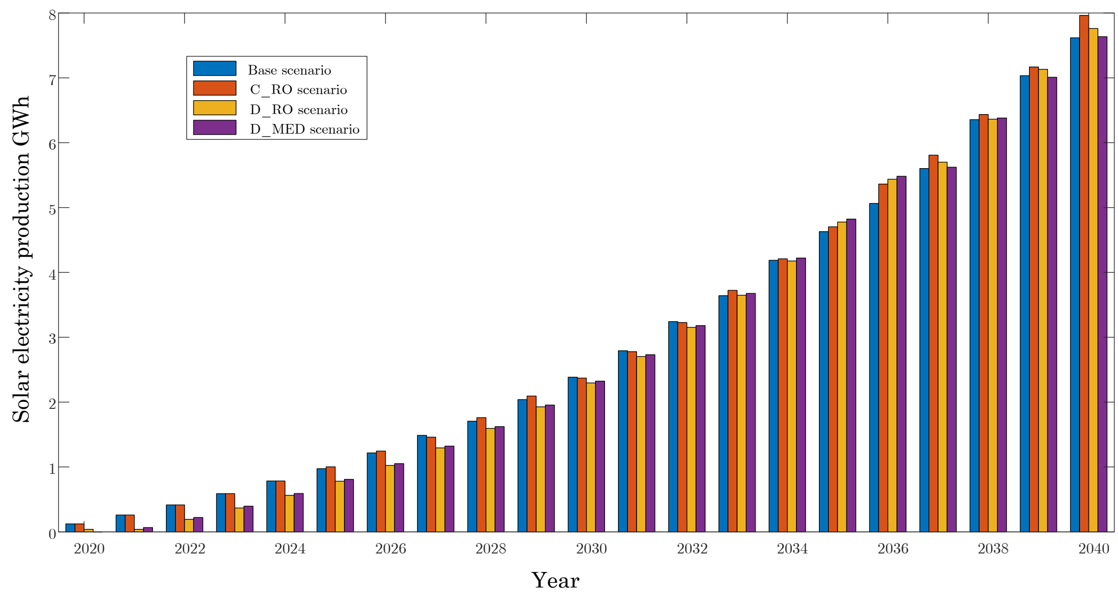


Figure 3-5. Photovoltaic electricity generation.

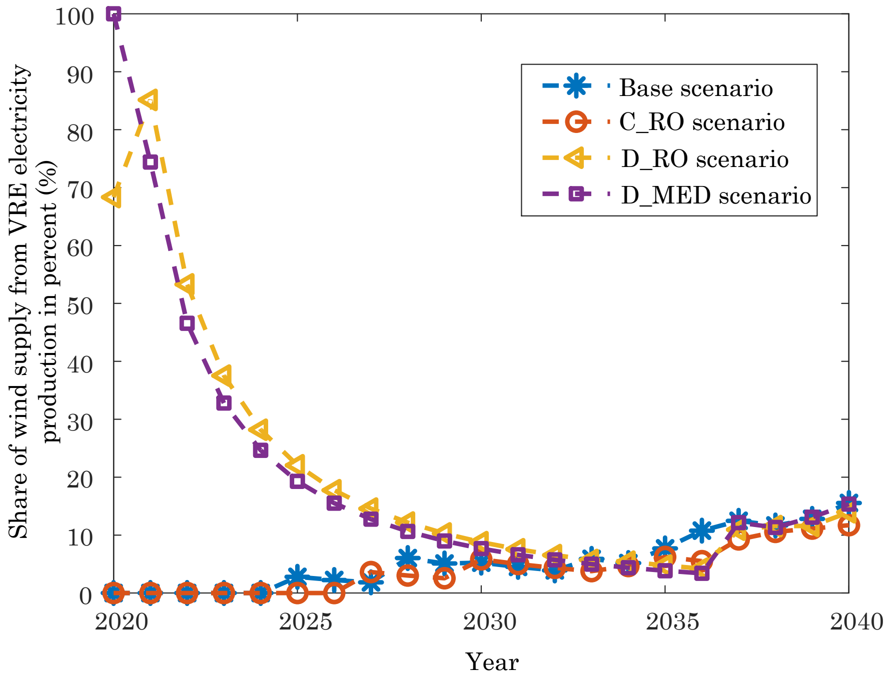


Figure 3-6. Share of wind in the total VRE electricity generation.

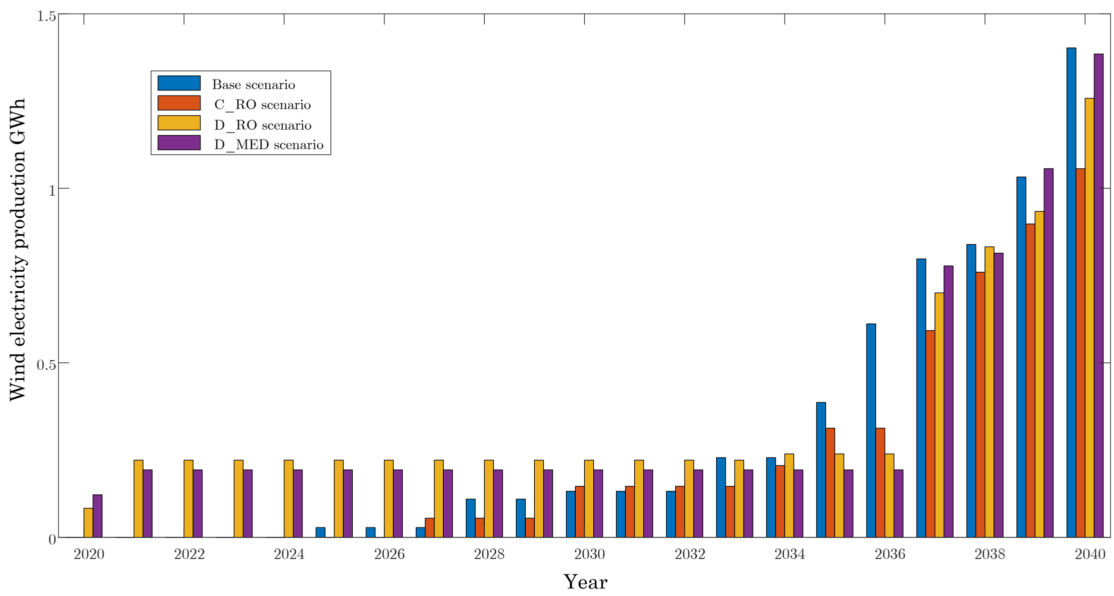


Figure 3-7. Wind electricity generation.

Mismatches between VRE electricity generation profiles and electric demand due to the variability of VRE power generation can cause instability in electricity grids. As defined in Chapter 2, the portion of VRE electricity generation exceeding the electric load is defined as the excess renewable electricity generation in this study, and self-consumption refers to a portion that is consumed directly by the county of the study and is not fed into the national electricity grid. Figure 3-8 shows the amount of excess electricity generation and share of self-consumption from the entire VRE electricity generation for all the scenarios. The amount of excess power generation from VRE in 2040 reaches about 17.4% of total renewable electricity generation for the base scenario, while this excess energy generation is around 14.3% for the C_RO and D_RO scenarios and 16.1% for the D_MED scenario.

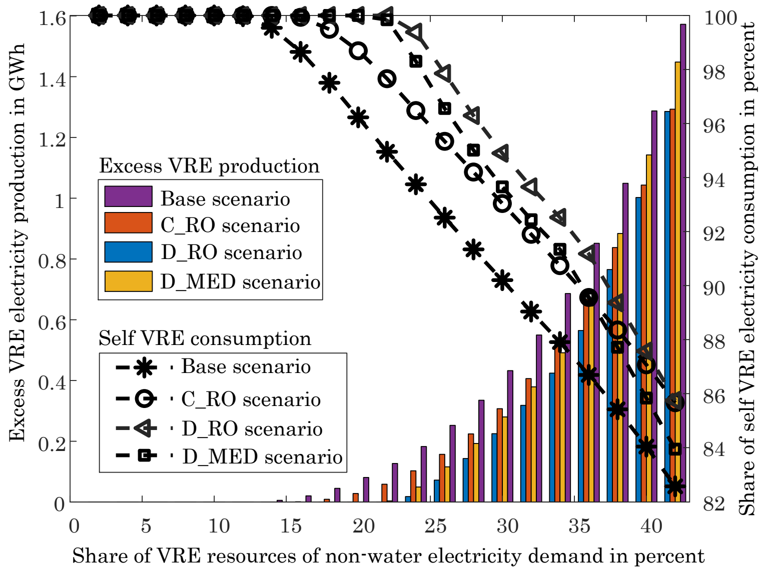


Figure 3-8. Share of self-consumption from VRE electricity production and amount of excess renewable electricity generation.

Figure 3-9 depicts the electricity demand of the water sector and its share from the total electricity demand. Although the water sector's electricity demand is rising for all the scenarios from 2020 to 2040, due to a higher portion of desalination and demand growth in proportion to Iran's population growth (World Bank, 2020a), its share from the total electricity demand shrinks from 6.6% in 2020 to 3.9%, 6.3%, and 2.9% for the base, D_RO, and D_MED scenarios in 2040, respectively. For the C_RO scenario, this share rises slightly from 6.6% in 2020 to 7.1% in 2040. This comes from differences between the yearly growth rate of water demand influenced by the population growth in the current module and the growth rate of electricity demand, which is a 6.5% yearly growth based on national data predictions (Statistical Center of Iran, 2018). The RO desalination technology requires more electricity to desalinate water compared to the electricity consumption of MED technology. As a result, scenarios with RO technology, the C_RO and D_RO scenarios, have a higher electricity demand compared to the scenarios with MED technology, the base and D_MED scenarios. Furthermore, as can be seen in Figure 3-9, the scenarios with the decentralized water sector, the D_RO and D_MED scenarios, benefit from energy-saving due to less electricity consumption for water distribution.

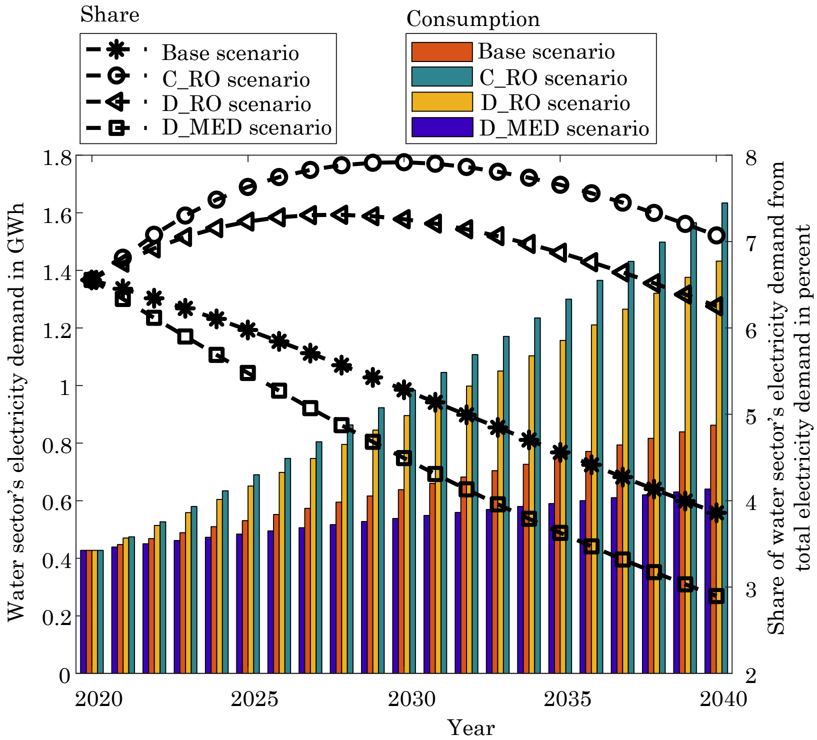


Figure 3-9. Water sector's electricity consumption and share of total electricity demand.

3.3.2 Energy Storage

In the next step, based on the results of the supply-demand module, an optimization problem was solved using GAMS software to find the required batteries equivalent to the operational capacity of the flexible water sector. The results of this optimization module are summarized in Figure 3-10.

The flexibility of the water sector as an electric load in D_RO and D_MED reaches its highest capacity between 2030 to 2034, at about 18 MWh and 15 MWh, respectively. This flexibility is higher in the C_RO scenario compared to the scenarios with the decentralized water sector in most of the studied time horizon, which was not expected due to stricter constraints on the decentralized water sector. This flexibility is sensitive to the share of each VRE supply in the total renewable power generation. In the scenarios with the decentralized water sector, by reaching above 90% share of solar electricity in total VRE power generation in 2030 (see Figure 3-4), the equivalent capacity of batteries reaches the highest value and starts declining after 2035, when the portion of wind electricity is increasing (see Figure 3-6). This means the decentralized water sector has local optimum flexibility around 90% share of solar electricity in the total VRE power generation. For the C_RO scenario with the centralized water sector, the equivalent battery capacity is growing with the rising share of wind electricity in total VRE power generation (see Figure 3-10(d)). This shows that the centralized water sector operates more flexibly with a higher percentage of wind electricity compared to the decentralized water sector. It is noteworthy to mention that the objective function of the supply-demand module, the results of which are the baseline for the current storage module, is to find the optimal capacity of VRE supplies for reaching minimum overall electricity exchange with the national grid, which is not identical with finding the maximum flexibility of the water sector as an electric load.

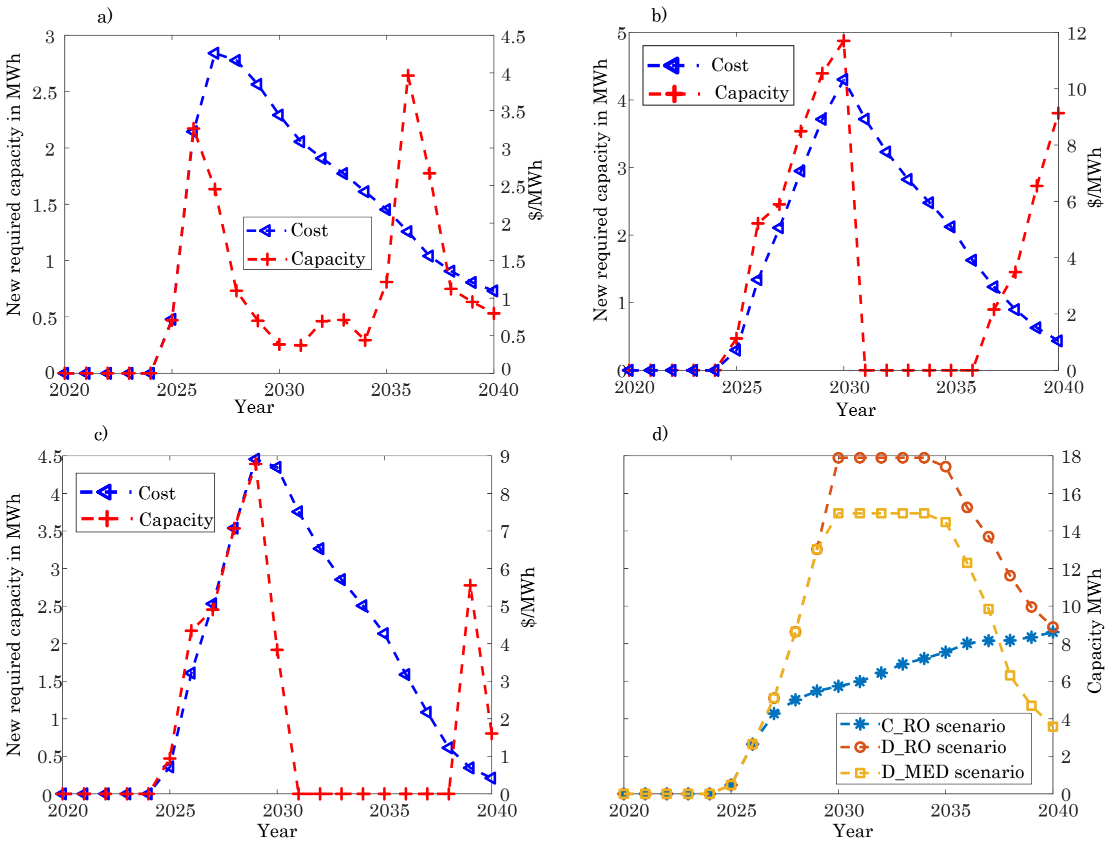


Figure 3-10. Capacity and cost of the battery unit to reach the same VRE self-consumption for: **(a)** C_RO scenario; **(b)** D_RO scenario; **(c)** D_MED scenario. **(d)** The required total capacity of batteries in each year.

3.3.3 Learning Curve

The parameters of the two-factor learning curve for utility-scale photovoltaic, wind, RO technologies have been estimated in Chapter 2. The estimated levelized cost of water for the MED desalination technology is also obtained by applying the two-factor learning curve, which is depicted in Figure 3-11. The estimations indicate that the LCOW for MED technology reaches 2.46 $/m^3$. For the MED desalination technology using data between 2012 to 2020 (ALMAR Water Solution, 2017; Water Scarcity Atlas, 2020), the obtained LDR is 12.9%, and the LSR is 57.2% with a goodness of fit (R^2) of 98.9%. Other studies (Mayor, Beatriz, 2018), estimated a range of 12% to 23% for LDR of the MED technology with a goodness of fit (R^2) of 99.1%.

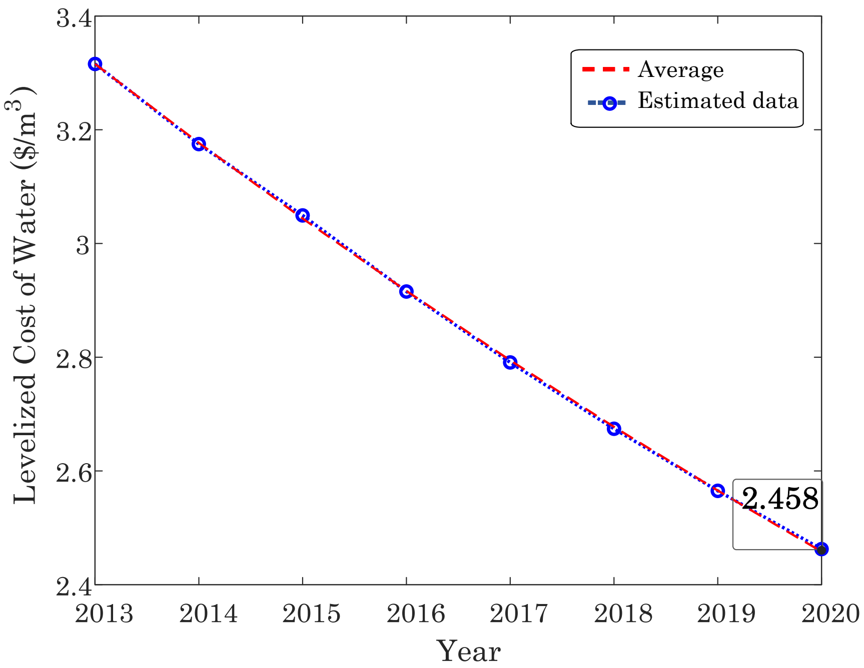


Figure 3-11. Learning-curve model fitting of the multi-effect desalination (MED) technology investment cost.

3.3.4 Economic Analysis and Emissions

Based on the results of the supply-demand module, storage module, and the estimated rates of the two-factor learning curve and costs of the utility-scale photovoltaic, wind, RO, and MED technologies, an economic analysis has been conducted for the region of the case study. Furthermore, the reduction of GHG emissions for the proposed scenarios has been calculated. Lastly, a sensitivity analysis has been conducted to investigate the role of R&D in the development of the mentioned technologies. The electricity and water demand in 2020–2040 have been obtained based on national predictions (Statistical Center of Iran, 2018) and the World Bank's population estimation (World Bank, 2020a) for the region of the case study.

The cost of batteries for a unit of VRE electricity generation, as can be seen in Figure 3-10, which was obtained for the C_RO, D_RO, and D_MED scenarios due to a lower required capacity of batteries compared to the base scenario, is considered as a saved budget for the energy sector in these scenarios. Countries have pledged to increase public and private R&D spending substantially by 2030 as part of the Sustainable Development Goals. The latest available data from the UNESCO Institute for Statistics show that the current maximum R&D spending as a percentage of GDP is around 5% (UNESCO Institute for Statistic, 2020). Therefore, 5% of this saved budget is assumed to be invested in R&D of the wind and photovoltaic technologies in proportion to the share of each supply in VRE electricity generation. It is assumed that the rest of this saved budget, 95%, finances further generation of renewable electricity from utility-scale photovoltaic and wind. This budget covers all the fixed and variable costs of the VRE electricity generation during the lifetime of these technologies, which is 20 years.

Studies (Gude, 2016a; Sood and Smakhtin, 2014; World Bank, 2019) showed that about 40% and 7% of LCOW of the RO desalination technology and the MED desalination technology goes to electricity consumption, respectively. As a result, a lower cost of electricity in the C_RO, D_RO, and D_MED scenarios compared to the levelized cost of electricity in the base scenario causes a cost-saving in the water sector. Moreover, the scenarios with the decentralized water sector benefit from energy-saving due to less electricity consumption for water distribution, causing additional cost-saving for these scenarios. These cost-savings are considered as a saved budget for the water sector in the C_RO, D_RO, and D_MED scenarios. Similar to the energy sector, it is assumed that 5% of this saved budget is invested in R&D of desalination technologies and 95% of this budget finances more water desalination to increase the share of desalination from water supplies. This budget covers all the fixed and variable costs of the desalination water production during the lifetime of the RO and MED technologies, which is considered 20 years in this study.

Table 3-2 to Table 3-3 summarize the LCOE of renewable supplies and LCOW of the MED and RO desalination technologies for the proposed scenarios from 2020 to 2040 in the region of the case study.

Table 3-2. Estimated future levelized cost of wind electricity ($/MWh).

Year/ Scenario	Base	C_RO	D_RO	D_MED
2020	34.7	34.7	34.7	34.7
2021	34.6	34.6	25.7	26.3
2022	34.5	34.5	25.7	26.2
2023	34.5	34.5	25.7	26.2
2024	34.4	34.4	25.6	26.2
2025	32.1	34.4	25.6	26.1
2026	32.0	34.3	25.5	26.0
2027	32.0	30.4	25.4	25.9
2028	28.2	30.3	25.2	25.8
2029	28.1	30.2	25.1	25.6
2030	27.4	26.9	24.9	25.5
2031	27.4	26.8	24.7	25.3
2032	27.3	26.8	24.6	25.2
2033	25.1	26.7	24.4	25.1
2034	25.1	25.3	24.0	25.0
2035	22.9	23.6	23.9	24.8
2036	21.1	23.5	23.7	24.7
2037	20.0	20.9	19.8	19.5
2038	19.8	19.9	19.0	19.3
2039	19.0	19.2	18.6	18.3
2040	17.8	18.6	17.5	17.4

Table 3-2 shows that the levelized cost of wind electricity generation will reach 17.8 $/MWh, 18.6 $/MWh, 17.5 $/MWh, and 17.4 $/MWh for the base, C_RO, D_RO, and D_MED scenarios, respectively. In the base, C_RO, D_RO, and D_MED scenarios, 94%, 92%, 89%, and 90% of this cost reduction in 2040, compared with the cost of wind electricity in 2020, is driven by the experience effect of cumulative production, and 6%, 8%, 11%, and 10% is driven by the knowledge stock of the cumulative increase in R&D spending, respectively. In the C_RO scenario, the share of wind electricity generation from the total VRE electricity generation in 2040 is the lowest amongst the proposed scenarios, with 12%, as depicted in Figure 3-6, causing the highest LCOW for the wind supply in the C_RO scenario due to the effect of production experience.

Table 3-3. Estimated future LCOE of solar photovoltaic ($/MWh).

Year/ Scenario	Base	C_RO	D_RO	D_MED
2020	55.2	55.2	55.2	55.2
2021	37.8	37.8	49.5	46.8
2022	34.4	34.4	39.8	38.9
2023	31.9	31.9	35.2	34.7
2024	30.0	30.0	32.2	31.9
2025	28.5	28.3	29.9	29.7
2026	27.1	26.8	28.0	27.8
2027	25.8	25.6	26.3	26.2
2028	25.0	24.2	24.7	24.6
2029	24.0	23.0	23.1	23.0
2030	23.1	22.1	21.6	21.6
2031	22.2	21.1	20.2	20.3
2032	21.4	20.2	19.0	19.2
2033	20.8	19.3	17.9	18.1
2034	20.1	18.5	17.0	17.2
2035	19.6	17.8	16.1	16.4
2036	19.2	17.1	15.3	15.6
2037	18.7	16.6	14.9	15.4
2038	18.2	16.1	14.4	14.8
2039	17.7	15.5	13.9	14.4
2040	17.3	15.0	13.5	14.1

For utility-scale photovoltaics in Table 3-3, the LCOE in 2040 is equal to 17.3 $/MWh, 15.0 $/MWh, 13.5 $/MWh, and 14.1 $/MWh, for the base, C_RO, D_RO, and D_MED scenarios, respectively. About 96%, 83%, 76%, and 78% of this cost reduction in 2040 as compared with 2020 is caused by the experience of cumulative production, and 4%, 17%, 24%, and 22% comes from the knowledge stock of the cumulative increase in R&D spending for the base, C_RO, D_RO, and D_MED scenarios, respectively.

Similar to the results in Chapter 2, the cost reduction of wind electricity is lower than the cost reduction of photovoltaic electricity. For instance, in the D_MED scenario, the LCOE of photovoltaic electricity reduces from 55.2 $/MWh in 2020 to 14.1 $/MWh, while the wind electricity experiences a cost reduction from 34.7 $/MWh in 2020 to 17.4 $/MWh in 2040. As discussed in Chapter 2, several factors cause this difference, including, first, the share of wind power from total renewable electricity generation varies from 11% to 15% in 2040, affecting the cost reduction by the experience of cumulative production. Moreover, in this proposed module, the VRE technologies are gaining budget from the saved budget for spending on R&D and adding new capacity in proportion to their share of total VRE generation based on the results of the previous technical modules, as can be seen in Figure 3-4 and Figure 3-6. In other words, the photovoltaic technology gets more share from the saved budget because it is more attractive based on the technical modules.

Even though the LSR is higher than the LDR for both photovoltaic and wind technologies, the main percentage of the cost reduction is driven from the experience of cumulative production showing these technologies are facing an inadequate R&D budget for development. The circumstances are improved for the C_RO, D_RO, and D_MED compared to the base scenario. For example, the share of cost reduction due to knowledge stock increased from 4% in the base scenario to 22% for the D_RO scenario for the photovoltaic technology because a fraction of the saved budget is dedicated to spending on R&D.

Table 3-4. Estimated future levelized cost of desalinated water ($\$/m^3$).

Year/ Scenario	Base	C_RO	D_RO	D_MED
2020	2.46	2.19	2.19	2.46
2021	2.19	2.05	2.05	2.19
2022	1.99	1.94	1.94	1.99
2023	1.83	1.84	1.84	1.83
2024	1.70	1.75	1.75	1.70
2025	1.59	1.67	1.67	1.58
2026	1.49	1.60	1.60	1.48
2027	1.40	1.54	1.53	1.40
2028	1.33	1.48	1.47	1.32
2029	1.26	1.42	1.42	1.25
2030	1.20	1.37	1.36	1.18
2031	1.14	1.32	1.31	1.12
2032	1.09	1.28	1.27	1.06
2033	1.04	1.24	1.22	1.01
2034	1.00	1.20	1.18	0.97
2035	0.96	1.16	1.14	0.92
2036	0.92	1.13	1.11	0.88
2037	0.88	1.10	1.07	0.84
2038	0.85	1.07	1.04	0.80
2039	0.82	1.04	1.01	0.77
2040	0.79	1.01	0.98	0.74

Table 3-4 shows that the levelized cost of desalinated water for the base, C_RO, D_RO, and D_MED scenarios will reach 0.79 $\$/m^3$, 1.01 $\$/m^3$, 0.98 $\$/m^3$, and 0.74 $\$/m^3$, respectively. For MED desalination technology in the base and D_MED scenarios, about 55% and 56% of the cost reduction is caused by the knowledge stock in 2040 as compared with 2020 and around 45% and 44% is driven by the experience effect of cumulative production, respectively. Around 36% and 39% of the RO desalinated water reduction cost is driven by the experience of the cumulative production for the C_RO and D_RO scenarios, respectively. These results indicate that RO and MED desalination technologies received adequate R&D budget compared to photovoltaic and wind technologies.

As can be seen in Table 3-2 and Table 3-3, the obtained LCOE in the scenarios with the integrated water and energy sectors, the C_RO, D_RO, and D_MED is lower the LCOE in the base scenario with separated water and energy sectors. Even though the VRE costs are likely to decrease dramatically, these costs will remain more expensive than natural gas power plants in 2040. Natural gas plants produce electricity with an LCOE of 10 $/MWh in Iran (Azadi et al., 2017; Noorollahi et al., 2019). The levelized cost of renewable electricity is equal to 17.6 $/MWh, 16.8 $/MWh, 15.5 $/MWh, and 15.7 $/MWh for the base, C_RO, D_RO, and D_MED scenarios, respectively. Even though the D_RO reaches a cheaper LCOE and higher penetration of VRE (see Figure 3-12) compared to the D_MED scenario, in this scenario, the LCOW will be 13% more expensive than the base scenario, and the required budget to meet the same targets in the water sector is 16% higher than the base scenario.

Figure 3-12 depicts the synergy results of the integration of the water and energy sectors for the energy sector. The C_RO, D_RO, and D_MED scenarios, with the integrated water and energy sectors, generate 32%, 64%, and 53% more renewable electricity, respectively, during the lifetime of the newly installed capacities in 2020–2040 compared to the renewable electricity generation of the base scenario with the separated water and energy sectors. These scenarios have 7%, 14%, and 12% less required budget, respectively, compared to the required budget for the base scenario. As can be seen in Figure 3-12, for the water sector, only the D_MED scenario shows a synergistic effect from the integration of the water and energy sector. This scenario produces 4% more desalinated water during the lifetime of the newly installed facilities with 3% less required budget compared to the desalinated water production and required budget in the base scenario while the C_RO and D_RO scenarios require 18% and 16% more budget compared to the budget in the base scenario to meet the same targets. Furthermore, the D_MED scenario reaches a levelized cost of desalinated water of 0.74 $/m^3$, which is 5% lower than the cost in the base scenario in 2040.

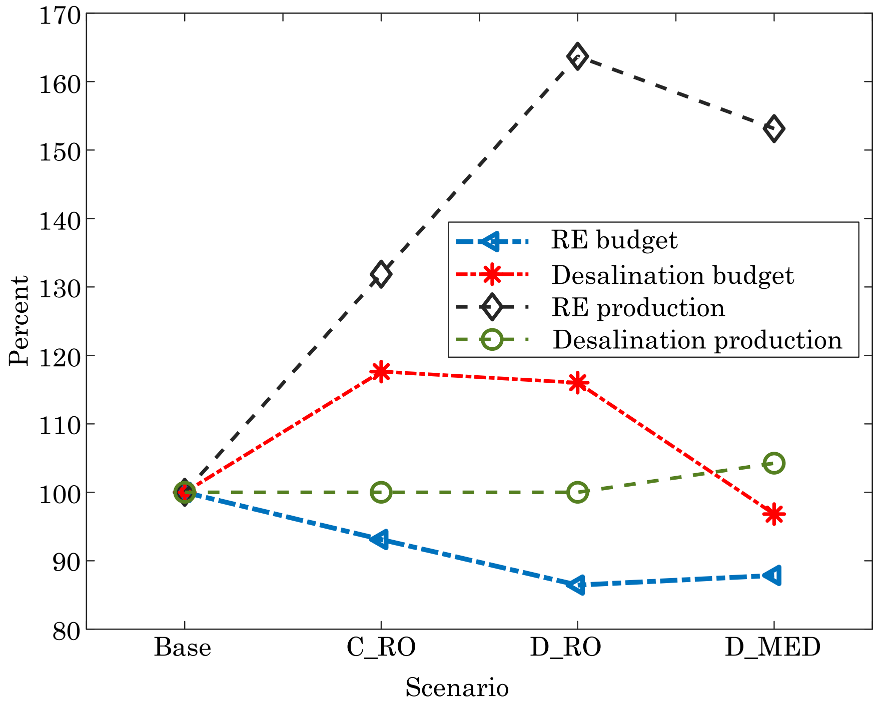


Figure 3-12. Share of lifetime VRE electricity production from the saved budgets out of the total VRE electricity production of the base scenario and required budget. Share of lifetime RO water production from the saved budgets out of the total RO production of the base scenario and required budget.

The number of jobs was calculated based on the lifetime and capacity of the newly installed renewable supply and desalination facilities (Afgan and Darwish, 2011; Ram et al., 2020; Rustum et al., 2020). The job creation from renewables is around 6.5 times more than the job creation from desalination. Figure 3-13 depicts the number of lifetime job creation from the energy sector and water sector from the newly installed renewable supply and desalination facilities between 2020 to 2040.

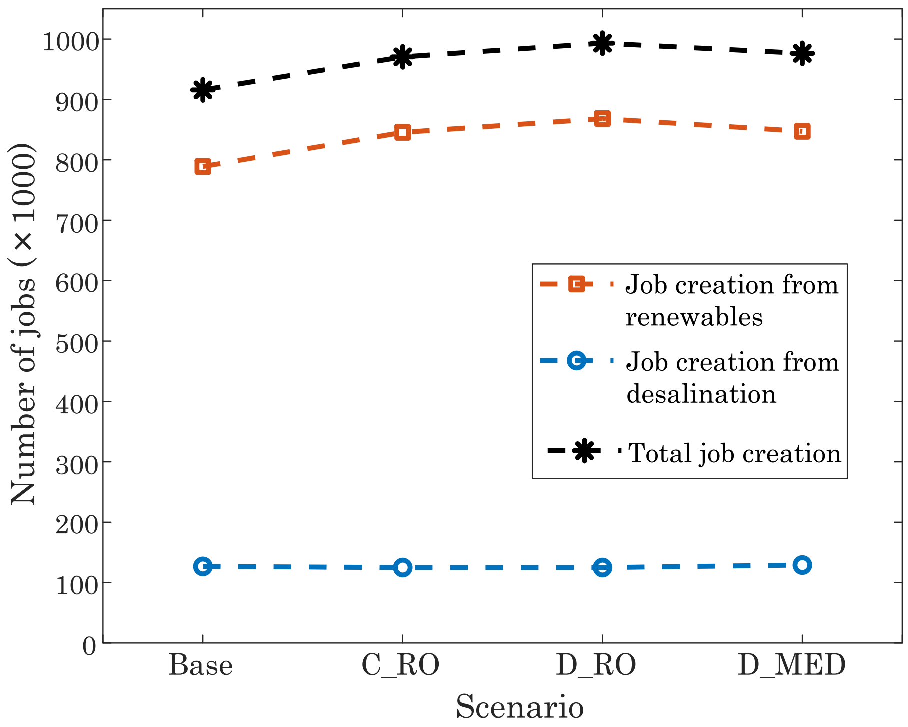


Figure 3-13. Job creation from the proposed scenarios.

Figure 3-14 depicts the GHG emissions from energy consumption in the proposed scenarios. The D_MED scenario with 444 Mt of CO_2, 7913 tons of CH_4, and 794 tons of N_2O reduction by 2040 has a better performance in GHG emissions reduction compared to the other scenarios. These reductions were calculated based on the Iranian electricity mix and with an assumption of providing the thermal energy for the desalination process from Iranian natural gas in the base scenario and from solar thermal resources for the D_MED scenario (National Petrochemical Company, 2017; Statistical Center of Iran, 2018). Although the C_RO scenario generates more renewable electricity compared to the D_MED scenario, as depicted in Figure 3-12, the D_MED scenario, as explained in the introduction, has the potential to provide thermal energy for the desalination process from the solar thermal resources due to decentralized water sector and its size compatibility.

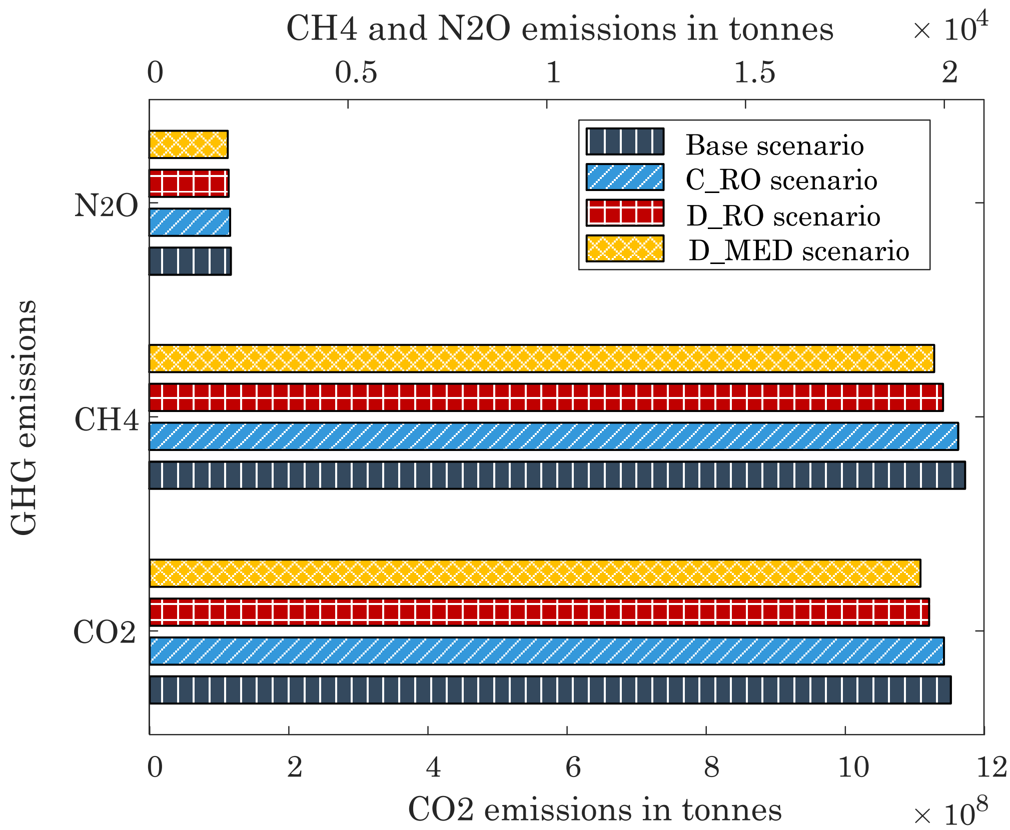


Figure 3-14. Greenhouse gas (GHG) emissions for each scenario.

3.4 Conclusions

The model is expanded to conceptualize the decentralized water sector for planning on-grid decentralized renewable-powered desalination systems for sustainable water and energy supply planning. The nexus approach in this chapter revealed that the configuration of each sector has direct impacts on the other sector. In almost all the proposed scenarios, the energy sector benefitted greatly from an integrated design. Among these scenarios, only the decentralized water sector using multiple effect distillation desalination technology scenario brings synergistic results for the water sector. This results in a lower required budget and a lower levelized cost of desalinated water, compared to the base scenario with separated water and energy sectors. On the other hand, other scenarios imposed a higher levelized cost of desalinated water and required budget on the water sector, revealing a conflict between the water and energy sectors. The synergy results for a 5% research and development share from the saved budget showed that by modeling the water and energy sectors at the same time, the levelized cost of variable renewable electricity decreased 4% for the scenario with the centralized reverse osmosis water sector, 12% for the scenario with reverse osmosis decentralized water sector, and 11% for the multiple effect distillation decentralized water sector compared to the 17.6 $/MWh for the base scenario with separated sectors. Meanwhile, renewable electricity generation grows 32%, 64%, and 53% with 7%, 14%, and 12% less budget, respectively. Although the scenario with the reverse osmosis decentralized water sector has a better performance in the energy sector, this scenario requires 16% more budget for the water sector and reaches a levelized cost of desalinated water of 0.98 $\$/m^3$, which is 24% higher compared to the base scenario. In the meantime, the scenario with the multiple effect distillation decentralized water sector reaches a levelized cost of desalinated water of 0.74 $\$/m^3$, which is 6% lower than the base scenario while producing 4% more desalinated water with 3% less required budget. Furthermore, this scenario showed a better performance in reducing greenhouse gas emissions due to its size compatibility with renewable-powered desalination facilities. As a result, the scenario with the decentralized water sector and renewable-powered multiple effect distillation desalination technology showed the best overall performance among the proposed scenarios. Moreover, the sensitivity analysis revealed the role of the levelized cost of energy in the cost of water desalination, indicating that the multiple effect distillation water production rises about 7%, with a 17% lower budget compared to the budget with no share for research and development.

The operating results show that even with a high capacity factor of desalination plants — 80% capacity factor which makes desalination projects economically feasible — the water sector provides a great amount of flexible electricity load. This flexibility of the water sector is extremely sensitive to the share of wind and photovoltaic electricity generation from total variable renewable electricity generation.

In summary, if planned together, these transformations can offer significant synergies and avoid conflicts, making desalinated water cheaper and more environmentally friendly, while creating a considerable amount of storage available to the grid.

Chapter 4

Integrated Planning of Sustainable Water and Energy Supply with Consideration of Social Equity

4.1 Introduction

Thombs (Thombs, 2019) highlights that depending on the system configuration, (centralized versus decentralized, technologies chosen, etc.), energy transitions will result in an array of different sociotechnical regimes. The current Chapter assesses different approaches of designing transition pathways for interconnected energy and water sectors — first, as two isolated systems and second, as one system together — and the influence of the derived pathways on social equity.

Currently, states mostly have plans for the deployment of large-scale and centralized desalination projects, especially in developing regions such as the Middle East. These plans neglect decentralized solutions that are critical for rural areas, thereby excluding rural households from the benefits of a secure water supply, who remain in a situation of water scarcity while facing the impact of contributing through taxation to heavy national investment. Failure to adequately engage rural communities throughout the transition process may lead to aggravated poverty, inequitable outcomes within society and unjust water and energy transition plans as outcomes or by-products of blinkered decision-making. The Environmental Justice Atlas (EJOLT, 2020) indicates that out of 417 social conflict cases related to the water sector worldwide, 318 cases are located in rural areas, 58 in the semi-urban areas, and only 41 cases in urban areas. Among the social conflict cases related to the energy sector from the same reference, the share of rural areas was 734 cases out of total 1,006 conflict cases. This Chapter, therefore, utilizes decentralized desalination as a solution for a more effective engagement of rural areas in transition plans.

Providing fair equality of opportunity and benefiting the least advantaged members of society the greatest were addressed as one of the principles of justice by John Rawls in *A Theory of Justice*, which is the most widely discussed theory of distributive justice in the past four decades (Rawls, 1971). This leads us to address the aforementioned issue of excluding rural households from the benefits and opportunities provided by renewable-powered desalination projects as distributive justice.

This Chapter aims to reveal the social impacts of different system types and configurations on transition plans for interconnected energy and water sectors with a share of VRE and desalination in regions facing water scarcity. The main contributions of this chapter include (1) establishing social equity as a key factor in designing transition plans with a share of desalinated water supply; (2) comparative equity evaluation of sustainable water and energy supply planning with decentralized desalination and on-grid VRE.

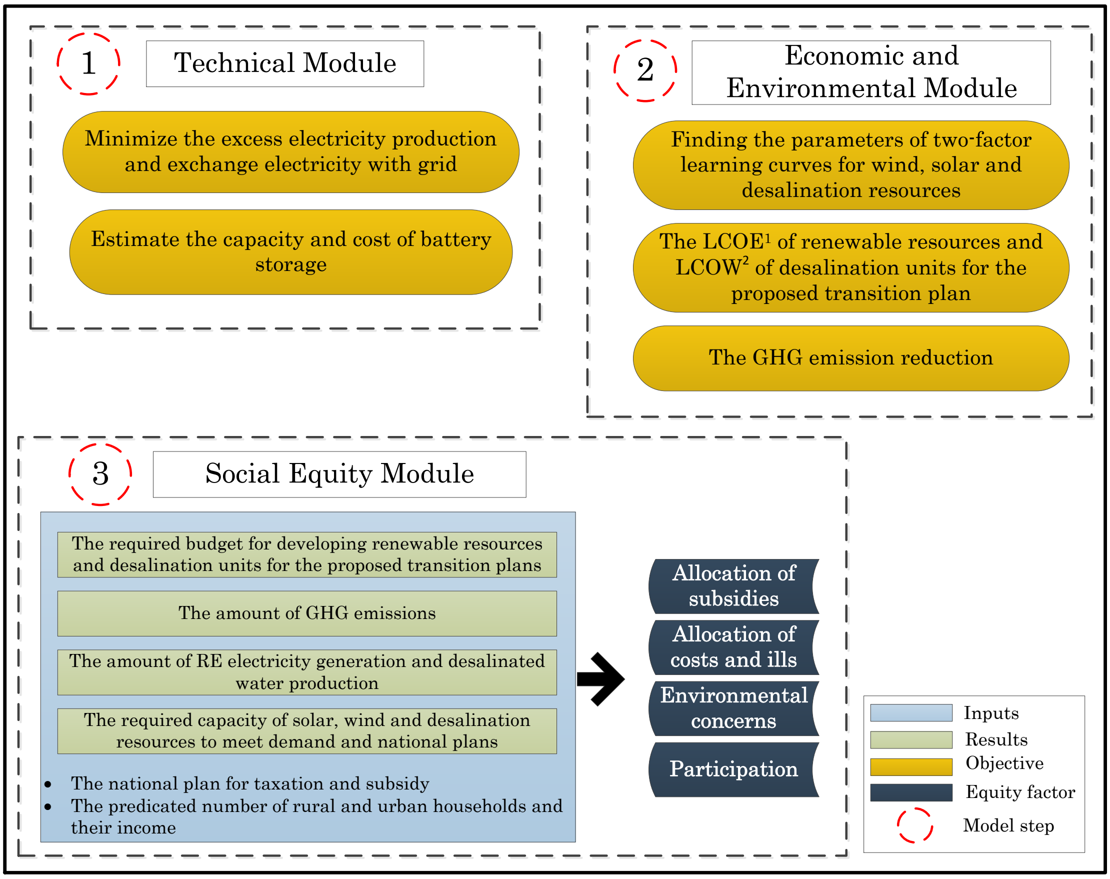
4.2 Methodology

We consider the same four scenarios in Chapter 3, which are summarized in Table 4-1. In the base scenario, water and energy sectors are assumed to be separated systems, in which the water sector is considered as an exogenous factor for the energy sector, without any interconnected control between the sectors. The water sector is considered to be an external demand with no deliberate influence on the energy sector or its planning. In the other scenarios, water and energy sectors are assumed to be an integrated system, in which both sectors are studied together, as endogenous parts of one single system. Utility-scale photovoltaic and wind — on-grid energy systems — are utilized as the renewable energy resources for all the scenarios. In the base scenario, with MED desalination technology, and C_RO scenario, with RO desalination technology, a centralized water sector refers to a desalination system in which saline water is desalinated by one unit and distributed among all target users, while in the D_RO scenario and D_MED scenario, there are more than one desalination unit providing water demand as a decentralized desalination configuration.

Table 4-1. Proposed scenarios.

Scenario	System type	Water sector	Desalination technology	Renewable technology
1 (base)	Separated	Centralized	MED	PV, wind
2 (C_RO)	Integrated	Centralized	RO	PV, wind
3 (D_RO)	Integrated	Decentralized	RO	PV, wind
4 (D_MED)	Integrated	Decentralized	MED	PV, wind

Figure 4-1 outlines the three modules undertaken within the methodology proposed in this Chapter: (1) the technical module, (2) estimating learning curves for the region of the case study and economic and environmental analysis — economic and environmental module —, and (3) proposing a framework to evaluate social equity and conducting equity analysis — social equity module. The current Chapter focuses on the third module, as the first two modules have been presented in detail in Chapter 2 and Chapter 3.



¹ Leveled cost of renewable electricity
² Leveled cost of desalinated water

Figure 4-1. The proposed methodology in Chapter 4. Note: This Chapter mainly focuses on the 3rd step. The 1st and 2nd steps were discussed in the previous Chapters.

4.2.1 Technical Module

A linear supply-demand model was developed to find the optimal size of VRE supplies, desalination supplies, and hourly operation of the energy sector and water sector. The energy and water demands are predicted based on demographic trends, historical data, and national plans. This model aims to minimize the electricity exchange with the electricity grid. In the next step, these results are used to calculate the required battery cost and capacity, which is equivalent to the operational capacity of a flexible water sector. The proposed scenarios with the integrated system benefit from a flexible water sector — as a flexible electric load — compensating for the fluctuating VRE generation. The details of these optimization models and this module were described in detail in Chapter 3.

4.2.2 Economic and Environmental Module

A two-factor learning curve approach is chosen to estimate the path of technology deployment and the pace of cost reduction in this study. As the underlying assumption of the two-factor learning curve, cumulative production, as well as investment in research and development, can improve technology performance that leads to unit cost reduction.

Using the learning curves obtained in this module and the results of the previous module, the future cost of variable renewable energy and desalinated water, job creations, as well as GHG emissions are estimated for the proposed scenarios in the region of the case study. The details of these estimations and calculations were similar to the previous chapter.

4.2.3 Social Equity Module

The definition of sustainable development in this study, follows others (Agyeman and Evans, 2003) as "the need to ensure a better quality of life for all, now and into the future, in a just and equitable manner, whilst living within the limits of supporting ecosystems''. The current Chapter addresses social equity in designing transition plans towards sustainable development goals (SDGs) for the energy and water sector with a share of VRE and desalinated water supply. Despite the uncertainty of these transition plans — due to their strong path dependent nature and a high degree of system complexity — it is essential to identify factors that can provide information to evaluate the equity and viability of the system. For identifying these representative factors, first, common factors were identified through a literature review. The number of factors need to be as small as possible, but as large as essential (Bossel, 1999). Therefore, a number of these factors were defined and determined to represent the social equity.

The initial social impact factors of renewable energy systems and desalination systems that would contribute to evaluating the social equity index were determined through a literature review. The main keywords used were: “Energy Justice”, “Energy Social Equity”, “Water Justice”, “Water Social Equity”. The relevant articles were chosen based on three criteria: First, relevance to the scope of this research topic. Researches that addressed social justice or equity, including the water sector or energy sector, were considered as relevant studies. Second, the impact of these studies as measured using the number of citations. For articles from 2020 having more than 10 citations, and articles from 2016 to 2019, having more than 20 citations per year and articles before 2016 having higher than 100 citations in total.

Table 4-2 summarizes the factors and type of studied justice in these articles. The following factors were identified as the most repetitive social impact factors: (1) distribution of costs or ills; (2) distribution of benefits; (3) participation; (4) mapping stakeholders; (5) gender equity; and (6) environmental concerns.

Table 4-2. Factors derived from literature review (As of 1 July 2020).

Article	Type of justice	Factor					
		Distribution of costs or ills	**Distribution of benefits**	**Participation**	**Mapping stakeholders**	**Gender equity**	**Environmental concerns**
(Rice et al., 2020)	Recognition		x				x
(Szulecki, 2018)	Procedural				x		x
(Healy et al., 2019)	Procedural	x					x
(Jenkins et al., 2018)	Procedural	x					x
(Aized et al., 2018)	Distributive	x					x
(Milakis et al., 2017)	Recognition	x	x				x
(Burke and Stephens, 2017)	Procedural	x	x	x			x
(Healy and Barry, 2017)	Procedural			x			
(Moreau et al., 2017)	Procedural	x	x				x
(Sovacool and Dworkin, 2015)	Recognition, procedural	x	x		x		
(Dearing et al., 2014)	Distributive, recognition	x	x	x		x	x
(Ernstson, 2013)	Distributive, procedural		x				x

Gyamfi (Gyamfi et al., 2013)	Distributive	x	x	x			
(Miller et al., 2013)	Distributive, procedural	x	x	x			
(Hall et al., 2013)	Distributive, procedural		x	x	x		
(Newell and Mulvaney, 2013)	Distributive, procedural		x	x	x		x
(Devine-Wright, 2013)	Procedural			x			
(Cole, 2012)	Distributive	x		x	x		x
(Hanjra et al., 2012)	Distributive	x	x		x		x
(Echenique et al., 2012)	Distributive	x	x				x
(Goldthau and Sovacool, 2012)	Distributive, procedural	x				x	x
(Walker and Day, 2012)	All	x		x			
(Lozano and Huisingh, 2011)	Distributive	x	x	x			x
(Nieusma and Riley, 2010)	Distributive, procedural	x	x	x			
(Solomon, 2010)	Distributive	x	x	x			
(Cai, 2008)	Distributive, procedural	x	x		x		x
(Zoellner et al., 2008)	Distributive, procedural	x	x	x			x
(Kemmler and Spreng, 2007)	Distributive	x	x				x
(Agyeman and Evans, 2003)	Distributive, procedural	x	x				x
(Syme et al., 1999)	Procedural		x				x

As discussed, the current study is mainly concerned with distributive justice. Therefore, the factors related to mapping stakeholders and gender equity — which are not in the scope of distributive justice — have not been considered in this research.

Distribution of costs or ills: Transition plans towards sustainability goals impose burdens on society. These burdens are spread among the beneficiaries in a socially just society. Deployment of renewables and desalination facilities will likely cause an increase in electricity and water costs or related taxes. Tax upsurge — due to the proposed transition plans — is chosen to track this burden factor on households in the current study. NO_x emissions, as another representative indicator of burden, are also calculated in order to compare the proposed transition plans. Long term exposure to NO_x can trigger and exacerbate health issues. The contribution of NO_x in the formation of fine particles (PM) and ground-level ozone causes further impacts because both PM and ozone are associated with adverse health effects (Bernard et al., 2001).

Distribution of benefits: This factor arises primarily because the benefit distribution of the transition plans such as income, wealth, welfare, etc. need to be measured if they are going to be distributed according to some pattern. This factor is concerned with equity issues of these distribution patterns. As an example, Hall et al. (Hall et al., 2013) stated that nearby neighbors of commercial wind farms in Australia criticized the current practice and found it unjust because these wind farms only provide direct financial benefits to turbine hosts. The distribution of required subsidies — for achieving sustainable development goals through the proposed transition plans — among households represent this factor in the current research.

Participation: The distribution of opportunities to participate in transition plans is also important to achieve a socially just society (Lamont, Julian and Favor, Christi, 2017). Transitions to renewable resources and desalination water supply create new jobs. Chapman et al. (Chapman et al., 2016) investigated the nature of created jobs from newly-installed renewables in order to represent the participation pattern of societal income levels in Australia. Similarly, employment is defined as a factor in evaluating the participation of households in the transition plans in this study.

Environmental concerns: Decreasing the GHG emissions of the energy sector in order to limit climate change, and reducing the amount of excess water extraction in order to protect and conserve groundwater, are two ultimate goals of the studied transitions. Excess water extraction refers to the difference between the amount of water extraction from underground and surface water resources and the amount of water returned to these resources from neighboring secondary basins and precipitation over the period of one year. The volume of desalinated water will offset the requirement for extracting water from ground-water and surface-water sources which are connected in most landscapes. These environmental outcomes benefit the whole society, which increases the overall welfare level by securing sustainable water supply and energy supply. Therefore, the amount of renewable energy generation and the volume of desalinated water are considered as equity factors, which are beneficial to evaluate the proposed transition plans.

In order to compare and combine these indicators, the scores are normalized. Min-max normalization, one of the common ways to normalize data, is chosen to normalize the equity factors. For every factor, as described in Equation (4-1), the maximum value of that factor among scenarios gets transformed into a 1, the minimum value gets transformed into a 0, and every other value gets transformed into a decimal between 0 and 1.

$$Norm_{valu} = {valu - \min}\Big/{\max - \min} \tag{4-1}$$

Min-max normalization identifies the relative cost and benefit distribution bias for each of the proposed scenarios. This normalization method guarantees all factors will have the same final scale. An overall equity score is obtained using a summation of normalized benefits, positive values, and normalized burdens, negative values, for the scenarios and then these overall summations are normalized. This equity assessment takes an equally weighted assessment of each of the equity factors.

Case Study

Persian civilization, which inhabited modern-day Iran since the 6th century BCE, was already concerned with water shortages, and had established ethical rules on the use of water both in their religious practice of Zoroastrianism (the original pre-Islamic religion of the region) in which it is imperative to keep the water pure and unpolluted, and also in practical infrastructure, through the construction of an elaborate system of underground aqueducts called Qanat which provide fresh water access to all even in arid regions. This shows that Ancient Persia recognized first the social imperative to conserve and distribute water in a way that ensures its availability to all; and second, the ecological realities of the plateau's desert climate from ancient times (Foltz, 2002).

While it is true that decentralized desalination could be applied to urban areas and centralized systems to rural areas, this is typically not the case. Centralized, large-scale desalination is typically used for systems with well-connected water networks, which are typically urban areas. Centralized and large-scale desalination are the most frequent systems investigated among the studies in planning water supply with a share of renewable energy, as a result of which, the less-connected and widely-dispersed rural areas are repeatedly excluded from these plans and have no opportunity to participate or benefit directly. The current research investigates the impacts of these different approaches for designing transition plans on social equity. As explained, the scenarios with centralized desalination provide water for the urban areas. Figure 4-2 illustrates the schematic of these scenarios, namely, base and C_RO scenarios.

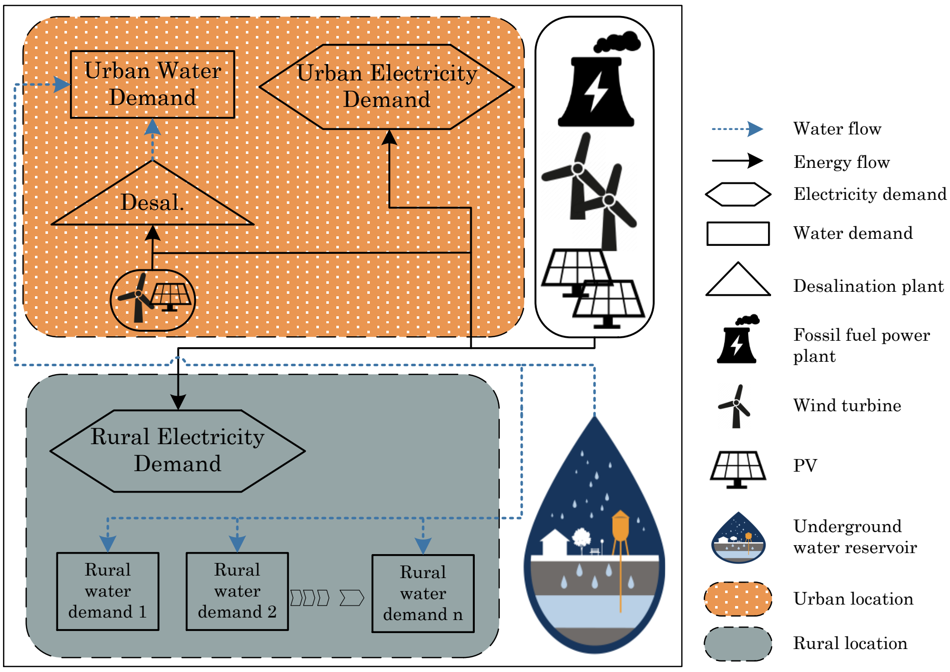


Figure 4-2. The proposed scenarios with centralized desalination.

Figure 4-3 represents the location of desalination facilities and their energy supplies in the scenarios with decentralized desalination, namely, D_RO and D_MED scenarios. In the decentralized water sector, a number of desalination plants are supplying water for different target demands, instead of a centralized desalination plant providing water for all the target users. As a result, in these scenarios the benefits of these desalination facilities — such as jobs, subsidies and a portion of energy supply from renewables — are reallocated from the urban areas to rural areas.

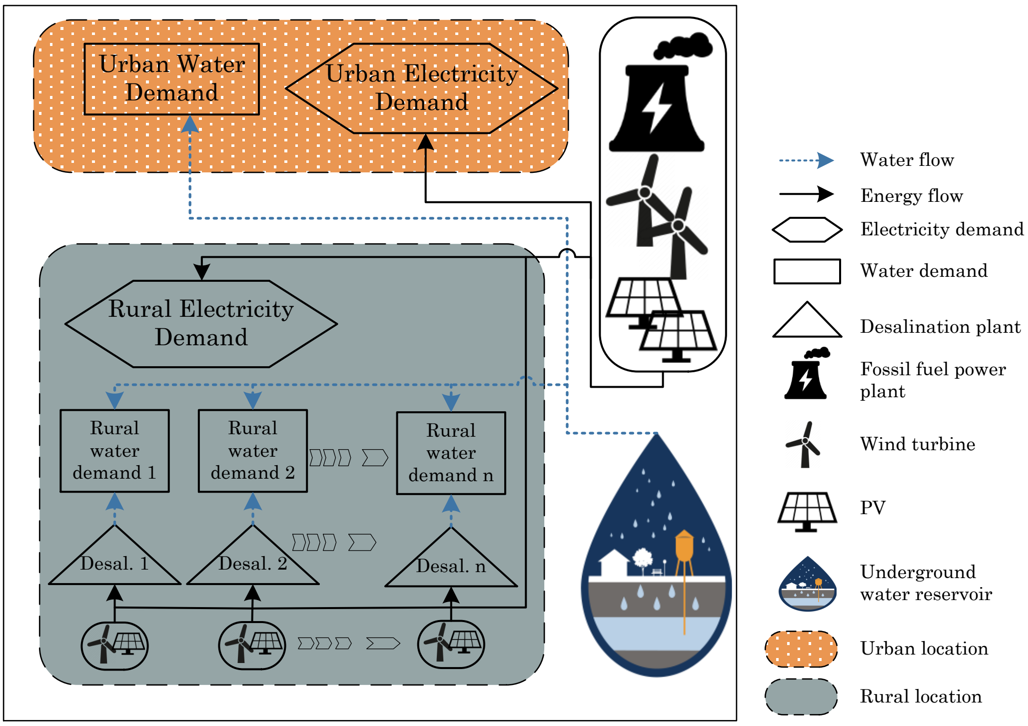


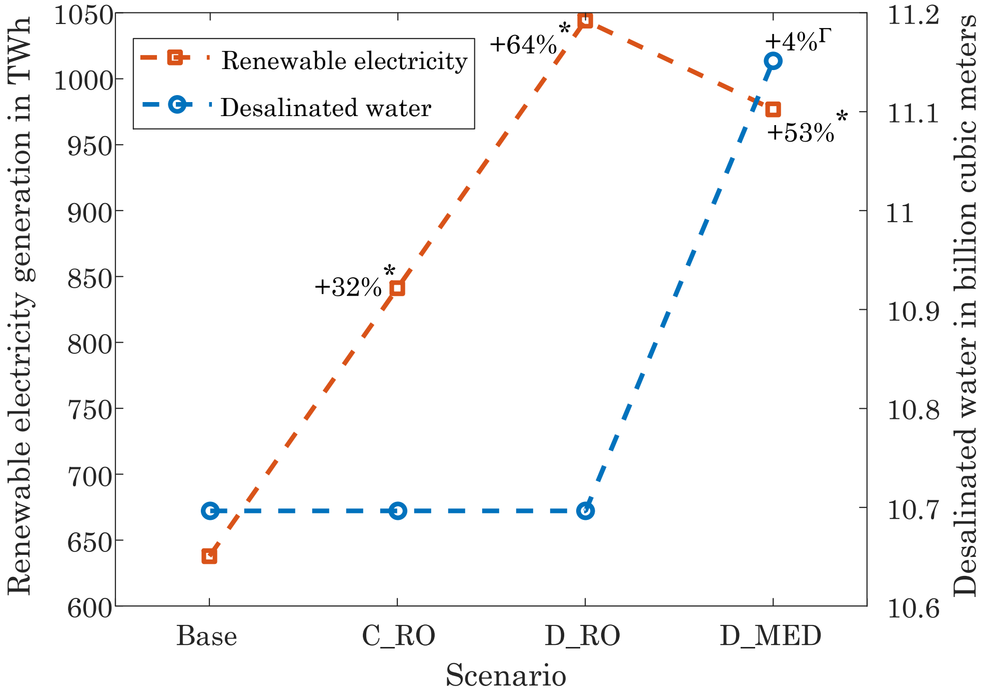
Figure 4-3. The proposed scenarios with decentralized desalination.

4.3 Results & Discussion

In Chapters 2 and 3, the supply-demand module coded into GAMS 26.3.5 and solved for the long-term planning horizon from 2020 to 2040, considering hourly operational performance. As the next step, the parameters of the two-factor learning curves for wind power, utility-scale PV, RO and MED desalination industries are estimated. Using these learning curves and outcomes of the supply-demand module, the renewable energy generation, desalinated water production, and overall required cost are calculated. The cost covers all the fixed and variable costs of renewable electricity generation and desalinated water production.

Similar to Chapter 2, the scenarios with a flexible water sector need lower battery capacity in order to compensate for the fluctuations arising from VRE electricity generation. As a result, these scenarios require less budget to provide renewable electricity compared to the base scenario, which is considered as a saved budget for the energy sector. It is assumed that 5 percent (UNESCO Institute for Statistic, 2020) of this saved budget is invested in research and development of VRE technologies, resulting in further cost reduction driven by the experience effect of cumulative production. The rest of the budget finances further renewable generation, driving further cost reduction by the knowledge stock. Since 40 percent and 7 percent of the levelized cost of desalinated water from RO technology and MED technology goes to electricity consumption, respectively, a lower levelized cost of electricity causes a cost-saving in the water sector. Furthermore, the scenarios with a decentralized water sector benefit from a further cost-saving due to less electricity consumption for water distribution. Similarly, 5 percent of this saved budget goes to research and development and 95 percent of this budget is dedicated to desalinate more water.

Figure 4-4 shows the lifetime renewable electricity generation from wind and PV resources and lifetime desalinated water from desalination units, newly installed from 2020 to 2040. As discussed, all the proposed scenarios generate more renewable electricity compared to the base scenario. The C_RO, D_RO, and D_MED scenarios, with the integrated water and energy sectors, generate 203 TWh (32%), 406 TWh (64%), and 339 TWh (53%) more variable renewable electricity, respectively, during the lifetime of the newly installed supply in the period of 2020 to 2040 compared to the variable renewable electricity generation in the base scenario with separated sectors. For the water sector, only the D_MED scenario — with a decentralized water sector and MED desalination technology — generates more desalinated water, which is 4% more desalinated water during the lifetime of the newly installed facilities, compared to desalinated water production in the base scenario.



* Renewable electricity generation compared to the base scenario in percent
Γ Desalinated water compared to the base scenario in percent

Figure 4-4. Lifetime VRE electricity generation and desalinated water production.

In 2019 the Iranian Parliament approved two articles to assign 25 percent of the value-added tax income from utility bills for the deployment of renewable resources and 1/90th of total income from the country's value-added tax for developing potable water supply (IEIS, 2020). It is estimated that these budgets cover around 10 percent of the required budget to meet the aforementioned targets in the energy and water sector (IEIS, 2020). Therefore, it is assumed that national subsidies cover 90 percent of the required budget in each proposed scenario in this study and the remaining 10 percent is provided through the taxation system.

Figure 4-5 shows the required subsidy for the energy sector and the water sector in each scenario. In almost all the proposed scenarios, the energy sector benefits greatly from an integrated design. The required subsidy in the C_RO, D_RO, and D_MED scenarios is 13%, 26%, and 23% less than the required subsidy for the base scenario during 2020-2040 for the energy sector, respectively. Taking into account the required subsidy for the water sector, only the D_MED scenario experienced synergistic results. Other proposed scenarios imposed a higher subsidy budget for the water sector, causing a higher overall required subsidy budget. While the D_MED requires 11.3 percent lower subsidy budget, the C_RO and D_MED scenarios require 19% and 17% higher budget compared to the water sector in the base scenario.

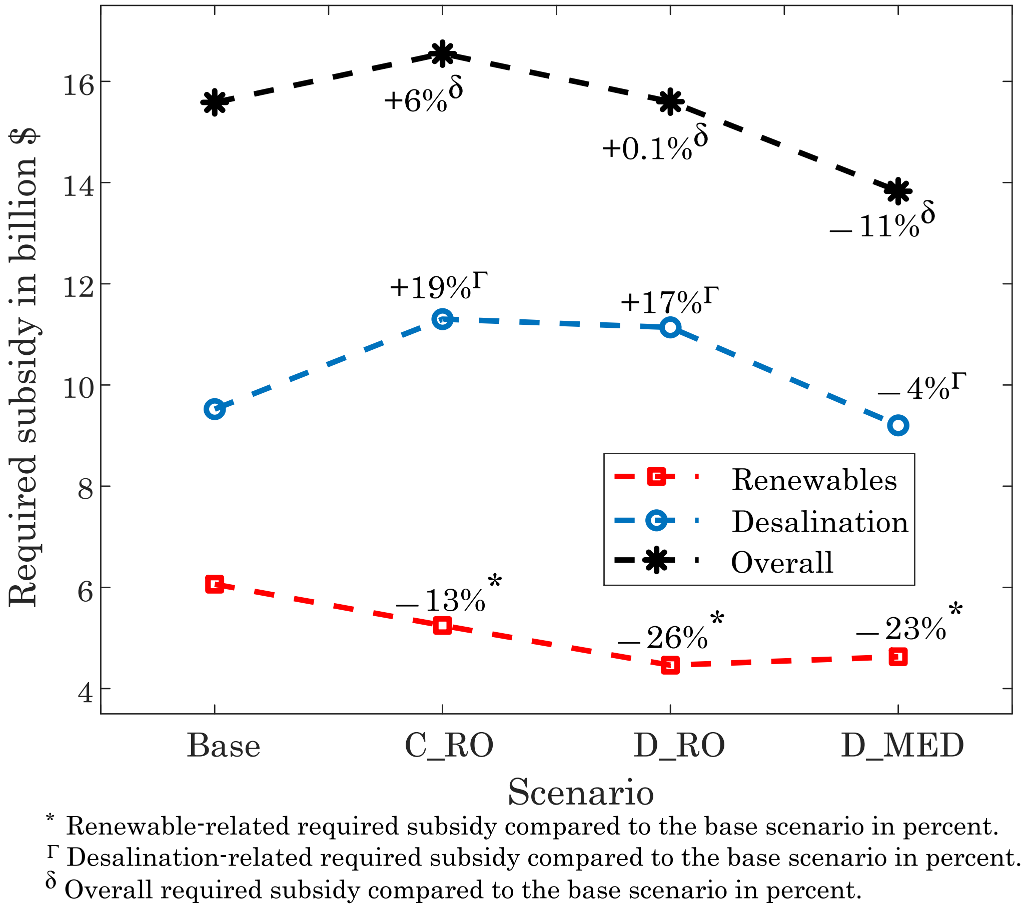


Figure 4-5. Required subsidy for the proposed scenarios from 2020 to 2040.

The energy sector and the water sector are highly subsidized in Iran. According to an IEA report in 2019 (IEA, 2019a), Iran ranked first among the world's top countries in terms of the subsidies allocated to energy consumption which accounts for 18.8 percent of its total GDP. These subsidies are mainly funded by oil revenues in Iran — as one of the world's top energy-rich countries — which provide cheap energy and water for consumers. As discussed, it is planned that the required subsidies for the transitions in the water and energy sectors will be funded by the national resources such as the National Development Fund of Iran. Figure 4-6 depicts the allocation of the subsidies among urban and rural households. In the base scenario and C_RO scenario with a centralized water sector, it is assumed that the newly installed desalination facilities provide water for the urban regions. As mentioned earlier, these tend to be better-connected, making them more favorable targets for centralized systems. In comparison, D_RO and D_MED consider the newly installed desalination facilities to be supplying water for rural households. Accordingly, a share of subsidies for desalination and part of the electricity consumption from renewables is reallocated from urban areas in the base and C_RO scenarios to the rural areas in the D_RO and D_MED scenarios, securing potable water supply for rural residents. As can be seen in Figure 4-6, there is a considerable gap in subsidy allocations between urban and rural households in all the scenarios.

The average electricity consumption of households in the region of the case study is 9,194 KWh per year which costs $263.5 based on the current Iranian residential electricity price (Statistical Center of Iran, 2018). The average rural household water consumption is 219.2 m^3 per year which currently estimated around $6.7. This average is 209.0 m^3 per year for the urban households costing about $6.4 (Statistical Center of Iran, 2018). These average utility consumptions are specifically for the 4 provinces in the region of the case study. As discussed, it was assumed that the taxation system on household utility covers 10 percent of the required budget. This tax causes $12.5, $10.8, $9.2 and $9.5 increase in average household's electricity bill from 2020 to 2040 in the Base, C_RO, D_RO and D_MED scenarios, respectively. The average household's water bill rises $19.6, $23.2, $22.9 and $18.9 during the same period in the Base, C_RO, D_RO and D_MED scenarios, respectively.

The average GDP per capita of Iran from 2010 to 2017, available until 2017, is $6,198 (World Bank, 2020b). The average required subsidy per household for the period of 2020 to 2040 is between 4.1% to 4.9% of the GDP per capita in the proposed scenarios for 20 years. There is a range of 0.2% to 1.4% for renewable energy investment as a share of GDP (Our World in Data, 2020).

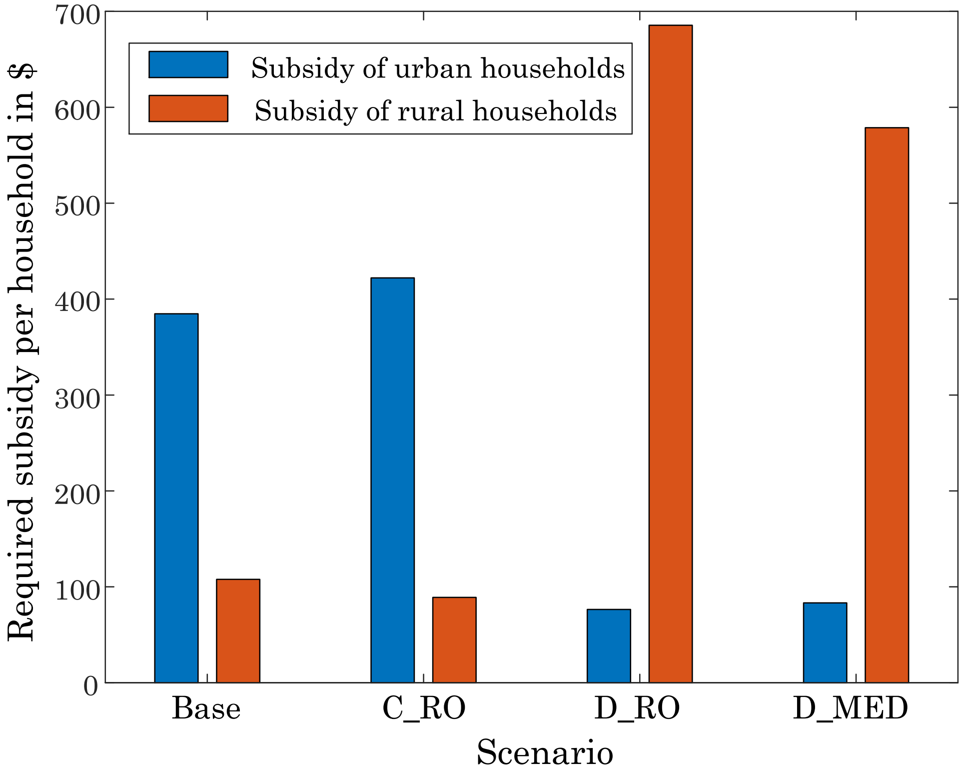


Figure 4-6. Allocation of subsidies, the yearly average from 2020 to 2040.

As can be seen in Figure 4-7, the impact of electricity and water cost increase is investigated based on the average income of urban and rural households. Due to a lower income level, the burden of water and electricity cost increase on rural households is almost twice that of the burden on urban households. Although the D_MED scenario imposes a lower burden on both urban and rural households — because of lower levelized cost of renewable electricity and desalinated water — the gap is still considerable, which is around 1.8 times higher for the rural households compared to the urban households.

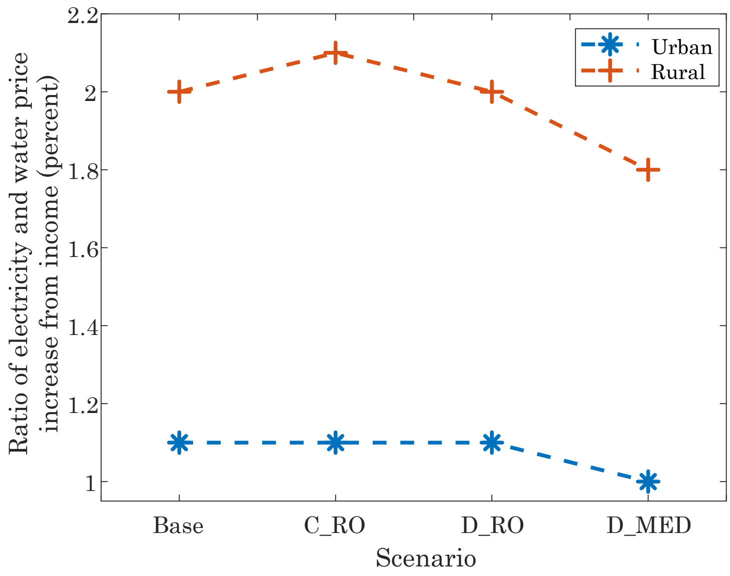


Figure 4-7. Burden of water and electricity cost increase on households from 2020 to 2040.

Table 4-3 depicts the GHG and NO_x emissions from energy consumption in the proposed scenarios. The D_MED scenario with 1,108 megatons of CO_2, 19,746 tons of CH_4, 1,975 tons of N_2O, and 3,368 kilotons of NO_x emissions by 2040 has the lowest emissions compared to the other scenarios. These emissions were calculated based on the Iranian fuel mix for electricity generation and it was assumed that the thermal energy for the MED desalination process was provided from Iranian natural gas in the base scenario (National Petrochemical Company, 2017; Nazari et al., 2010; Statistical Center of Iran, 2018).

Table 4-3. Greenhouse gas (GHG) and NOx emissions for each scenario from 2020 to 2040.

Scenario	**CO_2 (megaton)**	**CH_4 (kiloton)**	**N_2O (ton)**	**NO_x (kiloton)**
1 (base)	1151.7	20.5	2052.5	3501.0
2 (C_RO)	1141.8	20.3	2034.8	3470.8
3 (D_RO)	1120.4	20.0	1996.8	3406.0
4 (D_MED)	1108.0	19.7	1974.6	3368.1

Figure 4-8 illustrates the allocation of jobs created from renewables and desalination. The number of jobs was calculated based on the lifetime and capacity of the newly installed renewable supply and desalination facilities (Afgan and Darwish, 2011; Ram et al., 2020; Rustum et al., 2020). A portion of these jobs, providing energy for the desalination facilities, is allocated to the location of the desalination facilities. For the rest of the new jobs from the energy sector, it is assumed that these jobs distribute based on the current distribution of industrial and service-related jobs between rural and urban areas in the region of the case study (Statistical Center of Iran, 2018). In the base and C_RO scenarios, the desalination-related jobs are allocated to the urban areas, while in the D_RO and D_MED scenarios, these jobs go to the rural areas. This reallocation of desalination-related jobs from urban to rural areas is beneficial to increase the share of rural households in the newly created jobs from 0.2 job per household in the base scenario to around 0.36 job per household in the D_RO and D_MED scenarios, thereby decreasing the gap in job distribution between urban and rural households, as can be seen in Figure 4-8. Although the required subsidy for the water sector accounts for between 61 to 71 percent of the total required subsidy budget, the job creation from renewables is around 6.5 times more than the job creation from desalination.

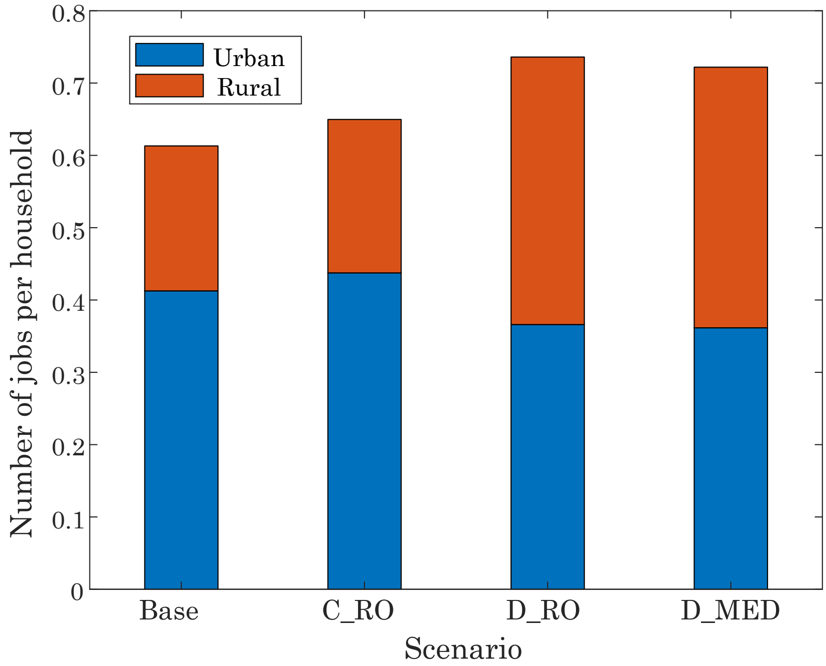


Figure 4-8. Allocation of employment.

Figure 4-9 depicts the equity score of the proposed scenarios based on the equity factors. All the proposed scenarios showed synergetic results in the energy sector and generated a higher amount of renewable electricity, while spending a lower budget compared to the results of the base scenario with separated water and energy sectors. The C_RO scenario ranked the highest in generating renewable electricity. Only the D_MED scenario achieved synergistic results to desalinate more water compared to the base scenario, and ranked the highest based on this factor. The C_RO and D_MED imposed a higher budget on the water sector for desalinating the same amount of water compared to the base scenario.

Reallocating the subsidy of the desalination facilities and their electricity demand from the urban to rural households caused the D_RO and D_MED scenarios to get a higher equity score in the rural regions while the base and C_RO scenarios have a better performance in the urban regions. The rural equity score of the D_RO is higher than the score of the D_MED in terms of the subsidy allocation factor because in this scenario, the water sector's subsidy budget is higher and the RO technology requires a higher level of electricity for operation, thereby getting more resources to reallocate from urban to rural areas.

On the other hand, the higher required budget of the D_RO scenario imposes a higher cost burden on households. As a result, the D_MED with the lowest required budget ranked the best in term of the cost burden factor. Although the proposed scenarios decreased the overall cost burden on households compared to the base scenario, there is still a significant gap between the cost burden for rural or urban households.

As discussed, reallocating a portion of job creation from desalination and their electricity consumption in the D_RO and D_MED scenarios caused both rural and urban households to benefit with almost the same equity score in terms of the job allocation factor.

As expected, the D_RO and D_MED ranked better based on the NO_X factor because these scenarios generated a higher amount of renewable electricity while consuming a lower level of electricity, since the decentralized water sector requires a lower level of electricity for water distribution. The D_MED desalination with integrated water and energy sectors and multi-effect desalination technology achieved the highest equity score among the proposed scenarios. The scenarios with a decentralized water sector give the rural households an opportunity to benefit from a secure water supply and its required subsidy, distributing the overall costs and benefits of the water and energy sectors with a higher equity level.

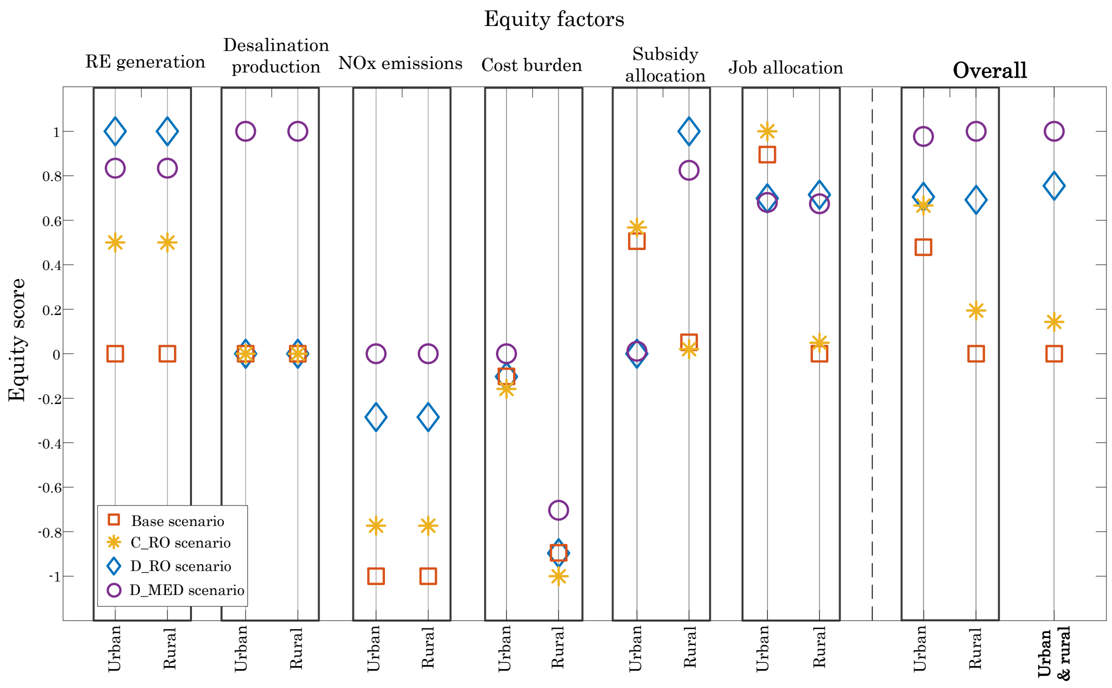


Figure 4-9. Per scenario equity level from 2020 to 2040.

Sensitivity Analysis

As discussed, it was assumed that the taxation system — which is provided by household taxes — covers 10 percent of the required budget in each proposed scenario. The tax is to be provided through electricity and water price increases. The cost burden is defined as the impact of this price increase on urban and rural households based on their average income. The results for uniform distribution of the cost burden among all the households were explained in the previous subsection.

A sensitivity analysis was conducted to investigate the influence of shifting a portion of the cost burden from rural households to urban households. By increasing the share of the urban households from the cost burden, the overall equity score is improved and the C_RO scenario imposes a more severe burden on the households compared to the other scenarios. As can be seen in Table 4-4, with 65 percent share of the cost burden, the scenarios still impose a higher burden on the rural households, while with 85 and 95 percent shares, the burden is shifted drastically from the rural households to urban households. On the other hand, this sharp shift caused a significant gap between the cost burden on the urban and rural households compared with the gap for the 65 percent share. Increasing the burden share on the urban households to 65.2

percent makes the cost distribution fairer, resulting in equal proportion of income spent for all the households.

Table 4-4. Sensitivity analysis on the cost burden factor.

Share of urban households from the cost increase	Scenario	Cost burden		Overall equity score		
		Urban	Rural	Urban	Rural	Urban & Rural
65 percent	1 (base)	0.61	0.66	0.29	0.00	0.00
	2 (C_RO)	0.95	1.00	0.40	0.08	0.05
	3 (D_RO)	0.62	0.67	0.49	0.69	0.56
	4 (D_MED)	0.00	0.05	0.84	1.00	1.00
80 percent	1 (base)	0.90	0.08	0.12	0.00	0.00
	2 (C_RO)	1.00	0.13	0.30	0.16	0.20
	3 (D_RO)	0.91	0.08	0.35	0.77	0.70
	4 (D_MED)	0.73	0.00	0.65	1.00	1.00
95 percent	1 (base)	0.94	0.01	0.10	0.00	0.00
	2 (C_RO)	1.00	0.02	0.29	0.17	0.23
	3 (D_RO)	0.94	0.01	0.33	0.79	0.72
	4 (D_MED)	0.82	0.00	0.62	1.00	1.00

4.4 Conclusions

As equity is an important issue within sustainability, this Chapter provides a quantitative methodology to establish social equity as a key factor in the design and evaluation of the transformation plans towards, first, energy systems with a high share of variable renewable resources, in order to cut greenhouse gas emissions; and second, water systems with a share of supply coming from desalination, because of water scarcity.

The results provide evidence that the system type (integrated versus separated) and configurations (centralized or decentralized, components and technologies) have direct impacts on the equity of the proposed transition plans.

Collectively, this study identifies that rural areas are repetitively excluded in the planning for water supply with desalination and a share of renewables, due to the focus of policymakers on large-scale and centralized desalination. Although rural areas in Iran are given priority for development in strategies for achieving sustainable development goals (SDGs), the current perspective of the policymaking is unable to engage rural areas in the transition plans, and therefore fails to provide a just opportunity to benefit from a secure water supply and heavy subsidies. The alternative scenarios using decentralized desalination and an integrated planning of the water and energy supply, constitute a possible solution to distribute the benefits and burdens of the transition plans between urban and rural areas, while considering equity issues. Shifting a portion of job creation and subsidies of desalination and their renewable energy supply from urban areas in the scenarios with a centralized water sector, and reallocating them to rural areas in the scenarios with a decentralized water sector, caused both rural and urban households to reach a balance in distribution of benefits and burdens and improves the social equity level of the whole system.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Two transitions are ongoing in the Middle East, first, the transition towards energy systems with a high share of variable renewable resources; second, the transition towards water systems with a share of supply coming from desalination. As sustainability is the ultimate aim of these transitions, a novel methodology is outlined to design sustainable transition plans for interconnected energy and water sectors with a share of renewable resources and desalination in the regions facing water scarcity.

A nonlinear model, which represents the characteristics of the nexus concept, is proposed in order to quantitatively analyse these synergies. This research showed that considering the nexus between the water and energy sectors in designing the studied transition plans could bring technical, economic, environmental and social synergistic benefits.

5.1.1 Technical Perspective

Mitigating the fluctuation of variable renewable power generation constitutes one of the main challenges to the widespread utilization of renewable resources in regions facing water scarcity, where hydropower may not be viable. The operating results showed that if the water sector has a share of desalination water supply operated efficiently as a flexible electric load, it can compensate for the fluctuating variable renewable power generation to some extent. This flexibility of the water sector is extremely sensitive to the share of wind and photovoltaic electricity generation from total variable renewable electricity generation. In order to fully benefit from this flexibility, an integrated planning of the energy and water sectors, with a regard for operational aspects in long-term planning, is necessary.

Another finding is that solar electricity resources perform better in following the electrical load pattern in the region of the case study, Iran. With a share of more than

80 percent of the total renewable electricity generation, solar electricity resources are therefore the dominant renewable resource for all the proposed scenarios. Although the capacity factor of solar electricity supply is lower than the wind supply, this supply imposes less fluctuations on the electricity system. The seasonal variability of wind power is higher than the variability of photovoltaic power.

5.1.2 Economic & Environmental Perspective

For studying synergies, the path of technology deployment and the pace of decline in overall costs are assumed to be a function of experience and knowledge as two-factor learning curves, instead of modeling technology cost just as a function of time, the common approach in the literature. In this study, the two-factor learning curves are developed in order to estimate the path of technology deployment and the pace of cost reduction, which showed a good fit for the decline in investment costs in the Middle East over the past decade. The estimated learning rates of the two-factor learning curves showed that the research and development investment have a significant role in deployment and cost reduction of photovoltaic, wind, multiple effect distillation, and reverse osmosis technologies. Despite the fact that the learning-by-searching rate is higher than the learning-by-doing rate for all these technologies, in the case of wind and photovoltaic technologies the main percentage of the cost reduction is driven from the experience of production. This shows that these technologies are facing an inadequate R&D budget for further innovation. Nevertheless, in the proposed scenarios, investing a portion of the saved budgets on R&D solved this issue to some extent.

Moreover, the nexus approach revealed that the configuration of each sector has direct impacts on the other sector. While the energy sector greatly benefitted from an integrated design in almost all the scenarios, the water sector only experienced synergic results in the scenario with a decentralized water sector and multiple effect distillation desalination technology. This generated a decrease both in the required budget and in the levelized cost of desalinated water, compared to the base scenario with separated water and energy sectors. It also performed better in terms of reducing greenhouse gas emissions due to its size compatibility with renewable-powered desalination facilities. It is assumed that thermal energy for the desalination process is provided through solar thermal resources in this scenario. In our specific case study, other scenarios caused a higher levelized cost of desalinated water and a higher budget required on the water sector.

Additionally, the assessment showed that in the current markets, compensating for fluctuating renewable electricity generation using battery technology has a much higher value than renewable electricity, in the region of case study, Iran. This implies that the electricity system is still far from the level of renewable energy penetration when the battery storage availability becomes a constraint. As indicated, the water sector — especially with a share of desalination supply — could operate as a flexible electric load in order to partially address this issue. However, targeting a high share of variable renewable deployment in the near future requires ensuring that other solutions are also in place in order to deal with fluctuating renewable power generation. As an assumption in the current study, the battery capacity merely operated in order to avoid imbalances between supply and demand due to excess renewable power generation.

5.1.3 Social Perspective

Lastly, policymaking's focus on large-scale and centralized desalination has repetitively excluded rural areas in planning for water supply with desalination and a share of renewables. Even though rural areas are listed as a priority in strategies for achieving sustainable development goals (SDGs), policymakers are unable to engage rural areas in the transition plans, resulting in their failure to provide a just opportunity to benefit from a secure water supply and heavy subsidies. The identification of social equity as a key factor in design and quantitative evaluation of interconnected transitions addresses this issue in the current research.

Considering equity as an essential aspect of sustainability, this research provides a methodology to establish social equity as a key factor in the design and quantitative evaluation of plans for these transitions. The results revealed that the equity level of the proposed transition plans is strongly impacted by the system type, namely integrated versus separated system, and the configurations, namely centralized or decentralized, components, and technologies. The proposed scenarios with decentralized desalination in an integrated planning of both water and energy supply, constitute an alternative solution to distribute the benefits and burdens of transition plans between urban and rural areas, while addressing equity issues. Shifting a portion of job creation and subsidies of desalination and their renewable energy supply from the urban areas, and reallocating them to the rural areas led to a balance between rural and urban households in the distribution of benefits and burdens. It also improves the overall social equity level of the system.

Lastly, designing integrated plans for interconnected transitions may provide alternative solutions, which were previously not considered in a separated design but would become feasible through the simultaneous transformation of the other sector. Currently, the poor energy infrastructure is one of the impediments in the consideration of decentralized desalination systems suitable for deployment in rural areas due to size compatibility. The transformation of the energy sector towards a high share of renewables brings decentralized desalination as an alternative solution for the transformation of the water sector in both rural and urban areas. Currently, in the region of the case study, Iran, planning for the water and energy sector is being conducted independently. The results revealed the indispensability of an integrated planning of the energy and water sectors, with a regard for operational aspects in long-term planning.

5.2 Future Work

The nexus concept is related to the inherently interconnected sectors which must be designed or governed in a holistic manner. As shown in the results of Chapter 3, the nexus approach is deemed necessary to highlight potential synergies and identify critical conflicts which need to be dealt with. This work addressed example synergies and conflicts taking place when integrating energy and water in a single system, thereby increasing its complexity. An interesting future direction of research could be focused on this complexity as a cost of system integration at different levels.

Another perception found in this work and in most of the literature is that desalination is assumed to be a secure and resilient water supply. However, different sector configurations could result in different levels of security and resilience. Desalination is economically and politically important for achieving self-reliance for specific regions, such as the Middle East and Singapore. When achieving this goal, it is vital to examine the resilience of desalination systems further. For instance, in the case of technical failure, the centralized desalination systems and potable desalination units are more vulnerable, while the decentralized desalination configuration and agriculture users are more resilient compared to domestic users. The agriculture water demand has not been considered in the current study. However, relocating the desalination facilities from the urban areas to rural areas in the proposed decentralized scenarios, enables the country to readily expand or develop these desalination facilities for agriculture targets in the future. Another direction of future research could address the role of desalination water supply in food security of Iran.

Appendices

Nomenclature.

Subscripts	Description
t	Set of time, hour
d	Set of time, day
y	Set of time, year
l	Set of location for the decentralized water sector
r	Reservoir
pmp	Pump
des	Desalination
$conv$	Conventional
w	Water
i	Integrated system
s	Separated system

Variables	Description
$w_r(l,d,y)$	Amount of water in the reservoir
$w_{conv}(l,t,y)$	Amount of water extraction from conventional water supplies
$w_{pmp,des}(t,y)$	Pumped water from the desalination plant's reservoir
$w_{r,des}(t,y)$	Amount of water in the desalination reservoir
$w_{des}(l,t,y)$	Water production by the desalination plant
$Cap_{conv}(l,y)$	Water production capacity of conventional water supplies
$Cap_{des}(l,y)$	Water production capacity of desalination plants
$Cap_{wind}(y)$	Wind energy capacity
$Cap_{pv}(y)$	Capacity of the photovoltaic panels
$Cap_{bat}(y)$	Capacity of battery unit
$p_{ch}(t,y)$	Electricity charge of battery unit
$p_{dch}(t,y)$	Electricity discharge of battery unit
$C_{new}(y)$	Unit cost
$Prd_{new}(y)$	Cumulative production
$K_{new}(y)$	Cumulative investment

Parameters	Description
$w_d(l,d,y)$	Water demand
$Cap_r(l,y)$	Capacity of the water reservoir
$Cap_{r,des}(y)$	Capacity of the desalination unit's reservoir
$Cap_{pmp,des}(y)$	Capacity of the pumping from the desalination's reservoir
$Des_{share}(y)$	Share of desalination from total water demand
p_{des}	Required energy for producing a unit of desalinated water
p_{pmp}	Required electricity for pumping unit of water from a desalination plant to the reservoir
p_{conv}	Energy needed to extract and transfer unit of water from conventional water resources
$p_{wind}(t,y)$	Wind electricity production
$v(t)$	Wind speed
$p_{pv}(t,y)$	Electricity production from photovoltaic panels
$I(t)$	Solar radiation
$p_{RE}(t,y)$	Renewable energy production
$RE_{share}(y)$	Target share of renewable energy production
$p_d(t,y)$	Electricity demand
$p_w(t,y)$	Electricity consumption of the water sector
$p_{grid}(t,y)$	Electricity exchange with the national grid
eff_{bat}	Efficiency of the battery storage
$E_{bat}(t,y)$	Energy stored in the battery unit
$C_{initial}$	Initial unit cost
α	Learning-by-doing elasticity
β	Learning-by-searching elasticity
$\Pr d_{initial}$	Initial cumulative production
KS	Knowledge stock
In	Investment expenditures
OM	Operations and maintenance expenditures
F	Fixed expenditures
C_f	Capacity factor
d_r	Discount rate
Lf	Lifetime of the technology

APPENDIX A: Renewable-Powered Desalination Technologies

Table A1. List of the reference studies to outline the development state of renewable-powered desalination technologies.

Technology	**Size (m^3/day)**	**Cost (\$/m^3)**	**Year**	**Ref.**
PV RO	1–250	3.6–33.0	2017	(Manju and Sagar, 2017)
PV RO	400	1.5–3.4	2015	(IRENA, 2015)
PV RO	<100	6.5–15.6	2013	(Al-Karaghouli and Kazmerski, 2013)
PV RO	-	12.5–16.8	2017	(Alkaisi et al., 2017)
PV RO	<100	11.7–15.6	2017	(Shahzad et al., 2017)
Wind RO	80	-	2017	(Alkaisi et al., 2017)
Wind RO	2400–3360	0.7–2.0	2017	(Manju and Sagar, 2017)
Wind RO	-	1.8–5.4	2015	(IRENA, 2015)
Wind RO	50–2000	1.9–9.0	2013	(Al-Karaghouli and Kazmerski, 2013)
Wind RO	50–2000	2.0–5.2	2017	(Shahzad et al., 2017)
Solar thermal MED	20	-	2017	(Alkaisi et al., 2017)
Solar thermal MED	> 5000	2.4–2.8	2017	(Manju and Sagar, 2017)
Solar thermal MED	>5000	2.5–3.0	2017	(Alkaisi et al., 2017)
Solar thermal MED	>5000	2.0–2.5	2017	(Shahzad et al., 2017)
Solar thermal MED	-	1.0–7.3	2015	(IRENA, 2015)
Solar still	0.01–0.2	1.3–6.5	2017	(Manchanda and Kumar, 2018; Manju and Sagar, 2017)
Solar still	<1.2	-	2019	(Gopi et al., 2019)
Solar still	<1.0	1.3–6.5	2013	(Al-Karaghouli and Kazmerski, 2013)
PV ED	<1.0	5.8–16.0	2017	(Manju and Sagar, 2017)
PV ED	<1.0	1.2–12.6	2017	(Alkaisi et al., 2017)
PV ED	0.001–0.2	0.2–13.0	2015	(Fernandez-Gonzalez et al., 2015)
Geothermal MED	200	-	2017	(Alkaisi et al., 2017)
Geothermal MED	1920	1.7	2017	(Manju and Sagar, 2017)
Geothermal MED	80	2.0–2.8	2013	(Al-Karaghouli and Kazmerski, 2013)
Geothermal MED	50–1000	-	2017	(Shahzad et al., 2017)
Geothermal MED		3.8–5.7	2018	(Khalilpour, 2018)
Geothermal MED	1440	1.7	2019	(Kucera, 2019)
Solar HDH	0.005–1.2	3.0–7.0	2016	(Giwa et al., 2016)
Solar HDH	-	8.6–9.7	2017	(Manju and Sagar, 2017)
Solar HDH	-	2.8–7.0	2017	(Alkaisi et al., 2017)
Solar HDH	0.001–0.1	2.6–6.5	2017	(Shahzad et al., 2017)
Solar thermal MSF	-	1.0–5.0	2017	(Manju and Sagar, 2017)
Solar thermal MSF	0.2–10	-	2011	(Ali et al., 2011)
Solar thermal MSF	1–10	-	2019	(Darawsheh et al., 2019)
Solar MD	0.002–0.1	10.5–19.5	2017	(Manju and Sagar, 2017)
Solar MD	0.002–0.1	10.5–19.5	2013	(Al-Karaghouli and Kazmerski, 2013)
Wind/MVC	< 100	5.2–7.8	2017	(Manju and Sagar, 2017)
Wind/MVC	<100	5.2–7.8	2013	(Al-Karaghouli and Kazmerski, 2013)

Wind MVC	<100	5.6–8.4	2017	(Alkaisi et al., 2017)
Ocean-based RO	1000–3000	0.7–1.2	2017	(Shahzad et al., 2017)
Ocean-based RO	500–1800	0.9–1.0	2014	(Ylänen and Lampinen, 2014)
Wind ED	72–192	-	2011	(Ma and Lu, 2011)
Wind ED	-	2.0–3.5	2018	(Khalilpour, 2018)
Geothermal MD	17	13	2018	(Gude, 2018b)
Geothermal MD	20,000	0.5	2018	(Khalilpour, 2018)
Geothermal HDH	3	1.2	2005	(Bourouni and Chaibi, 2005)
Geothermal HDH	-	1.2	2007	(Rizzuti et al., 2007)
Geothermal HDH	-	1.2	2019	(Kucera, 2019)
Geothermal HDH	-	1.2	2016	(Gude, 2016b)

APPENDIX B: Learning Curve

Two-factor learning curve is chosen to estimate the future costs of different renewable energy production from the resources and desalinated water in this study which follow Equation (B.1).

$$C_{new}(y) = C_{initial} \times (\frac{Prd_{new}(y)}{Prd_{initial}})^{-\alpha} \times (\frac{K_{new}(y)}{KS})^{-\beta} \quad \text{(B.1)}$$

Where C_{new} is the unit cost in year y, $C_{initial}$ depicts the initial unit cost, $Prd_{initial}$ is the initial cumulative production, Prd_{new} is the historical cumulative production in year y, obtained from Eq. (B.2), α is the learning-by-doing elasticity, KS depicts the knowledge stock which is the initial cumulative investment on R&D, K_{new} is the historical cumulative investment on R&D in year y, described in Equation (B.3), and β is the learning-by-searching elasticity.

$$Prd_{new}(y) = \sum_{Y=0}^{y} Prd(Y) \quad \text{(B.2)}$$

Where Prd is the amount of new production each year and $Prd(0)$ depicts the starting year of applying the technology.

$$K_{new}(y) = \sum_{Y=0}^{y} K(Y) \quad \text{(B.3)}$$

Where K is the amount of new investment in R&D in each year and $K(0)$ depicts the R&D investment in the starting year of applying the technology.

The decreasing rate is illustrated by the learning-by-doing ratio (LDR) is obtained as $1-2^{-\alpha}$ and Learning-by-searching ratio (LSR) is calculated as $1-2^{-\beta}$ which denote the percentage of change in cost as consequence of doubling the cumulative production and R&D budget, respectively.

Because of a lack of data, a new approach is applied to estimate the Learning-by-searching elasticity and the average research and development budget using particle swarm optimization in MATLAB software. To validate this approach, the results for US residential photovoltaic (Barbose et al., 2017) and wind resources (Electricity Markets and Policy Group, 2017) are compared with reference (Zhou and Gu, 2019) and the IEA R&D budget database. For residential PV for 17 years between 2000 to 2016, with time delay of one year for investment R&D, the obtained LDR was 9.52 %, LSR was 18.77% and a goodness of fit (R^2) of 94.04%. Reference (Zhou and Gu, 2019) has reached 94.9% of goodness of fit (R^2) for the US residential PV in 2009 to 2016 based on real data. The real yearly average investment on research and development of US residential PV (IEA, 2019b) is equal to $0.128 Billion and the estimated average by PSO approach is $0.124 Billion.

For US wind power in 2009 to 2018, with a time delay of three years for invested R&D, the obtained LDR was 17.07%, LSR was 38.68% and a goodness of fit (R^2) of 92.21%. Reference (Zhou and Gu, 2019) has reached 97.4 of goodness of fit (R^2) for the US wind power in 2009 to 2016 based on real data. The actual yearly average investment on R&D of US residential PV (IEA, 2019b) is equal to $0.059 Billion and the estimated average by PSO approach was $0.056 Billion in this study.

By considering the decay factor between 2.5 to 10.5 percent for invested R&D on PV and wind technologies based on literature, the proposed approach is applied for this study. As a result, the parameters of two-factor learning curves for the levelized cost of water (LCOW) of RO desalination technology and the levelized cost of energy (LCOE) for utility-scale solar and wind technologies are estimated using the proposed approach in the Middle East.

Due to a lack of data for LCOE of wind and photovoltaic supplies in the Middle East, 32 wind projects and 49 PV projects have been studied to estimate the LCOE for wind and PV resources in the Middle East. These projects are summarized in Tables B.1 and B.2. The levelized cost of electricity (LCOE) is calculated as (B.4) in this study.

$$\frac{\sum_{y=0}^{Lf-1} In(y)+OM(y)+F(y) \Big/ (1+d_r)^y}{\sum_{t=1}^{n} Cap(y)\times C_f(y)\times 8760} \tag{B.4}$$

Where In is the investment expenditures in year y, OM is the operations and maintenance expenditures in year y, F depicts the fixed expenditures in year y, C_f describes the capacity factor of the supply technology in each year and Cap is the installed capacity of the technology in each year, d_r is the discount rate and Lf describes the life of the technology.

The investment costs, fixed and variable costs and the average capacity factor of wind and PV electricity resources in the Middle East have been obtained through overall VRE electricity production of the countries (IRENA, 2020, 2019, 2018) and the studied mentioned projects in Tables B.1 and B.2 which is depicted in Figure B.1. The capacity of wind and photovoltaic resources from 2000 to 2018 in the Middle East is depicted in Figure B.2. Middle East in this study refers to these countries: Oman, Qatar, Islamic Republic of Iran, Bahrain, Egypt, Iraq, Palestine, Turkey, Israel, Jordan, Kuwait, Lebanon, Kingdom of Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen.

Table B.1. List utility-scale wind projects for obtaining LCOE.

Project	Capacity in MW	Investment M$ 2018	LCOE ($/MWh)	Year
Bahçe Wind Farm	135	230.31	107.8	2010
Sayalar Wind Power Plant	23	32.93	73.8	2011
Samurlu Wind Power Plant	30	49.45	77.8	2011
Kozbeyli Wind Power Plant	29.9	47.97	77.0	2011
Usak Wind Power Plant	54	62.14	69.1	2012
Sadilli Wind Power Plant	38.5	54.75	68.8	2012
Karadere Wind Power Plant	15	29.75	77.7	2012
Edincik Wind Power Plant	30	52.43	74.0	2012
Günaydın Wind Power Plant	12.5	18.75	70.1	2012
Geres Wind Power Plant	27.5	38.156	67.8	2013
Söke Wind Power Plant	45	57.79	66.1	2013
Salman Wind Power Plant	27.5	39.43	68.5	2013
Mocha Wind Park Project	60	155.22	87.5	2013
Geres Wind Power Plant	27.5	37.57	60.9	2014
Bozyaka Wind Power Plant	4.8	8.64	66.1	2014
Ova Wind Power Plant	18	24.09	60.5	2014
Edincik Ii Wind Power Plant	26.4	36.01	60.9	2014
Pitane Wind Power Plant	4.8	9.10	69.2	2014
Tafila Wind Farm	117	304.06	80.1	2014
Amasya Wind Power Plant	42	76.77	64.4	2015
Bozyaka Wind Power Plant	12.5	8.66	46.5	2015
Umurlar Ext Power Plant	26.4	35.81	52.6	2016
Soma Wind Power Plant	30	36.55	50.8	2016
Edincik Iii Wind Power Plant	21	26.20	51.2	2016
Incesu Wind Power Plant	14	20.85	54.4	2016
Çakıl Wind Power Plant	31.55	50.53	54.5	2017
Çamseki Plant (Extension)	42.3	39.98	45.6	2017
Alibey Adası Wind Power Plant	30	36.64	49.3	2017
Gulf Of El Zayt Farm, El Zayt	200	348.30	56.4	2017
Egypt - Development Project	250	409.77	55.0	2018
Lekela Egypt Power Boo S.A.E	252	339	30.1	2018

Yahşelli Wind Power Plant	20	31.4	30.1	2018

Table B.2. List of photovoltaic projects for obtaining LCOE.

Project	Capacity in MW	Investment M$ 2018	LCOE ($/MWh)	Year
Belectric And Solel Boneh	10	-	169.0	2013
Talmei Bilu Solar Power Plant	21	48.39	256.4	2013
Falcon Ma An For Solar Energy	10	50	179.8	2014
Shamsuna Power Company Llc.	10	21	171.9	2014
Zahrat Al-Salam For Energy	10	31	200.2	2014
Al-Zanbaq For Energy Generation Psc	10	31	200.2	2014
Al-Ward Al-Joury For Energy Generation PSC	40	31	200.2	2014
Ketura Solar Facility	200	83.7	139.3	2015
Mohammed Bin Rashid Almaktoum Solar Park Phase II	10	345.38	130.7	2015
Maan Development Area	10	31.78	164.8	2015
Martifer Solar	52.5	27.55	154.8	2015
First Solar	28.3	158.92	161.2	2015
Scatec Solar Asa	43	50.3	131.9	2015
Sunedison	12.9	105.94	148.0	2015
Zaatari Syrian Refugee Camp	50	15.69	110.1	2016
Al Sharika Al Mahaliya Li Aamal Al Miya Wa Al Taka Al Shamsia Psc	85	72	115.2	2016
Akfen Solar Power Project	17.9	100	109.2	2016
Soho Solar PV Power Plant	200	25.46	114.8	2016
Mohammed Bin Rashid Al Maktoum Solar Park II	29.68	327.82	119.7	2016
Hipot Solar PV Power Plant	500	38.07	111.6	2016
MGES Power	200	261.56	94.3	2016
Baynouna Solar Energy Company Psc	66.6	266.35	103.1	2017
Alsafawi For Green Energy PSC	5.814	35	78.1	2017
İven Solar PV Power Plant	17.988	7.84	96.1	2017
Caba Solar PV Power Plant	7	23.77	95.5	2017
Stars Solar PV Power Plant	48.946	11.56	102.8	2017
Met-Gün Solar PV Power Plant	34.5	56.49	91.8	2017
Çiftay Solar PV Power Plant	10.3	47.48	96.7	2017
Başarı Solar PV Power Plant	35.9	13.65	95.6	2017
Zen Solar PV Power Plant	15.25	57.37	101.6	2017
Aktaş Solar PV Power Plant	10.59	19.40	94.4	2017
Zigana Solar PV Power Plant	8.15	15.23	98.1	2017
Koyuncu Nevşehir Solar PV Power Plant	950	9.62	92.4	2017
Mohammed Bin Rashid Al Maktoum Park	1177	962.96	88.8	2017
Noor Abu Dhabi Solar PV Plant in Sweihan	100	891.25	83.1	2017
Pdo Amin PV Plant	100	100.00	80.8	2018
Askar Landfill	9.98	-	49.2	2018
Mt Dogal Solar PV Power Plant	9.95	18.93	98.8	2018
Omicron Engil Solar PV Power Plant	9.9	18.45	97.9	2018
Me - Se Solar PV Power Plant	9.98	16.46	94.1	2018
Yaysun Solar PV Power Plant	12.2	19	99.0	2018
Sunfarming Eurasia Asset Enerji Yat	500	16	86.2	2018
Ibri PV Plant	9.95	500.00	80.8	2018
Omicron Ercis Solar PV Power Plant	9.95	17.47	55.4	2019
Iota Solar PV Power Plant	9.95	17.91	55.4	2019
Psi Engil Solar PV Power Plant	26	17.80	55.4	2019
Cingilli Solar PV Power Plant (Licensed)	-	38.35	55.4	2019
Sakaka Project	200	300.00	23.4	2019
Al-Muwaqqar Solar Energy Project	10	253.83	55.4	2019

Table B.3. Average capacity factor and LCOE of wind and PV electricity resources in the Middle East.

Year	Wind CF	Photovoltaic CF	Wind LCOE ($/MWh)	Photovoltaic LCOE ($/MWh)
2000	0.19	0.17	-	-
2001	-	0.17	-	-
2002	0.21	0.21	-	-
2003	-	0.17	-	-

2004	0.23	0.16	-	-
2005	0.23	0.19	-	-
2006	0.20	0.15	-	-
2007	0.17	0.21	-	-
2008	0.25	0.19	-	-
2009	0.18	0.16	-	-
2010	0.26	0.20	107.8	-
2011	0.31	0.17	76.2	-
2012	0.29	0.17	72.7	-
2013	0.28	0.20	72.5	212.7
2014	0.29	0.20	66.3	190.5
2015	0.29	0.19	55.4	147.2
2016	0.34	0.20	52.2	110.7
2017	0.34	0.21	51.5	94.2
2018	0.37	0.23	42.5	85.8
2019	-	0.23	-	50.1

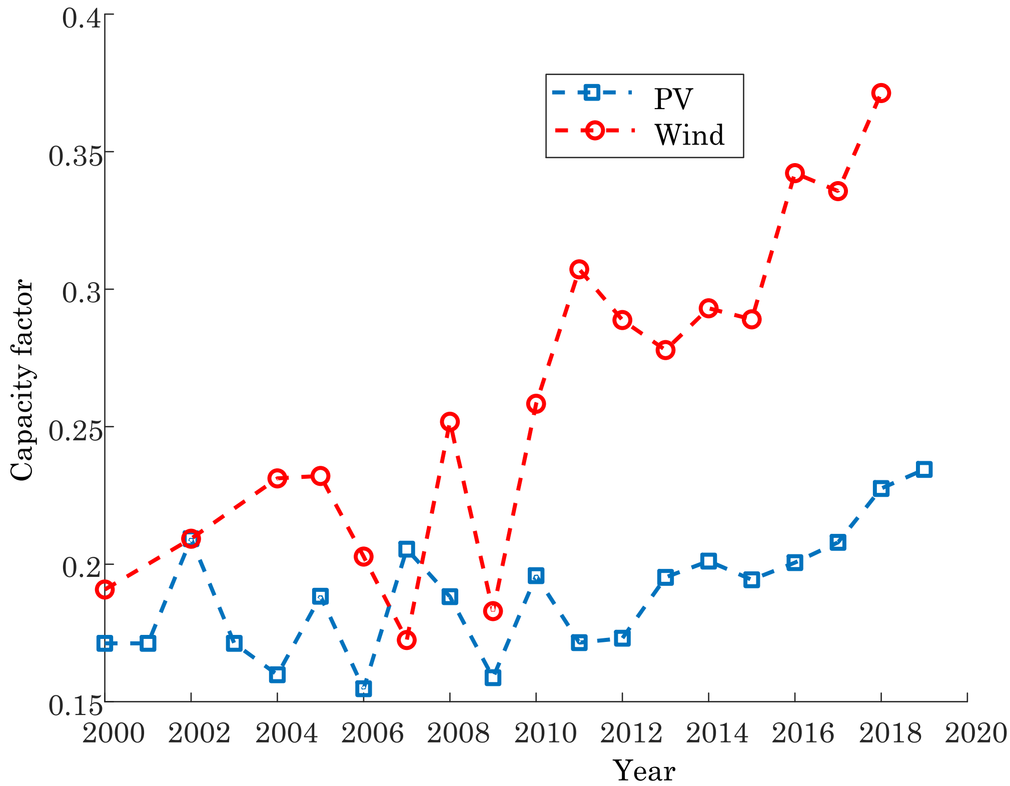


Figure B.1. Average capacity factor of wind and PV electricity resources in the Middle East.

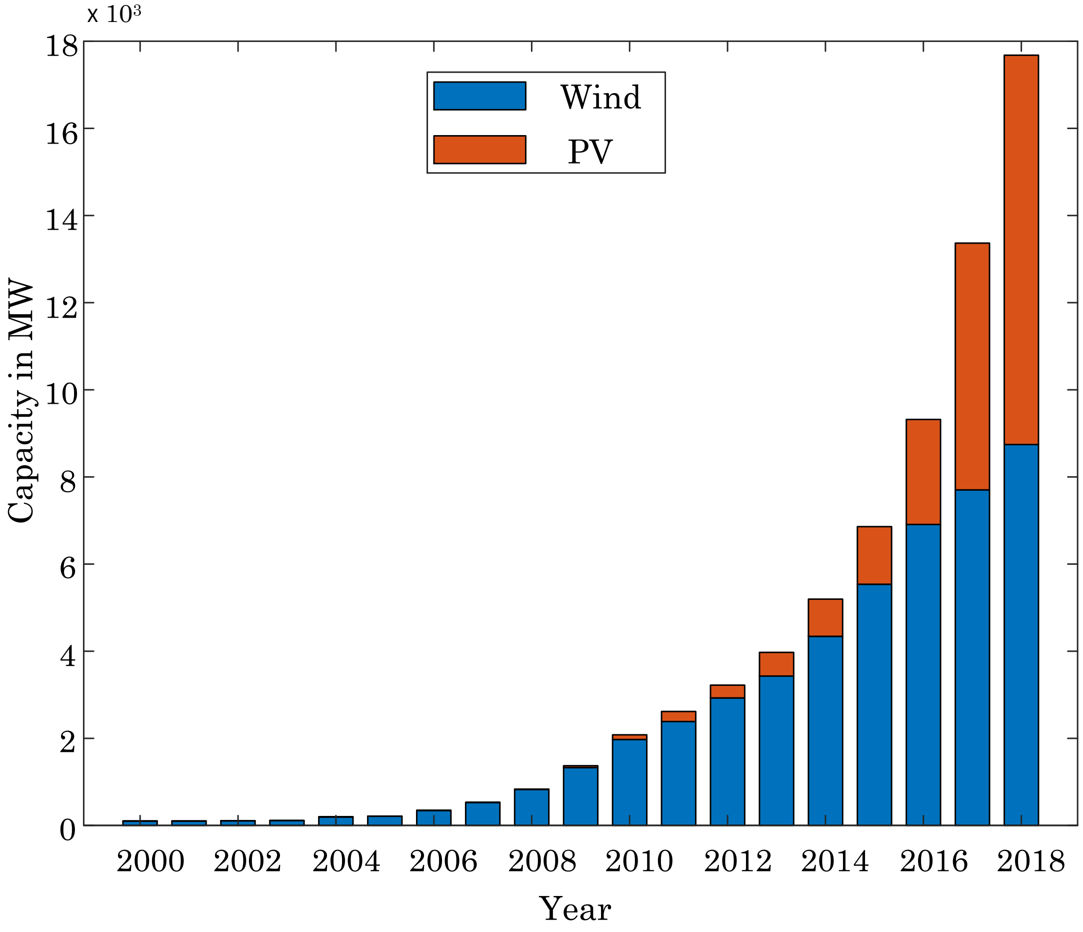


Figure B.2. Capacity of wind and photovoltaic electricity resources from 2000 to 2018 in the Middle East.

APPENDIX C: Location of Rural Districts

The name and location of 19 rural districts in Jask county, which are selected in this study, are summarized in Table C.1.

Table C.1. List of rural locations selected as the case study.

Name of Rural District	**Population** (Statistical Center of Iran, 2018)	**Households** (Statistical Center of Iran, 2018)	**Link of Location** (Google Maps, 2020)
Bahl	1755	426	https://www.google.com/maps/place/Bahl,+Hormozgan+Province,+Iran/@25.6905931,57.8505706,16z/data=!3m1!4b1!4m5!3m4!1s0x3ef245334b39178d:0xbcdfde949993da52!8m2!3d25.6921894!4d57.8509418
Jāsk-e-kohne	1202	288	https://www.google.com/maps/place/J%C4%81sk-e-kohne,+Hormozgan+Province,+Iran/@25.7422102,57.7639997,15z/data=!3m1!4b1!4m5!3m4!1s0x3ef24eda7e4c933b:0x39806870cdc083c1!8m2!3d25.7411497!4d57.7714829
Koeek	786	210	https://www.google.com/maps/place/Koeek,+Hormozgan+Province,+Iran/@25.7583282,57.6670104,11z/data=!4m5!3m4!1s0x3ef249017572c2df:0x42d897398e4154ba!8m2!3d25.7942639!4d57.778575
Gazdan	1258	317	https://www.google.com/maps/place/Gazdan,+Hormozgan+Province,+Iran/@25.7694311,57.7917444,16z/data=!3m1!4b1!4m5!3m4!1s0x3ef248cf39072dff:0xc39d472d0a032940!8m2!3d25.766858!4d57.7962176
Zaminlashkari	464	131	https://www.google.com/maps/place/Zaminlashkari,+Hormozgan+Province,+Iran/@25.7484823,57.7553738,16z/data=!3m1!4b1!4m5!3m4!1s0x3ef24eca56ac286b:0x799bae564cc8787c!8m2!3d25.7472196!4d57.7587182
Bahmadi	505	133	https://www.google.com/maps/place/Bahmadi,+Hormozgan+Province,+Iran/@25.7871894,57.5510557,11.79z/data=!4m5!3m4!1s0x3ef23541f3128313:0x9ddef543c32eaa32!8m2!3d25.8285336!4d57.6644487
Negar	711	181	https://www.google.com/maps/place/Negar-e-p%C4%81yin,+Hormozgan+Province,+Iran/@25.8007038,57.4989623,11.79z/data=!4m5!3m4!1s0x3ef3cae3da854af5:0x47584c97d37659c!8m2!3d25.8385738!4d57.6148668
Gangan	509	96	https://www.google.com/maps/place/Gang%C4%81n,+Hormozgan+Province,+Iran/@25.8542635,57.3436244,11.83z/data=!4m5!3m4!1s0x3ef3cf59b0851fb7:0x125e05cd1f4c4417!8m2!3d25.8631558!4d57.4606046
Bunji-ye Maski	748	176	https://www.google.com/maps/place/Bunji-ye+Maski,+Hormozgan+Province,+Iran/@25.8960276,57.2979087,14z/data=!3m1!4b1!4m5!3m4!1s0x3ef3dd2d6ca6c17f:0x22f178da9751952a!8m2!3d25.8960291!4d57.3154183
Gattan-e Olya	1123	271	https://www.google.com/maps/place/Gattan-e+Olya,+Hormozgan+Province,+Iran/@25.9936337,57.2757001,11.88z/data=!4m5!3m4!1s0x3ef3de3d57d9b5f7:0xfa9800a611b82b84!8m2!3d25.9924426!4d57.2937363
Gazi	689	158	https://www.google.com/maps/place/Gazi,+Hormozgan+Province,+Iran/@26.0719969,57.2147293,14z/data=!3m1!4b1!4m5!3m4!1s0x3ef15f06250a5fcb:0x1debd5ced9d9e613!8m2!3d26.0719984!4d57.2322389
Gavan-e Pain	991	235	https://www.google.com/maps/place/26%C2%B005'31.0%22N+57%C2%B016'43.0%22E/@26.0922704,57.294239,10.96z/data=!4m5!3m4!1s0x0:0x0!8m2!3d26.091944!4d57.278611?hl=en
Karti	736	191	https://www.google.com/maps/place/Karti,+Hormozgan+Province,+Iran/@25.4438073,58.8945826,10.83z/data=!4m5!3m4!1s0x3eed201474dd91e3:0x3604e51b3390f5d5!8m2!3d25.4589232!4d59.0867475
Gati	466	122	https://www.google.com/maps/place/25%C2%B035'48.3%22N+58%C2%B057'18.3%22E/@25.596758,58.955089,11z/data=!4m5!3m4!1s0x0:0x0!8m2!3d25.596758!4d58.955089?hl=fa
Pyveshk	1220	349	https://www.google.com/maps/place/Pyveshk,+Hormozgan+Province,+Iran/@25.55363,58.8967607,14z/data=!3m1!4b1!4m5!3m4!1s0x3eed1084afeaabbd:0xba1cfd33f0e42fc0!8m2!3d25.5551815!4d58.9120326
Vanak	486	126	https://www.google.com/maps/place/Vanak,+Hormozgan+Province,+Iran/@25.5372237,58.8738763,17z/data=!3m1!4b1!4m13!1m7!3m6!1s0x3eed1084afeaabbd:0xba1cfd33f0e42fc0!2sPyveshk,+Hormozgan+Province,+Iran!3b1!8m2!3d25.5551815!4d58.9120326!3m4!1s0x3eed10e3416e1997:0x81243b597e74c6f2!8m2!3d25.536638!4d58.8755018

Lirdaf	1734	451	https://www.google.com/maps/place/Lirdaf,+Hormozgan+Province,+Iran/@25.6407523,58.8608408,16z/data=!3m1!4b1!4m5!3m4!1s0x3eed0ef9bb94f749:0x5fd6f536fdd98172!8m2!3d25.6400557!4d58.8661929
Sourgalm	447	96	https://www.google.com/maps/place/Sourgalm,+Hormozgan+Province,+Iran/@25.6336313,58.0429605,11.83z/data=!4m13!1m7!3m6!1s0x0:0x0!2zMjXCsDQyJzA4LjAiTiA1OcKwMTEnMjguMCJF!3b1!8m2!3d25.702222!4d59.191111!3m4!1s0x3ef2639faffc5071:0x9c61b7e42e113f9e!8m2!3d25.656382!4d58.142395?hl=en
Gouhert	1025	264	https://www.google.com/maps/place/Gouhert,+Hormozgan+Province,+Iran/@25.6304412,58.8011349,16z/data=!3m1!4b1!4m13!1m7!3m6!1s0x0:0x0!2zMjXCsDM5JzA1LjAiTiA1OMKwNDknMjYuMCJF!3b1!8m2!3d25.651389!4d58.823889!3m4!1s0x3eed0c49d0625f91:0x8c9b1145fa7ca564!8m2!3d25.6305382!4d58.8032055?hl=en
Total	16,855	4221	

APPENDIX D: Sensitivity Analysis

For investigating the role of R&D budget in the deployment wind, solar MED, and RO technologies, a sensitivity analysis has been conducted. To this end, the share of R&D investment from the saved budgets is assumed to differ by up to 10%. The resulting LCOE of VRE electricity and LCOW of desalination technologies in 2040 for the proposed scenarios are summarized in Table 5. The levelized cost of photovoltaic electricity (around 20% for the C_RO scenario, 32% for the D_RO scenario, and 28% cost reduction for the D_MED scenario) was most affected by increasing the share of R&D budget compared to the LCOE of wind power (around 2% for the C_RO scenario, 6% for the D_RO scenario, and 4% cost reduction for the D_MED scenario) and LCOW of MED and RO desalination technologies (around 1% for the C_RO scenario, 8% for the D_RO scenario, and 14% cost reduction for the D_MED scenario) due to the higher effect of cumulative production and receiving a higher share of the R&D budget. In the C_RO scenario, the share of wind electricity generation from the total VRE electricity production in 2040 is the lowest amongst the proposed scenarios causing higher LCOW for the wind supply as can be seen in Table D.1 to Table D.3.

Table D.1. Sensitivity analysis on the share of research and development (R&D) from the saved budgets for LCOE of wind electricity in 2040.

Share of R&D (%) / Scenario	LCOE of wind electricity ($/MWh)			
	Base	C_RO	D_RO	D_MED
0	17.8	18.8	18.0	17.8
2	17.8	18.7	17.8	17.6
4	17.8	18.6	17.6	17.4
6	17.8	18.5	17.4	17.3
8	17.8	18.4	17.2	17.1
10	17.8	18.4	17.0	17.0

Table D.2. Sensitivity analysis on the share of R&D from the saved budgets for LCOE of solar electricity, in 2040.

Share of R&D (%) / Scenario	LCOE of solar electricity ($/MWh)			
	Base	C_RO	D_RO	D_MED
0	17.3	17.0	16.9	17.0
2	17.3	16.1	15.3	15.7
4	17.3	15.4	14.1	14.6
6	17.3	14.7	13.0	13.7
8	17.3	14.1	12.2	12.9
10	17.3	13.6	11.5	12.2

Table D.3. Sensitivity analysis on the share of R&D from the saved budgets for LCOW of desalination in 2040.

Share of R&D (%) / Scenario	Levelized cost of desalinated water ($/m^3)			
	Base	C_RO	D_RO	D_MED
0	0.79	1.01	1.01	0.79
2	0.79	1.01	1.00	0.77
4	0.79	1.01	0.99	0.75
6	0.79	1.01	0.97	0.72
8	0.79	1.00	0.95	0.70
10	0.79	1.00	0.93	0.68

As mentioned, it is assumed that a share of the saved budget goes into the renewable and desalinated water production, adding new capacities to the supply sides of the water and energy sector. This budget covers all the fixed and variable costs of the VRE electricity generation and desalinated water production within the lifetime of these technologies, which is 20 years. The renewable generation and desalinated water production of these new capacities from the saved budget are described in Figures D.1 and Figure D.2 for the proposed scenarios. By increasing the share of R&D in Figure D.2, as expected, the VRE electricity generation is diminished because the budget for the VRE generation is reduced and invested in R&D instead. For the water sector in the D_MED scenario, although the MED water production rises from 1% for no R&D share to 8% for 10% R&D share because of the same reason, the required budget decreases 17% because of the high cost reduction of photovoltaic electricity (around 28%). This reveals the role of LCOE in the cost of water desalination, indicating that with a 17% lower budget compared to the budget for no share of R&D in the D_MED scenario, the MED water production rises about 7%.

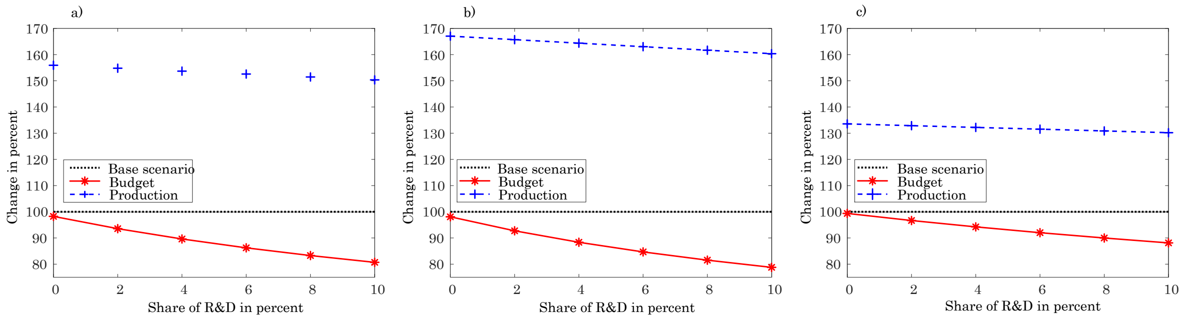


Figure D.1. Sensitivity analysis on the share of R&D from the saved budgets for the share and budget of VRE power production for: **(a)** The C_RO scenario; **(b)** the D_RO scenario; **(c)** the D_MED scenario.

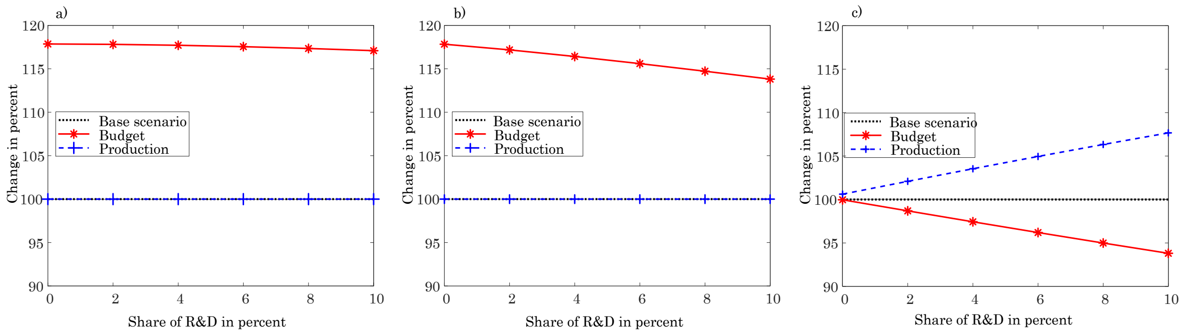


Figure D.2. Sensitivity analysis on the share of R&D from the saved budgets for share and budget of desalination water production for: **(a)** the C_RO scenario; **(b)** the D_RO scenario; **(c)** the D_MED scenario.

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List of Related Publications

① [Peer-Reviewed Journals]

1) Ahmadi E, McLellan B, Mohammadi-Ivatloo B, Tezuka T. “The Role of Renewable Energy Resources in Sustainability of Water Desalination as a Potential Fresh-Water Source: An Updated Review.” *Sustainability*. 2020 June;12(13):5233.

2) Ahmadi E, McLellan B, Ogata S, Mohammadi-Ivatloo B, Tezuka T. “An Integrated Planning Framework for Sustainable Water and Energy Supply.” *Sustainability*. 2020 May;12(10):4295.

3) Ahmadi E, McLellan B, Tezuka T. “The Economic Synergies of Modelling the Renewable Energy-Water Nexus Towards Sustainability.” *Renewable Energy*. 2020 December; 162:1347-1366.

4) Ahmadi E, McLellan B, Ogata S, Tezuka T. “Integrated Planning of Sustainable Water and Energy Supply with Consideration of Social Equity.” *Energy Research & Social Science*. Under review.

② [Conference Papers]

5) Ahmadi E, McLellan B, Ogata S, Tezuka T. “Modelling the Water-Energy-Nexus to Assist the Design of Economic and Regulatory Support Instruments Towards Sustainability.” *Chemeca 2019: Chemical Engineering Megatrends and Elements*. 2019 Oct:550.

6) Ahmadi E, McLellan B, Ogata S, Tezuka T. “Technical Potential of Water-Energy-Nexus to Deployment of Renewable Electricity Resources: A Case Study of Iran.” エネルギーシステム・経済・環境コンファレンス講演論文集. 2019 Jan; 17(2).