Somayeh Asadi
Behnam Mohammadi-Ivatloo *Editors*

Food-Energy-Water Nexus Resilience and Sustainable Development

Decision-Making Methods, Planning, and Trade-Off Analysis

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Editors
Somayeh Asadi
Department of Architectural Engineering
Pennsylvania State University
University Park, PA, USA

Behnam Mohammadi-Ivatloo
Faculty of Electrical
and Computer Engineering
University of Tabriz
Tabriz, Iran

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Preface

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change have left us with no choice but to accelerate the world's transition to sustainability. In the coming decades, we are likely to see increasing pressure on the food, energy, and water (FEW) demands from increasing population and rising threat on the FEW supplies from climate change. As discussed in a recent report published by the International Renewable Energy Agency (IRENA), patterns of FEW systems are changing and the move to more sustainable supply systems may be inevitable. Increasing populations as well as resource scarcity challenge long-term FEW systems sustainability. Previously, many researchers had studied and analyzed sustainability across the FEW sectors in a fragmented and isolated way. Recent studies show that FEW systems are highly interconnected and improving system function while ensuring sustainability cannot be borne by research on food, energy, or water systems individually. More nexus-wide research is needed to pursue both understanding the behavior of FEW systems and developing technological enablers necessary to improve the system performance. This book provides recent advances and scientific practices for operation, design, and decision making of FEW nexus systems.

Chapter 1 uses the concept of climate, land, energy, and water (CLEW) nexus to study the electricity supply options in Lebanon. In this chapter, resource-efficiency assessment (REA) is used to evaluate the potential impacts of the electricity technologies on the nation's environmental and economic resources, and the sustainability performance assessment (SPA) is done. Then, the relative performance of each energy is calculated based on the results of REA and SPA by implementing the Aggregate Performance Index (API).

Chapter 2 provides an overview of the food, energy, and water (FEW). This chapter reviews each sector of FEW, availability, production, consumption, interaction, and interconnection between them and finally suggests some action to improve the operation of the FEW nexus. This chapter studies the opportunities to improve food, energy, and water security via the Nexus concept.

Chapter 3 deals with the assessment of water-energy-food nexus in Saudi Arabia. This chapter proposed a spatial-temporal decision support tool that analyzes energy requirements in the food sector. The tool was developed using a web-based Geographical Information System (GIS). It provides a web-mapping platform and helps users determine when and where they can grow crops based on the objective functions of water and energy requirements.

Chapter 4 presents an optimization-based framework to design an integrated palm oil based complex (POBC) with food-energy-water nexus (FEW) integrations. This chapter focuses on palm oil exporting countries such as Malaysia. A fuzzy multi-objective optimization model-based approach is proposed to find the planning of an optimum POBC with maximum satisfaction among economic advantage, food, energy, and water security.

Chapter 5 presents a solar-based combined power and desalination (CPD) system driven by the waste heat of Kalina cycle (KC) using the humidification-dehumidification (HDH) desalination system. The waste heat of KC is utilized as the main source of the HDH unit. Also, a compound parabolic collector (CPC) is designed as a source supply of KC.

Chapter 6 studies the biodiesel application for ignition engines from sustainability perspectives. The biodiesel derived from vegetable oils is called as first-generation biofuels. The biodiesel has lower volatility, lower heating value, and slightly higher viscosity. Hence, additives are added with biodiesel to enhance its fuel properties. The utilization of biodiesel in the compression ignition (CI) engine as fuel causes slightly lower thermal efficiency and lower carbon monoxide (CO) and hydrocarbon (HC). Various biodiesel production methods, biodiesel oxidation stability, modification required to use biodiesel in CI engine and dual-fuel engine, effect of biodiesel on engine components, engine performance, and emissions are comprehensively discussed in this chapter.

Chapter 7 studies the net-zero energy buildings (nZEB) with its home energy management system (HEMS). Real-time operation and protection approaches of nZEB are studied in this chapter. Different nZEB components such as solar photovoltaic (PV) array, home load demand, energy storage systems (ESS), electric vehicle (EV), and heat pump (HP) are modeled using data-driven approaches. Online control techniques, such as online scheduling, model predictive control (MPC), and stochastic dynamic programming (SDP), are presented and the protection methods investigated to increase the security of the system.

Chapter 8 studies the solar power potential as a sustainable energy resource in two different regions of Turkey. The analysis is performed to plan a photovoltaic system (PV) for maximal performance under climate circumstances in the country. A mathematical model of a photovoltaic system design under a set of circumstances is proposed to find the most efficient and appropriate panel choice under the environmental circumstances to obtain results closer to the PV system's actual ecologic circumstances.

Chapter 9 studies the nexus of food, energy, and water at a basin scale. This framework is applied to the Lake Urmia Basin in Iran to reveal the most important conflicts derived from food, energy, and water interdependencies. The necessity of using an integrated and comprehensive resource management strategy, such as the food-energy-water nexus approach, is discussed in this chapter.

Chapter 10 studies water-smart agriculture technologies and their impact on energy efficiency. It presents an approach to integrate real-time condition monitoring of soil and climate data through wireless sensor nodes that can enable the control system to achieve optimal scheduling of water actuation for high irrigation efficiency.

Chapter 11 computes the desirability of energy generation alternatives for Indonesia using a stochastic multi-criteria decision making (MCDM) framework. The applied evaluation model considers the trade-offs among independently managed yet interlinked energy systems and other interacting systems, namely, water, land, climate, and economy. The aggregate desirability of energy alternatives is determined for Indonesia as a whole and individually for its seven main Islands. The study indicates nuclear and geothermal to be among the desirable technologies, and biomass and hydropower are among the least desirable technologies for Indonesia.

Chapter 12 provides a comprehensive review of the operation and planning of zero-energy building (ZEB) and zero-water building (ZWB). The various existing net ZEBs and NZWBs frameworks, progress and implementations of the NZEB and NZWB, development policies for design and operation worldwide, the interrelationship between net ZEB and net ZWB, as well as study areas that have potential for developing net ZEBs and net ZWBs, are comprehensively discussed in this chapter.

Chapter 13 studies the food, energy, and water (FEW) nexus from sustainability perspectives. Different food crises are studied and the impact of food wastes on energy and water pollution is discussed in this chapter.

Chapter 14 aims to provide a stochastic programming approach to model the uncertain parameters of costs, available water and energy resources, and demands of energy and food in integrated modeling of FEW nexuses. In order to provide a practical insight into the presented optimization and make a tractable framework, ten probable scenarios are considered in the planning of the FEW nexus.

Chapter 15 provides a system of the systems approach to sustainable energy development in East Africa. The desirability of energy alternatives across East Africa across four vital systems, namely, economy, climate, land, and water are investigated. The Relative Aggregate Footprint (RAF) of different energy options in East Africa is measured with respect to the resource availability conditions of the countries in the region. The study results show geothermal and solar to be among the most desirable energy technologies for East Africa, while biomass and oil are the least desirable alternatives.

University Park, PA, USA — Somayeh Asadi
Tabriz, Iran — Behnam Mohammadi-Ivatloo

Contents

Chapter 1
A Multi-attribute Assessment of Electricity Supply Options in Lebanon

Romy Abou Farhat, Maral Mahlooji, Ludovic Gaudard, Jad El-Baba, Hassan Harajli, Vahakn Kabakian, and Kaveh Madani

1.1 Introduction

The rapid growth in energy demand leads to new challenges for governments. In growth-focused economic systems, decision-makers aim to guarantee the cheapest energy while often overlooking the impacts on future generations [20]. This has spurred deployment of fossil fuel technologies to meet booming energy demand due to population and income growth. These technologies consequently account for the largest contribution toward GHG emissions at a global scale [44, 56] and the main driver of depleting fossil fuel reserves [35], increasing global warming and energy insecurity. These challenges also represent opportunities to tackle economic growth, national stability, social development, and acceptable living standards through sustainable and green developments [52]. This calls for a transition from conventional energy supply systems toward new options.

R. A. Farhat
Enea Consulting, Paris, France

M. Mahlooji · L. Gaudard
Center for Environmental Policy, Imperial College London, London, UK
e-mail: maral.mahlooji12@ic.ac.uk

J. El-Baba · H. Harajli
United Nations Development Program, CEDRO Project, Beirut, Lebanon

V. Kabakian
Department of Mechanical Engineering, University of Bath, Bath, UK

Sustainable Energy Research Team (SERT), University of Bath, Bath, UK

K. Madani (✉)
Center for Environmental Policy, Imperial College London, London, UK

The MacMillan Center for International and Area Studies, Yale University, New Haven, CT, USA
e-mail: kaveh.madani@yale.edu

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In some parts of the world, energy planners have provided some incentives to deploy renewable energy to achieve sustainability goals [31, 49, 72]. However, such policies disregard the harmful impacts these new technologies might have on other valuable and competing resources. The sole focus on one aspect of the energy sector, such as carbon emissions, may prevent sustainable development if additional pressure is exerted on other resources including but not limited to land, water, the economy, the social environment, and the technical operation of energy systems [19, 23]. But, for sustainable development, energy planners should solve current problems without forming new ones.

Lebanon's power sector heavily relies on imported fossil fuels. Diesel and heavy fuel oils made up approximately 93% of total electricity generation in 2017, with six thermal plants (73%) and two offshore power barges (20%). Hydropower accounted for 3%, solar PV 0.35%, while the remaining 4% of electricity supply was imported from Syria [17]. The national utility, EDL, also faces a large shortfall in power capacity. In 2017, Lebanon's main grid controlled 2066 MW, while the demand was 2900 MW on average and peak demand was 3400 MW [17]. This gap represents a deficit in energy production of 1334 MW and had been exacerbated due to the ongoing Syrian refugee crisis that began in 2011 [17]. It causes structural blackouts ranging from 3 to 12 hours per day depending on regions in Lebanon [24, 47]. Private distributed diesel generators replace more than 85% of this missing supply, which have drastically been increasing pollution [67]. In 2017, a short-term Rescue Plan supported the country's principal national energy plan devised in 2010 in order to alleviate the country's energy security issues [17, 47]. The plan consists in installing another 825 MW of temporary power barges, 569 MW of Combined Cycle Gas Turbines (CCGT), and 831 MW of various renewable power sources (including large-scale and micro hydropower, onshore wind, solar photovoltaics, concentrated solar panels, bioenergy, and geothermal power) by 2020 [36]. In the medium term (2025), 2500 MW of conventional power plants are planned, while another 1000 MW of conventional power plants and 655 MW of renewable energy projects are expected in the longer term (2030+). This energy plan mainly aims to solve the country's energy production deficit; it does not directly offer solutions to mitigate or prevent other energy sustainability challenges from occurring.

Rescue Plan does not consider the water–energy nexus. Power deployment can compete with water, jeopardizing this resource [3, 21]. Energy generation life cycle requires water, which is becoming a scarce resource in Lebanon [46]. Irrigation has been reducing water availability, limiting the generation potential of Lebanon's five large-scale hydropower plants [48]. Frequent droughts and climate change aggravate the situation by reducing precipitations and increasing evapotranspiration [48]. In comparison to renewable energies, some conventional energies have lower water footprints and exert less pressure on the water resources. In contrast, water extraction, treatment, and distribution contribute to energy demand [39, 43]. The latter is also highly susceptible to impacts of climate change; for example, temperature increase will add to the cooling demand [15, 18].

Land availability and usage must also be considered in energy planning. For instance, biomass energy generation would become unsustainable if it competes with the land required for food production [7]. Installation locations also matter to limit environmental and social risk. Energy production can degrade biodiversity, ecosystem productivity, water quality, and affect soil erosion. It can hinder residential settlements at their proximities, thus exacerbating issues between the rising urban population and the shortage of local land availability [2].

Lebanon's coastal power plants have been endangering marine fauna and flora, public health, and coastal landscapes with the gaseous emissions and liquid wastes [45]. As a result, deterring the country's socio-environmental sustainability. On the other hand, energy sectors could reduce regional land if synergies are created with other sectors. For instance, valorizing abundant waste streams in Lebanon into energy can avoid the construction of land-intensive landfills and dumpsites, in a country with scarce land due to rising population densities and costs [34].

Urbanization, population growth, and climate change exacerbate competition between land, energy, and water resources. If the Climate–Land–Energy–Water (CLEW) nexus is not considered in policies, the long-term development of human well-being can be undermined [61]. Energy policies must consider trade-offs when it comes to building synergies across systems, improving socio-ecological sustainability of energy systems [28]. On average, 50% of the Lebanese spend 10% of their income on on-grid and backup power bills [24]. The energy sector, therefore, represents strong leverage to improving the socioeconomic conditions. It also represents a source of job creation [32]. In turn, social acceptance of energy technologies can determine the success of new power projects and the satisfaction of energy policy goals [14]. It is crucial to acknowledge the socioeconomic system and the CLEW nexus in energy decisions to develop practical and sustainable solutions with minimal secondary impacts on valuable resources [54, 59]. These issues underline the complexity of making sustainable decision in the energy sector.

Local resource availability conditions further complicate energy planning. Regional difference and variability of resources mean no global solutions exist. Local conditions and resource availability should be the basis of decisions [22, 55]. They should integrate the region-specific trade-offs between energy, natural, social, and economic systems.

A holistic system perception of local energy challenges may prevent policies to develop unexpected risks on the nations' sustainability. System of Systems (SoS) approach can provide such an assessment [37, 53]. SoS supports energy planners to understand the interactions between energy and other relevant systems, despite them being independently managed. It informs decision-makers in their attempts to mitigate climate change and the risk of unintended and irreparable secondary impacts across other systems [53].

Studies within the energy industry are now more focused on combining sustainability concerns and nexus approaches across SoS frameworks. Hadian and Madani, [38] established a quantitative SoS-based sustainability evaluation framework to consider the global desirability of various renewable and conventional energy alternatives with respect to the trade-offs between their water footprints, carbon footprints, land footprints, and cost of energy production. Ristic et al. [55] and Mahlooji et al. [42], respectively, analyzed the desirability of electricity generation alternatives in the European Union (EU) and Middle East and Nortth Afcrica

(MENA) with respect to the same four natural and economic indicators with consideration of regional resource availability.

This study applies a similar SoS approach as Ristic et al. [55] and Mahlooji et al. [42] to tackle energy planning in Lebanon, with additional consideration of local social dynamics. As the first attempt to study energy solutions in Lebanon through an SoS approach, this chapter identifies electricity generation alternatives that can support the nation in overcoming its most critical energy insecurity challenges while reducing impacts on its valuable natural, economic, and social resources.

1.2 Method and Data

This chapter uses two assessment approaches, each employing sets of decision-making criteria that address the most considerable energy sustainability issues and target levers that have a direct impact on the nation's scarcest resources. The first set, used in Resource Efficiency Assessment (REA), represents a set of criteria that help to evaluate the impacts of the 16 electricity supply technologies that together make up its current and planned energy mixes in Lebanon on the nation's economic and natural resources. Following Hadian and Madani [38], four resource-use performance criteria are considered (Table 1.1), namely, water consumption, land footprint, GHG emission, and Levelized Cost Of Electricity (LCOE). The second set of criteria (Table 1.2), used in the Sustainability Performance Assessment (SPA), represents the economic, environmental, societal, and technological considerations of energy planning in Lebanon.

Table 1.1 and Table 1.2 provide the collected data for REA and SPA, respectively. Data were collected from an extensive review of information in the literature, qualitative analyses, and surveys. Sources which covered a larger number of technologies were prioritized to reduce the number of references. This increases the consistency in the methods, hypotheses, and assumptions used by different studies for calculation of the performances. Consistency has been checked if data for the same indicator have been collected from different sources. Some values are presented in ranges, which indicates uncertainties in the performances due to geographical, technological, or other deviations across the nation or global scales. When available, the most up-to-date data specific to Lebanon were selected to provide an assessment that considers the current specificities of this country.

The SoS model of Hadian and Madani [38], used in this study, implements a Monte Carlo multi-criteria decision-making (MC-MCDM) approach [19, 40, 54] which evaluates the desirability of the 16 electricity supply alternatives in Lebanon with respect to their uncertain performance under a set of different criteria (Tables 1.1 and 1.2). The model used five different MCDM methods to add to the robustness of the ranking system and decrease the results' sensitivity to different notions of optimality [23, 38, 41]. These MCDM methods include lexicographic [65], simple additive weighting [6], maximin [68], dominance [13], and TOPSIS [74]. For more information on these methods, readers are referred to Madani et al. [37].

Table 1.1 Energy performance data for the Resource Efficiency Assessment (REA) framework *When performances are represented by two data points (minimum–maximum values)*, the entire range was considered. Some performances consist of minimum–median–maximum

Primary energy source	Electricity generation technology	LCOE** [USD/kWh]	Carbon footprint*** [kgCO_{2eq}/kWh]	Land footprint**** [km^2/TWhr] (Area of Direct Footprint)	Water consumption*** [m^3/MWh]
Light fuel oil (LFO)	Diesel generators	0.087–0.138 a	0.321 e	0.12–0.95 *f	0.54 e
	OCGT	0.045–0.095 a	1.050 e	0.12–0.95 *f	7.84 e
	CCGT	0.054–0.116 a	0.647 e	0.12–0.95 *f	3.61 e
Heavy fuel oil (HFO)	Steam plants (SP)	0.045–0.095 a	0.814 e	0.12–0.95 *f	91.84 e
	Floating barges	0.212–0.259 a	0.814 e	0	91.84 e
Natural gas	CCGT	0.025–0.400 a	0.417 e	0.12–0.95 *f	0.697 e
Hydropower	Hydroelectric power plants	0.023–0.400 a	0.015 e	6.45 – 16.86 – 86.95 *f	29.68 e
Solar energy	Utility solar photovoltaic (PV)	0.069–0.179 a	0.040 e	12.30 – 15.01 – 16.97 *f	2.95 e
	CSP with storage	0.165–0.295 a	0.009 – 0.027 – 0.063 *b	12.97 – 19.25 – 27.96 *f	32.78–605.56 *d
	CSP without storage	0.233–0.296 a	0.009 – 0.027 – 0.063 *b	12.97 – 19.25 – 27.96 *f	32.78–605.56 *d
Waste and biomass residues	Landfill gas recovery	0.055–0.166 a	0.110–0.140 *g	38.00–77.00 t	0.22–5.17 *d
	Waste combustion plants	0.093–0.191 a	0.140–0.350 *g	0.09–0.39 *u	0.22–5.17 *d
Wind energy	Onshore wind turbines	0.069–0.150 a	0.019 e	0.34 – 1.31 – 1.37 *f	0.42 e
	Offshore wind turbines	0.094–0.217 a	0.019 e	0	0.42 e
Geothermal energy	Hydrothermal power plants	0.028–0.101 a	0.060 e	2.14 – 5.14 – 10.96 *f	13.55 e

(continued)

Table 1.1 (continued)

Primary energy source	Electricity generation technology	LCOE** [USD/kWh]	Carbon footprint*** [$kgCO_{2eq}$/kWh]	Land footprint**** [km^2/TWhr] (Area of Direct Footprint)	Water consumption*** [m^3/MWh]
Nuclear energy	Nuclear power plants	0.031–0.087 a	0.004 – 0.012 – 0.110 *b	0.02 – 0.13 – 0.24 *f	5.00–402.78 *d

OCGT open cycle gas turbine, *CCGT* combined cycle gas turbine, *CSP* concentrated solar panels
a: LCOEs computed specifically for this paper (using a 10% discount rate)
b: Schlomer et al. [56]
c: Arif and Doumani [1]
d: Mekonnen, Gerbens-Leenes and Hoekstra [43]
e: Life Cycle Assessment (LCA) results developed specifically for this paper
f: Trainor, McDonald and Fargione [64]
g: World Energy Resources [73]
* Not specific to Lebanon
** The levelised cost of energy (LCOE) of each technology was calculated based on the financial indicators and capacity factors of the SPA (Table 1.2) and with adiscount rate of 10%.
*** Carbon and water footprints were estimated for this study by the authors using the SimaPro life cycle assessment software (V8.3.0) based on the Ecoinvent 3.1 database. The impact assessment method used is ReCiPe Midpoint (E) V1.12 / World Recipe E. Carbon footprint was calculated using IPCC 2013 GWP 100a V1.01 method.
**** Land footprints have been assumed to be the directly impacted area.

Table 1.2 Energy performance data for the Sustainability Performance Assessment (SPA) framework

		Economic criteria				Environmental criteria			Technical criteria			Social criteria	
Primary energy	Energy conversion technology	Capital cost [$/kW]	Fixed O&M [$/MW/y]	Variable O&M [$/MW/y]	Fuel cost [$/MWh]	Carbon footprint [$kgCO_{2eq}$/kWh]	Land footprint [km^2/TWhr]	Water consumption [m^3/MWh]	Efficiency [%]	Flexibility of dispatch [%]	Capacity factor [%]	Social acceptance [0–100]	Employment [jobs/MW]
Light fuel oil	Diesel generators	253–790 h	28,000 k	5000 k	44.31–78.97–102.84 p	0.321 e	0.12–0.95 *f	0.54 e	37 r	100 *n	31 r	32.16**	2.78 *v
	OCGT	1101*g	31,570–33,820 q	10,680–12,930 q	44.31–78.97–102.84 p	1.050 e	0.12–0.95 *f	7.84 e	38 r	100 *n	54 r	39.83**	2.78 *v
	CCGT	627–1289 *b	29,041–29,975 q	17,225–18,159 q	44.31–78.97–102.84 p	0.647 e	0.12–0.95 *f	3.60 e	44 r	100 *n	83 r	41.77**	2.78 *v
Heavy fuel oil	Steam plants	1100 i	47,180–51,224 q	16,176–20,220 q	16.3–50.26–70.24 p	0.814 e	0.12–0.95 *f	91.84 e	39 r	100 *n	62 r	32.94**	2.78 *v
	Floating barges	0	1,370,000 w	0 *q	16.3–50.26–70.24 p	0.814 e	0	91.84 e	39 r	100 *n	62 r	38.83**	2.78 *v
Natural gas	CCGT	627–1289 *b	29,041–29,975 q	5125–6059 q	14.27–26.02–44.85 p	0.417 e	0.12–0.95 *f	0.70 e	59.7 r	100 *n	89 r	56.88**	2.78 *v
Hydropower	Hydroelectric power plants	598–8687 *b	57,200–71,500 o	18,921–20,139*q	0	0.015 e	6.45–16.86–86.95 *f	29.68 e	90–95 r	30 *n	25–63 r	75.50**	7.80–17.00 –22.90 *s

(continued)

Table 1.2 (continued)

		Economic criteria				Environmental criteria			Technical criteria			Social criteria	
Primary energy	Energy conversion technology	Capital cost [$/kW]	Fixed O&M [$/MW/y]	Variable O&M [$/MW/y]	Fuel cost [$/MWh]	Carbon footprint [$kgCO_{2eq}$/kWh]	Land footprint [km^2/TWhr]	Water consumption [m^3/MWh]	Efficiency [%]	Flexibility of dispatch [%]	Capacity factor [%]	Social acceptance [0–100]	Employment [jobs/MW]
Solar energy	Utility-scale solar PV	937–2563 *b	29,400 q	0*q	0	0.040 e	12.30–15.01–16.97 *f	2.95 e	10–20 r	0 *n	20 r	84.22**	18.20–33.60–69.80 *s
	CSP with storage	7100–9800 *a	48,790–56,790 *q	11,680 *q	0	0.009–0.027–0.063*b	12.97–19.25–27.96 *f	32.78–605.56 *d	14–20 *o	50 *n	40–53 *o	81.72**	7.60–20.80–36.50 *s
	CSP without storage	4600 *a	48,790–56,790 *q	11,680 *q	0	0.009–0.027–0.063 *b	12.97–19.25–27.96 *f	32.78–605.56 *d	14–20 *o	0 *n	20–25 *o	81.72**	7.60–20.80–36.50 *s
Waste and biomass residues	Landfill gas recovery	1540–2470 *j	169,400–494,000 *o	20,017–28,023 *l	9.9–22 *o	0.110–0.140 *u	38.00–77.00 t	0.22–5.17 *d	25–36 *o	50 *n	60–90 *j	67.83**	13.20 *s
	Energy from waste combus-tion plants	2000–5400–7770 *j	410,320 *l	18,415–20,017 *l	16.20–29.52 *o	0.140–0.350 *u	0.09–0.39 *u	0.22–5.17 *d	23–25 *o	50 *n	80–85 *j	67.83**	13.20 *s
Wind energy	Onshore wind turbines	1200–2990 *b	31,221–44,800 q	0–13,579 q	0	0.019 e	0.34–1.31–1.37 *f	0.42 e	35–44 *q	0 *n	27 r	77.16**	6.50–12.88–27.70 *s
	Offshore wind turbines	3700–5933 *b	15,630–130,420 *o	0–58,411 q	0	0.019 e	0	0.42 e	36–45 *q	0 *n	40–48 *q	81.44**	18.30 *s
Geothermal energy	Hydrothermal power plants	1500–6625 *b	86,190–184,340 *o	0 *q	0 *q	0.060 e	2.14–5.14–10.96 *f	13.55 e	12 *m	30 *n	87–95 *q	65.55**	7.23–11.10 *s

Nuclear energy	Nuclear power plants	1800–6215 *b	70,060–93,770 *q	1416–5694 *q	2.66–3.13 *b	0.004–0.012–0.110 *b	0.02–0.13–0.24 *f	5.00–402.78 *d	33 *q	10 *n	89–90 *q	51.38**	16.55 *v

a: The Guardian [62]
b: IEA [29]
c: Bouri, Elie; El Assaad [4]
d: Mekonnen, Gerbens-Leenes and Hoekstra [43]
e: LCA results developed specifically for this paper
f: Trainor, McDonald and Fargione [64]
g: EIA [10]
h: Torrero [63]
i: Business News [5]
j: Word Energy Council [72]
k: Ghaddar machinery, local PG manufacturer
l: EIA [11]
m: Zarrouk and Moon [75]
n: Hirschberg et al. [25]
o: IRENA [30]
p: EIA [9]
q: NREL [51]
r: Kabakian [33]
s: IRENA [32]
t: Arif and Doumani [1]
u: World Energy Resources [73]
v: Rutovitz and Disclaimer [56]
*Not specific to Lebanon
**Qualitative indicators derived from a survey that evaluated the social acceptance of the studied energy technologies by people who live or lived in Lebanon. Out of the 73 participants, more than 70% were 18–34 years old, students or employed, 50% were from Beirut, and 70% were male. Most of the respondents declared to have moderate to advanced knowledge of power systems and electricity-generating options, implying that social acceptance results reflect a well-resourced and knowledgeable pool of respondents. Their awareness can be declared as moderately to well aware of the current situation of the Lebanese electricity system, which shows to what extent the current electricity situation affects the public. All participants rated each technology based on how they perceive its noise level, visual impacts, health and safety, and reliability to be and how tolerant they are of it being in the proximities of their dwellings. The respondents' overall level of acceptance toward each technology is displayed in this table

The applied model accounts for the performance uncertainties by performing a Monte Carlo selection. In each of the 300,000 selection rounds, random values are generated from the ranges in performance values, if existent (Tables 1.1 and 1.2). In contrast to Hadian and Madani [38], who considered uniform probability distributions for Monte Carlo selection, this study assumes a truncated normal distribution when the median is close to the mean or a log-normal distribution when median differs from the mean significantly, following the same approach as Ristic et al. [55]. This reduces the biases of skewed distributions. For example, the land footprint of hydroelectric plants has a long-tailed range. Using a uniform distribution would result in a median that is significantly bigger and might unfairly penalize this technology. Once the MC-MCDM rankings under each MCDM method are determined, the aggregate performance index (API) is used to calculate the overall performance value of each energy technology relative to one another under each assessment method. API [54] sums the ranks of an energy technology attained under each MCDM framework by utilizing the following equation:

$$\mathrm{API}_i = 100 \times \left(\frac{C \times N - B_i}{N(C-1)} \right) \tag{1.1}$$

where C is the number of alternatives, N is the number of MCDM methods, and B_i is the sum of the scores (ranks) given to each energy alternative i by different MCDM methods. The index values range from 0, i.e., absolute worst relative performance, to 100, i.e., absolute best relative performance. For further details on the SoS modeling approach applied in this chapter, readers are referred to as Hadian and Madani, [38] and Ristic et al. [55].

1.2.1 Weights Assigned to REA's Indicators

The natural and economic resource availability of a region can greatly influence the relative desirability of electricity supply alternatives within the region. For instance, given Lebanon's increasing water scarcity, highly water-consumptive energy options might not be really desirable for the country. To support this premise, the four REA criteria must be weighed with respect to the regional resource availability (or use intensity) [22, 55]. Here, Lebanon's carbon emission per capita [69], freshwater withdrawal as a percentage of total renewable water resources [70], available land per capita [71], and GDP with purchasing power parity (PPP) [71] were used as the basis for criteria weighting.

Following Ristic et al. [55] and Mahlooji et al. [42], to calculate the weight, the country's position within a worldwide benchmark is considered under each indicator. The benchmark values are split into five 20th percentile ranges. Each percentile group is given a score from 1 (presenting nations with the largest resource availability) to 5 (presenting nations with the lowest resource availability), reflecting the desirability of resources for a country. The relative weight of each criterion is then normalized with respect to the sum of the scores across the four criteria.

It is worth noting that the performance of GDP PPP and available land areas are evaluated relative to a reversed scale in comparison to water withdrawal and carbon emission. For example, the lower the freshwater withdrawal of a country, the lower the water use to availability ratio of the nation. This means lower weight is assigned to water resources and energy technologies with higher water use have higher desirability. In contrast, the lower the GDP PPP, the less the economic power a country would have, thus a higher weight will be assigned to economic cost. This means that the country has to reduce the share of capital intensive alternatives as their undesirability increases. Figure 1.1 illustrates the performance of Lebanon under the weighting criteria considered here with respect to the global benchmarks.

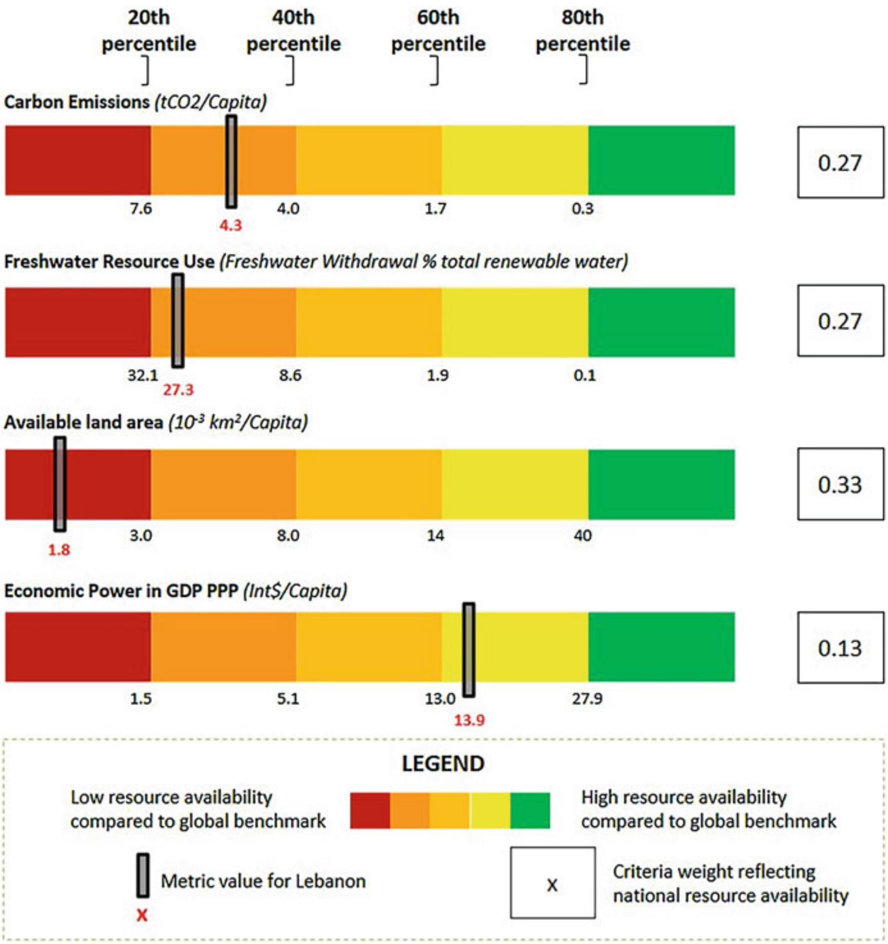


Fig. 1.1 Resource availability across Lebanon relative to the global benchmark and the associated criteria weights for REA

1.2.2 Weights Assigned to SPA's Indicators

A sustainable electricity supply technology would contribute to mitigating the nation's most important existing and future energy issues. Thus, each of the considered 12 sustainability criteria (Table 1.2) and their respective impacted systems (economic, environmental, technical, and social) are attributed weights in accordance to their performance with respect to the energy sustainability challenges they each portray. Consumers at both industrial and domestic levels, private diesel generator companies, and fuel supplier firms were interviewed and used in the prioritizing the energy challenges in this research. Using their input, indicator weights were determined to balance conflicting priorities, improve social acceptance, and ensure buy-in of decision-makers.

A two-level Analytical Hierarchy Process (AHP) MCDM model [60] incorporated the judgments of nine governmental representatives, seven target groups (industrial, private power generator, and fuel companies), and 12 influencers (academia and environmental NGOs). They were contacted with information on the study, definition, and explanation of the 12 sustainability criteria, along with a justification of their association and role to Lebanon's energy sustainability challenges. The AHP method then evaluated each stakeholder's viewpoint of the relative impact of 1) the higher level sustainability dimensions among each other and 2) the 12 lower level criteria. Each stakeholder's response contributed equally to the final weights. Figures 1.2 and 1.3 show the resulting weights.

All three groups ranked fuel cost as the most important criterion and the economy as the most impacted system. This reflects the significant detriment that expensive oil

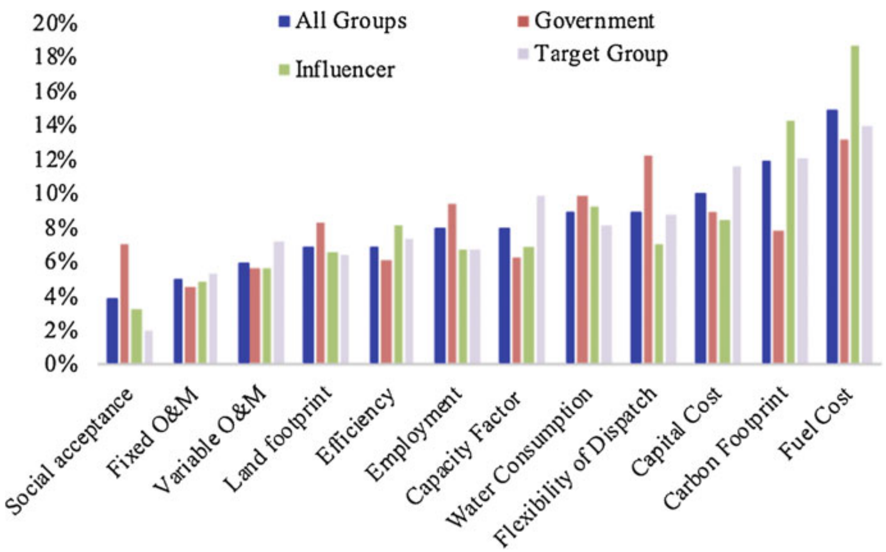


Fig. 1.2 Weights reflecting the stakeholder groups' viewpoints of sustainability priorities

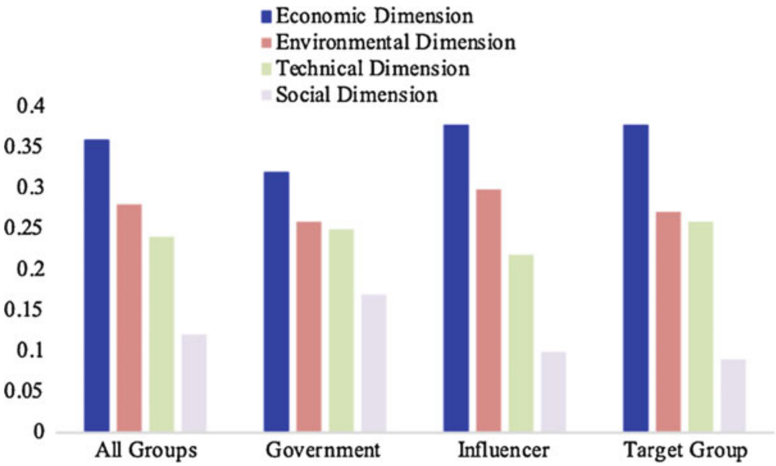
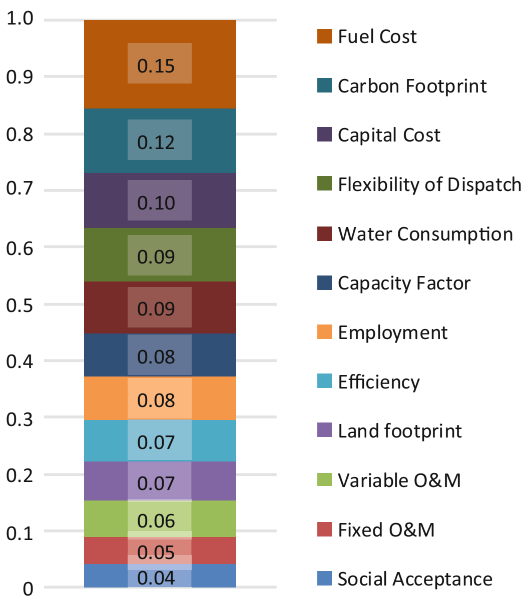


Fig. 1.3 Weights reflecting the stakeholders' viewpoint of the most impacted systems by the Lebanese electricity sector

Fig. 1.4 Final indicator weights for SPA based on stakeholders' inputs



has on Lebanon's economy, a region where 93% of its electricity generation mix relies on imported fuel and dwelling's private backup generators [36]. A significant amount of government subsidies are handed yearly to EDL, reaching between $1 and 2 billion yearly, depending on the price of oil, absorbing 2–6% of the country's GDP [12]. This, in turn, has lowered the social acceptance of oil-based generation. Other criteria weights tend to slightly vary across the groups of stakeholders. Figure 1.4 presents the final weight used in the SPA. These were computed by multiplying the average of each lower level weight determined by the stakeholders by the average of their higher level weights.

1.3 Results

1.3.1 Aggregate Performance of Electricity Generation Technologies Under the REA Framework

Figure 1.5 illustrates the outcomes of the four indicator-based REA. The ranking is based on country-specific weights reflecting Lebanon's resource availability. Once more, the higher the API score, the higher the efficiency (desirability) of the technology is in its use of Lebanon's resources for energy production.

Figure 1.5 demonstrates that no relative ultimate best (score = 100) or worst (score = 0) energy technology option exists for Lebanon. The low land footprint of waste combustion technologies and offshore wind and the high land footprint of CSP and onshore wind, together with the low land resource availability in the country, lead to their high and low desirability across Lebanon. CSP and onshore wind can, therefore, have long-term impacts on local resources. Steam plants, OCGTs, and floating barges stand among the least desirable alternatives. Interestingly, even with their assumed null land footprints, floating barges have an undesirable performance. On top of their high water and carbon footprints, their significantly high LCOE means there is a high economic drain of the national budget that can be expected. As

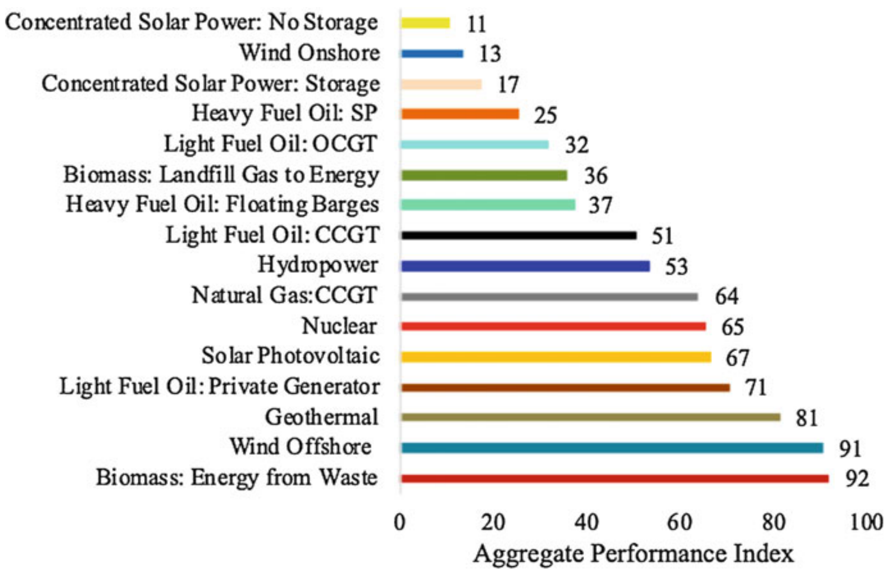


Fig. 1.5 REA scores of electricity supply alternatives for Lebanon

they make up a large share of current and planned energy mixes, this SoS evaluation demonstrates their undesirable effect on the nation's economic and carbon resources. However, full objection to fossil fuel may not be optimal at this stage of Lebanon's development, as natural gas and private light fuel oil have relatively high performances. Thus, they might be included in a resource-use efficient energy mix for Lebanon in the future.

1.3.2 Aggregate Performance of Electricity Generation Technologies Under the SPA Framework

Figure 1.6 shows the SPA results when weights are assigned to the 12 considered indicators. Lower/higher API of technology reflects its lower/higher desirability in overcoming Lebanon's energy sustainability challenges. Based on this figure, no relatively absolute best (score = 100) or worst (score = 0) energy technologies exist for Lebanon. Non-fossil-fuelled energy sources tend to be desirable, except for CSP technologies and waste-based technologies. The former performs weakly across the environmental, economic, and technical dimensions. Waste to energy's relatively low performance stems from its high economic impacts in a country where the energy sector absorbs a large portion of the GDP. Landfill to energy's even lower performance is rooted in its very high land footprint and relatively high O&M costs. In parallel, all fossil fuel technologies are undesirable, except for the lower

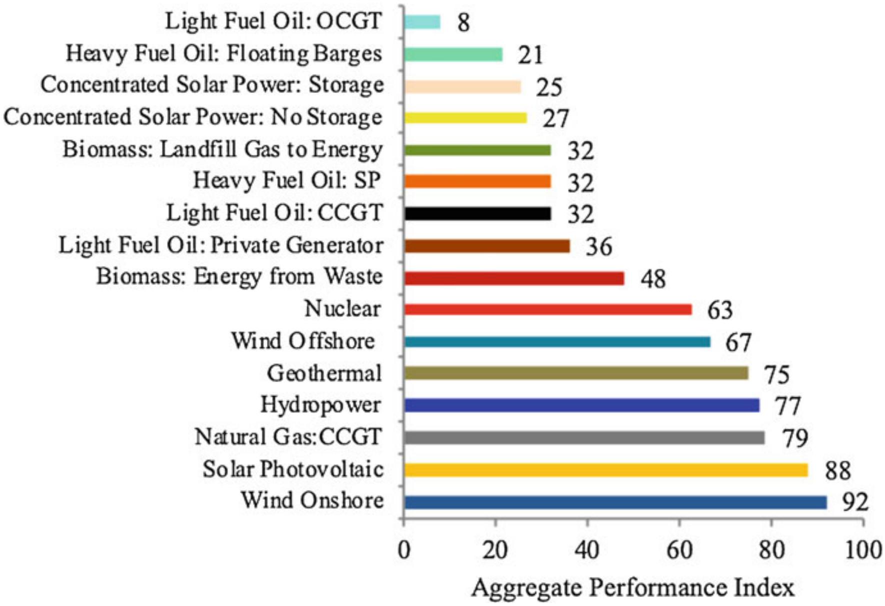


Fig. 1.6 SPA scores of electricity supply alternatives for Lebanon

carbon-emitting natural gas. Oil-based energy options signify the biggest share of Lebanon's current energy mix and future national energy plans, which can jeopardize Lebanon's energy sustainability and security.

In comparison to the REA framework, hydropower's desirability increases when social dynamics, technical performance, and local stakeholders' perspectives are taken into account. The SPA rewards its high technical performance in comparison to other renewable technologies, namely, its higher capacity factor and flexibility of dispatch. It has also no fuel costs and the low-carbon emission value (based on the life cycle calculations and assumptions here). These four criteria are also assigned the highest assigned weights in this framework.

A more desirable portfolio includes high shares of onshore wind, solar photovoltaic, natural gas CCGT, hydropower and geothermal, and minimal shares of light fuel oil OCGT, floating barges, and CSP technologies. Recent research has shown that the carbon emissions of hydropower might be higher than perceived [8]. In that case, the desirability of hydropower would be lower in Lebanon.

To appreciate the impact of national priorities and energy plan's objectives in the determination of how the desirability of energy sources vary, five weighting sensitivity analysis scenarios are used, each having different criteria weights as shown in Table 1.3. Four scenarios represent energy plans that prioritize the economic, environmental, technical, or social dimension, respectively. The last case represents a plan where equal priorities are given to each dimension. For the first four sensitivity cases, weights are set in such a way that the prioritized dimension's criteria would receive 80% of total weights (equally weighted), with the rest 20% distributed equally among the other criteria.

Here, the least-cost energy plan exposes traditional energy plans that focused on implementing the cheapest energy alternatives with a mix, regardless of their impacts on the environment or society. Environmental plans represent the emerging plans to mitigate energy sectors' impacts on global warming, natural resource depletion, and air pollution. Technical plans reflect the plans that focus on deploying the most efficient energy technologies and most optimal energy systems that can balance supply and demand at all time. Social energy plans represent the plans that drive employment and social well-being.

Figure 1.7 shows the impact of shifts in energy plan objectives on the desirability of electricity generation technology. In general, renewable energy becomes undesirable in a technical energy plan because of their relatively low efficiency, capacity factor, or high intermittency [16, 50], leaving a way to more flexible and reliable fossil fuels with more mature technologies. Innovation in these three factors would enhance their desirability. Implementation of a storage facility may also temper the situation, as observed with CSP. However, this would be costly. In contrast, renewables are all desirable in the social plan, thanks to large public acceptance. All fossil-fuel-based technologies suffer from public disapproval and low level of employment as jobs are being increasingly allocated to the "green" energy sector leading to their low performance in the social scenario [32]. All renewables are relatively desirable in the environmental scenario, contrary to land- and water-intensive CSP technologies.

Table 1.3 Assigned indicator weights for the sensitivity analysis scenarios analyzed for SPA (bolded figures represent the highest indicator weights in each sensitivity scenario)

	Economic criteria				Environmental criteria			Technological criteria			Social criteria	
Scenarios analyzed	Capital Cost	Fixed O&M	Variable O&M	Fuel cost	Carbon footprint	Land footprint	Water consumption	Efficiency	Flexibility of dispatch	Capacity factor	Social acceptance	Employment
Least-cost plan	**0.20**	**0.20**	**0.20**	**0.20**	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Environmental plan	0.02	0.02	0.02	0.02	**0.26**	**0.26**	**0.26**	0.02	0.02	0.02	0.02	0.02
Technical plan	0.02	0.02	0.02	0.02	0.02	0.02	0.02	**0.26**	**0.26**	**0.26**	0.02	0.02
Social plan	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	**0.37**	**0.37**
Equal priority plan	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**

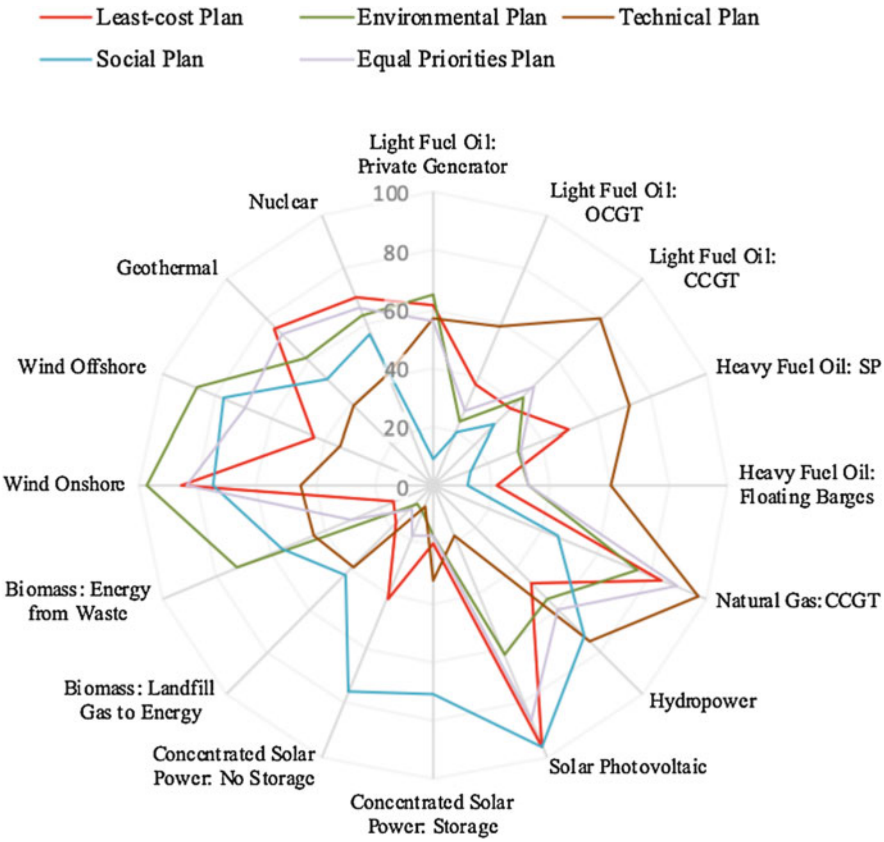


Fig. 1.7 Desirability of different energy generation options under different sensitivity analysis scenarios. The center point indicates an API of 0 (less desirable), the edge returns a score of 100 (more desirable)

Based on the numbers used in this study (Table 1.2), even the least-cost energy plan (scenario) gives privilege to natural gas CCGT, geothermal, onshore wind, and solar PV. The reason behind this is the poor performance of the oil-fired energy options, which form the highest share of the current portfolio, due to high O&M and fuel costs. Floating barges do not offer a better alternative because of their drastically higher fuel costs and fixed O&M. On the other hand, CSP and waste combustion technologies are even worse, as their capital and O&M costs are high. However, these new technologies can still expect technological and operational improvements.

The equal priority plan gives equal significance to the most and least pressing energy-related issues in Lebanon. Private diesel generators are more desirable in this plan than in the assessment done by the stakeholders. The difference between the results implies that this technology would become undesirable when the country's energy challenges are considered more carefully, underlining the importance of considering local characteristics and dynamics in devising energy plans. Solar PV, natural gas, and wind technologies have robust desirability as they have the highest APIs both when regarding and disregarding local characteristics, respectively, in the stakeholder assessment and in this scenario.

1.4 Discussion

1.4.1 Variations Between API Scores Under the REA and SPA Frameworks

The Lebanese energy transition must overcome current energy challenges while averting undesired secondary impacts of energy development on society and valuable natural and economic resources. Lebanon needs an energy mix which is resource-use efficient and at the same time, it is simultaneously resilient against current and future energy challenges.

Figure 1.8 illustrates the differences in the desirability of electricity supply alternatives in REA and SPA. Rankings of the energy alternatives differ under the two frameworks considered. This reflects the impact of the considered criteria and performance information on the desirability of energies. The difference also shows that the energy that might be desirable from the resource efficiency standpoint might not be desirable when some other criteria (e.g., social) are brought into the decision-making.

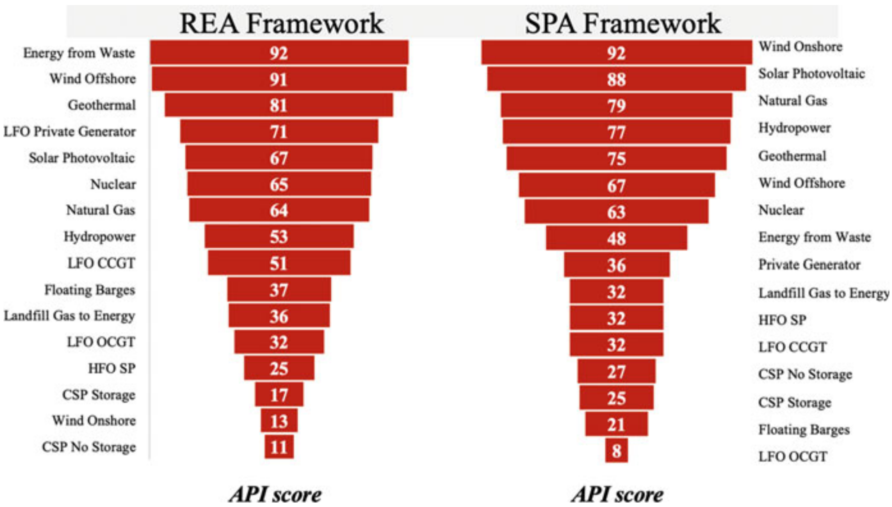


Fig. 1.8 Differences in ranks, trends, and desirability of energy technologies under the SPA and REA frameworks

As shown in Fig. 1.8, some technologies saw their ranks strongly change from one framework to another, underlying the required areas for improvement in performances. Strikingly, the rank of onshore wind was strongly penalized in the REA assessment in comparison to SPA as a result of its large land footprint. This criterion was assigned the highest weight under REA, reflecting the country's scarce land resources. Due to its low carbon, energy plans are now more focused on expanding its exploitation. Nevertheless, large-scale penetration of this energy might result in it aggravating local land availability challenges as well as ecological and landscape impacts, which emphases the need to develop energy deployment plans more carefully until technical improvements arise.

Including social dynamics, technical performances, and stakeholder perspectives into the SPA have penalized ranks of the fossil fuel technologies that make up the country's current energy mix while making natural gas more desirable. The three added dimensions have also put waste-based technologies at a disadvantage, highlighting the need to improve their social impacts, high O&M costs, and technical efficiencies.

Results demonstrate that the inclusion of social elements in the SPA has a major influence on the overall desirability. Indeed, the poor social perception of waste, the expensive blackout of diesel generation, and the low job creation potential and low performance of the current oil-based mix penalized their ranks in the SPA in comparison to the REA. Moreover, the energy system cannot overlook technical issues. Managing intermittent renewable energy is challenging and that penalizes the aggregate performance of these technologies in the SPA.

Among the medium to highly desirable technologies in both frameworks (Fig. 1.8) stand offshore wind, solar PV, geothermal, natural gas, nuclear, and hydropower. This reflects their robustness against worsening local energy challenges and depleting scare local resources, therefore their high desirability for a resource-efficient and sustainable energy future in Lebanon.

The substitution of oil with the more desirable natural gas option can be leverage to shift to a sustainable energy future due to a simpler conversion of existing oil-powered plants. If important quantities of natural gas were to ever be drilled from Lebanon's identified 122 trillion cubic feet offshore reserves [57], investments into gas terminals and an extensive gas transport and supply infrastructure can be attractive. It can both facilitate the expansion of the sector and enable the introduction of hydrogen and power to gas sectors in a longer term.

If managed properly and securely, nuclear is a relatively desirable energy option to alleviate Lebanon's power shortages challenges, satisfy its decarbonization goals, and improve its sustainability and resource-use efficiency. It can be considered when, or if ever, Lebanon experiences a stable and secure economic and political environment to reduce safety risks, planning time, and consequently improve social acceptance.

Some desirable renewable energy technologies are still at the lowest of their readiness level for large-scale deployment. For geothermal power in particular, and as per the recommendations of the Geothermal Power Assessment of Lebanon [66], a few demonstration projects in the key identified hot spots are required to further validate the potential of this resource, determine its full capacity for power contributions, and contribute to its production cost reductions. Investments in utility-scale solar PV can reduce impacts on water and climate resources while creating employment opportunities and promoting social well-being. It can further improve energy security and independence from imported fuel. While hydropower seems desirable for Lebanon, land-intensive large-scale hydropower can disturb local ecosystems and negatively impact scarce water resources. Existing hydropower plants could be rehabilitated, and small-hydro projects could be developed to avoid extra-economic and environmental costs of new large-scale projects.

The technologies that lie within the medium to low API categories in both frameworks (Fig. 1.8) portray options that are unsustainable and inappropriate for a Lebanese energy future based on the assumptions used in this study and current state of technology. These include HFO steam plants, OCGTs, CSP technologies, and landfill gas to energy technologies. This implies the need to steer away from the first two technologies in Lebanon's energy mix. Also, foregoing the targets on the other two energies in Lebanon's future energy plans could be beneficial for the nation, until technological improvements render these technologies more resource-use efficient. However, one must note that forming synergies between the energy and waste sectors could improve mutual benefits in tackling Lebanon's energy and waste disasters. Although results have demonstrated the low desirability of land-intensive landfills, policies may consider restricting the development of new landfills but encouraging energy valorization in existing ones while improving social perception.

New policies, policy reforms, and subsidized incentive mechanisms—i.e., Feed-in tariffs—that support the identified desirable renewable energy technologies are recommended. Creating the ripe environment for investments in these technologies and the involvement of the private sector through public–private partnerships can lead to more effective integration of these energy systems. Investing in the grid infrastructure to cater for the "paradigm" shift toward distributed low-carbon power generation and distribution and creating the long-term, stable, and transparent legal environment will assist in lowering the long-term power purchasing prices of these technologies [33]. The latter could further be improved through securing long-term guarantees and soft financing from international financial institutions to counter political risks in Lebanon.

1.4.2 Limitations

The study develops conclusions to support and guide energy decision-makings in Lebanon and highlights the importance of a holistic approach in energy assessments. Similar to other models, the nexus frameworks used in this study have limitations that can be tackled in the future. Further research could concentrate on expanding the SoS applications in Lebanon's energy desirability studies to include both the targets and the demand-side considerations [49] in the analysis. Future research could as well not be limited to utility-scale technology options but include decentralized options and consider electricity sector reforms such as deregulation or feed-in tariffs as a necessary requirement for greater renewable energy penetration.

The framework utilized in this chapter considers each technology independently. The outcomes demonstrate that while desirability matters, there is no "one ultimate" technology that can become the solution to a sustainable electricity mix. Instead, the results call for a diversified energy portfolio where a range of alternatives are selected based on their desirability against the local resource conditions of each country [22]. The decarbonization targets of Lebanon call for disregarding the rich fossil fuels reserves of the country, while the impacts of renewables on other valuable resources should not be overlooked for the purpose of reducing emissions. Thus, an electricity mix is needed with varying contributions from both renewables and conventional sources based on their desirability. In future studies, feasibility could also be taken into consideration following the desirability assessment. If a technology is desirable but not readily available, then it simply cannot become part of a diversified portfolio of a country. Transition pathways can also be considered in future studies. The dynamics of energy development is complex and can be very political. Therefore, a detailed transition pathway to a more sustainable mix is needed that considers the practical complexities of energy adoption and reforms. Transition analysis helps capture deployment limitations of energy options and consequently convey the impact of sustainable alternatives on the energy system more extensively.

Results are highly sensitive to the input variables. The selection of indicators and weighting systems are to some extent subjective, and performance data can differ among sources or might be computed according to a subjective method when data are lacking. Thus, the results are by no means certain. But they provide very valuable insights.

Land footprint has been taken as the "area of direct impact" in this study, portraying the direct footprint, i.e., the area directly impacted by the technology. Another land use indicator, the "landscape level indicator," represents the total area needed, as a "*conservative indicator of the area experiencing ecological impacts, which can extend beyond the project boundary of any particular energy development*" [64], in line with the concept of the life cycle-based energy production impact of this study. Additionally, water calculations in this study consider only water use (mainly blue water) which differ from water footprint, considered to be the total amount of freshwater used for the production of various products [26, 27, 39]. Future studies could also evaluate technology desirability relatively to life cycle-based indicators as to account for additional ecological footprint of land, water, and carbon impacts. Future research could also try to incorporate the unaccounted practical limitations such as baseload supplies, storage abilities, available fuels, and needs for optimal system operation across a range of technologies.

1.5 Conclusion

The study has generated unique sets of results based on two parallel System of Systems (SoS) frameworks—the Resource Efficiency Assessment (REA) and the Sustainability Performance Assessment (SPA)—that together try to provide insights into sustainable energy development in Lebanon. While they demonstrate that not all renewables can be considered as equally "green", outcomes offer insight into determining the optimal sustainable energy mix of renewable and nonrenewable electricity-generating alternatives. The results also revealed the policies and technologies that can potentially lead to secondary impacts and unintended consequences.

For an energy transition that resolves current energy challenges while averting undesired impacts on valuable economic and natural resources, Lebanon could:

- Adopt desirable offshore wind, geothermal, and solar PV while apprehending trends in global technological improvements;
- Consider the desirability of nuclear energy and incorporate it only conditionally to management with high security, transparent decision-making, improved social acceptance, and appeasement of political deadlocks;
- Rehabilitate existing hydropower plants and develop small hydropower projects while avoiding the construction of new large hydropower reservoirs;
- Steer away from its current oil-based generations, namely, its light fuel oil OCGTs and CCGTs and heavy fuel oil floating barges and steam plants, and gradually substitute them with natural gas and more desirable renewable energies;
- Forgo the development of immature renewable energy technologies that can have significant unintended consequences until technological developments portray these technologies to be more desirable;
- Form synergies with the waste sector to enhance social acceptance of waste, valorize energy solely from existing landfills, and consider energy from waste options.

Caveat Parts of this chapter have been reproduced from a master's dissertation report of Romy Abou Farhat at Imperial College London.

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Chapter 2
Introduction to FEW Nexus

Amir Lotfi, Behnam Mohammadi-Ivatloo, and Somayeh Asadi

2.1 Introduction to FEW Nexus

Human beings have consumed food, energy, and water for over 10,000 years in separate. They have traded food for over 3000 years. In recent decades, humans have faced the consequences of separate natural resource consumption which affected water, atmosphere, and biodiversity [1].

Food, energy, and water (FEW) are inextricably connected, which is called "Nexus" [2]. "Nexus" is defined as "a link or links, connecting two or more sectors". This means FEW Nexus is applicable to different connections such as water-energy, energy-food, food-water, and food-energy-water [3, 4].

It is being noticed that sector-by-sector policy must be put aside and an approach that considers the interactions between food, water, and energy mush be put to use [2, 4]. Food, energy, and water Nexus tries to achieve better food security, better water access, and a grown supply of energy [5]. Moreover, trade-offs and synergies must be taken into account while implementing the Nexus approach [2]. Recognizing FEW interconnection and interdependence is important because global resource estimation reveals that the need for FEW sources will increase in the next decades due to alteration in climate, reformation in culture and technology, increase in population and economic expansion (Fig. 2.1) [6].

A. Lotfi (✉)
Electrical Engineering Department, Sharif University of Technology, Tehran, Iran

B. Mohammadi-Ivatloo
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: bmohammadi@tabrizu.ac.ir

S. Asadi
Department of Architectural Engineering, Pennsylvania State University,
University Park, PA, USA
e-mail: asadi@engr.psu.edu

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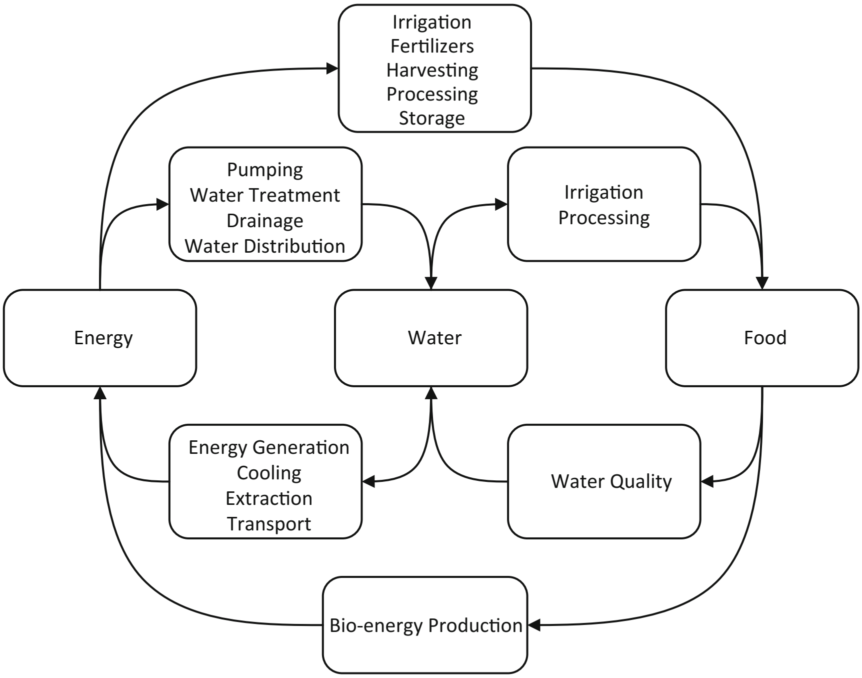

Fig. 2.1 Interconnections of FEW Nexus [4]

FEW Nexus is formed on three main ideas:

1. Considering people and their primary needs as the starting point of FEW Nexus
2. Initiating public knowledge for prosperous operation
3. Calling for local groups in the preparation and operation process [4]

FEW sources are under growing pressure owing to activities such as population increase, climate alteration, and urbanization [7]. FEW systems are of paramount importance on which all human activities rely on. FEW resources are crucial for human social welfare, privation decrease, and sustainable growth [8]. Disturbing events like the crisis and the unpredictability of food prices that happened in 2008 and reoccurring electricity and water insufficiency in the Middle East and Africa have gathered the researchers' interest on FEW limits and interdependence [9].

In some cases, unpredicted action can cause harm and increase vulnerability in FEW such as groundwater depletion because of excessive water usage by farmers for irrigation, groundwater contamination due to high fertilizer usage in farms, electricity blackouts because of high electricity usage for irrigation pumping and surface water drainage because of energy production [7].

Water, energy, and food are inseparably connected in which action in one case affects the other two sectors and also implying that constraints of each sector may limit the availability of another sector [7]. For example, food production needs water; water extractions, treatment, desalination, drainage, and distribution are in need of energy [10]; and energy generation needs water in order to cool power plants, energy production in hydroelectric power plants and natural gas and coal extraction for thermoelectric power plants [7]. In addition, biofuel for energy generation requires food [7]. So the policymakers and researchers have highlighted the necessity of studying food-water-energy nexus (FEW), which aims to use the resources efficiently [10].

The nexus method indicates that, as a replacement for focusing on food, energy, and water sectors independently, managing and decision making should address them concurrently and relatedly. The base belief is interconnection across these three systems, and their interlinkage affects the other sectors' accessibility. The integrated management of these three sectors is advantageous than a single sector approach. This idea suggests an integration method due to external factors such as population increase, environmental alteration, and growing urbanization, which put the network under high stress. However, the operation and effectiveness of FEW nexus require the integration of all sectors via systematic change. This nexus method demands integration as a paramount measure for resource assurance in a wide condition of growing demands [9].

Implementing the nexus raises noticeable issues due to the interconnection and interdependence of FEW sectors which were processed and evaluated separately before. Measures used in each sector have inadvertent and serious consequences in the other sections. The examples of these consequences are shown in Fig. 2.2. For instance, the uncontrolled use of agricultural fertilizers in the US Midwest causes the chemicals to arrive at the Gulf of Mexico via rivers and then causing the widespread increase of alga and a decrease in dissolved oxygen in the Gulf. Another example worth mentioning is the excessive water usage of the Aral Sea in which water levels decreased to its half size in a few decades. The electrical energy subsidy for irrigation water pumps in 2012 in South Asia in drought caused the power network to fail, leading to the largest blackout in the world. Another major catastrophe happened in 2008, when excessive land usage, in order to increase biofuel generation resulted in a massive food crisis [7].

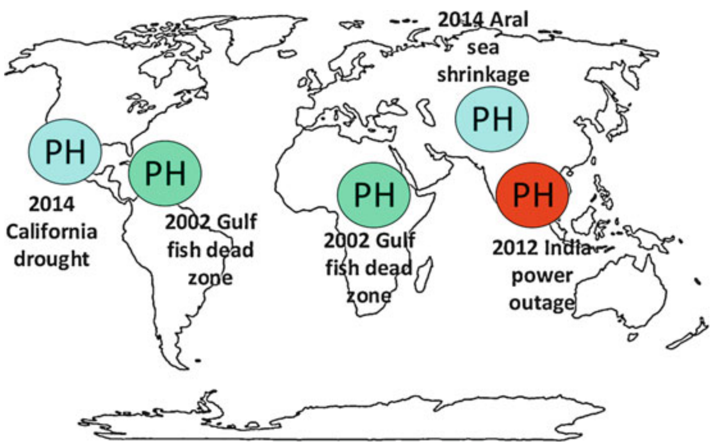

Fig. 2.2 FEW phenomenon locations that occurred in the last decade [7]

2.2 Water

Water is one of the most valuable resources on earth and it is vital for supporting the ecosystem [11]. There is enough freshwater source in the world to supply the worldwide demand but non-equal and non-uniform distribution of water reserves has led to water shortage and scarcity in some regions [4]. Water scarcity has affected every continent on earth. About one-fifth of the world's population deal with scarcity issues [11]. The United Nations approximates that 1.2 billion people who are living in Middle East and North Africa regions are facing water shortage [4]. Almost another quarter of the world lives in areas that have water shortage problems [11]. It is approximated that 50% of the world's population is going to face high water stress with high effect of food and energy security. Although water is a renewable source and plenty of it is available to meet the world's expanding population, the water supply does not satisfy the demand in most areas of the planet, which is mostly seen in North Africa and the Middle East [12]. In these regions, the importance and value of water are even more noticed because these areas are considered the world's most water-stressed places [11]. The shortage of renewable freshwater affects these regions due to their location in arid regions, rainfall scarcity, and high evaporation rates [11]. Water scarcity mainly affects human consumption; however, it has other effects of ecosystem, supply of energy, and food production [4]. Yet, the increasing water problems are not the only major issue of these regions. Weak management and governance, worsening the quality of natural water resources, has become noticeable in recent decades. Water scarcity is one of the most challenging matters in these regions which will present real menace that will surely affect the socio-economic developments [11].

Typically, water source expansion mostly is based on the demand of the growing population including food, energy, and clothing. However, nowadays the standards of the people have risen which led to a sharp increase in water consumption. The growth of water needs is almost two times that of population increase in the twentieth century and high living standards in combination with economic growth could be the reason [4].

The global water withdrawals were 4500 billion m^3 of which almost 70% was accounted for agriculture, 17% for industry, and 13% for domestic and municipal use [13]. In another report, water demand is estimated to grow by 55% in 2050 which will be mostly caused by domestic use, thermal power plants, and industrial section [14].

2.3 Food

There are growing concerns about the global capacity to produce food and meet the demand for the increasing population. The amount of farmable land is decreasing while it has to face industrialization and urbanization requiring the same assets. The most popular way to rating the world food consumption and availability condition is in kcal/person/day. The world average food availability for direct human consumption was 2770 kcal/person/day in 2005–2007 [4]. As shown in Fig. 2.3, food consumption differs region by region in the world. The global need for agricultural products is estimated to increase at 1.1% per year from 2005/2007–2050 which is lower than 2.2% in the past four decades per year. It is projected in 2050 that almost 52% of the world population will live in regions with an average of over 3000 kcal/person/day which is 28% for the same consumption now. In addition, people living in regions with an average consumption of under 2500 kcal will decrease from 35% to 2.6% until 2050 [15].

Developing countries are expected to tend to use livestock products while developing countries move slowly to adopt livestock-based diets (Fig. 2.4). Some big countries like Brazil and China have moved faster toward this diet but they tend to slow down as they achieve high consumption. Considering the decreasing population and high consumption per capita leads to the slowdown of the total demand growth. The supply and demand for agricultural products also are affected by non-food uses such as biofuel [15].

The 2018 Global Report on Food Crises demonstrates the latest approximate of severe need for food in the world. It is approximated that 124 million people in 51 countries are now dealing with food insecurity. Insecurity and conflict continued

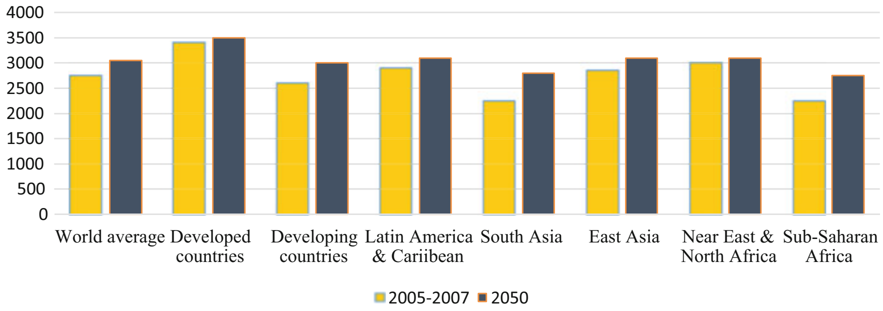

Fig. 2.3 Food consumption in different regions per capita kcal/person/day [15]

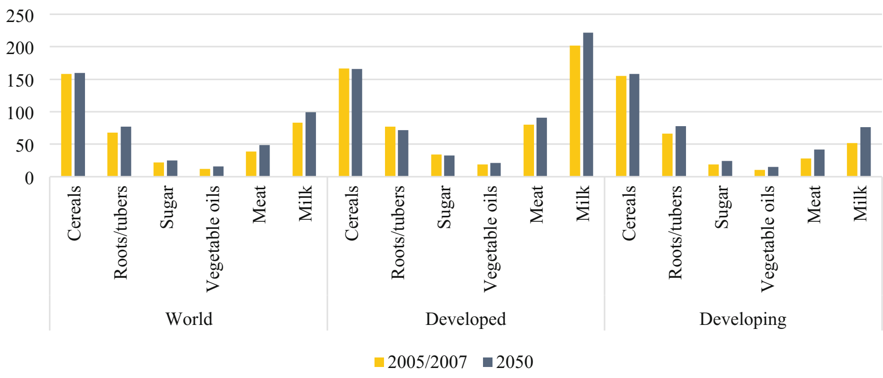

Fig. 2.4 Food consumption per capita, major commodities kg/person/day [15]

to be the main drivers of food insecurity in 18 countries, where nearly 74 million food-insecure people are in need of urgent help [16].

2.4 Energy

Energy demand is growing mainly owing to population increase and GDP. The world population is growing and expected to reach 8.8 billion by 2035. In addition, GDP is increasing and projected to be two times at the same time. GDP increase mainly comes from population growth and productivity improvement which accounts for 20% and 80% respectively. Growth in the economy of the world requires extra energy and it is estimated that energy consumption will increase by 34% between 2014 and 2035. Consumption growth by region and energy consumption by region is depicted in Fig. 2.5 [17]. Fossil fuels are projected to be the main source for most human activities and provide almost 80% of the world's energy supply by 2035. Renewable energy is expected to be more popular but it will account for less than 10% of the total energy supply in 2035 [4]. As shown in Fig. 2.6, gas is growing fast (1.8 p.a.) while oil increases continuously (0.9%). In opposition, coal is facing a downfall in popularity, moving toward its lowest point ever, while gas is catching on. Most of the growth in the energy sector is used for power generation. By 2035, the share of energy consumption for electricity generation grows 45% [17].

Below the interconnection between every two sectors of FEW nexus is explained.

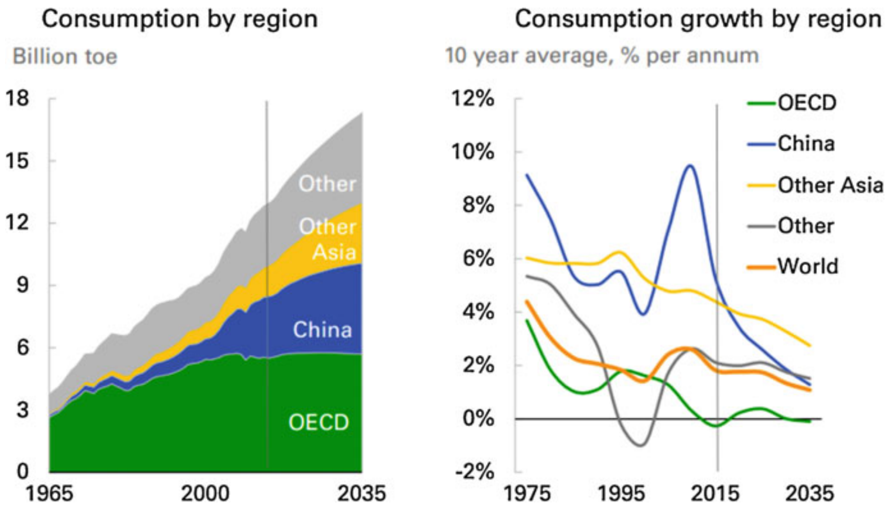

Fig. 2.5 Energy consumption by region and consumption growth by region. (Source: Reproduced with permission of [17])

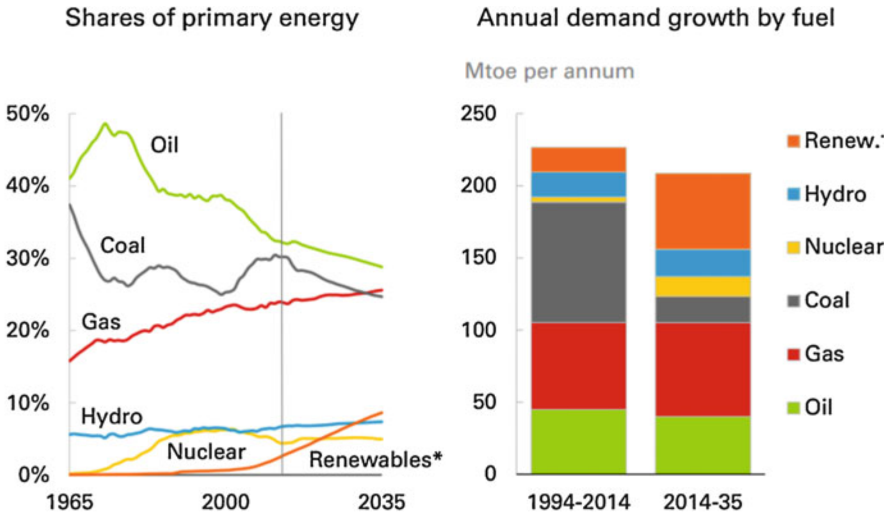

Fig. 2.6 Shares of primary energy and annual demand growth by fuel. (Reproduced with permission of [17])

2.5 Energy and Water

Energy is closely interconnected with water. Almost all kinds of energy need water during their generation process. Thermal power generation and hydropower require a huge amount of water. In reverse, energy is needed for the collection, treatment, transportation, and distribution of water. Also, water and energy provide interdependent services at the household level in which energy is necessary for extraction of water from wells and to produce hot water for cleaning and cooking [14].

Water and energy accessibility is vital to achieving development. If water scarcity exists in an area, eventually lack of access to electricity happens which causes the people to rely on solid fuels for cooking. Almost 750 million people are without access to a modern source of drinking water. Almost 2.5 billion people lack access to upgraded sanitation. Additionally, 1.3 billion people do not have access to electrical power and 2.6 billion people use solid fuels for domestic purposes. It is estimated that 400 million people use coal for heating and cooking which causes air pollution [14].

About 1.3 billion people do not have electrical energy. It is approximated that the demand for energy and electricity will grow by 50% and 70% respectively by 2035. It is also predicted that the Middle East, China, and India will double their demand for energy by 2035 while in Africa and Latin America, the demand will increase by 40% [12].

2.5.1 Energy for Water

Electrical energy is necessary for pumps that abstract, collect water, transport, and distribute. The quantity of electrical energy is based on the depth of water source and distance. Also water treatment needs electricity to convert different water types like saline, waste and brackish water to water which fits for a specific use. Reports show that in 2014, 4% of the global electrical energy is used in water which will be doubled by 2040 because of the increase in wastewater service and desalination. It is estimated that by 2040, almost 16% of total electrical energy in the Middle East will be consumed in water sector [10].

The description below demonstrates how energy can affect water systems (energy for water). The details are categorized into three parts: water systems operation, water use, and energy sector's impact on water systems [10].

Pumping
The energy usage is based on the factors below:

- Water source: groundwater or surface
- Resource availability
- Separation of water source and the demand side (the longer the separation is, the more energy is needed for extraction)
- Distribution technology type (pipeline, canal, or water tank)
- Water losses via evaporation and leakage (the higher the losses are, the more water is needed for extraction) [18].

Purification
The next action after extraction is water purification. This action is also dependent on the water sources owing to different sources that have various chemical features. Water quality improvement at source via upstream catchment management may bring about the reduction of the cost water treatment, leading to a reduction in energy consumption [18].

Wastewater Treatment
Energy consumption varies among wastewater plants. Energy can be generated using sewage sludge, which leads to the reduction of the energy cost. Sewage sludge may be used in thermal conversion when dried. Anaerobic digestion of sewage sludge will produce biogas, which can be used to generate electricity [18].

The Modern Production of Freshwater
This section consists of seawater desalination and wastewater reuse. In this case, the consumed energy, in this case, is more than the traditional way to abstract water. Desalination is an efficient way to supply freshwater only in places facing water shortage, which receives low rainfall and low water flows from outside, for it is the most expensive and energy-intensive way for water treatment. It is also efficient in countries where freshwater sources are far away from demand so that water must be pumped for long distances like the Middle East [18].

Pump Storage Power Plants Operation
This case only concerns the energy sector, not the water systems. This is a way of pumping that is different in each sector. Water is pumped to the reservoirs when the generated energy is more than demand in a period of time and can be used later when there is a generation shortage [18].

Water Consumption
It is known that end-use is the most energy-intensive level in water-energy interaction. Hence, end-use consumption has the greatest potential for saving energy linked with water [18].

Water Heating
Energy for water heating is important in industrial processes and household water usage. The efficiency of the heating system affects energy intensity [18].

End-Use
Activities like cleaning require energy for water. Other examples of such activities are washing, dishwashers, and industrial cleaning. Energy may be gathered from end-user water use. For example, used hot water can be recycled by heat-pump to heat incoming cold water. This process reduces the energy required for heating purposes [18].

Agriculture
The main need for energy in agriculture is to power the pumps for irrigation. This case is true for both surface and groundwater extraction. However, this process is not as intensive as water system operation or end uses [18].

Effect on Water Systems
Many factors affect the operation of electricity production technologies on water quantity and quality. Below the effects of electricity generation on water systems are analyzed. Production of biofuels is related to water resources, for biofuel crops require irrigation [18].

Water Quality

1. Wastewater production, resulted from cooling towers disposal, including high salinity and biocides
2. Thermal pollution, which affects the water temperature and increases evaporation [18]

Water Quantity

The amount of water used for the cooling systems of power plants can differ based on the season, generation, fuel type, and cooling system technology. The consumed water during the cooling process (evaporative water) does not return to the water source which it was abstracted from. Thus, it affects water availability [18].

2.5.2 Water for Energy

In this section, it is focused on how water resources can affect energy systems. It is necessary to divide two types of water use in water withdrawal which is the water removed from the water source and water consumption which is the water not returned to the original water source [12].

The downfall of freshwater availability will affect energy generation in a big way. According to OECD, the energy sector needs 15% of the world's freshwater in 2010. The energy consumption of the emerging economies like Brazil and India will be doubled and due to the increase of electrical energy in Latin America, the need for water will be tripled by 2060. Thus, managing water supply will be of paramount importance specially in the regions in which water stress is huge [12].

Water is needed to produce almost all forms of energy. Water is necessary for resource extraction, biofuel feedstock irrigation, fuel refining, and transportation. It is estimated the energy demand will increase by up to 70% by 2035. With 90% of worldwide energy systems relied on water, the water consumption management and planning in a more efficient way is highly noticed [12]. It is estimated that 70% increase in electrical power plants will cause 20% increase in freshwater withdrawal by 2035. It is also estimated that water use will grow by 85% which will definitely shift the power generation toward more efficient power plants with high-technology cooling systems [14].

Also, another category is introduced. The first group is water for fuel cycle that comprises fuel extraction, conventional fuel production, and biofuel cultivation. The second group is called water for energy conversion which consists of water use in electricity generation and transport [18].

2.5.2.1 Water for the Fuel Cycle

Water for Fossil Fuel Extraction

The water use depends on the type of fuel (oil, gas, coal) and extraction type. Extraction types are mining, drilling, or fracturing. For example, underground mining requires more water, while drilling for conventional natural gas is less intensive than the extraction of shale gas. Researches show that almost all of the water withdrawn in the extraction step is consumed. In oil production, water use varies due to the geography and geology of the extraction site. Table 2.1 shows some examples of water use for fuel production [18].

Fuel Processing

Water use depends on the type of fuel being processed, technologies used, and the by-products produced. Petroleum refineries require water for the cooling system and steam generation for distillation, reforming, and cracking [18].

Table 2.1 Average water requirement values for fuel production [18]

Energy source	Water use
Crude oil	1.1
Non-conventional oil	3–4
Coal	0.16
Natural gas	0.11
Biomass	45

Biofuel Cultivation

Production of biofuels (methanol, ethanol, and biodiesel) requires a huge amount of water, which is used in cultivation process due to irrigation proposes. The water use depends on various factors such as the crop being farmed, cultivation practices, plant site climates, and soil types. Meanwhile, the second-generation biofuels such as forest wood residues, algae, and municipal waste require less water, as they are not grown for biofuel production [18].

2.5.2.2 Energy Conversion

Transportation Sector

Water intensity in transportation is based on the type of vehicle and its fuel. It is worth knowing that biofuels are more water-intensive than fossil fuels [18].

Electricity Generation

The consumption of water in electrical energy generation is based on the generation technology. For example, in hydropower plants, water is circulated through turbines to generate electricity, then it returned to its source. Next, the water will be reserved in the reservoirs or may be pumped up to high altitude reservoirs when needed, especially when the demand is at its peak. This usage is an example of non-consumptive water use, neglecting the evaporation of the water in the reservoir, for the water is returned to the watercourse. So in hydropower generation, water consumption is mostly dependent on the type of power plant and evaporation losses. In thermal power plants, water usage must be assessed in terms of consumption and withdrawal. In this case, the amount of water used is based on the thermal power plant technology and cooling technology. In some cooling systems, the withdrawn water is high and the consumed water is low. Meanwhile, other cooling systems are the opposite might be true. Also the amount of used water can be different. For example, in nuclear power plants more water is needed, whereas natural gas necessitates less water. All kinds of used water including consumptive and non-consumptive water will impact the quality and quantity of the water sources in the region [18].

Water use in hydropower generation: Water consumption is dependent on various elements such as watercourse characteristics, region's climate, power plant site, flow seasonal variability details, the size and type of the power plant, and electricity demand.

The water losses in hydropower power plants are related to the type of power plant. For example, the run of the river hydropower plant has inconsiderable amount of water loss; however, this is not true for reservoir power plants. Here, the water loss is only related to evaporation. Nonetheless, the water in the reservoir may be allocated for different uses such as public or industry supply, irrigation, and flood control. So all the different uses should be held responsible for the water loss caused by evaporation, not just electricity production [18].

Water use in thermal power generation: The cooling system of power plants requires 43% of Europe's freshwater withdrawals, 50% in the United States, and 10% in China. However, high water withdrawal does not necessarily mean high consumption. In these power plants, the cooling system usually works with evaporative tower which is used to reduce the temperature of the water, circuit in the power plant. There are two kinds of cooling systems. The first type is dry cooling in which air is used for cooling and the second type is wet or evaporative cooling in which water is used to maintain the temperature of the power plant. Wet cooling can be divided into three technologies:

1. Once-through cooling: water is extracted from its resource (river or lake) and transferred into the condenser. All of the withdrawn water is brought back to its source with its temperature increased. This method requires a large amount of water and increased water source temperature. This technology is shown in Fig. 2.7 [18].
2. Once-through cooling with the cooling tower: In this technology, the water extracted from the source is implemented multiple times. In the cooling tower, the heat which was gained from water circulation in the power plant is dissipated into air. In this method it is obvious that water is withdrawn less than the previous case but water consumption is noticeably high due to evaporation. In this case more than 60% of the water is consumed and not returned to its source. This method is shown in Fig. 2.8 [18].
3. Recirculating cooling: The heated water is cooled in the cooling tower and then returned to the condenser. This method requires less water withdrawal and consumption than the previous method (Fig. 2.9) [18].

Fig. 2.7 Once-through cooling system

Fig. 2.8 Once-through cooling system

Fig. 2.9 Recirculating cooling system

The next technology is dry cooling in which water is replaced by air, the cooling agent. In this technology, water consumption can be decreased by up to 90%. This method has some disadvantageous over wet cooling including its high cost and low cooling efficiencies which requires more energy for its operation. This method is mostly used in power plants with low capacity and natural gas combined-cycle power plants (Fig. 2.10) [18].

As mentioned before, the once-through cooling system requires high water withdrawal (over 150 cubic meters per MWh) but low consumption while cooling towers cause high water consumption and low withdrawal. The consumption rate is two times high in cooling tower comparing the same fuel and capacity [18].

Comparing different fuel technologies, but similar operation cycle, the most water demanding is coal and nuclear while natural gas requires less water. Combined cycle power plants using natural gas as fuel and cooling towers as the cooling system is the least water demanding. Water use in different power plants for different cooling systems is shown in Table 2.2 [18].

The interaction between the energy and water sector is illustrated in Fig. 2.11 [19].

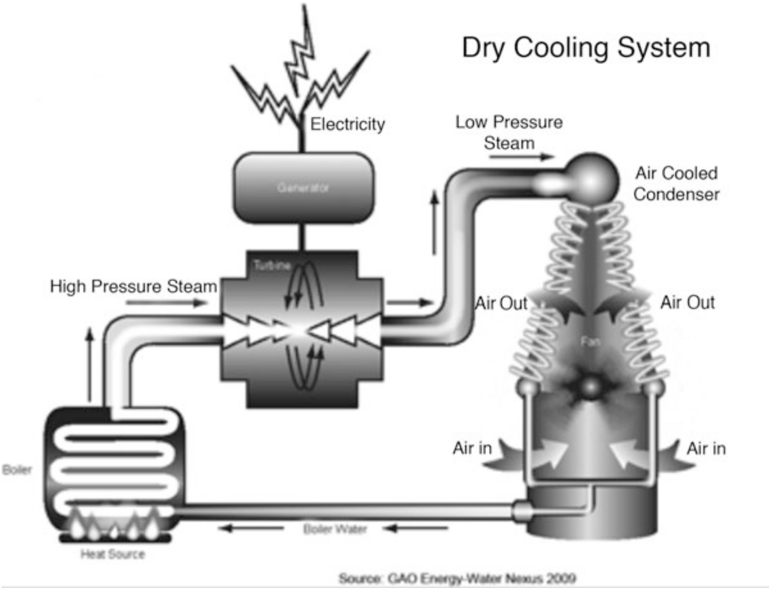

Fig. 2.10 Dry cooling system

The overall effects and risks of water-energy nexus are shown hereunder (Table 2.3) [10].

2.6 Water-Food

Almost 70% of total withdrawn water is used in agriculture which is consumed or food, fibers, and seed production [6, 10]. Also, water evaporation from open water places must be taken into account in locations like irrigation canals and rice fields. Due to the world's population increase and thus food consumption growth, by 2050, 60% increase in food supply is needed to match the world's demand, which will cause 11% growth in water consumption in agriculture. This growth in water demand will put stress on water-intensive sectors to find alternative supplies [10].

Increasing agriculture production will affect water quality because of non-point source pollution. The main issue is sediment runoff which brings about siltation problems. Also nutrient runoff including phosphorous and nitrogen is the main pollutant that exists in agricultural runoff, implemented in farms via fertilizer, animal manure, and municipal wastewater [12].

Irrigation can cause salinity, for every type of water contains some dissolved salts. Plants do not use salts, dissolved in water. Thus, salt begins to accumulate [9].

The relation between food and water is discussed in the sections below.

Table 2.2 Water use of different power plants [18]

Fuel type	Cooling system	Technology	Consumption			Withdrawal			Consumption-withdrawal ratio
			Median	Min	Max	Median	Min	Max	
Nuclear	Tower	Generic	2.54	2.2	3.2	4.17	3.03	9.84	0.61
	Once-through	Generic	1.02	0.38	1.51	167.88	94.64	227.12	0.01
	Pond	Generic	2.31	2.12	2.73	26.69	1.89	49.21	0.09
Natural gas	Tower	CC	0.78	0.49	1.14	0.97	0.57	1.07	0.80
		Steam	3.13	2.51	4.43	4.55	3.60	5.53	0.69
		CC with CCS	1.49	1.43	1.54	1.92	1.84	2.06	0.78
	Once-through	CC	0.38	0.08	0.38	43.08	28.39	75.71	0.01
		Steam	0.91	0.36	1.10	132.49	37.85	227.12	0.01
	Pond	CC	0.91	0.91	0.91	22.52	22.52	22.52	0.04
	Dry	CC	0.01	0.00	0.02	0.01	0.00	0.02	1.00
Coal	Tower	Generic	2.60	1.82	4.16	3.80	1.89	4.54	0.68
		Subcritical	1.81	1.49	2.51	2.22	1.75	2.70	0.82
		Supercritical	1.87	1.68	2.25	2.40	2.20	2.54	0.78
		IGCC	1.44	1.20	1.66	1.49	1.36	2.29	0.97
		Subcritical with CCS	3.49	3.41	3.57	5.03	4.63	5.49	0.69
		Supercritical with CSS	3.20	3.09	3.43	4.34	4.16	4.38	0.74
		IGCC with CCS	2.08	1.98	2.29	2.43	1.81	2.81	0.86
	Once-through	Generic	0.95	0.38	1.20	137.60	75.71	189.27	0.01
		Subcritical	0.43	0.27	0.52	102.54	102.4	102.63	0
		Supercritical	0.39	0.24	0.47	85.51	85.36	85.59	0
	Pond	Generic	2.06	1.14	2.65	46.28	1.14	90.85	0.04
		Subcritical	2.95	2.79	3.04	67.81	67.60	67.85	0.04
		supercritical	0.16	0.02	0.24	56.96	56.77	57.00	0

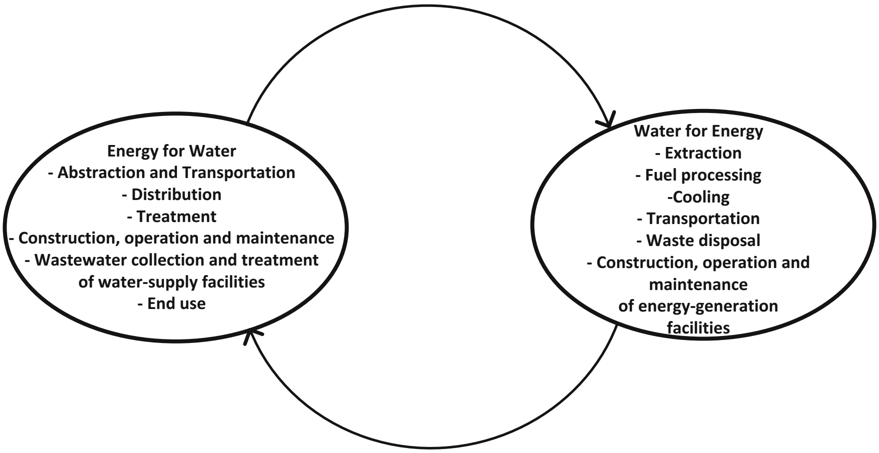

Fig. 2.11 Interaction between the energy and water sector

Table 2.3 Overall impacts and risks of water-energy nexus

	Risks	Impacts
Water risks to energy	Change in availability and quality because of human or natural causes Energy demand growth in water production, treatment, transfer, and distribution	Decrease availability of supply and dependence on more expensive types of generation Possibility of water economic pricing leading to an increase in costs of energy production Reduced availability of water for fuel extraction and processing stages leading to reduced output Various demand for water and energy causing efficiency decrease
Energy risks to water	Unreliable or limited access to energy for water withdrawal Water resources reallocation from other users to energy Water resources contamination owing to energy production and refining	Disruption in the water supply to end-users or diversion of resource away from other core activities, for example, agriculture Changes in water delivery costs due to swinging costs of energy inputs Water resources, especially drinking water, becomes contaminated, which need extra treatment

2.6.1 Food for Water

Water quality and quantity are strongly connected to food production and consumption. Water is vital for photosynthesis and animal-based products which are directly needed for animal drink and indirectly to produce feed for animals. Water is also important for processing, packaging, and transport of food [18].

Table 2.4 Impact of food consumption and production on water quality and quantity

	Impact of water quantity	Impact on water quality
Food production	Crop-based: water requirement of crop and its irrigation require upgrades in water management and irrigation structure. Animal-based: direct water consumption to drink and indirect for animal feed production. Food industry: water needs for food production and processing.	Crop-based: overuse of agrochemicals pollute water. Animal-based: antibiotics, hormones, manure, and fertilizer cause eutrophication of water sources. Fish-based: fisheries and aquaculture cause algae biomass and increase chemical content of water.
Food consumption	Food consumption needs food production that can be gained from crops, animals, and fish which requires water.	The waste and trash thrown away from processed and canned food cause blocked sewage system. Clogged sewage results in an overflow of the sewage system.

In the world, agriculture requires 69% of freshwater withdrawals including groundwater and surface water while 19% is used by industrial sector and 12% for municipal use. The statistics are not the same around the world. In Europe, agriculture, industrial, and municipal sectors account for 21%, 57%, and 22%, respectively [18].

The food system can be divided into three groups which are primary food production (crop, animal, and fish), secondary food production (industrial processing), and food consumption [18].

The impact of food on the water is different region by region which depends on local climate, produced foods, import, and export of food and water infrastructure. The impact of food consumption and production on water quality and quantity is demonstrated in Table 2.4 [18].

Heavy farm machinery uses lead to rain and irrigation water infiltration to a decrease and this matter affects the restoration of groundwater and water is run off at above the ground [18].

Considering direct water requirements (drinks) and indirect water requirements (food production), the effects of water in animal production is much higher than crop production. Exporting meat will increase the need for water in this section [18].

The three types of food production will result in eutrophication. Using fertilizers and manure in agriculture activities and sewage runoff increases the amounts of nutrients like nitrogen and phosphorus [18].

Agricultural effects on water quality are much due to water contamination including manure, agrochemicals, nutrients, and pathogens. Manure is a production of live stocks and animal husbandry which is operated in order to produce food for human. Excessive use of manure (more than required) and bad timing of applied manure or fertilizers contaminate ground and surface water, putting water supplies at risk and spreading disease [18].

The modernizing of agriculture has led to overuse of agrochemicals which causing the levels of phosphorus and nitrogen to increase three and two times in soil respectively. It is approximated than only one-fifth of the nutrients used in agriculture are consumed and the rest of them is washed away. The increasing demand for food due to the population increase in the world has caused the conversion of large areas of wetlands into agriculture farms which results in an increase in agrochemicals being solved in water [18].

Fisheries and aquaculture require water for ponds and to keep water fresh. Fish feed and waste products from fisheries increase nutrient of water which leads to excessive algae growth and this matter adds to oxygen demand [18].

Food consumption has an effect on water sources as it is required for food processing, packaging, and transportation. In modern era, the change in diet affects the water requirement for food production [18].

Extravagant use of nutrients for food production will lead to algae blooms which create low dissolved oxygen zones. Eutrophication will affect water treatment expenses and may make the water source inconsumable for humans [18].

The agricultural impacts on water quality are shown in Table 2.5 [10]. The overall interaction of water and food nexus is shown in Table 2.6 [10].

Table 2.5 Effects of agriculture on water quality

Agricultural activity	Impacts	
	Surface water	Groundwater
Tillage and ploughing	Sediments containing pesticides and phosphorous River siltation	
	Habitat loss	
Fertilizing	Eutrophication caused by nutrients runoff, including phosphorous	Leaching of nitrate to groundwater
Manure spreading	High levels of contamination of incoming water by nitrate, phosphorous, and microorganisms, causing eutrophication	Contamination of groundwater by nitrogen
Pesticides	Runoff of pesticides pollutes surface water, causing malfunction of the ecological system owing to growth inhibition	Pesticides leaching into groundwater and contaminating wells, causing health problems for human beings
Feedlot	Surface water contamination with microorganisms and residues of veterinary drugs	Leaching of nitrogen and metals to groundwater
Irrigation	Salts runoff lead to surface water salinization, pesticides, and fertilizers runoff to surface waters with ecological damage and bioaccumulation in fish species	Groundwater contamination with nutrients and salts
Clear cutting	Land erosion, causing turbidity in rivers and bottom habitat siltation.	Disruption of the hydrological regime, leading to surface runoff growth and groundwater recharge decrease

Table 2.6 Overall interaction of water and food nexus

	Risks	Impacts
Water risks to food	Water availability variability owing to climatic and non-climate trends Impact of water quality on food production and consumption	Variation of food product supply, leading to high volatility of the price Utilization of poor-quality water along different stages of the food supply chain can have negative impacts, for example, soil degradation, accumulation contaminants within the food chain
Food risks to water	Impacts of agricultural activities on water resources Inefficient agricultural investments Water resource overuse because of food production	Use of external inputs for agriculture and food production can lead to water-polluting affecting all users, human, and natural Increased land leasing for agricultural purposes may cause high use of water resources with potential local economic effects Depletion freshwater reserves

2.7 Food and Energy

Food security is defined as the actions needed to be taken to maintain food supply and energy security is known as the security actions a community must follow to maintain adequate energy supply [20]. The food section supplies almost 30% of energy consumption in the world. Energy consumption in agriculture section is divided into two categories. The first one is direct energy which is referring the energy (fuel and electricity) that is used to power farm activities and the second one is indirect energy which is the energy required to produce the agricultural inputs that are produced in the factories such as fertilizers and chemicals. Most of the energy is used directly on farms. In the United States, where almost 1.8% of total energy is used in agriculture, almost 60% percent of the energy is used directly. The form and amount of energy consumption vary from case to case. For example, cotton production consumes more energy of irrigation pumps while wheat production does not. Also countries with arid climate use more energy for groundwater pumping. Also fertilizers and chemicals which increase the output of farms need energy for their production, distribution, and transport. Fertilizers are the most used in agriculture, whereas pesticides are the most energy-intensive material (on a per-kilogram chemical basis) [10].

Nowadays, the demand for bioenergy is rapidly increasing. The production of liquid biofuels has grown eight times from 2000 until 2011 in the world. It is approximated that almost 3 billion people depend on biomass for cooking and heating as it is mostly used in off-grid communities. Replacing biofuel with traditional combustion of biomass will result in reduction of indoor pollution and poor health [10].

The interconnection between food and energy can be demonstrated in the sections below.

2.7.1 Energy for Food

Diet

The change of diet in the world has a significant impact on energy use. Nowadays most people abandon their traditional habits and prefer a modern diet. This change leads to more processed food and more meat and fish. Also, the increase in the population leads to more food consumption which requires more energy to meet the transportation needs within the factories. Using boats, trains, and trucks for food transportation lead to increase in fossil fuel consumption. Neglecting the factories using renewable energies, most of the factories use fossil fuel for food processing [18].

Using Fertilizers and Pesticides

In order to increase productivity in farms, farmers usually prefer to use pesticides and fertilizers. These products need energy to be processed and produced in factories [18].

Pumping and Desalinating Water

Due to the increasing food consumption, more cultivated lands are put to use to produce food which most of them use irrigation to deliver water. Many of the irrigated lands use pumps to deliver water from distant water sources which could be surface or groundwater source. Pumping water requires a huge amount of energy due to water density. Thus, increasing cultivated lands leads to an increase in energy consumption [18].

Regions like the Middle East require water desalination in order to be used for irrigation purposes. Although these areas have access to seawater, freshwater scarcity is noticeable. Processing seawater and converting it to freshwater for irrigation requires considerable amount of energy which increases the need for energy in the food sector [18].

2.7.2 Food for Energy

In recent years, farmers face the debate in which farmland should be used to grow food crops or biofuel crops [20]. The worldwide food section is very much dependent on fossil fuels. It is estimated that there will be a 70% growth in food production by 2050 to supply the increasing demand. The food sector is responsible for 30% of worldwide energy consumption. The distribution of energy consumption is not the same around the world. Low-GPD countries mostly use energy for processing and transport while high-GPD countries require most of the energy for cooking [18].

Food Waste
Almost 33% of the energy used in the food sector is wasted, for it is not used and this matter is different country by country. In low-GPD countries, the great quantity of the food wastes happens during harvest and storage, whereas in high-GPD countries, food losses happen during cooking, preparation, selling, and consumption [18].

Anaerobic Digestion
Anaerobic digestion of food waste creates methane (landfills produced 18% of methane emission in 2013). In order to gather the emitted methane, policymakers take action to separate food waste from landfills. Food waste can be directed to composting facilities and anaerobic digesters in order to generate energy. Digesters capture the produced gas methane, direct it into a generator and then convert it into electricity. Anaerobic digestion has another residue, a solid substance with high nutrient which could be used as fertilizer [18].

Biodiesel
Biodiesel is a replacement fuel similar to fossil diesel. Biodiesel can be from vegetable oil, animal fat, tallow, and waste cooking oil. Oil crops like palm and rapeseed are the largest source of suitable oil for biodiesel. This fuel is non-toxic and biodegradable [18].

Ethanol
Ethanol is a sustainable fuel that can be obtained from various plants. Food processing wastes that have a high amount of hydrocarbon, like potato chips are a good source of ethanol [18].

An overall interaction of food-energy nexus is presented in Table 2.7 [10].

Table 2.7 Overall interaction of food-energy nexus

	Risks	Impacts
Energy risks to food	High reliance on fossil fuel creates volatility of food prices Potential trade-offs between food crops and bioenergy production Energy production risk on food availability	Reliance of upstream (production) and downstream (transportation) of food supply chain on fossil fuel Supply shortage and price volatility of energy, causing risks in the food supply chain Agricultural products allocation to supply bioenergy production with possible effects on food prices Negative impacts of energy generation on food production such as hydropower
Food risks to energy	Growth in food production and changes in diets increase the energy demand in the food supply chain Quality and availability of energy can rely on feedstock accessibility	Rising demand for energy in agriculture can strain the energy system, especially in areas with the potential to expand irrigated agriculture with pumped water Crop-based feedstock affects the production of bioenergy

2.8 Spatial Computing in FEW

Spatial computing can help understand and predict FEW resources like weather forecasting. The vision behind implementing spatial computing is that it offers insights into interaction and dependencies of different sectors of FEW, as well as helps the decision-makers predict and reckon future happening. This can be done via spatial data management, analytics, visualization, and decision support. As an illustration, if the connection patterns between the food crisis and biofuel production, which happened in 200, was noticed, the broad crisis could be avoided [1]. Another example of spatial analytics practicality is water management at a global level as virtual water trade could reposition water-intensive crops from dry countries to water-rich countries [7].

FEW Observation and Data Collection
FEW data can be gathered using techniques such as a global position system (GPS), remote sensing satellites, ground sensor networks, and planes. The collected data can locate resourceful regions in each sector of FEW nexus [7].

2.8.1 FEW Data Mining

Improvements in machine learning and spatial data mining help scientists understand and study the resources of FEW Nexus. For instance, crop production used to be analyzed and modeled at province or county level, but nowadays implementing high-resolution remote sensing imagery using drones, a new practice called precision agriculture has been evolved to analyze crop production at much wider level. Spatial data techniques play an important role in producing real-time. This technology also identifies interesting patterns that were unknown previously in FEW data. For example, LCA (Life Cycle Assessment) is a technique that evaluates and assesses the environmental effects related to all levels in a life cycle of a product, including material extraction, production, processing, usage, and disposal. Some examples are water and land use, smog creation, climate change, resource depletion, and acidification. Implementing LCA method in FEW Nexus helps scientists understand the effects of a particular change in food, energy, or water on the other sectors and improve the chances for decreasing these effects at another stage of a lifecycle of a product [7].

2.8.2 FEW Decision Support

Spatial computing uses FEW data in spatial decision support systems to raise the renewability and efficiency of FEW sectors which looks at FEW Nexus like a system

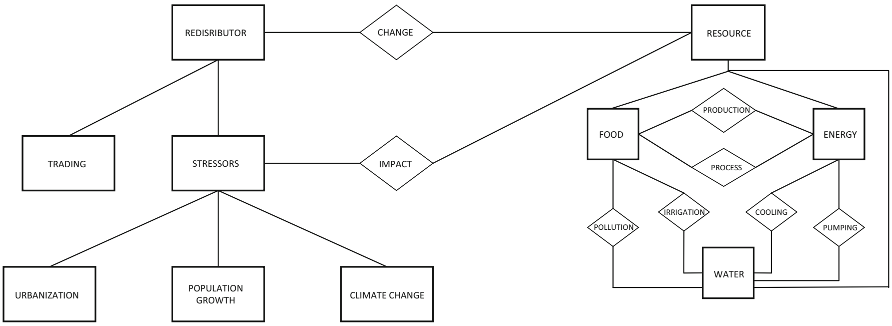

Fig. 2.12 ER diagram of FEW Nexus as a system of systems [7]

of systems. For instance, water is consumed for crop irrigation which is for food production and also for the cooling system of power plants, energy is used for pumping water from water sources for irrigation and producing fertilizer for food production and food is used for producing energy. The system of systems view can help spatial decision support systems to improve the efficiency of FEW sources. To give an example, GIS soil maps with details including humidity, nutrient, and chemical compound details can help the decision-makers decide optimal crop type in each field and increase the production using suitable pesticide and fertilizer. An example of energy sector is hydro-electric power plants which the amount of produced energy is dependent on demand. This technique determines the peak electricity demand hours and the produced energy is set on these data. In Fig. 2.12, an ER-diagram (entity relationship) demonstrates FEW Nexus as a system of systems [7].

2.9 Solutions for FEW Nexus Management and Improvement

The complexity of the FEW has been shown in this chapter. It is clear that each sector has considerable impacts on others. The demand for resources is increasing, the competition will become more noticed and serious, so it affects the supplies of all sectors. Decision-makers now face real challenges managing different sectors considering economic, social, and environmental issues. As the world faces the limits of sources on earth, it is more evident that development strategies must be designed not just for one sector but for all three. Two opinions are now in conflict with each other. The first group believes that managing the Nexus requires proper changes in protocols, rules, and procedures that upgrade governance systems and does not require major restructuring. On the other hand, the latter thinks that a huge reform is needed to solve the incoordination between institutions.

2.9.1 Operationalizing the Planning for FEW Nexus

In this section, an analytical framework is introduced for operationalizing FEW Nexus. The basic planning process is described below [21]:

1. Assessing FEW security systems
2. Picturing future landscape scenarios
3. Investing in a FEW secure futures
4. Transforming the whole system

Step 1: Assessing FEW Security System

Analyzing current status: The first step starts with analyzing the current status of key aspects of FEW security.

Understand pass stresses and adaptations: A broad historical analysis of the region is vital to understand the changes over time and how humanity has affected FEW resources. In order to perform such a historical analysis, it is necessary to look back several centuries ago.

Describe future risks: After historical analysis and collecting data, the key risks of the future are predicted [21].

Step 2: Picturing Future Landscape Scenarios

Develop principals for desired future landscape: In this step, reasonable and plausible scenarios are developed considering the drivers of change in the region. In the beginning, a set of principles that can lead to the desired future must be built. At this level, detailed elements of the future are not needed (like types of water usage or nutrition sources) but features of desired future can be beneficial (like efficient use of resources) [21].

Identify critical uncertainties and generate feasible scenarios: Scenario planning is done using scenario axis technique. In this method, the most important factors which influence FEW security in the region for the next 50 years are acquired. These factors can include population growth, new technologies, and urbanization. The next move is to rank and sort these factors according to their importance and uncertainty over the period. The most important trends and factors lead to a number of feasible future scenarios. Experience demonstrates that it is quite difficult to generate more than four scenarios [21].

Develop adaptations and transformation: After generating scenarios for the future, actions for FEW security can be discussed. This can be done via an adaptive and transformative point of view. From the adaptive look, the opportunities and threats caused by each scenario and the strengths and weaknesses are evaluated. From the transformative point of view, the scenarios are analyzed to see which one is better for the community and region. Then the responsibilities must be assigned [21].

Step 3: FEW Security Investments

In this level, a shared, innovative, and motivating scenario for the future which can secure FEW resources is introduced. This action requires using the scenario created in step 2, communicating it across the region and community [21].

Step 4: Transforming the System
Communication: Transforming the system requires action and action demands communication. So a separate communication plan is crucial which can create the necessary policy, financial, and public support for action [21].

Implementation: There are many strategies that are not implemented creating a state called implementation gap. There have been some actions that can lead to narrow the gap, for example, active communication, making sure that the suggested actions are supported by policy and financial commitments [21].

Monitor, adapt, and improve managing and monitoring this transformation is vital to a successful implementation, as it is impossible to predict whether the actions are going to work fine. Thus, a regular process of monitoring the process, learning from the failures and successes and enhancing the performance is needed to modify what is not working and strengthen what is working [21].

2.9.2 Opportunities to Improve Food, Energy, and Water Security via Nexus

There are no definite and complete solutions for improving FEW securities but some areas of opportunities emerge [22]. These areas are:

1. Enhancing the resource productivity
2. Using waste as a cheap resource in multi-use systems
3. Stimulating improvement through economic motivation
4. Benefiting from productive ecosystems
5. Poverty assuagement and green growth

These areas are illustrated in the following section.

1. Increasing Resource Productivity
Increasing resource productivity can be reached via technological innovation, recycling, and reducing wastage [22]. Technological innovation includes:

- Rainwater harvesting
- Second or third-generation biofuels
- Pumping water using photovoltaic
- Using renewable energy for desalination
- Genetic engineering for drought-resistant crops
- Aerobic direct seeding of rice in order to decrease water and energy need

These are some noticeable chances to raise resource productivity and efficiency.

2. Using Waste as a Cheap Resource in Multi-use Systems
Multi-section management can lead to an increase in resource consumption efficiency. In other words, in these systems, by-products, residues, and wastes can be used and turned into a cheap resource for other products in other sections. Productive

sanitation in integration with wastewater recycling is an example of reusing water and nutrients. Other examples are land rehabilitation with biofuel crops. Recycling and reusing waste products instead of dismissing them will also decrease cleaning expenses [22].

3. Stimulating Improvement Through Economic Motivation
Improvement in resource efficiency and productivity needs investment and reduction in economic perversion. Economic assets for stimulating investment are resource pricing, water markets, and tradeable rights. The private sector can drive change [22].

4. Benefiting from Productive Ecosystems
Maintaining and restoring ecosystems have a big role in drawing pathways. Improved management and investment in natural capital will provide many services

Table 2.8 Reference category and case systems

Source	Planning/ operation/report	Case system
[1]	Planning-Operation	Middle East
[2]	Operation	Mekong Delta-Gujarat-Egypt
[3]	Planning	–
[4]	Planning-Operation	Eastern Nile Basin-South Asia-South Africa-USA-West Asia-Southeast Nepal-Bangladesh
[5]		
[6]	Planning-Operation	Egypt
[7]	Planning	–
[8]	Planning-Operation	Egypt
[9]	Planning	–
[10]	Planning-Operation	New York-Singapore-Massachusetts-Ontario-Denmark-Korea-Colorado River Basin-Murray Darling River Basin-Rhine River Basin
[11]	Planning-Operation	Arab Region
[12]	Planning	–
[13]	Planning	–
[14]	Planning	–
[15]	Report	World Agriculture
[16]	Report	World Food crisis
[17]	Report	World Energy Outlook
[18]	Planning	–
[19]	Planning	–
[20]	Planning	–
[21]	Planning	–
[22]	Planning	–

and increase overall social welfare and benefits. Soft path solutions and natural infrastructure need to work with a hard path and human-made solutions in order to deliver more efficiencies. Further benefits can be gained via foreign investment into agriculture in developing countries [22].

5. Poverty Assuagement and Green Growth
This leads to smarter resource usage and integrated agricultural and ecosystem management. It also widens the range of ecosystem services and healthy environment. Providing energy and clean water enhances productivity and health. It also creates more jobs [22].

Below, the references used in this chapter are categorized and the case system of each one is demonstrated in Table 2.8.

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Chapter 3
A Decision Support Tool for the Assessment of Water–Energy–Food Nexus in Saudi Arabia

Sa'd Shannak and Michele Vittorio

3.1 Introduction

Energy has been a key element for the production of food [1]. As the population grows, future food production will drastically increase. Most agricultural inputs have energy requirements. The concept of food security and the intensive use of agricultural inputs, especially when growing non-native crops, have provided an increase in food production in a non-sustainable way and added additional burden on energy requirements. Growing crops requires significant energy inputs through synthetic fertilizers, tillage, transport, harvest, and water supply [2]. Some types of fertilizers that are rich in potassium and phosphorus are usually mined, which consumes more energy. In 2004, 317 billion cubic feet of natural gas was consumed in the industrial production of ammonia in the USA alone [3].

Water is also needed to sustain crop growth. In the USA, 31% of the water withdrawals go for crop irrigation [4]. Energy is also needed to secure water supply, through pumping surface and groundwater, desalinate sea and brackish water, treat wastewater, and distribute water to end users. Water, energy, and food are highly interlinked systems, and therefore, integrative planning is needed to ensure the sustainability of these resources.

Recently, there has been a significant increase in the literature in the water, energy, and food nexus [5–7], but it rarely considers space and time across the entire nexus spectrum. Space and time are vital factors which cause variation in natural

S. Shannak (✉)
Texas A&M University, College Station, TX, USA
e-mail: shannok@neo.tamu.edu

M. Vittorio
University of New Haven, Henry C. Lee College of Criminal Justice and Forensic Sciences, West Haven, CT, USA

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resources distribution. Therefore, supporting resource management at the national, regional, watershed, and project levels requires integrating space and time.

The Food and Agriculture Organization (FAO) has developed a water–energy–food nexus framework to facilitate a better understanding of the nexus. This framework focuses on defining the interlinkages between human and natural resources. The approach is to address resources by integrating socioeconomic and biophysical factors [8]. Dasher et al. [9] suggested a different type of model to analyze the nexus. They advised to analyze the nexus by addressing seven essential questions that aim to outline the borderline of analysis: (1) What is the critical question in the case study? (2) Who are the players/stakeholders? (3) At what scale? (4) How is the system of systems defined? (5) What do we want to assess? (6) What data is needed? (7) How do we communicate it? Where do we involve the decision-maker in the process? McCarl et al. [10] suggested a similar model to analyze the nexus based on addressing key challenges in the assessment of the Nexus. Some of these important challenges are: (1) establishing the scope of the Nexus issue, (2) the appropriate selection, development, and integration of diverse component models, (3) developing models that are useful and provide meaningful insight, (4) characterizing uncertainties (e.g. in future scenarios), and (5) representing new technological and resource development alternatives that have not been previously adopted in the region.

Biggs et al. [11] suggested a theoretical framework to analyze environmental security indicators for livelihoods in Southeast Asia and Oceania. The focus of the framework is to address global challenges in terms of water–energy nexus to achieve sustainable livelihoods.

Detailed reviews of the available methodologies introduced in the last few years can be found in Shannak et al. [1], Endo et al. [12], Kurian [13] and Albrecht et al. [14]. Very few studies have focused on the policy implications of intensive energy use in the food sector, but none of the available studies provided energy estimates in the food sector over space and time. Most of the available databases provide detailed information on water requirements for food production.

Though these available tools and models are useful for planning purposes on a watershed scale and very specific to a particular geography, policymakers would require tools and databases capable to assess the potential impacts of water and food sectors on energy consumptions on a larger scale, such as a national level [15]. Furthermore, quantifying and analyzing the impact of weather conditions over space and time on energy consumption for food production can provide useful information to establish energy prices and improve energy productivity in the sector.

This paper describes a spatial-temporal decision support tool for assessing energy requirements in the food sector in Saudi Arabia. The tool provides policymakers with essential information to evaluate which energy inputs in food production are the largest and which factors influence the increase in energy use over space and time.

The tool was developed using a web-based Geographical Information System (GIS) application in a way that allows the user to navigate over different spatial locations, select a point of interest to grow a certain quantity of a specific crop, and calculate water, land, and energy requirements accordingly. This application provides a web-mapping platform and helps users determine when and where they can grow crops based on water and energy requirements objective functions. This application is very useful especially in areas with limited information on natural resources. It utilizes satellite imagery to identify major environmental features that are important for analysis. It also allows comparison between different scenarios of food production, promotes natural resources use efficiency, and encourages greater policy coherence.

3.2 Tool Design and Development

The tool consists of three main components: database, visual interphase, and coding protocol. The database consists of three sections covering the three elements: water, food, and energy. The food section was built by retrieving crop production and land requirements data for each province in Saudi Arabia from the Ministry of Agriculture website. Growing stage duration and dimensionless crop coefficients for each type of crop to adjust water requirements were retrieved from the United Nations Food and Agriculture Organization (FAO). The database provides 25 years of weather data, including solar radiation, temperature, wind speed, and humidity ranging from 1985 to 2010, and was acquired from Jeddah Regional Climate Center South West Asia [16]. Standard application rates for fertilizers were used to estimate total amounts of fertilizers needed for each crop produced. Working hours in land preparation and maintenance (using machinery and human power) were also assessed based on standards for each hectare and converted into energy equivalents.

The water section in the database was created by estimating water requirements to grow any crop in any location on the map. Potential evaporation from the soil surface and plant transpiration—known as evapotranspiration—was assessed using weather parameters, including net radiation at the crop surface, soil heat flux density, mean daily air temperature, wind speed, saturation vapor pressure, and actual vapor pressure. The evapotranspiration data were used to determine water demand for irrigation and, accordingly, the energy needed to meet this demand.

Evapotranspiration was calculated using the Food and Agricultural Organization (FAO) Penman—Monteith procedure, presented by Allen et al. [17]. This method is regarded as a reliable tool for appropriately assessing the impact of weather conditions on water requirements for crop production. According to this method, evapotranspiration can be expressed as follows:

$$\mathrm{ET}_0 = \frac{0.408\,\Delta\,(R_\mathrm{n} - G) + \frac{900}{(T_\mathrm{a}+273)}\gamma\,U_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34U_2)}$$

where:

$\mathrm{ET_o}$: daily reference evapotranspiration [mm day^{-1}]
R_n: net radiation at the crop surface [MJ m^{-2} day^{-1}]

G: soil heat flux density [MJ m^{-2} day^{-1}]
T_a: mean daily air temperature at 2 m height [°C]
U_2: wind speed at 2 m height [m s^{-1}]
e_s: saturation vapor pressure [kPa]
e_a: actual vapor pressure [kPa]
Δ is the slope of vapor pressure curve [kPa °C^{-1}]
γ is the psychometric constant [kPa °C^{-1}]

The next step was to convert the potential ET_o into actual water requirements based on crop type. Crop coefficients were used to adjust water requirements and to account for the actual crop canopy and aerodynamic resistance relative to the hypothetical reference crop [17]. The crop coefficient serves as an aggregation of the physical and physiological differences between a certain crop and the reference crop. Geostatistical analysis procedures were followed to estimate ET_0 for every cell on a map.

Lastly, the energy section in the database was created to reflect the energy intensity for food production. The amounts of energy required to supply water and distribute it, manufacture fertilizers, prepare the land for planting, including man- and machine power, were calculated.

The main water supply source for agriculture in Saudi Arabia comes from groundwater aquifers [18]. Therefore, the assessment of energy to supply water was based on this fact. A groundwater wells spatial layer was prepared and digitized for the entire country. The depth of each well was assessed for the main aquifers (Fig. 1.1), based on formation type and statistical analysis of data published by the Ministry of Water and Electricity. The energy needed to extract the water down from the well and to deliver it horizontally over a surface was calculated using the following equations:

Vertical Energy [19]

$$WP = \frac{TDH \times Q}{3960}$$

where:

WP = Annual average water power (hp)
TDH = Total Dynamic Head (feet)
Q = Annual average flow rate of well (gallons per minute)
3960 = Unit conversion constant (feet•gallons/minute to horsepower)

In practice, the dynamic head would be a function of the depth to water and also includes a term for friction losses in the piping. To simplify our calculations and make it easier for the user to describe their well system, we calculate dynamic head using the well depth

$$\mathrm{EP} = \mathrm{WP} \times 0.746 \times 1/\mathrm{eff}$$

where:

EP = Electrical power (kW)
WP = Water power (hp)
eff = Overall efficiency of pump and motor system (decimal value, 0–1), assumed eff = 0.5

Horizontal Energy (Bernoulli Equation)

$$P_{\mathrm{p}} = \frac{1}{2}\rho v^2 + \rho.g.h2 - \rho.g.h1 + l_{\mathrm{f}}$$

$$W_{\mathrm{in}} = P_{\mathrm{p}} \times \frac{Q}{\gamma}$$

where:

P_{p}: pump pressure requirements
ρ : density of the fluid [kg/m^3]
v: velocity of the fluid at point 1 [m/s]
g: acceleration due to earth's gravity (9.81) [m/s/s]
h1-2: height (from a given datum) of the fluid at point 1-2 [m]
l_{f}: friction losses
γ: pump efficiency
W_{in}: power requirement in Watts that needs to be supplied to the pump

$$l_f = f\frac{L}{D}\frac{v^2}{2g}$$

where:

f: friction factor
L: length of the pipeline
D: diameter of the pipeline

The second component of this tool is visual interphase. ArcGIS for Desktop 10.3 and ArcGIS Pro environments were used to build a visual tool that allows the user to insert input parameters through a dialog window, select a location of interest, execute the workflow, and display the results of the model on a map and as a tabular data.

The third component is a coding protocol that was built to enable the communication between the developed database and the visual interphase. This code was written using Python 2.7 and by utilizing the ArcPy package. ArcPy is part of the ArcGIS software and provides an efficient way to perform spatial analysis and map automation with Python.

3.3 Land Suitability Classification

The tool was designed to display information on a map that shows different zonings for the potential development of agricultural activities. The map was developed by a land suitability analysis workflow that identifies areas within the country that are much preferable for agricultural activities considering different physical characteristics of the territory, infrastructures, water resources, and energy consumption. These factors are useful for decision-makers to determine the quality of lands for food production and design proper cropping systems based not only on soil characteristics but also on water and energy requirements. The major factors considered were soil type, distance from road network, slope gradient, and land cover. Distance from a water body, average rainfall, depth of wells, and irrigation requirements are additional factors used to determine which areas of land are most proper. The classification of each factor can be shown in Table 3.1.

All the previous factors were converted into energy equivalents to meet crop water demand and land preparation (tillage). GIS, spatial, and statistical analysis techniques were adopted to develop a weighted overlay map. Based on the suitability of each factor for each land use, a weight value was given from 0 (unsuitable/very poorly suitable) to 1 (very suitable). Thereafter, the weight values were used to categorize the whole area of Saudi Arabia into five classes: very suitable, suitable, moderately suitable, poorly suitable, and unsuitable. The process steps are depicted in Fig. 3.1.

Soil color was used as an index of soil fertility and was classified based on [20]. The darker the soil color the less erodible the soil, the fewer fertilizers needed, and more energy will be saved on producing these fertilizers. Lands with a high slope gradient would require higher fuel due to the multiple trips that machinery needs to take to till the land. Additionally, lands with slopes between 0% and 2% will experience a loss in productivity of less than 1% over a 50-year time horizon. The same soils on a 6–12% slope, however, may experience a loss in productivity of 15–20% during a similar time period [21]. The loss in soil productivity is usually treated by adding more fertilizers, especially chemical fertilizers that require substantial amounts of energy to manufacture. Lastly, weather parameters, including precipitation, daily temperature, were also used to determine areas with potential high evaporation rates and, accordingly, higher water requirements and areas with less evaporation.

The input factors and indexes cell values were multiplied by the weight, representing the importance values. The weighted values of each index were reclassified in the input rasters into a common evaluation scale of suitability preference. A weighted overlay map was created by adding the results of each index.

Table 3.1 Suitability classes

Suitability	Soil type	Annual evapotranspiration [mm]	Annual precipitation [mm]	Slope gradient [%]	Land cover	Road distance [km]	Distance to well [km]
Very poorly suitable	Sand	3000–3500	0–75	26–60	Water	125–225	550–810
Poorly suitable	Loam	2500–3000	75–225	15–25	Barren/minimal vegetation	75–125	350–550
Moderately suitable	Sandy loam	2000–2500	225–375	7–15	Shrub/scrub	40–75	200–350
Suitable	Loamy sand	1500–2000	375–525	2–7	Grassland	13–40	80–200
Very suitable	Clay loam	0–1500	525–605	0–2	Agriculture, general	0–13	0–80

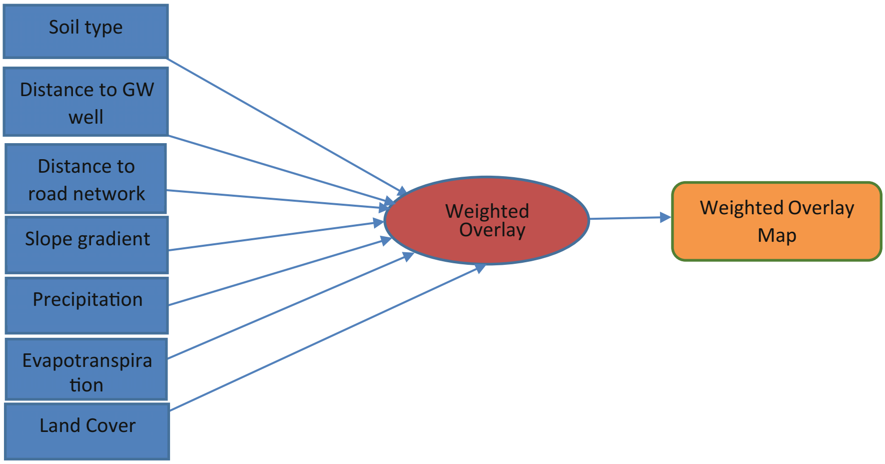

Fig. 3.1 Process for developing a weighted overlay map

3.4 The Decision Support Tool at a Glance

The tool estimates the amounts of energy required for a user-defined scenario to grow crops in the Kingdom of Saudi Arabia. The scenario considers the location of the farm field, the type of crop being grown, the growing month, and the growing stage (Fig. 3.2).

The location of a farm field is selected by the user using a weighted overlay map. This suitability map was created based on overlaid maps for climatic variables, soil characteristics, water resources, land coverage, and access to main roads. The suitability maps for precipitation conditions show that 1%, 2.5%, 3.6%, 48.6%, and 44.4% of lands in Saudi Arabia are located in very suitable (VS), suitable (S), moderately suitable (MS), poorly suitable (PS), and very poorly suitable (VPS) suitability classes, respectively, while the suitability map for soil characteristics indicates that 5.11%, 45.0%, 16.72%, 9.07%, and 24.10% of lands in Saudi Arabia are located in very suitable (VS), suitable (S), moderately suitable (MS), poorly suitable (PS), and very poorly suitable (VPS) suitability classes, respectively. The classification for the additional indexes is shown in Fig. 3.3).

3.4.1 Scenarios and Feeding Input Data

The tool offers four main scenarios to assess the energy requirements to allow food production in Saudi Arabia. These scenarios aimed to provide policymakers with options to direct agricultural activities spatially and temporally in order to minimize energy and water costs. These scenarios are based on the use of weather, soil, distance, and a combination of all factors as shown in Table 3.2. The user of the

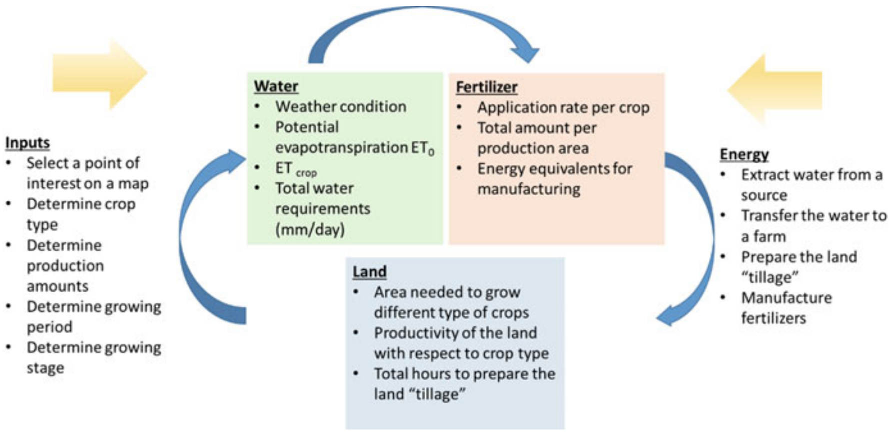

Fig. 3.2 Tool’s inputs, outputs, and the interaction among different components

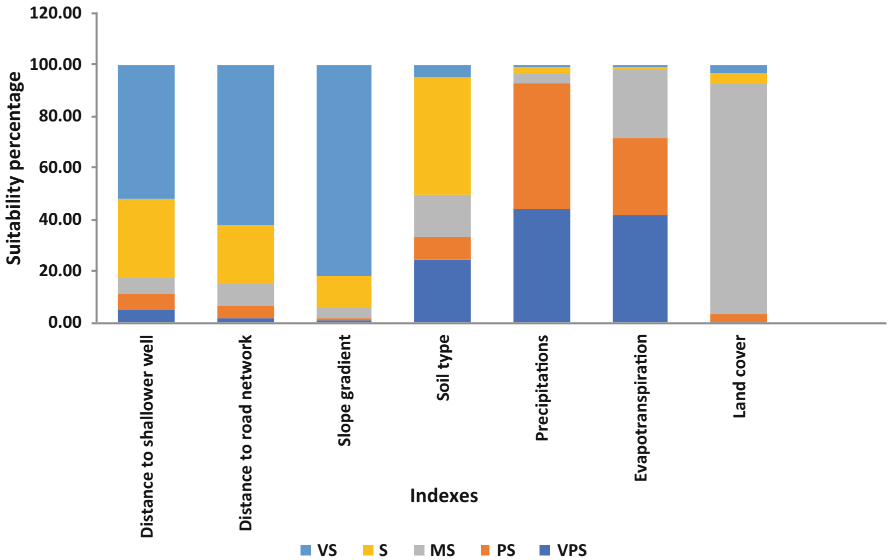

Fig. 3.3 Suitability analysis for different factors. Very suitable (VS), suitable (S), moderately suitable (MS), poorly suitable (PS), and very poorly suitable (VPS)

tool will have the option to choose the proper scenario or select combined scenarios before executing the tool.

For each scenario, an overlay weighted map will be created (Fig. 3.4). Area requirements for food production will be calculated based on land productivity at the province level (hectare/ton). Input data, including crop, water, energy factors, will be called from the local database.

Table 3.2 Scenarios

Scenario	Factors included
1	Soil type, land cover, slope gradient
2	ET, precipitation
3	Road distance and distance to shallower groundwater well
4	Combination of all previous factors

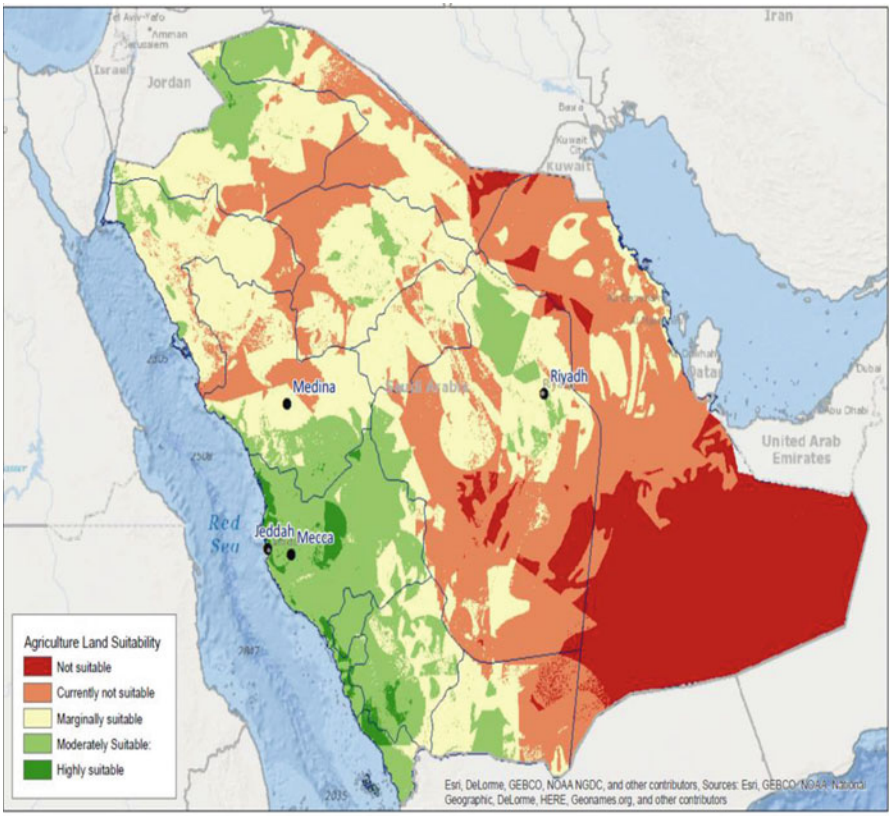

Fig. 3.4 A weighted overlay suitability analysis map for scenario 4. (Source: Authors)

Annual evapotranspiration raster layer will be generated based on weather parameters as in Fig. 3.5. Water requirements for each crop will be estimated in each cell and, accordingly, the energy needed to supply water, manufacture fertilizer and prepare the land will be calculated. Based on the location of a selected farm, potential water supply sources will be identified and optimized based on the depth of a well and distance from a farm.

The factors used to build the four scenarios result in 1392 options (29 crops × 12 provinces × 4 scenarios = 1392) based on 1 point for each province, multiple points

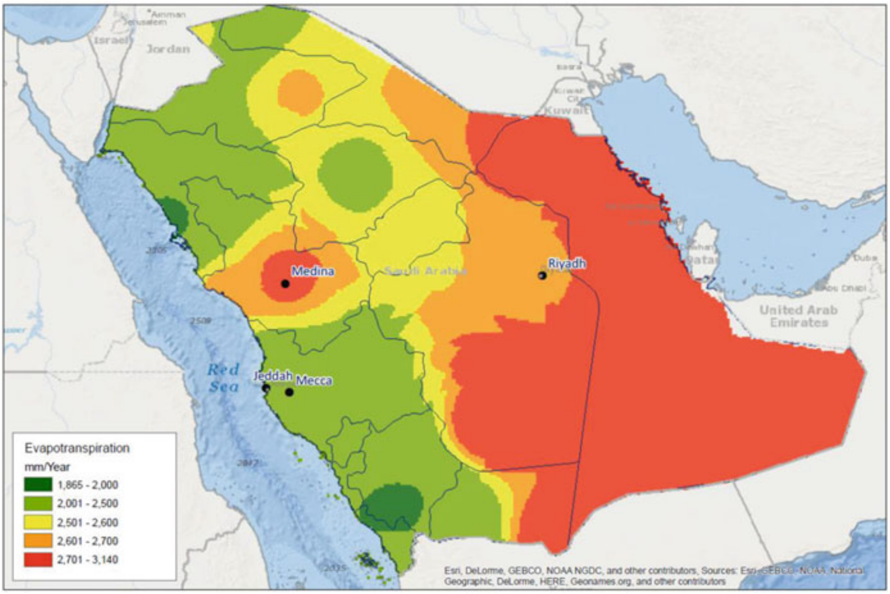

Fig. 3.5 Annual evapotranspiration in Saudi Arabia. (Source: Authors)

in each province can be selected, and this would further increase the number of possible combinations. It is worth noting that these scenarios are built to provide policymakers with insights on potential energy savings in the food sector without compromising food security. Additional factors can be added and integrated based on necessity and geographic specificity.

The output of the tool is divided into four sections. First, it shows the breakdown of energy consumption in food production for the current scenario. The current scenario reflects existing vegetation cover in the Kingdom and actual crop productions per province as were reported by the local ministry of agriculture (Fig. 3.6a, b). Results showed high variations in energy requirements. The highest energy requirements for both crops were for supplying water (extracting water from a supply source, which is groundwater well, and deliver it to a demand point) by 81%, followed by land preparation 10%, and finally manufacturing fertilizers by 9% for a current scenario (Fig. 3.7a, b).

Second, the tool shows the energy consumption for the different scenarios selected. The user can always go back and adjust the selected scenarios and other inputs data and measure the sensitivity for each input.

This example shows a comparison between the developed scenarios: scenario 4, where all factors of analysis are combined, results as the scenario with the least energy requirements. Growing alfalfa by utilizing scenario 4 resulted in an average energy reduction of 27%, 47%, and 43% than scenarios 2, 3, and, 1, respectively. Growing tomato by utilizing scenario 4 resulted in energy reductions equivalent to 5%, 30%, and 15% than scenario 2, 3, and 1, respectively (Figs. 3.7a, b).

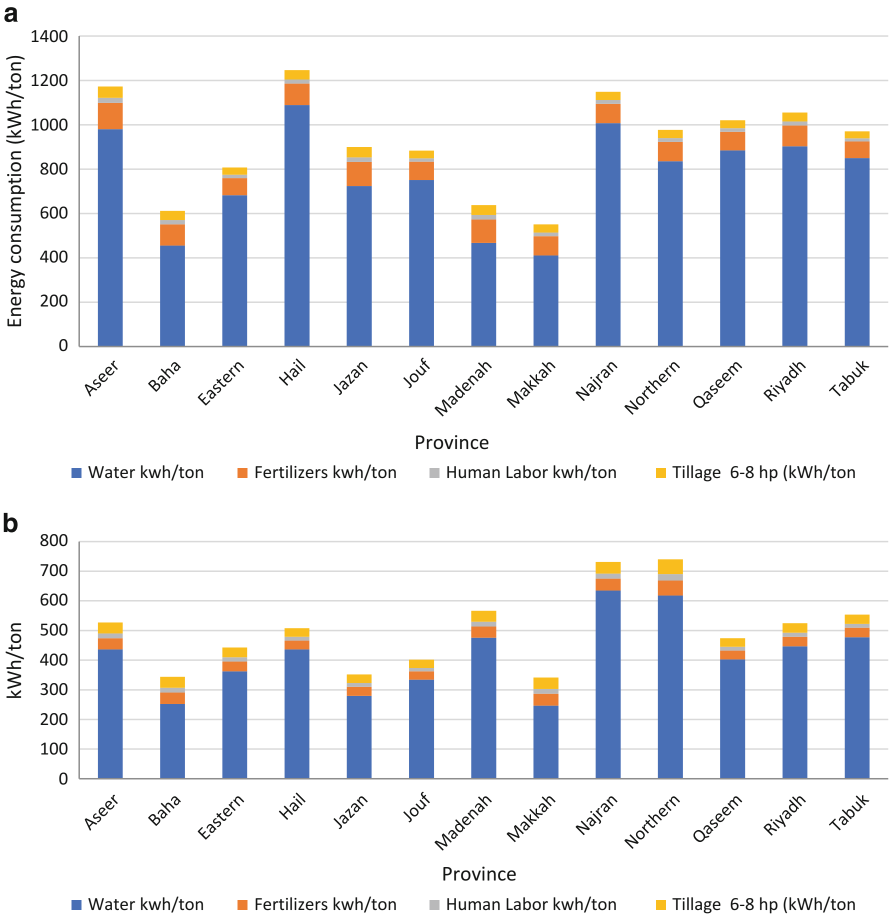

Fig. 3.6 (**a**) Example: distribution of energy consumptions for the production of alfalfa (current scenario). (**b**) Example: distribution of energy consumptions for the production of tomato (current scenario)

Third, the land requirements to grow the different crops will be reported in a tabular format.

Table 3.3 shows how land requirements for tomato and alfalfa production also differ from one province to another.

Fourth, the tool further analyzes the potential CO_2 emission for each kWh being burned by using different sources, fossil fuel, and renewable sources in order to give the user an option to choose a certain technology over another or a mix between available options.

Additionally, understanding the implications of zoning agriculture activities based on soil, weather, water, and energy factors provides policymakers with insights on shifting natural resources policies towards a more comprehensive one.

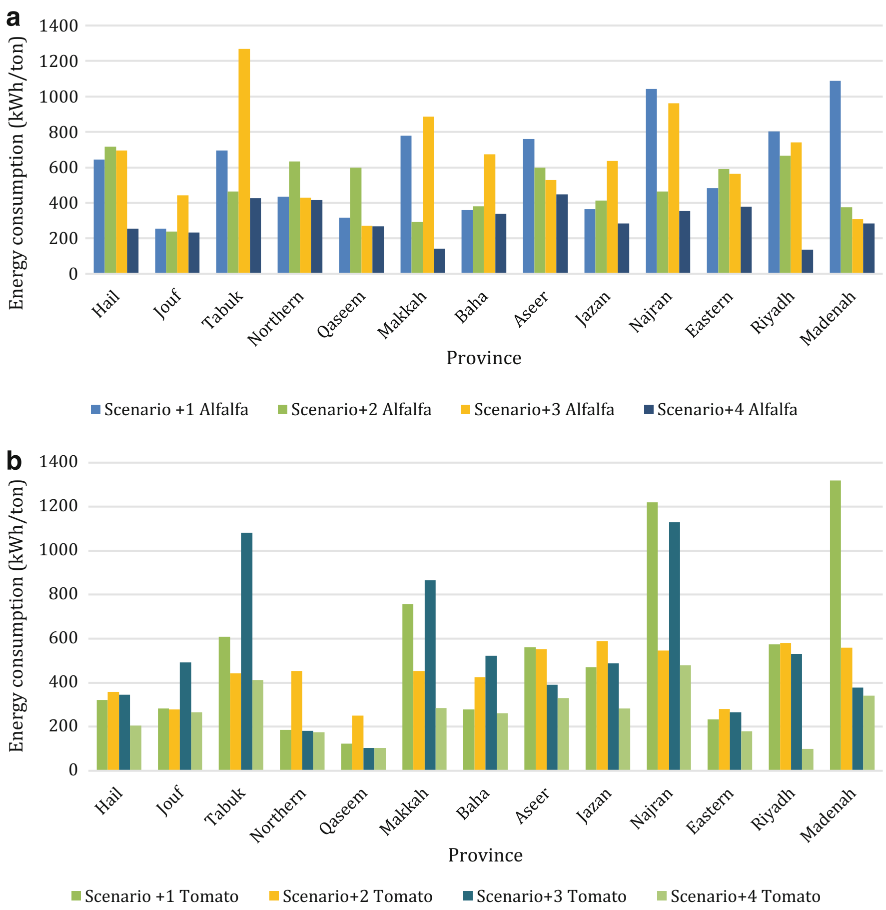

Fig. 3.7 (**a**) Energy consumption for Alfalfa production by utilizing different scenarios. (**b**) Energy consumption for tomato production by utilizing different scenarios

3.5 Conclusions

The scholarly work on the water-energy-food nexus in the last decade has brought the issue to the attention of policymakers who are now working to incorporate it into their institutions and plans. The literature recognizes that there is a great need for more sophisticated modeling approaches to assess the water-energy-food nexus across sectors and actors. Such tools will help policymakers enact evidence-based policies that can achieve sustainability and resource-use efficiency. Additionally, there is a need to study the interlinkages across resource systems spatially and

Table 3.3 Land requirements for alfalfa and tomato production in Saudi Arabia

	Land requirements (HA/Ton)	
Province	Alfalfa	Tomato
Northern	76.92	25.24
Jouf	42.46	36.82
Tabuk	47.72	33.54
Madenah	57.18	56.14
Makkah	59.64	47.41
Baha	57.54	36.31
Aseer	57.03	34.47
Jazan	45.37	47.66
Najran	60.56	58.16
Riyadh	48.80	27.80
Qaseem	45.23	13.98
Hail	45.37	17.86
Northern	76.92	25.24
Eastern	50.95	19.10

temporally as many of the nexus' parameters change over time and space. Providing a systematic, quantitative assessment of energy consumption in both water and food systems at a country level offers a chance to explore the broader implications related to environmental and future planning and provide various policy options.

This study developed a spatial-temporal decision-support tool that provides a great asset to analyze multi-sectoral layers of data spatially and quantitatively. It also provides reliable estimates of energy requirements for crop production. Additionally, the tool offers to policymakers the opportunity to adjust energy demand on a local and national level using a range of suitability analyses scenarios. The tool could help the users in selecting different types of energy sources to meet the demand for food production based on global greenhouse gas emission requirements in general and CO_2 emission, in specific. Significant savings in water and energy can be attained by considering a range of potential future scenarios for growing crops.

Additionally, understanding the implications of zoning agriculture activities, based on soil, weather, water, and energy factors, provides policymakers with insights on shifting natural resources policies towards a more comprehensive one.

Results from the KSA study demonstrate that increasing the number of trade-offs policymakers are able to consider when seeking to balance food security goals and wider supply, and demand of water/energy can deliver significant savings in water and energy. For instance, growing alfalfa by utilizing scenario 4 resulted in an average energy reduction of 27%, 47%, and 43% than scenario 2, 3, and 1 respectively. Growing tomato by utilizing scenario 4 resulted in energy reductions equivalent to 5%, 30%, and 15% than scenarios 2, 3, and 1, respectively.

This study should help the policymaking process through its findings in the following areas:

- The developed decision-support tool offers reasonable estimates of energy and water consumption over space and time for different crops.
- The tool demonstrates how policy decisions taken by any institution affect other aspects of the water energy food nexus.
- The tool offers a mechanism to assess different scenarios of water and energy intensity, which can be used to inform decision-making by diverse actors (including policymakers from diverse ministries) in the agricultural sector.
- These capacities will support policy development and implementation of effective Water Energy Food policy for arid climate regions at local, regional, or national levels. Also, the tool supports the design of cost-effective policies by setting multiple objectives targeting several resources across sectors.
- The tool encourages multi-context stakeholder engagement, so emerging solutions find greater acceptance across the sectors.

Appendix: Land Suitability Analysis

- Hundred Landsat 8 satellite scenes covering all of Saudi Arabia for the month of June and July 2015 have been downloaded from USGS and processed in ArcGIS 10.3 environment.
- Satellite imagery was georeferenced. Color enhancement was done in such a way to be able to digitize various sections and features of the land layer.
- The Normalized Difference Vegetation Index (NDVI) procedures were applied to assess whether the target being observed contains live green vegetation or not.
- The next step was to classify the imagery into two main classes; vegetated and not- vegetated. This was followed by vectorization, which involves the conversion of raster data to vector by digitization.
- Street and residential layers were placed on the top of the analyzed imagery layer. Points of intersections were exported to exclude potential future agriculture activities where residential and paved streets took place.
- DEM layer was generated and slopes were calculated all over the topography to determine hilly and flat areas.
- Potential new agricultural areas were determined based on closeness to water sources, distance from the road network, soil cover, soil type, and land productivity.

Example: monthly crop water requirements for different cities in Saudi Arabia (Fig. 3.8).

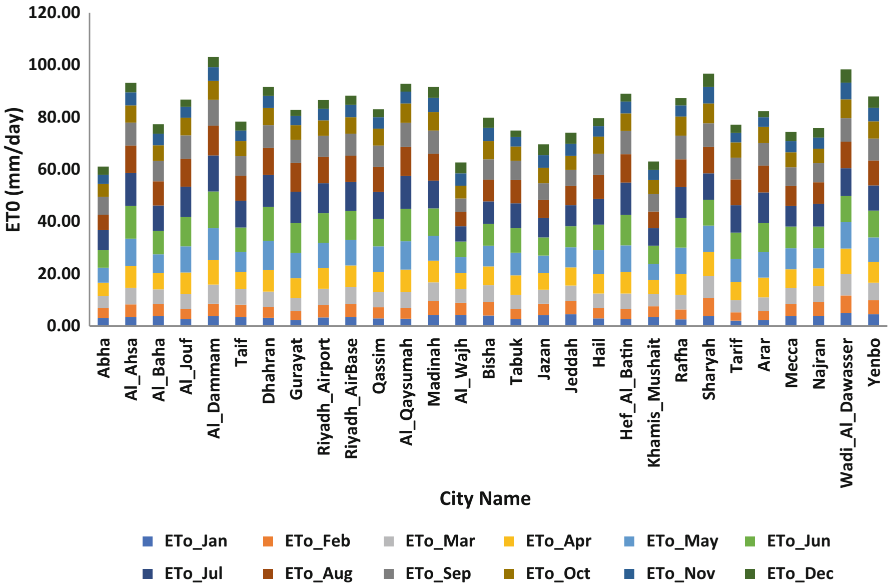

Fig. 3.8 The spatial distributions of monthly ET_0 values

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Chapter 4
Design of Integrated Palm Oil Based Complex via Food-Energy-Water Nexus Optimization Framework

Yue Dian Tan, Jeng Shiun Lim, and Sharifah Rafidah Wan Alwi

4.1 Introduction

Palm oil has been playing a prominent role in satisfying global food demand; it contributed to 34% of the global vegetable oil market in 2017 [1]. Malaysia, as the second largest palm oil exporting country [2], has produced and exported 19.92 and 16.56 M t of palm oil respectively in 2017 [3]. As of 2017, 454 operating palm oil mills (POMs) were reported in Malaysia [4]. Nonetheless, there is a great concern about sustainability of palm oil production in terms of waste generation, greenhouse gas (GHG) emission, land security, and freshwater scarcity. First, conventional palm oil milling practices generate an enormous amount of effluent termed palm oil mill effluent (POME) which is a great source of water pollution. The traditional anaerobic digestion (AD) treatment for POME is economically satisfying but results in another environmental burden due to the emission of biogas consisting of 60–65% methane from the anaerobic pond. The national strategies in tackling this issue include energy recovery from biogas capture and POME composting [5]. However, the unattractive investment cost associated with both strategies requires support from resource utilization and integration optimizations to enhance their economic feasibility.

The abundant biomass waste such as empty fruit bunches (EFB), palm mesocarp fiber (PMF), and palm kernel shells (PKS) creates opportunities for value-added product conversion such as biofuel, palm pellets, palm briquettes, bio-oil to increase POM profit. The concept of an integrated biorefinery is thus applied for the optimization of palm-based resource allocation within a POM. In previous optimization works for palm-based integrated biorefineries, various energy recovery applications

Y. D. Tan · J. S. Lim (✉) · S. R. Wan Alwi
Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
e-mail: ydtan2@graduate.utm.my; jslim@utm.my; Syarifah@utm.my

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of trapped biogas were considered to improve the rate of biogas plant investment while minimizing environmental impacts. Despite support from optimization studies, the progress of nationwide implementation of the mentioned methane mitigation approaches is still unsatisfying. According to a survey, less than 25% and 18% of Malaysian POMs have installed effective biogas plants and composting plants respectively across 13 years [6]. This scenario suggests the need to provide more alternative options for POM owners to participate in methane mitigation due to the operation complexity and high capital expenditure (CAPEX) of biogas plants. In this study, POME elimination is proposed to be considered in POM design as an alternative POME treatment strategy. Instead of recovering energy from generated POME via biogas capturing, eliminating, and minimizing POME generation via palm oil processing route optimization within a POM could be more effective [7]. The POME eliminated POM configuration is adapted from the undiluted clarification process [8] and POME evaporation technology [9] presented by previous researchers.

Therefore, it is desired to optimize the process configuration of a POM in consideration of POME reduction and elimination strategies as well as conventional POME generating process pathways to consider the opportunity for biogas applications. As mentioned before, biomass utilization provides profitability enhancement for POMs and has been considered in previous biorefinery optimization work. Further integration opportunities such as material, waste, and utility exchange between POM and palm oil refineries (PORs) in the form of industrial symbiosis are also beneficial in improving company profit margins, palm oil quality, and food safety. According to literature, previous optimization works for palm-based biorefineries and an integrated complex focused on biomass utilization, biogas applications, and material integration between facilities. For example, Ng et al. (2013) have demonstrated a systematic framework in synthesizing an integrated palm oil processing complex (POPC) that achieves material exchange between a POM, a refinery, a palm-based biorefinery, and a cogeneration system as individual blocks [10]. A flexibility optimization model was developed by Kasivisvanathan et al. (2016) for retrofitting a POM into an integrated biorefinery with demand uncertainties [11]. To date, no work has yet considered the POME evaporation technique and its water and waste integration opportunities within the POM as well as between the POM and a POR in the optimization of a palm oil processing complex. Therefore, an integrated palm oil based complex (POBC) is presented as a new conceptual zone of the palm oil processing complex with optimized material, waste, and utility exchange between POM and POR with consideration of POME elimination processing routes.

Recently, there has been increasing attention in considering possible synergies between food, energy, and water resources by incorporating a food-energy-water (FEW) nexus in the optimal planning of the food production system [12]. As the palm oil industry is a great contributor to the global food market, the integration of the FEW nexus within the industry is significant to ensure sustainable development of this sector [13]. The challenges of incorporating the FEW nexus in optimization of a processing complex lies in the trade-off evaluation between food production, energy consumption, and freshwater security. For example, palm-based biomass conversion into biofuel is advantageous in terms of energy recovery but results in undesirable water footprint. The integration of the FEW nexus in the proposed POBC requires decision making between POME generation and elimination approaches; this integration is essential due to the potential impacts on FEW nexus synergies by both POME management approaches. Hence, a multi-objective optimization tool is required to perform a trade-off evaluation between the high energy value of biogas generated from POME, recycling of evaporated POME for freshwater substitution, potential oil product recovery via POME reduction, improved refined palm oil production from integrated POR and other possible synergies to optimize the POM configuration. Modeling optimization attempts with FEW nexus considerations is still limited. Zhang and Vesselinov (2017) proposed an integrated multi-period modeling framework to evaluate trade-offs between economic advantage, food supply, energy supply, and water consumption for hypothetical FEW problems [14]. The study of López-Díaz resulted in a mixed integer linear programming (MILP) optimization model to optimize a biofuel production system in consideration of the FEW nexus [15]. Recently, Loh et al. (2019) conducted an experimental-based study to investigate the FEW nexus aspects of using POME as an organic fertilizer for vegetative crops [5]. There is limited work on FEW nexus considerations in the palm oil complex optimization study.

This chapter aims to present an optimization-based systematic framework to design an integrated palm oil based complex (POBC) with food-energy-water nexus (FEW) integrations. A fuzzy optimization approach is applied to solve the multi-objective optimization problem for the POBC design to achieve maximum satisfaction between economic objectives and FEW evaluation criteria. The FEW nexus considerations of the POBC planning are reflected as multiple optimization objectives: maximum food product revenue, maximum net electricity balance, minimum external heat supply, and minimum freshwater consumption. The fuzzy multi-objective optimization model developed is capable of integrating multiple objectives into a single parameter using an overall degree of satisfaction (λ). The optimum process configuration as well as material, water, waste, and energy allocation network for the POBC is determined via the proposed approach.

This chapter is organized as follows: Sect. 4.2 proposes the problem statement. The mathematical formulation is then provided in Sect. 4.3. In Sect. 4.4, an illustrative case study is solved using the proposed framework and the results are discussed in Sect. 4.5. Sect. 4.6 provides the conclusion of this chapter.

4.2 Problem Statement

A palm oil enterprise operates a POM with 60 t/h capacity of fresh fruit bunches (FFB) supplied by its oil palm plantation. Crude palm oil (CPO) is extracted from FFB via a series of palm oil milling processes as the main product of the POM. By-products such as empty fruit bunches (EFB), palm kernel (PK), palm mesocarp fiber (PMF), palm kernel shells (PKS), and decanter solid, can either be sold directly to the market or utilized for utility generation. The thermal energy and electricity required by the mill can be imported or supplied by a conventional heat and power (CHP) system consisting of a biomass boiler and a steam turbine using PMF and PKS as boiler fuel. POME generated from the POM is conventionally treated in an anaerobic ponding system.

Due to Malaysia's methane avoidance policy, the enterprise is required to retrofit the POM with methane mitigation strategies. The configuration of the retrofitted POM can be decided based on two types of POME management approaches, POME utilization or POME elimination.

In the POME utilization pathway, POME generated from sterilization, diluted clarification, and kernel separation processes will be treated in an anaerobic digester tank to produce biogas before delivering POME to the treatment plant. Biogas applications for selection include on-site electricity generation via a gas engine, on-grid biogas power plant, and co-firing with biomass for utility generation. The revenue from the on-grid biogas power plant is based on Malaysian feed-in tariff (FiT) rates.

For the POME eliminated configuration, POME evaporation and solvent extraction units are required, and an undiluted clarification method is applied to the existing clarification unit. POME from each unit is fed into the undiluted clarification unit and subsequently, the evaporation unit to achieve zero effluent discharge. The process condensate exits from the POME evaporation unit (double-effect evaporator) and can be regenerated as water utility via boiler feedwater treatment. The process concentrate is further processed into decanter solid after oil recovery via solvent extraction. External water demand for steam generation is supplied by the nearest river source.

The palm oil enterprise also operates a POR with a production demand of 10 t/h refined, bleached, deodorized palm olein (RBDPOL) as the main product; and refined, bleached, deodorized palm stearin (RBDPS) and palm fatty acid distillate (PFAD) as by-products. The POR plant includes physical refining processes and fractionation technology to process CPO purchased from external sources. The CPO produced from the mill can be directly fed into the POR for refined palm oil products production to improve the profit margin. The water, steam, and electricity demand of POR can be supplied by the CHP system in the retrofitted POM. The palm oil refinery effluent (PORE) generated from the POR can be treated via POME elimination technology in the POM or sequential batch reactor (SBR) before being sent to the effluent treatment plant. The superstructure for the POBC design is as illustrated in Fig. 4.1.

Given a set of resources *i* and potential technologies *p* for palm oil milling and refining (*y1* POME elimination and *y2* POME generation configuration), POME management strategies, biomass-to-energy conversions and biogas applications, economic data (technology capital and processing cost, resource cost, utility cost, and product price), process and operating data for each technology (conversion yield, capacity, utility, and material requirement), the problem consists of evaluating: (a) the product portfolio and pathway selection of a FEW nexus integrated POBC; (b) overall economic performance in terms of economic potential; (c) total

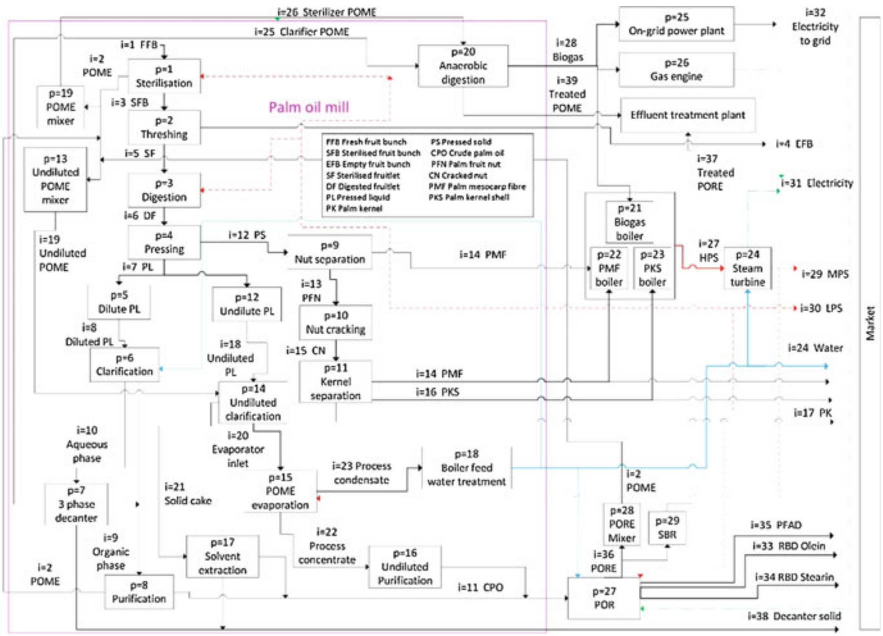

Fig. 4.1 Superstructure for POBC case study

food product revenue; (d) electricity generation; (e) external heat consumption; and (f) freshwater consumption. The optimization objective is to trade-off all objectives simultaneously via fuzzy optimization. The generic superstructure for the material balance is as shown in Fig. 4.2.

4.3 Problem Formulation

Based on Fig. 4.2, set p denotes the type of process whereas set i denotes the type of resource considered in the model. The amount of resource RES_i existing in the system can be either the total self-generated resource $\mathrm{SGRES}_{i,p}$ produced from different processes p, or the total external resource EXRES_i imported, as shown in Eq. (4.1). Subsequently, these resources can be utilized by the system as feed resource $\mathrm{MAT}_{i,p}$ for each specific process or sold to the market as product PRO_i, as represented by Eq. (4.2).

$$\mathrm{RES}_i = \sum\nolimits_p \mathrm{SGRES}_{i,p} + \mathrm{EXRES}_i \quad \forall i \tag{4.1}$$

$$\mathrm{RES}_i = \sum\nolimits_p \mathrm{MAT}_{i,p} + \mathrm{PRO}_i \quad \forall i \tag{4.2}$$

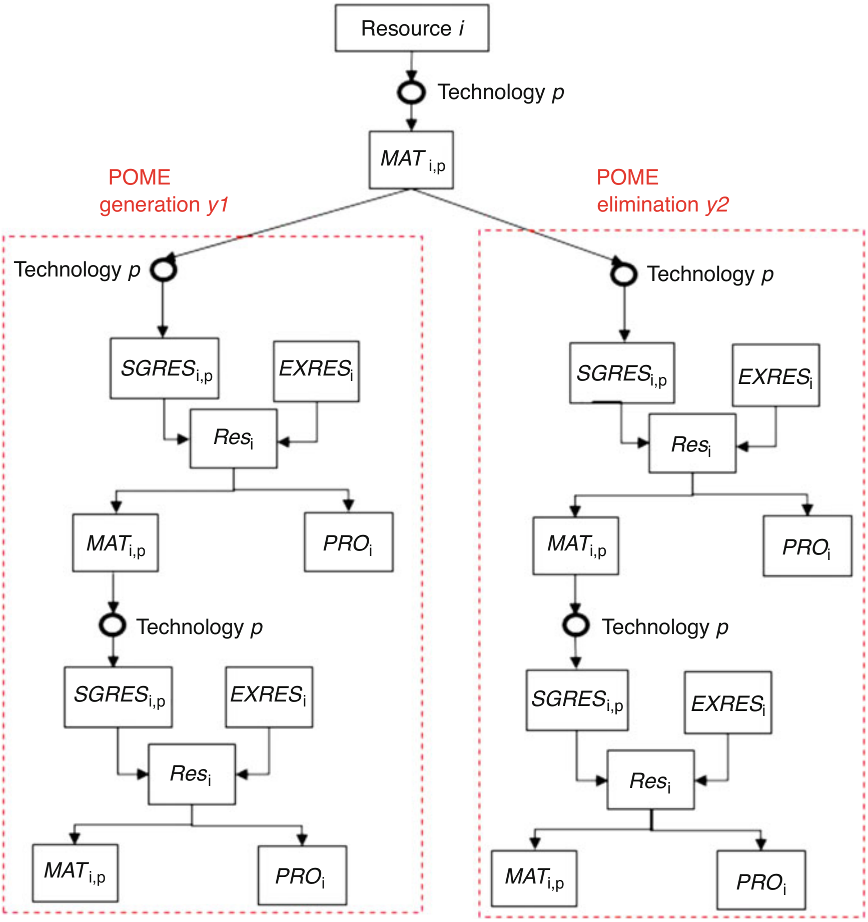

Fig. 4.2 Generic superstructure for POBC material allocation

The intermediate resource indicator BYIND_i is assigned as a binary parameter to ensure that certain intermediate products from specific processes are fully consumed by the subsequent process. BYIND_i is declared as 0 for the intermediate resources. Equation (4.3) is declared to ensure that the intermediate resource is not retained in the system as a product where an infinitely large value, 1000, is multiplied with the binary parameter to perform linearization.

$$\mathrm{PRO}_i \leq 1000 \times \mathrm{BYIND}_i \quad \forall i \tag{4.3}$$

Equations (4.4) and (4.5) represent the limiting constraints for product demand and external resources. The amount of product PRO_i should not be less than the designated product demand DEMPRO_i whereas the quantity of external resource

$EXRES_i$ should not be more than the resource availability $AVRES_i$. To ensure that the POM is operating at the expected capacity, $RES_{i=1}$, the amount of resource ($i = 1$) processed in the system should not be less than the amount of available resources, $AVRES_i$ as described in Eq. (4.6).

$$DEMPRO_i \leq PRO_i \ \ \forall i \tag{4.4}$$

$$EXRES_i \leq AVRES_i \ \ \forall i \tag{4.5}$$

$$AVRES_i \leq RES_i \ \ \forall i = 1 \tag{4.6}$$

The quantity of resource i fed into process p, $MAT_{i,p}$, is determined by the material conversion matrix $MCM_{i,p}$ and the total amount of the resource fed into process p, $PRES_p$, as shown in (Eq 4.7). Equation (4.8) describes the conversion of the total fed resource to self-generated resource $SGRES_{i,p}$ from the respective process based on the process resource conversion matrix, $PRCM_{i,p}$ [16].

$$MAT_{i,p} = MCM_{i,p} \times PRES_p \ \ \forall i \forall p \tag{4.7}$$

$$SGRES_{i,p} = PRCM_{i,p} \times PRES_p \ \ \forall i \forall p \tag{4.8}$$

The number of process units cap_p assigned for each process p is based on the limiting design capacity $descap_p$ of certain reference resource, i associated with each process p as shown in Eq. (4.10). With reference to Eq. (4.9), the binary indicator $yref_{i,p}$ identifies the reference resource and is assigned the value 1 if the amount of feed resource $MAT_{i,p}$ or self-generated resource $SGRES_{i,p}$ limits the capacity process p.

$$capres_p = \sum\nolimits_i \left(yref_{i,p} \times MAT_{i,p}\right) + \sum\nolimits_i \left(yref_{i,p} \times SGRES_{i,p}\right) \ \ \forall p \tag{4.9}$$

$$cap_p \times descap_p \geq capres_p \ \ \forall p \tag{4.10}$$

$y1$ and $y2$ are the binary variables to choose POME generation or POME elimination pathway respectively. Take note that for the POBC model, the selection of specific technologies and material flow depends on the type of POME management approach decided as illustrated in Fig. 4.2. In order to achieve this limitation, Eqs. (4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, and 4.22) are declared to ensure that the feed resource for each POME generation configured or POME elimination configured process is only consumed for either one pathway. In Eqs. (4.11, 4.12, 4.13, and 4.14), UDPLFLOW is the total amount of undiluted PL ($i = 18$) converted from POME via the undiluted process ($p = 12$), therefore it is multiplied with $y2$, whereas the amount of diluted PL ($i = 8$), produced via PL dilution process ($p = 5$) for the POME generation milling configuration is multiplied with $y1$. Similarly, UDPOMEFLOW, the amount of undiluted POME ($i = 19$) generated from undiluted POME mixing ($p = 13$) that will be treated in the POME elimination pathway and POMEFLOW, the amount of sterilizer POME

($i = 26$) converted from POME mixing ($p = 19$) which will be fed to the digester are assigned to $y2$ and $y1$ respectively in Eqs. (4.15, 4.16, 4.17, and 4.18). In terms of waste integration, the PORE generated from palm oil refinery can only be fed into the POME elimination considered process pathway, otherwise it will be treated via SBR. Hence, the amount of POME converted from PORE, POMEMIXFLOW is multiplied by $y2$ whereas the amount of PORE treated by SBR POREFLOW is multiplied by $y1$ as represented by Eqs. (4.19, 4.20, 4.21, and 4.22). Due to the multiplication of positive variables and binary variables, linearization is performed by multiplying the binary variables with a large value to avoid complexity.

$$\text{UDPLFLOW} = \text{SGRES}_{i=18,p=12} \tag{4.11}$$

$$\text{UDPLFLOW} \leq 1000 \times y2 \tag{4.12}$$

$$\text{DPLFLOW} = \text{SGRES}_{i=8,p=5} \tag{4.13}$$

$$\text{DPLFLOW} \leq 1000 \times y1 \tag{4.14}$$

$$\text{UDPOMEFLOW} = \text{SGRES}_{i=19,p=13} \tag{4.15}$$

$$\text{UDPOMEFLOW} \leq 1000 \times y2 \tag{4.16}$$

$$\text{POMEFLOW} = \text{SGRES}_{i=26,p=19} \tag{4.17}$$

$$\text{POMEFLOW} \leq 1000 \times y1 \tag{4.18}$$

$$\text{POMEMIXFLOW} = \text{SGRES}_{i=2,p=28} \tag{4.19}$$

$$\text{POMEMIXFLOW} \leq 1000 \times y2 \tag{4.20}$$

$$\text{POREFLOW} = \text{SGRES}_{i=37,p=29} \tag{4.21}$$

$$\text{POREFLOW} \leq 1000 \times y1 \tag{4.22}$$

The electricity demand of technology is based on the number of process units installed. The total electricity demand in MWh, ELECDEM, is obtained by multiplying unit power demand, UELECDEM_p for each technology with cap_p as described in Eq. (4.23). In Eq. (4.24), the excess power generated, EXCESSELEC and overall electricity demand, ELECDEM are balanced by system-generated electricity $\text{PRO}_{i\,=\,31}$ and external power purchased EXELEC. The electricity revenue and cost are calculated by multiplying with the respective price and cost as shown in Eqs. (4.25 and 4.26).

$$\text{ELECDEM} = \sum\nolimits_p \left(\text{UELECDEM}_p \times \text{cap}_p\right) \tag{4.23}$$

$$\text{ELECDEM} + \text{EXCESSELEC} = \text{EXELEC} + \text{PRO}_{i=31} \tag{4.24}$$

$$\text{ELECREV} = \text{EXCESSELEC} \times \text{ELECPRICE} \tag{4.25}$$

$$\text{ELECCOST} = \text{EXELEC} \times \text{URCOST}_{i=31} \tag{4.26}$$

In this study, the economic evaluation of the fuzzy multi-objective model is presented in the form of economic performance EP as described in Eq. (4.27). Note that a positive EP value indicates an economically feasible design [17]. The capital recovery factor, crf is included to annualize capital costs based on the operation lifespan. Gross profit GP, total capital cost CAPEX, and process operating costs OPEX can be calculated using Eqs. (4.28, 4.29, and 4.30). Economic parameters such as annual operating hours AOT, unit processing cost UOPEX_p, unit capital cost UCAPEX_p, unit product price PRICE_i, and unit material cost URCOST_i are based on case study.

$$\mathrm{EP} = \mathrm{GP} - \mathrm{CAPEX} \times \mathrm{crf} \tag{4.27}$$

$$\begin{aligned} \mathrm{GP} = \mathrm{AOT} \times \Big(\textstyle\sum_i \mathrm{PRO}_i \times \mathrm{PRICE}_i - \sum_i \mathrm{EXRES}_i \\ \times\ \mathrm{URCOST}_i + \mathrm{ELECREV} - \mathrm{ELECCOST}\Big) - \mathrm{OPEX} \end{aligned} \tag{4.28}$$

$$\mathrm{CAPEX} = \sum_p \mathrm{cap}_p \times \mathrm{UCAPEX}_p \tag{4.29}$$

$$\mathrm{OPEX} = \sum_p \mathrm{cap}_p \times \mathrm{UOPEX}_p \tag{4.30}$$

The FEW nexus evaluations of the POBC design can be reflected as multiple optimization objectives: food product revenue, net electricity balance, external heat demand, and freshwater consumption [14]. From the viewpoint of FEW nexus, the production of food should be prioritized in the resource value chain due to the forever increasing global food demand to satisfy the expanding population. The food production of the POBC is thus presented in the form of food product revenue denoted as FREV and calculated as the total revenue generated from refined palm oil products including RBDPOL, RBDPS, and PFAD as described in Eq. (4.31). In order to specify the products that should be considered for food product revenue, a binary parameter FIND_i is assigned to each resource i as the food product indicator. FIND_i is declared as 1 for refined palm oil products.

$$\mathrm{FREV} = \sum_i \mathrm{PRO}_i \times \mathrm{PRICE}_i \times \mathrm{FIND}_i \tag{4.31}$$

Two optimization criteria are considered for the energy aspect in the FEW nexus integrated POBC: the net electricity balance and the net heat demand. The utilization of biogas for heat energy and electricity generation is favorable in reducing fossil fuel consumption and generating renewable energy. The installation of the on-grid biogas plant can also provide regional electricity supply. On the other hand, the advantages of POME eliminated technologies are associated with additional energy demand and loss of opportunity to generated electricity from biogas. The net electricity balance of the POBC denoted as ELECBAL can be defined as the amount of excess electricity after fulfilling the electricity demand of the POBC. The negative value of ELECBAL indicates that external electricity is required whereas a positive value represents net electricity generation. Eq. (4.32) describes the calculation for

ELECBAL, which is the deduction of imported electricity EXELEC from the summation of excess on-site electricity EXCESSELEC and on-grid electricity ($i = 32$) supplied by biogas power plant $\text{PRO}_{i\,=\,32}$. Besides electricity, the resources in the POBC are also eligible for thermal energy recovery via specific boilers in the CHP system. Hence, it is also desired to evaluate the heat energy efficiency of the POBC in terms of net heat demand HEATDEM, as shown in Eq. (4.33), which equals the total amount of external LPS ($i = 30$) and MPS ($i = 29$) purchased. The higher the value of HEATDEM, the lower the energy efficiency of the POBC as more steam is to be imported to satisfy the unmet heat demand.

$$\text{ELECBAL} = \text{PRO}_{i=32} + \text{EXCESSELEC} - \text{EXELEC} \tag{4.32}$$

$$\text{HEATDEM} = \text{EXRES}_{i=29} + \text{EXRES}_{i=30} \tag{4.33}$$

The last element of the FEW nexus to be optimized in the POBC design is the freshwater consumption that can be defined as the external water demand for the POBC as presented in Eq. (4.34). The trade-offs between water security and other aspects require adequate evaluation to decide the optimal configuration of the POBC to be POME generation or POME elimination based, due to the differences in water consumption patterns and recycling possibilities. Moreover, high energy generation from biomass and biogas comes with high water footprint.

$$\text{WDEM} = \text{EXRES}_{i=24} \tag{4.34}$$

A fuzzy multi-objective optimization is an approach with the ability to integrate multiple objectives into a single parameter using an overall degree of satisfaction (λ) which is introduced by Zimmermann (1978) and bounded within the interval of 0–1 to satisfy multiple objective functions [18]. λ can be referred to as a membership function that determines whether the solution is near the predefined fuzzy optimized value (fuzzy goal) of each objective function obtained by maximizing or minimizing the objective functions. When λ approaches 1, the value of the objective function approaches the optimal solution with respect to the objective function. In order to evaluate the trade-offs between the multiple economic and FEW nexus integrated objectives, λ which represents the degree of satisfaction, is maximized as the optimization objective of the fuzzy multi-objective optimization model by integrating with the fuzzy constraints formulated from each optimization criterion using predefined upper and lower limits in Eqs. (4.35, 4.36, 4.37, 4.38, 4.39, and 4.40):

$$\frac{\text{EP} - \text{EP}^{\text{L}}}{\text{EP}^{\text{U}} - \text{EP}^{\text{L}}} \geq \lambda \tag{4.35}$$

$$\frac{\text{FREV} - \text{FREV}^{\text{L}}}{\text{FREV}^{\text{U}} - \text{FREV}^{\text{L}}} \geq \lambda \tag{4.36}$$

$$\frac{\text{ELECBAL} - \text{ELECBAL}^{\text{L}}}{\text{ELECBAL}^{\text{U}} - \text{ELECBAL}^{\text{L}}} \geq \lambda \tag{4.37}$$

$$\frac{\text{HEATDEM}^{\text{U}} - \text{HEATDEM}}{\text{HEATDEM}^{\text{U}} - \text{HEATDEM}^{\text{L}}} \geq \lambda \tag{4.38}$$

$$\frac{\text{WDEM}^{\text{U}} - \text{WDEM}}{\text{WDEM}^{\text{U}} - \text{WDEM}^{\text{L}}} \geq \lambda \tag{4.39}$$

$$0 \leq \lambda \leq 1 \tag{4.40}$$

EP^U and EP^L are the upper and lower limits of the economic objective EP, $FREV^U$ and $FREV^L$ are the upper and lower limits of the food productivity objective FREV; $ELECBAL^U$ and $ELECBAL^L$ are the upper and lower limits of the electricity generation objective ELECBAL, $HEATDEM^U$ and $HEATDEM^L$ are the upper and lower limits of the heat demand objective HEATDEM; whereas $WDEM^U$ and $WDEM^L$ are the upper and lower limits of the freshwater consumption objective WDEM. It is assumed that the upper and lower limits of each optimization objective are predefined as the maximum and minimum values obtained by solving the model with respect to the following objective functions:

- Maximize EP
- Maximize FREV
- Maximize ELECBAL
- Minimize HEATDEM
- Minimize WDEM

Take note that in order to obtain the predefined upper and lower limits for the FEW nexus evaluation criteria, the model is solved with respect to each FEW nexus integrated objective subject to an additional non-negativity constraint for EP as presented in Eq. (4.41). This is to ensure the economic feasibility of the optimal POBC design towards FEW nexus satisfactions.

$$\text{EP} \geq 0 \tag{4.41}$$

4.4 Case Study

The developed model was applied to a case study based on information collected from literature, a technology provider, and the Malaysian palm oil industry. In this case study, a palm oil enterprise in Malaysia is interested in retrofitting an operating POM into the proposed POBC to achieve methane mitigation and perform integration with its existing POR that produces RBDPOL as its main product, and RBDPS and PFAD as by-products. As mentioned in the previous section, FFBs obtained from the plantation are converted into products CPO and PK in a POM. Steam, electricity, and water are consumed as utilities for both the mill and the refinery. EFB, PMF, PKS, decanter solid, etc. are generated as POM by-products. The synthesis of POBC aims to integrate a POM with an operating capacity of 60 t/h FFB for 12 h daily with a POR that originally satisfied the product demand of RBDPOL at 10 t/h. The operational life span of the POBC is assumed to be 15 y; hence, the capital recovery rate, crf is 0.096. The annual operating hour for the POM is 4350 h/y. The superstructure for the case study is illustrated in Fig. 4.1. From the previous discussion, the POM consists of several unit operations that can be selected based on two pathways: 1) POME generation or 2) POME elimination pathway. Note that only one type of pathway configuration can be chosen for the optimal design of POBC. The type of POBC configuration also affects the integration pattern and resource allocation network between the POM and POR. Thus, it is important to screen the pathways to synthesize an optimal POBC configuration for the enterprise. Tables 4.1, 4.2, and 4.3 provide the important technology and resource data considered in this case study.

4.5 Results and Discussion

The case study is solved by the developed mixed integer linear programming (MILP) model and optimized in the General Algebraic Modelling System (GAMS) software (version 24.7.4) using the CPLEX solver (12.6.3.0). In order to evaluate the feasibility of POBC in terms of the economic and FEW nexus viewpoints, six scenarios are studied. In Scenario 1, an existing POM is retrofitted into the proposed POBC structure to avoid methane emission subject to maximum economic potential. To integrate the study of the FEW nexus in the POBC optimization, the following scenarios including maximizing food production (Scenario 2), maximizing electricity generation (Scenario 3), minimizing net heat demand (Scenario 4), and minimizing freshwater consumption (Scenario 5) are also considered. The optimization results obtained from Scenarios 1–5 are to be input as predefined fuzzy upper and lower limits for the simultaneous optimization of all objective functions in Scenario 6 by solving the fuzzy multi-objective optimization model developed. The predefined fuzzy upper and lower limits selected based on results obtained from Scenario 1–5 are tabulated in Table 4.4. The optimal POBC design obtained in Scenario 6 thus considered trade-offs between economic advantage and the FEW nexus contributions which makes it a sustainable production complex. The overall optimization results obtained for the six scenarios are summarized and tabulated in Table 4.5. They will also be further discussed in the following sections (Table 4.5).

4.5.1 Maximizing Economic Potential (Scenario 1)

In Scenario 1, the existing POM owned by the palm oil enterprise is retrofitted into a POBC to create maximum economic benefits in terms of EP. Thus, the case study is solved via the model developed as shown in Eqs. (4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8,

Table 4.1 Resource data for the POBC case study

i	Resource	Price (USD/t)	Cost (USD/t)	$BYIND_i$	$FIND_i$
1	Fresh fruit bunch (FFB)				
2	POME			1	
3	Sterilized fruit bunch (SFB)				
4	Empty fruit bunch (EFB)			1	
5	Sterilized fruitlet (SF)				
6	Digested fruitlet (DF)				
7	Pressed liquid (PL)				
8	Diluted pressed liquid				
9	Organic phase				
10	Aqueous phase				
11	Crude palm oil (CPO)	492	589	1	
12	Pressed solid (PS)				
13	Palm fruit nut (PFN)				
14	Palm mesocarp fiber(PMF)	22	23	1	
15	Cracked nut (CN)				
16	Palm kernel shell (PKS)	38	45	1	
17	Palm kernel (PK)	389		1	
18	Undiluted pressed liquid				
19	Undiluted POME				
20	Evaporator inlet				
21	Solid cake				
22	Process concentrate				
23	Process condensate			1	
24	Water		0.55	1	
25	Clarifier POME				
26	Sterilizer POME				
27	High pressure steam (HPS)				
28	Biogas			1	
29	Medium pressure steam (MPS)		17	1	
30	Low pressure steam (LPS)		12	1	
31	Electricity	90	140	1	
32	Electricity to grid	107		1	
33	RBDPOL	515.76		1	1
34	RBDPS	462.48		1	1
35	PFAD	406		1	1
36	Palm oil refinery effluent (PORE)				
37	Treated PORE			1	
38	Decanter solid	43		1	
39	Treated POME			1	

Table 4.2 Process yield data for the POBC case study

p	Process	Input resource *i*	Required amount	Product *i*	Yield	Power demand (MWh/unit)	Ref.
1	Sterilization	1	1 t	2	0.23 t	0.0754	[17]
		30	0.5 t	3	0.9 t		
2	Threshing	3	1 t	4	0.24 t	0.028	
				5	0.76 t		
3	Digestion	5	1 t	6	1.04 t	0.018	
		30	0.13 t				
4	Pressing	6	1 t	7	0.6 t	0.025	
				12	0.4 t		
5	Dilute PL	7	1 t	8	1 t		
6	Clarification	8	1 t	9	0.54 t	0.032	[17]
		24	0.696 t	10	1.156 t		
7	3-phase decanter	10	1 t	9	0.02 t	0.05	
				25	0.867 t		
				38	0.1137 t		
8	Purification	9	1 t	2	0.034 t	0.035	
				11	0.928 t		
9	Nut separation	12	1 t	13	0.59 t	0.0552	
				14	0.41 t		
10	Nut cracking	13	1 t	15	0.99 t	0.0311	
11	Kernel separation	15	1 t	14	0.19 t	0.0292	
				16	0.357 t		
				17	0.453 t		
12	Undiluted PL	7	1 t	18	1 t		
13	Undiluted POME mixer	2	1 t	19	1 t		
14	Undiluted clarification	18	1 t	21	0.91 t	0.05	
		19	0.578 t	21	0.09 t		
15	POME evaporation	20	1 t	22	0.625 t	0.1625	[19]
		29	0.5 t	23	0.625 t		
16	Undiluted purification	22	1 t	11	0.93 t	0.035	[17]
17	Solvent extraction	21	1 t	11	0.008 t	0.023	[20]
				38	0.992 t		
18	Boiler feed water treatment	23	1 t	24	1 t		
19	POME mixer	2	1 t	26	1 t		
20	Anaerobic digestion	25	0.6424 t	28	0.278 t		[10]
		26	0.3576 t	39	1 t		
21	Biogas boiler	24	0.87 t	27	0.87 t		[21]
		28	1 t				

(continued)

Table 4.2 (continued)

p	Process	Input resource *i*	Required amount	Product *i*	Yield	Power demand (MWh/unit)	Ref.
22	PMF boiler	14	1 t	27	2.364 t		
		24	2.364 t				
23	PKS boiler	16	1 t	27	3.482 t		
		24	3.482 t				
24	Steam turbine	27	1 t	29	0.4 t		[10]
				30	0.6 t		
				31	0.089 MWh		
25	On-grid power plant	28	1 t	32	0.11 MWh		[22]
26	Gas engine	28	1 t	31	0.026 MWh		
27	POR (physical refining)	11	1 t	33	0.76 t	1.5	[10]
		24	0.042 t	34	0.19 t		
		30	0.0315 t	35	0.05 t		
				36	0.076 t		
28	PORE mixer	36	1 t	2	1 t		
29	SBR	36	1 t	37	1 t		[23]

4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, and 4.30) subject to the objective function of maximizing EP. The optimal POBC configuration and process flow diagram obtained for Scenario 1 is as illustrated in Fig. 4.3 with maximum EP achieved as USD 36.62 M. The POME elimination configuration and its related milling technologies are chosen to process 60 t/h of FFB, yielding a total of 13,564 t/h of CPO to be fed into the integrated POR to produce 10.31 t/h RBDPOL, 2.58 t/h RBDPS, and 0.68 t/h PFAD as food products. The FREV obtained in Scenario 1 is 6784 USD/h. A total of 14.8 t/h of POME is generated from the milling processes and POR, and treated in the POME evaporation unit. The process condensate from the evaporation unit is regenerated via the boiler feedwater treatment to yield 14.57 t/h process water for recycling purposes. An additional 0.018 t/h of CPO is recovered from the solid cake exiting the undiluted clarification process via the solvent extraction unit. Although the POME evaporation unit and solvent extraction technology require additional capital investment, the additional CPO recovery from POME reduction and elimination significantly boosts product revenue due to the high market value of refined palm oil products. The CHP system operating in the POBC consists of biomass boilers that utilize PMF and PKS as fuel to generate heat and power for on-site usage. The HEATDEM of the POBC is 0.572 t/h. 8.89 t/h of PMF and 3.56 t/h of PKS produced from nut/kernel separation are all consumed by the biomass boilers to generate HPS. The steam extraction from HPS yields 13.37 t/h of MPS and 20.05 t/h of LPS. The operation of POME evaporation unit demands an

Table 4.3 Process capacity data for the POBC case study

p	Process	Capacity indicating resource *i*	Design capacity (t/unit or MWh/unit)	Unit capital cost (M USD/unit)	Unit processing cost (USD/unit)
1	Sterilization	1	20		180,000
2	Threshing	3	40		33,750
3	Digestion	5	20		15,000
4	Pressing	6	20		20,000
6	Clarification	8	7		15,000
7	Three-phase decanter	10	20		35,000
8	Purification	9	10		55,000
9	Nut separation	12	10		30,000
10	Nut cracking	13	10		36,000
11	Kernel separation	15	10		13,000
14	Undiluted clarification	18	20		35,000
15	POME evaporation	20	20	1.00	20,000
16	Undiluted purification	22	10		55,000
17	Solvent extraction	21	20	0.18	540
20	Anaerobic digestion	28	50	2.24	67,200
21	Biogas boiler	28	50	2.16	64,800
24	Steam turbine	31	5		100
25	On-grid power plant	32	1.8	5.04	151,200
26	Gas engine	31	50	0.24	105
27	POR (physi-cal refining)	11	30	0.34	870
29	SBR	36	157		10,170

Table 4.4 Fuzzy upper and lower limits for the case study

Objective function	Upper limit	Lower limit
EP	3.662E+07	3.446E + 07
FREV	6784	6693
ELECBAL	1.689	−2.681
HEATDEM	32.42	0
WDEM	52.98	0

Table 4.5 Summarized results for Scenario 1–6

	1	2	3	4	5	6
Scenario	Maximize EP	Maximize FREV	Maximize ELECBAL	Minimize HEATDEM	Minimize WDEM	Maximize □ (□ = 0.656)
EP (M USD)	36.62	34.46	36.18	36.45	34.46	36.59
FREV (USD/h)	6784	6784	6693	6693	6784	6784
ELECBAL (MWh)	0.294	−2.681	1.689	0.572	−2.681	0.186
HEATDEM (t/h)	0.71	32.42	0.703	0	32.42	1.43
WDEM (t/h)	19.43	0	51.81	52.98	0	18.22
POME generation	×	×	√	√	×	×
POME elimination	√	√	×	×	√	√
RBDPOL sold (t/h)	10.31	10.31	10.17	10.17	10.31	10.31
RBDPS sold (t/h)	2.58	2.58	2.54	2.54	2.58	2.58
PFAD sold (t/h)	0.68	0.68	0.67	0.67	0.68	0.68
CPO fed to POR (t/h)	13.564	13.564	13.383	13.383	13.564	13.564
Biogas generated (t/h)	0	0	11.11	11.11	0	0
On-grid electricity generated (MWh)	0	0	1.222	0	0	0
Water regenerated (t/h)	14.57	14.57	0	0	14.57	14.57

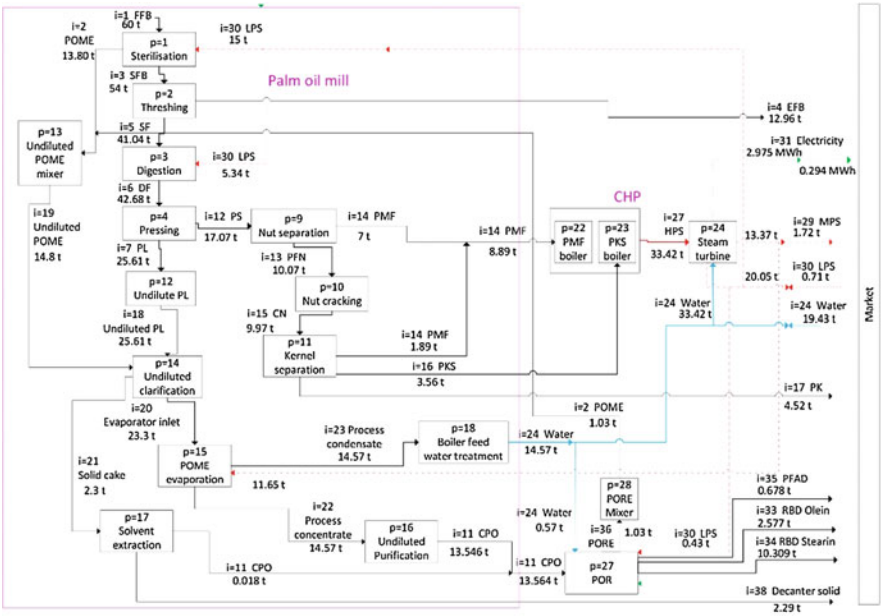

Fig. 4.3 The optimal POBC design for Scenario 1 (maximizing EP)

additional 11.65 t/h steam in the form of MPS, leaving unused 1.72 t/h of MPS. 0.71 t/h of LPS is imported with cost due to insufficient LPS generation for sterilization, digestion, and POR requirements. 33.42 t/h water is required for overall steam generation and cleaning water consumption which is partially satisfied by the regenerated water. An additional 19.43 t/h of freshwater is imported to meet the overall water demand for boilers and POR which can also be defined as the WDEM of the POBC. 2.975 MWh of electricity is generated from waste heat via steam turbines. The ELECBAL obtained for Scenario 1 is given as a positive value of 0.294 MWh, indicating excess electricity generation after satisfying the overall POBC power demand which is eligible for off-site purposes. On the other hand, 12.96 t/h of EFB and 4.52 t/h of PK are sold to the market as by-products.

4.5.2 *Maximizing Food Production (Scenario 2) and Minimizing Freshwater Consumption (Scenario 5)*

To evaluate the contribution of POBC in the food and water sector of the FEW nexus, Scenarios 2 and 5 are considered in which the optimization of POBC design is done with the objective function to maximize FREV (Scenario 2) and minimize WDEM (Scenario 5) respectively. Based on the optimization results, the optimal

POBC product portfolio and process pathway for both Scenario 2 and 5 are similar as illustrated in Fig. 4.4. The maximum FREV is achieved as 6784 USD/h and zero WDEM for minimum freshwater consumption. It is noted that the optimal process pathway of RBDPOL, RBDPS, and PFAD production in Scenarios 2 and 5 is similar to Scenario 1. The same amount of CPO is produced from 60 t/h of FFB processed via the POME eliminated milling process configuration in Fig. 4.4 to achieve maximum FREV and minimum WDEM. This indicates that the selection of the POME elimination approach is beneficial in terms of high food production rate and low freshwater consumption compared to the POME generating processes. In addition to minimum WDEM, the optimal POBC design in Fig. 4.4 results in 14 t/h of balance process water. In other words, the implementation of the POME elimination approach in POM can improve food and water security. According to the results, maximum FREV is also achieved in Scenario 1, indicating the positive relationship between increasing the palm oil based food production and profit of POBC. However, the EP achieved in Scenarios 2 and 5is less than Scenario 1, giving a value of USD 34.46 M despite the same amount of refined palm oil products being produced. The difference in the optimal POBC design for Scenarios 2 and 5 in comparison to Scenario 1 is reflected in the CHP system configuration, leading to the reduction in EP. With the primary objective in Scenario 2 being to maximize FREV, the electricity and steam generation technologies utilizing POM by-products are not considered in the optimal process network. Moreover, the excessive use of water in

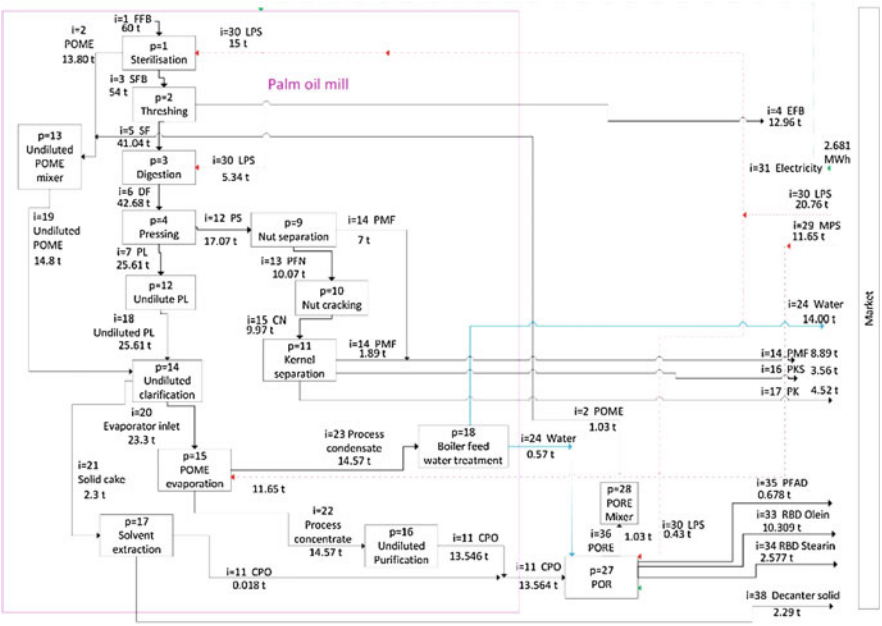

Fig. 4.4 The optimal POBC design for Scenario 2 (maximizing FREV) and Scenario 5 (minimizing WDEM)

generating steam also lowers the favorability of the CHP system installment in Scenario 5 which aims to reduce water consumption. Therefore, for both Scenarios 2 and 5, the power and heat demand of the POBC is supplied solely from external sources while the by-products, 8.89 t/h PMF and 3.56 t/h PKS, which can be used as biomass fuel, are sold directly to the market, resulting in high HEATDEM (32.42 t/h) and low ELECBAL(−2.681 MWh). This also explains the higher value of WDEM for the POBC in Scenario 1 which consumes more water for steam generation.

4.5.3 Maximizing Electricity Generation (Scenario 3) and Minimizing Net Heat Demand (Scenario 4)

To complete the sustainable FEW nexus-based POBC planning, the energy aspects of the POBC also require attention. Scenarios 3 and 4 are given as two energy efficient evaluation aspects for the optimization of POBC synthesis: net electricity generation declared as ELECBAL and net heat demand declared as HDEM. The MILP model is solved with the objective function of maximizing ELECBAL and minimizing HDEM to generate optimal results for Scenarios 3 and 4 respectively. Despite both objection functions being related to energy security, the overall process network and material flow for the optimum POBC in Scenario 4 (Fig. 4.6) is slightly different from Scenario 3 (Fig. 4.5). The ELECBAL is maximized at 1.689 MWh for Scenario 3 whereas the HDEM is minimized at 0 t/h in Scenario 4. In contrast to Scenarios 1, 2, and 5, the optimal configuration designed for the POBCs in Scenarios 3 and 5 are POME generation-based. Based on the optimization results from Scenarios 3 and 4, 60 t/h of FFB is processed via existing milling technology units to yield 13.383 t/h of CPO. The extracted and purified CPO is further refined in the POR to produce 10.17 t/h RBDPOL, 2.54 t/h RBDPS, and 0.67 t/h PFAD. A total of 39.97 t/h of POME is generated from the POM whereas a total of 1.02 t/h of PORE generated from POR is treated in an SBR. In order to comply with the methane avoidance policy, POME generated is treated in an anaerobic digester to recover 11.11 t/h of biogas before discharging the effluent. Although the biogas production flow in Scenarios 3 and 4 are identical, it is to be noted that the biogas application selected in each POBC design is different. In order to maximize ELECBAL in Scenario 3, the on-grid power plant is invested to convert biogas into renewable electricity. The potential 1.222 MWh of on-grid electricity to be generated can support the national grid for regional power supply and reduce demand from fossil fuel power stations. In this case study, the revenue for the on-grid power plant is supported by the Malaysian feed-in-tariff (FiT) system. The CHP system designed for Scenario 3 consists of only biomass boilers to generate 2.975 MWh of on-site electricity from consuming a maximum amount of biomass available as boiler fuel, including 8.89 t/h PMF and 3.56 t/h PKS. The amount of excess on-site electricity generated is 0.468 MWh. 0.703 t/h of LPS is imported to support the heat demand,

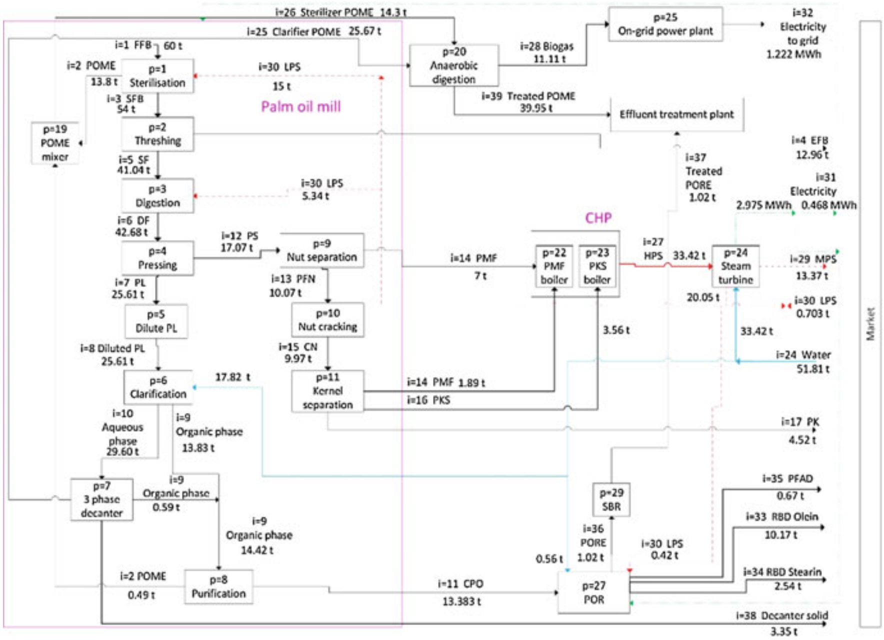

Fig. 4.5 The optimal POBC design for Scenario 3 (maximizing ELECBAL)

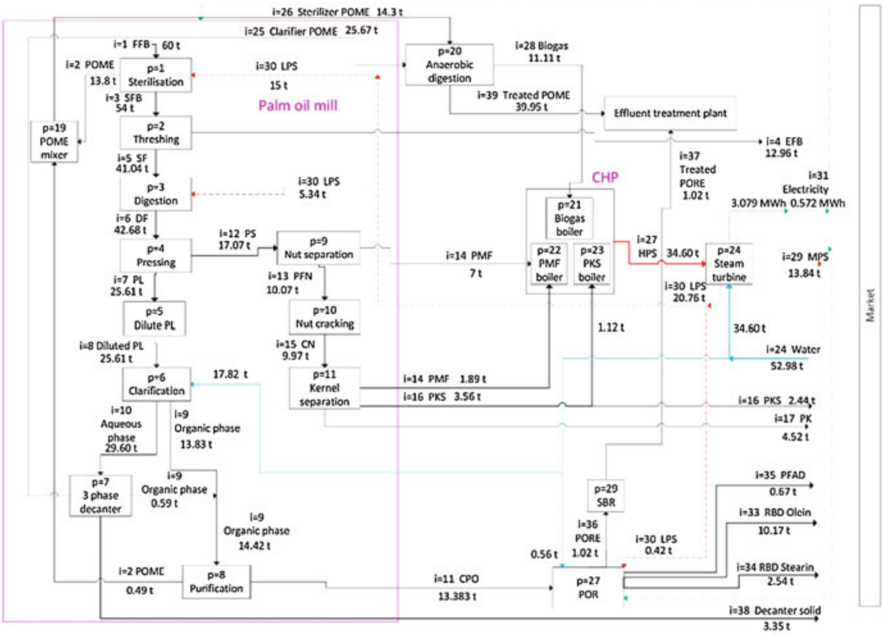

Fig. 4.6 The optimal POBC design for Scenario 4 (minimizing HDEM)

whereas the MPS generated is available in excess due to limited usage. On the other hand, the biogas produced in Scenario 4 is utilized by the invested biogas boiler in the CHP system to generate heat and on-site electricity in order to minimize HDEM. 20.76 t/h of LPS is extracted from the HPS produced to meet the POBC thermal requirements along with 13.84 t/h MPS and 3.079 MWh on-site electricity. The consumption of biogas in the CHP system serves as partial displacement for biomass fuel. Hence, with the generation of sufficient heat energy, only 1.12 t/h of PKS produced is burnt in the biomass boiler, whereas the remaining 2.44 t/h is sold to the market. From the economic perspective, the POBC synthesized in Scenario 4 accounts for higher EP (USD 36.45 M) compared to Scenario 3 (USD 36.18 M). This may be due to the high capital investment and operating cost associated with on-grid biogas plant installment. Nevertheless, due to the high demand for freshwater in energy generation and conventional milling processes, the WDEM of POBC in Scenarios 3 and 4 is relatively higher compared to Scenarios 1, 2, and 5. Besides, the selected POME generating milling technologies in Scenarios 3 and 4 are incapable of regenerating treated POME as process water. The WDEM in Scenario 4 (52.98 t/h) is slightly higher than Scenario 3 (51.81 t/h) due to the higher amount of steam generated in Scenario 4 which consumes more water.

4.5.4 Maximizing Overall Degree of Satisfaction (Scenario 6)

The ultimate goal of this study is to design a sustainable POBC with FEW nexus integrations. In order to consider the economic performance and FEW nexus evaluation aspects in the optimization work for POBC planning, a fuzzy optimization approach is adopted to solve the multi-objective optimization problem. In this work, the predefined upper and lower limits to set the fuzzy range for each objective function as summarized in Table 4.4 are selected from the optimization results for Scenarios 1–5. The developed model is then solved subject to the fuzzy constraints formulated as Eqs. (4.35, 4.36, 4.37, 4.38, and 4.39) with the selected values prior to the maximization of overall degree of satisfaction denoted as λ. The maximum value of λ obtained in Scenario 6 is 0.656, indicating the optimal satisfactory level achieved considering trade-offs between the optimization objectives. The optimal configuration for the POBC synthesized in Scenario 6 is as shown in Fig. 4.7. The synthesis of the POBC is projected to allocate USD 36.59 M of EP. The CPO, RBDPOL, RBDPS, and PFAD production network in Scenario 6 is similar to Scenarios 1, 2, and 4 in which the POBCs synthesized in these scenarios are POME elimination configured to support maximum production of palm oil products and generate 6784 USD/h FREV. The installation of POME evaporation unit provides 14.47 t/h of regenerated water to meet the freshwater demand for steam generation only due to zero water consumption in POME eliminated milling technologies. It is clear that the preference of synthesizing a POME eliminated based POBC over a POME generation configuration in Scenario 6 is due to its potential in optimizing simultaneously the economic, food production, and

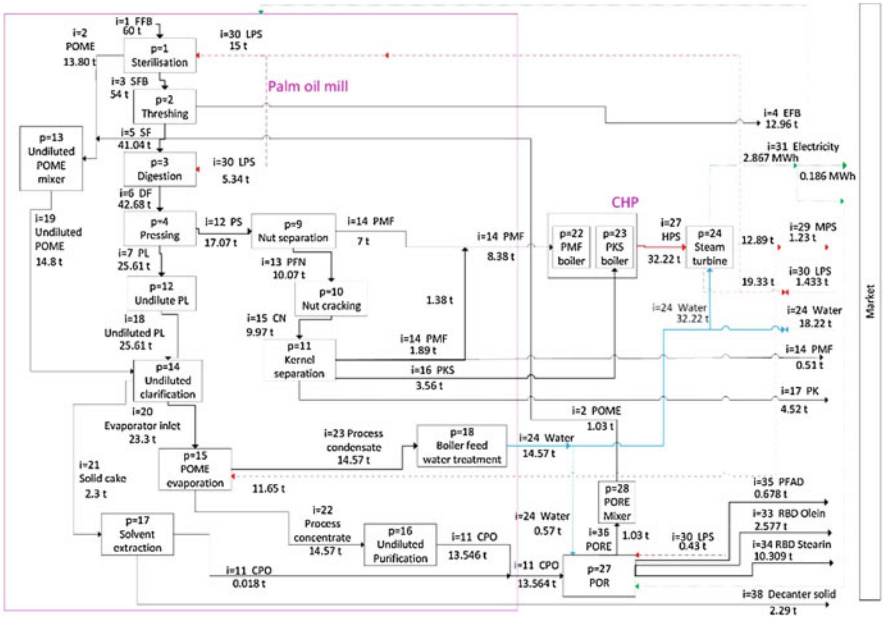

Fig. 4.7 The optimal POBC design for Scenario 6 (maximizing p)

freshwater consumption objectives. In order to balance the satisfaction of energy efficiency related objectives, steam and electricity are generated via the CHP system by utilizing available palm-based biomass: PMF and PKS. The optimal amount of PMF and PKS consumed for utility generation is difficult to determine in order to balance the trade-offs between ELECBAL, HDEM, EP, and WDEM. In terms of FEW nexus evaluations, a high consumption of PMF and PKS is beneficial toward ELECBAL and HDEM but will result in unfavorable value for EP and WDEM. This is because more steam and electricity can be generated when the consumption rate of PMF and PKS in the boiler is high. In the meantime, the utilization of PMF and PKS as fuel reduces the potential revenue that could be generated from selling them to the market. Besides, the water demand for the CHP system will increase with the amount of steam generated. Based on the optimization results, considering simultaneously the mentioned criteria, the optimal values for ELECBAL, HEATDEM, and WDEM are 0.186 MWh, 1.43 t/h, and 18.22 t/h respectively. Among the 8.89 t/h of PMF produced, 8.38 t/h is utilized in the CHP system whereas the remaining 0.51 t/h is sold to the market. 3.56 t/h of PKS yield is fully consumed for steam and electricity generation. The CHP system generates 12.89 t/h of MPS, 19.33 t/h of LPS, and 2.867 MWh of on-site electricity. The unmet LPS demand is satisfied by importing 1.43 t/h of external LPS whereas the balance of MPS and electricity is 1.23 t/h and 0.186 MWh respectively. 32.22 t/h of water is consumed by the CHP system and is partially fulfilled by the regenerated process water. The other by-products such as

12.96 t/h of EFB, 4.52 t/h of PK, and 2.29 t/h of decanter solid are sold to increase product revenue.

4.6 Conclusion

The integration of the FEW nexus with the palm oil industry is gaining significance to improve the sustainability of the palm oil sector. Possible synergies between the food, energy, and water sector can be achieved in a palm oil processing complex. A new conceptual zone of POBC considering POME elimination approach is introduced as a greener retrofit solution for POM. The FEW nexus concepts are suitable to be adapted in the optimal planning of the proposed POBC. The challenge in synthesizing a POBC with FEW nexus integrations lies in the trade-off considerations between contradicting optimization objectives in terms of food, water, and energy security. It is also crucial to ensure the economic feasibility of the POBC while improving its sustainability. In this chapter, a systematic framework for the synthesis of a sustainable FEW nexus integrated POBC is presented. It is expected that the proposed POBC could be the basis of a new POM construction or modification of existing POMs to obey the methane avoidance policy. The developed framework and model can be easily revised to perform FEW nexus evaluations for any production system of any industry.

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Chapter 5
Potable Water Production by Heat Recovery of Kalina Cycle, Using Solar Energy

Hadi Rostamzadeh, Hadi Ghaebi, Majid Amidpour, and Weifeng He

Nomenclature

Symbols

A	Area (m^2)
b	Width of absorber (m)
c_p	Specific heat at constant pressure ($kJ.\ kg^{-1}$)
C_R	Concentration ratio
D	Diameter, (m)
$\dot{E}x$	Exergy rate (kW)
ex	Exergy per mass ($kW.\ kg^{-1}$)
h	Enthalpy ($kJ.\ kg^{-1}$)

H. Rostamzadeh
Energy and Environment Research Center, Niroo Research Institute (NRI), Shahrak Ghods, Tehran, Iran

H. Ghaebi (✉)
Department of Mechanical Engineering, Faculty of Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
e-mail: hghaebi@uma.ac.ir

M. Amidpour
Energy and Environment Research Center, Niroo Research Institute (NRI), Shahrak Ghods, Tehran, Iran

Faculty of Mechanical Engineering, Department of Energy System Engineering, K.N. Toosi University of Technology, Tehran, Iran
e-mail: amidpour@kntu.ac.ir

W. He
Nanjing University of Aeronautics and Astronautics, College of Energy and Power Engineering, Nanjing, China
e-mail: wfhe@nuaa.edu.cn

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H	Height (m)
H_W	Height to aperture ratio
I	Radiation (W. m^{-2})
L	Length of tube
M	Molar mass (kg. $kmol^{-1}$)
$\dot{m}$	Mass flow rate (kg. s^{-1})
m_r	Desalination flow ratio
N	Number of tubes
N	The day of the year
N_r	Number of reflection
p	Pressure (bar)
$\dot{Q}$	Heat transfer rate (kW)
R	Title factor
$R_{C/A}$	Concentrator to aperture area ratio
s	Entropy (kJ. $kg^{-1}K^{-1}$)
S	Salinity (g. kg^{-1})
T	Temperature (K)
TEF	Total effective flux (W. m^{-2})
TTD	Thermal temperature difference (K)
U	Overall heat transfer coefficient (W. $m^{-2}K^{-1}$)
W	Width (m)
X_B	Basic ammonia concentration
z	Zenith angle ($^\circ$)

Abbreviations

CPC	Compound parabolic collector
CPD	Combined power and desalination
CGOR	Cogeneration-based GOR
GOR	Gain output ratio
HDH	Humidification–dehumidification
KC	Kalina cycle
TST	Thermal storage tank

Greek Letters

α	Absorptivity of the absorber surface
β	Slope angle of the aperture plane ($^\circ$)
ε	Effectiveness
δ	Declination
η	Efficiency (%)
θ	Angle of incident ($^\circ$)
ρ	Reflectivity of the concentrator surface
τ	Transmissivity of the cover
ω	Hour angle ($^\circ$)/humidity
ϕ	Latitude ($^\circ$)

Subscripts & Superscripts

a	Acceptance half angle
abs	Absorber
b	Beam
ch	Chemical
cond	Condenser
d	Diffuse
da	Dry air
Dhum	Dehumidifier
e	Effective
EV	Expansion valve
ex	Exergy
F	Fuel
g	Global
gen	Generator
H	Heater
Hum	Humidifier
in	Inlet
is	Isentropic
lo	Loss
mix	Mixer
net	Net value
out	Outlet
P	Product
ph	Physical
pum	Pump
Reg	Regenerator
sc	Solar collector
sep	Separator
sw	Sea water
TST	Thermal storage tank
tur	Turbine
u	Useful

5.1 Introduction

Seawater desalination processes via membrane-based technologies are very expensive since potable water is generated at the expense of direct electricity consumption by creating pressure difference through the membrane. Broadly speaking, the issue of electricity provision of the membrane-based desalination technologies can be resolved by employing renewable energy-based thermal desalination systems. This proposal can solve two fundamental crises of the growing population of the civilized societies from two vantage points. First and foremost, any amount of seawater can be distilled due to the endless availability of renewable energy resources. Secondly, using renewable energy-based technologies to produce freshwater at large scales without emitting any detrimental components to environment can be a precious remedy.

Meantime, waste heat capturing from operating energy systems via high-tech equipment for water distillation is a promising alternative due to a large amount of waste energy observed in various sectors of the industry. Among various basic energy systems, using waste heat of small-scale power generation systems to supply the required heating demand of a thermal desalination system can be an encouraging idea. Although in recent years using various heat pump cycles (HPCs) to improve the performance of a humidification–dehumidification (HDH) desalination unit has showed profitable outcomes [1]; however, providing the required low electricity in some regions of the globe can still be a dilemma. Therefore, it has been suggested to use waste heat of power generation systems such as organic Rankine cycle (ORC) or Kalina cycle (KC) that not only consume no electricity but also provide electricity in some extend for this duty. Due to the low-temperature characteristics of HDH desalination units, they have been run with direct waste heat from condenser of ORC by preheating seawater [2], heating its rejected brine [3] or humid air [4] via evaporator of ORC. The main aim of using the heat of the discharged brine of an HDH unit is a thermal augmentation of the desalination unit as well as decreasing the environmental impact of the rejected brine. To decrease distilled water dependency on the integrated set-up it was recommended to employ an air-blower in the closed-air loop. However, one of the main drawbacks of using condensation latent heat of ORC for HDH unit is a drastic reduction of the extracted electricity which can be resolved by using an extra extraction from the turbine for only desalination purpose [5]. Since low-grade heat sources like geothermal have high mass flow rate, thus applying direct use of such source for seawater desalination can be another alternative to improve performance of the ORC/HDH power and desalination systems. To achieve this aim, the binary Rankine cycle can be used, where the input thermal heat increases in such condition [6]. Other technologies like using zeotropic mixture in ORC/HDH system is also devised recently [7]. Sayyaadi and Ghorbani [8] devised a new scheme for cogeneration of freshwater and electricity by integrating a Stirling engine and an HDH unit in various configurations. They also optimized the overall performance of the devised set-up. Giwa et al. [9] recovered thermal energy of a photovoltaic (PV) for freshwater production by employing an HDH unit. They found that the devised integrated PV-HDH set-up is more appealing than the integrated PV-RO (reverse osmosis) set-up in terms of owning over 83% lower environmental impacts.

Meantime, many regions in the world suffer from potable water shortages, while many of these regions abundantly enjoy renewable-based resources such as solar energy. Additionally, high accessibility of these regions to free saline waters is undeniable, making these regions highly productive to devise solar-based desalination technologies for converting seawater into potable water. Solar energy can be captured by various tools which should be considered based on the objective of the plant. For instance, a salinity-gradient solar pond (SGSP) can be used to capture solar irradiance via convention processes inside a pond to derive a desalination plant like an HDH unit [10]. As Rostamzadeh et al. [10] maintained, application of a SGSP for an HDH unit is more appropriate for large-scale settings and can be economical for long-term applications. Also, SGSP provides low-temperature heat which cannot be appropriate in case of cascade HDH unit, or more specifically for power and desalination systems. In other words, in combined ORC/HDH systems where the condensation temperature should be set high in order to satisfy desalination top temperature pinch criterion, providing a solar collector to respond relatively high vapor generator temperature can be a great wisdom. For these reasons and many others, numerous scholars have used different solar collectors to capture solar energy for the sake of HDH unit. However, no investigation is deliberated to devise a solar-based CPD system based on HDH unit at small-scale applications. Fouda et al. [11] presented dynamic modeling of three configurations for a solar-based HDH unit. They found that the performance of the devised set-up can be maximized by setting open/closed mode depending on the outdoor conditions as well. On the other side, compound parabolic collectors (CPCs) are appropriate for temperature supply of up to 200 $^{\circ}$C with several merits including but not limited to easy fabrication, simple support structure, no need for continuous tracking, high reflectivity capability in absorbing wide incident radiations, etc. [12]. Therefore, extending applications of CPCs to a CPD system can be an interesting issue to address in this chapter.

In the light of reviewed literature, it is evident that capturing solar energy for seawater desalination is an urgent solution for water scarcity in arid and semi-arid regions. Regarding this requirement, several studies have considered this idea and have used HDH system directly or indirectly (in combination with power cycles like ORC) to produce freshwater. However, no previous works have deliberated waste heat of the KC for freshwater production by employing HDH unit and CPC (due to its low-temperature characteristics). To cover this shortcoming of the existing literature works, a solar-based integrated KC/HDH set-up is devised in this chapter and its feasibility and advantages over other available CPD systems are investigated. It should be noted that using the waste heat of a Kalina cycle for HDH unit can be competitive with that of the ORC-based one due to the use of NH_3-H_2O mixture instead of organic fluids. As a result of such deliberation, safety of the plant is increased since many organic fluids are flammable or toxic which can be dangerous in the case of release to the environment. The rest of this chapter is arranged in the following order. In Sect. 5.2, a brief description of the layout is presented. In Sect. 5.3, all employed mathematical relations and presumptions are displayed. In the fourth section, results are presented and discussed extensively. Finally, some concluding comments are listed in the last part.

5.2 Set-Up Description

The overall layout of the devised solar-based CPD system is displayed in Fig. 5.1. The set-up encompasses three subsets of a CPC, a KC, and an HDH unit. Water is used as circulating refrigerant through the solar collector with considering a thermal storage tank (TST).

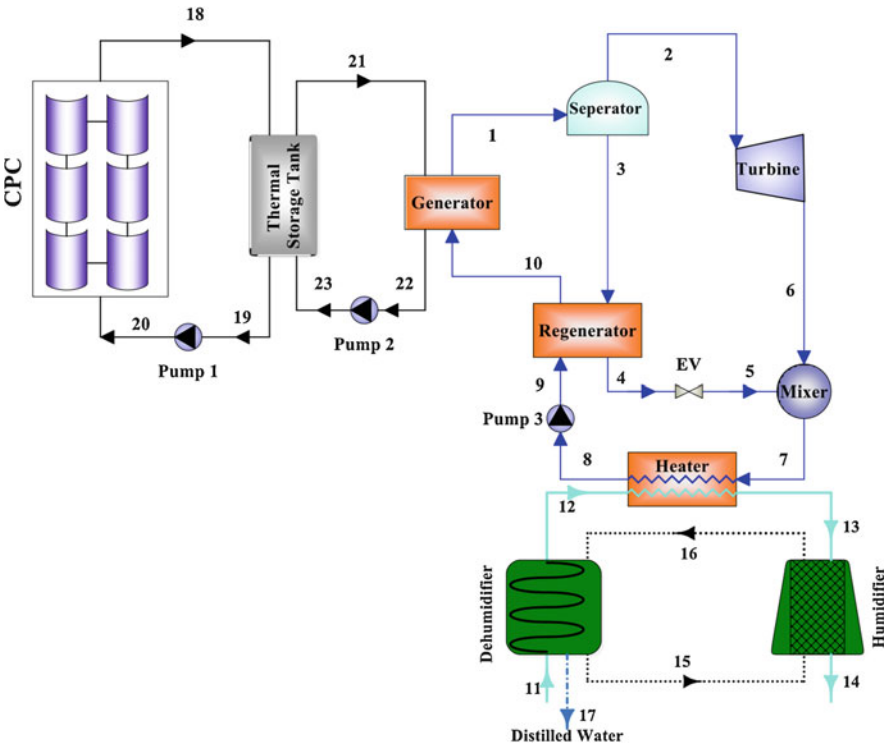


Fig. 5.1 Layout of the devised combined power and desalination (CPD) system, using CPC-based solar collector

In KC, the NH_3-H_2O blend at the saturated pressure of vapor generator is split into lean and rich mixtures. The rich mixture is rotated through the turbine to generate electricity, while the lean mixture loses its temperature prior to a throttling process via a regenerator and then is merged with an expanded rich mixture. The merged stream is next liquefied at the condensation temperature of heater and then is pressurized to the saturated pressure of vapor generator via a pump, ending KC flow process.

As NH_3-H_2O blend exchanges its waste heating capacity via a heater with seawater at the HDH side, HDH unit begins its working process. In this study, a basic closed-air open-water (CAOW) HDH unit is used since it has higher efficiency in comparison with its basic closed-water open-air (CWOA) counterpart [13]. As saline water is dehumidified through stage 11→12, it is heated up to the maximum accessible of desalination temperature and is sprayed through a humidifier, while leaving it. At the same time, air experiences a successive humidification and dehumidification process through a closed loop in order to provide evaporation and condensation processes of the seawater. Ultimately, freshwater can be extracted through this natural process, using waste heat of the KC.

5.3 Materials and Methods

Overall, in this section, simulation procedure, presumptions, and relations are presented. In the first subsection, all relations required for simulation of CPC and TST are presented. In the second subsection, thermodynamic presumptions are expressed and then basic relations from first and second laws of thermodynamics are presented. Ultimately, the main performance relations are extended.

5.3.1 CPC and Thermal Storage Tank Formulae

The CPC used in this chapter is located horizontally on the east–west axis with flat absorber and aperture angle of 45 degrees. Accordingly, the global radiation (I_g) can be expressed in terms of beam and diffuse radiations (I_b and I_d) respectively as [14]:

$$I_g = I_b + I_d \tag{5.1}$$

where

$$I_b = A \times \exp\left[-\frac{B}{\cos\theta_z}\right] \times \cos\theta_z \tag{5.2}$$

$$I_d = C \times A \times \exp\left[-\frac{B}{\cos\theta_z}\right] \tag{5.3}$$

In Eqs. (5.2) and (5.3), θ_z is the zenith angle (also known as the incident angle) and A–C are constant parameters. For Ardabil city, we have: $A = 1092$, $B = 0.185$, and $C = 0.137$ [14].

The tilt factor for beam radiation (R_b) is defined in terms of the declination (δ), latitude (ϕ), slope angle of the aperture plane (β), and hour angle (ω) as follows:

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta.\sin(\phi-\beta) + \cos\delta.\cos\omega.\cos(\phi-\beta)}{\sin\delta.\sin\phi + \cos\delta.\cos\omega.\cos\phi} \tag{5.4}$$

where,

$$\delta = 23.45 \times \sin\left[\frac{360}{365} \times (284+n)\right] \tag{5.5}$$

The tilt factor for diffuse radiation (R_d) is articulated as the radiation shape factor:

$$R_d = \frac{1 + \cos\beta}{2} \tag{5.6}$$

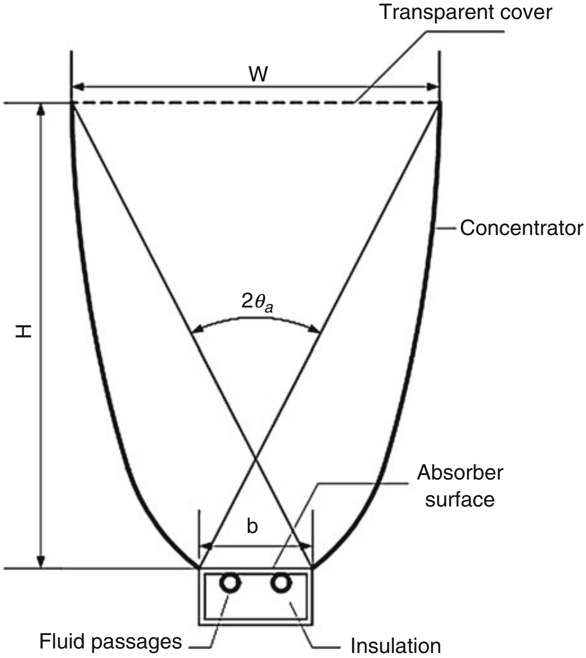


Fig. 5.2 Schematic of a CPC with some of its geometrical specifications [15]

Schematic of a CPC is illustrated in Fig. 5.2. According to this figure, the concentration ratio is defined as:

$$C_{\mathrm{R}} = \frac{W}{b} = \frac{1}{\sin\theta_{\mathrm{a}}} \tag{5.7}$$

In Eq. (5.7), θ_a is the acceptance half angle.

The height to aperture ratio of the concentrator (H_W) can be expressed as:

$$H_{\mathrm{W}} = \frac{H}{W} = \frac{1}{2}\left(1 + \frac{1}{\sin\theta_a}\right)\cos\theta_a \tag{5.8}$$

The concentrator to aperture area ratio ($R_{C/A}$) may be articulated as:

$$R_{\mathrm{C/A}} = \frac{A}{WL} = \sin\theta_{\mathrm{a}}(1 + \sin\theta_{\mathrm{a}})\frac{\cos\theta_{\mathrm{a}}}{\sin^2_{\theta_{\mathrm{a}}}} + \ln\left\{\frac{(1 + \sin\theta_a)(1 + \cos\theta_{\mathrm{a}})}{\sin\theta_{\mathrm{a}}\left[\cos\theta_{\mathrm{a}} + (2 + 2\sin\theta_{\mathrm{a}})^{0.5}\right]}\right\} - \frac{\sqrt{2}\cos\theta_{\mathrm{a}}}{(1 + 1\sin\theta_{\mathrm{a}})^{1.5}} \tag{5.9}$$

The average number of reflections for radiations within the acceptance angle is indicated by N_r and is articulated as:

$$N_r = \frac{R_{C/A}}{2 \times \sin \theta_a} - \frac{(1 - \sin \theta_a)(1 + 2 \sin \theta_a)}{2 \times \sin^2 \theta_a} \quad (5.10)$$

The effective reflectivity of the concentrator for all radiations (ρ_e) is written by:

$$\rho_e = \rho^{N_r} \quad (5.11)$$

where ρ is the reflectivity value of a single reflection.

The total effective flux (TEF) absorbed via absorber is calculated as:

$$\text{TEF} = \left[I_b R_b + \frac{I_d}{C_R} \right] \tau \rho_e \alpha \quad (5.12)$$

The useful thermal heat extracted from collector is computed as:

$$\dot{Q}_u = F_R WL \left[\text{TEF} - \frac{U_{lo}}{C_R} (T_{fi} - T_0) \right] \quad (5.13)$$

where,

$$F_R = \frac{\dot{m} c_p}{b U_{lo} L} \left[1 - \exp \left[\frac{F' b L U_{lo}}{\dot{m} c_p} \right] \right] \quad (5.14)$$

$$\frac{1}{F'} = U_{lo} \left[\frac{1}{U_{lo}} + \frac{b}{N \pi k D_i} \right] \quad (5.15)$$

For thermal storage tank (TST) analysis, a steady-state modeling is used, and hence the transferred heat from collector loop to TST is assumed equal to the useful heat. Thus [16]:

$$\dot{Q}_{u,t} = (UA)_{c-st} \cdot \frac{T_{sc,out} - T_{sc,in}}{ln \left(\frac{T_{sc,out} - T_{TST}}{T_{sc,in} - T_{TST}} \right)} \quad (5.16)$$

where T_{TST} is the uniform temperature of TST. The energy balance equation for the storage tank is expressed as below:

$$\dot{Q}_{stored} = \dot{Q}_{u,t} - \dot{Q}_{loss} - \dot{m}_{TST} c_{p,TST} (T_{TST,out} - T_{TST,in}) \quad (5.17)$$

For SS simulation, $\dot{Q}_{stored} = 0$ and $\dot{Q}_{loss}$ is computed as follows:

$$\dot{Q}_{\text{loss}} = U_{\text{TST}}A_{\text{TST}}(T_{\text{TST}-}T_0) \tag{5.18}$$

In steady-state (SS) simulation, $\dot{Q}_{\text{loss}} = 0$.

5.3.2 Thermodynamic Presumptions and Evaluation

Subsequent presumptions are reckoned in the present analysis:

- Condition through the simulation is presumed steady state.
- Pump and turbine operate with an isentropic efficiency.
- Expansion device works isenthalpically.
- Vapor generator and heater outlets are assumed saturated.
- June 12 is selected as the representative day for CPC modeling [15].
- Ardabil city is selected as a case study with $\phi = 38.15^{\circ}$, $T_0 = 284.6\ K$, and $P_0 = 0.929$ bar [17].
- In order to attain higher efficiency in CPD system, mass flow rate in the CPC is appointed in order to have a turbulent flow Re $= 2 \times 10^6$ [12].
- Water temperature at the inlet of CPC inlet is set on 140°C [15].
- Pressure drop through CPC and TST is assumed 5% [18].

Additionally, some other presumptions in terms of input data are listed in Table 5.1.

The general form of governing equations at steady state for thermodynamic evaluation of a unit can be articulated as:

$$\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} = 0 \tag{5.19}$$

$$\sum (\dot{m}h)_{\text{in}} - \sum (\dot{m}h)_{\text{out}} + \sum \dot{Q}_{\text{in}} - \sum \dot{Q}_{\text{out}} + \dot{W} = 0 \tag{5.20}$$

In terms of second law of thermodynamics, the balance relation of a unit may be articulated as:

$$\dot{\text{E}}\text{x}_{D,k} = \sum_{i=1}^{k} \dot{\text{E}}\text{x}_{\text{in},i} - \sum_{i=1}^{k} \dot{\text{E}}\text{x}_{\text{out},i} \tag{5.21}$$

The overall exergy of fluid stream is declared as:

$$\dot{\text{E}}\text{x}_k = \dot{\text{E}}\text{x}_{\text{ph},k} + \dot{\text{E}}\text{x}_{\text{ch},k} \tag{5.22}$$

where

$$\dot{\text{E}}\text{x}_{\text{ph},k} = \dot{m}(h - h_0 - T_0(s - s_0))_k \tag{5.23}$$

Table 5.1 Necessary input data for analysis of the devised CPD set-up

Parameter	Value	Ref.
Ambient temperature, T_0 (K)	284.6	[17]
Ambient pressure, P_0 (bar)	0.929	[17]
Reference salinity, S_0 (g/kg)	35	[17]
CPC sub-cycle		
Inner diameter of tubes, D_{in} (m)	0.014	[15]
Overall loss coefficient, U_{lo} (W. m^{-2}. K^{-1})	10.5	[15]
Number of days, N_{day}	163	[15]
Hour angle, ω (degree)	−15	[15]
Slope angle of the aperture plane, β (degree)	60	[15]
Width of the absorber plane, b_{abs} (m)	0.06	[15]
Concentration ratio, C_R	5	[15]
Length of absorber tube, L (m)	2	[15]
Reflectivity of concentrator, ρ	0.87	[15]
Absorptivity of absorber surface, α	0.94	[15]
Transmissivity of cover, τ	0.89	[15]
Heat transfer coefficient inside absorber tube, k (W. m^{-2}. K^{-1})	230	[15]
Number of tubes, N	1000	[15]
Thermal storage heat transfer coefficient, U_{TST} (kW. m^{-2}. K^{-1})	2.8	[16]
Thermal storage loss coefficient, $U_{TST,\ loss}$ (kW. m^{-2}. K^{-1})	0.5×10^{-3}	[16]
Diameter of storage tank, D_{TST} (m)	0.8	[15]
Height of storage tank, H_{TST} (m)	1	[15]
Pump isentropic efficiency, $\eta_{is,\ pum}$ (m)	90	[19]
Kalina sub-cycle		
Terminal temperature difference of vapor generator, TTD_{VG} (K)	5	[19]
Vapor generator pressure, P_{VG} (kPa)	50	[19]
Basic ammonia concentration, X_B (%)	90	[19]
Pump isentropic efficiency, $\eta_{is,\ pum}$ (%)	90	[19]
Heater temperature, T_H (K)	326	[19]
Effectiveness of regenerator, ε_{Reg} (%)	95	[20]
Turbine isentropic efficiency, $\eta_{is,\ tur}$ (%)	90	[19]
HDH unit		
Terminal temperature difference of heater, TTD_H (K)	3	[19]
Desalination maximum temperature, T_8 (K)	343.15	[21]
Salinity of seawater, S_{sw} (g/kg)	35	[1, 10]
Humidifier effectiveness, ε_{Hum} (%)	85	[1, 10]
Desalination flow ratio, m_r	2.5	[1, 10]
Dehumidifier effectiveness, ε_{Dhum} (%)	85	[1, 10]

$$\dot{E}x_{ch,k} = \dot{n}_k\left(\sum_k y_i\overline{ex}_i^{ch,0} + \overline{R}T_0\sum_i y_i \ln y_i\right) \tag{5.24}$$

where $\overline{ex}_i^{ch,0}$ is known as the standard chemical exergy found in Refs. [27,28] and y_i is concentration of the ith constituent.

Exergy of humid air is computed from Eq. (5.24) [22]:

$$\begin{aligned} \mathrm{ex_{da}} = & \left(c_{\mathrm{p,a}} + \omega c_{\mathrm{p,v}}\right) T_0 \left(\frac{T}{T_0} - 1 - \ln \frac{T}{T_0}\right) + (1 + 1.608\omega) R_{\mathrm{a}} T_0 \ln \frac{P}{P_0} \\ & + R_{\mathrm{a}} T_0 (1 + 1.608\omega) \ln \frac{1 + 1.608\omega_0}{1 + 1.608\omega} \\ & + 1.608\omega \ln \frac{\omega}{\omega_0} \end{aligned} \quad (5.25)$$

where ω is the humidity ratio:

$$\omega = \frac{\dot{m}_{\mathrm{v}}}{\dot{m}_{\mathrm{a}}} \quad (5.26)$$

The exergetic efficiency of the kth element is declared as:

$$\eta_{\mathrm{ex},k} = \frac{\dot{\mathrm{E}}\mathrm{x_{out}}}{\dot{\mathrm{E}}\mathrm{x_{in}}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{P},k}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{F},k}} \quad (5.27)$$

Some mass-, energy-, and exergy-based balance relations to each constituent of the reckoned set-up are enumerated in Table 5.2.

5.3.3 Main Performance Criteria

The first law of thermodynamics for desalination units is usually expressed in terms of gain output ratio (GOR). For the devised CPD system, cogeneration-based GOR (CGOR) is articulated as below:

$$\mathrm{CGOR} = \frac{\dot{m}_{17}.h_{\mathrm{fg@T_{17}}} + \dot{W}_{\mathrm{net}}}{\dot{Q}_u} \quad (5.28)$$

where

$$\dot{W}_{\mathrm{net}} = \dot{W}_{\mathrm{tur}} - \dot{W}_{\mathrm{pum1}} - \dot{W}_{\mathrm{pum2}} - \dot{W}_{\mathrm{pum3}} \quad (5.29)$$

Exergy efficiency of the devised CPD system is articulated as below:

$$\eta_{\mathrm{ex}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{17} + \dot{W}_{\mathrm{net}}}{\dot{\mathrm{E}}\mathrm{x_u}} \quad (5.30)$$

Table 5.2 Thermodynamic balance relations for the devised CPD system

Component	Mass and energy balance equations	Exergy balance equations
CPC	See Sect. 5.3.1	$\dot{E}x_D^{CPC} = \dot{E}x_u - (\dot{E}x_{18} - \dot{E}x_{20})$, $\dot{E}x_u = \dot{Q}_u\left[1 + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right)\right]$
TST	See Sect. 5.3.1	$\dot{E}x_D^{TST} = (\dot{E}x_{18} - \dot{E}x_{19}) - (\dot{E}x_{21} - \dot{E}x_{23})$
Pump1	$\dot{W}_{pum1} = \dot{m}_{20}(h_{20} - h_{19})$, $\dot{m}_{19} = \dot{m}_{20}$ $\eta_{is,\ pum1} = (h_{20s} - h_{19})/(h_{20} - h_{19})$	$\dot{E}x_D^{pum1} = \dot{W}_{pum1} - (\dot{E}x_{20} - \dot{E}x_{19})$
Pump2	$\dot{W}_{pum2} = \dot{m}_{23}(h_{23} - h_{22})$, $\dot{m}_{22} = \dot{m}_{23}$ $\eta_{is,\ pum2} = (h_{23s} - h_{22})/(h_{23} - h_{22})$	$\dot{E}x_D^{pum2} = \dot{W}_{pum2} - (\dot{E}x_{23} - \dot{E}x_{22})$
Separator	$\dot{m}_2X_2 + \dot{m}_3X_3 = \dot{m}_1X_1$, $\dot{m}_2 + \dot{m}_3 = \dot{m}_1$, $\dot{m}_2h_2 + \dot{m}_3h_3 = \dot{m}_1h_1$	$\dot{E}x_D^{Sep} = \dot{E}x_1 - (\dot{E}x_2 + \dot{E}x_3)$
Turbine	$\dot{W}_{tur} = \dot{m}_2(h_2 - h_6)$, $\dot{m}_2 = \dot{m}_6$ $\eta_{is,\ tur} = (h_2 - h_6)/(h_2 - h_{6s})$	$\dot{E}x_D^{tur} = (\dot{E}x_2 - \dot{E}x_6) - \dot{W}_{tur}$
Mixer	$\dot{m}_5h_5 + \dot{m}_6h_6 = \dot{m}_7h_7$ $\dot{m}_5 + \dot{m}_6 = \dot{m}_7$ $\dot{m}_5X_5 + \dot{m}_6X_6 = \dot{m}_7X_7$	$\dot{E}x_D^{mix} = (\dot{E}x_5 + \dot{E}x_6) - \dot{E}x_7$
Heater	$\dot{Q}_H = \dot{m}_7(h_7 - h_8)$, $\dot{m}_7 = \dot{m}_8$ $\dot{Q}_H = \dot{m}_{13}(h_{13} - h_{12})$, $\dot{m}_{13} = \dot{m}_{12}$	$\dot{E}x_D^{H} = (\dot{E}x_7 - \dot{E}x_8) - (\dot{E}x_{13} - \dot{E}x_{12})$
Pump3	$\dot{W}_{pum3} = \dot{m}_8(h_9 - h_8)$, $\dot{m}_9 = \dot{m}_8$ $\eta_{is,\ pum3} = (h_{9s} - h_8)/(h_9 - h_8)$	$\dot{E}x_D^{pum3} = \dot{W}_{pum3} - (\dot{E}x_9 - \dot{E}x_8)$
Regenerator	$\dot{Q}_{reg} = \dot{m}_3(h_3 - h_4)$, $\dot{m}_3 = \dot{m}_4$ $\dot{Q}_{reg} = \dot{m}_{10}(h_{10} - h_9)$, $\dot{m}_{10} = \dot{m}_9$	$\dot{E}x_D^{reg} = (\dot{E}x_3 - \dot{E}x_4) - (\dot{E}x_{10} - \dot{E}x_9)$
Expansion valve 1	$h_4 = h_5$, $\dot{m}_4 = \dot{m}_5$	$\dot{E}x_D^{EV} = \dot{E}x_4 - \dot{E}x_5$

(continued)

Table 5.2 (continued)

Component	Mass and energy balance equations	Exergy balance equations
Humidifier	$\dot{m}_{13}h_{13} + \dot{m}_{15}h_{15} = \dot{m}_{16}h_{16} + \dot{m}_{14}h_{14}$, $\dot{m}_{14} = \dot{m}_{11} - \dot{m}_{17}$, $\varepsilon_{\mathrm{Hum}} = \max\left\langle \left(\frac{h_{16}-h_{15}}{h_{16,\mathrm{ideal}}-h_{15}}\right), \left(\frac{h_{12}-h_{11}}{h_{12}-h_{11,\mathrm{ideal}}}\right) \right\rangle$	$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{D}}^{\mathrm{Hum}} = \left(\dot{\mathrm{E}}\mathrm{x}_{13} - \dot{\mathrm{E}}\mathrm{x}_{14}\right) - \left(\dot{\mathrm{E}}\mathrm{x}_{16} - \dot{\mathrm{E}}\mathrm{x}_{15}\right)$
Dehumidifier	$\dot{m}_{11}h_{11} + \dot{m}_{16}h_{16} = \dot{m}_{12}h_{12} + \dot{m}_{15}h_{15} + \dot{m}_{17}h_{17}$, $\dot{m}_{17} = \dot{m}_{15}(\omega_{16} - \omega_{15})$, $\varepsilon_{\mathrm{Dhum}} = \max\left\langle \left(\frac{h_{16}-h_{15}}{h_{16}-h_{15,\mathrm{ideal}}}\right), \left(\frac{h_{13}-h_{14}}{h_{13,\mathrm{ideal}}-h_{14}}\right) \right\rangle$, $m_{\mathrm{r}} = \frac{\dot{m}_{11}}{\dot{m}_{\mathrm{da}}}$	$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{D}}^{\mathrm{Dhum}} = \left(\dot{\mathrm{E}}\mathrm{x}_{16} - \dot{\mathrm{E}}\mathrm{x}_{15}\right) - \left(\dot{\mathrm{E}}\mathrm{x}_{12} - \dot{\mathrm{E}}\mathrm{x}_{11} + \dot{\mathrm{E}}\mathrm{x}_{17}\right)$

5.4 Results and Discussion

In this part, the results of the simulation are displayed in the form of figure for various central parameters.

Figure 5.3 illustrates variation of freshwater, net electricity, CGOR, and exergy efficiency at various hour angles and $\beta = 60^{\circ}$ on June 12. Accordingly, the extracted thermal heat from CPC is maximized at midday due to the strong solar irradiance, leading to a peak point of net electricity and freshwater at near $\omega = 0^{\circ}$. Based on the established results it is found that the maximum net electricity and freshwater are computed as 11.38 kW and 5.42 m^3/day, respectively. On the other hand, since the useful extracted heat from CPC ($\dot{Q}_u$) as well as its exergy rate ($\dot{Ex}_u$) are also maximized and their variation rate is subtly appreciable than that of freshwater and net electricity, thus a nadir point is observed for CGOR and exergy efficiency. Deliberating this justification, the minimum CGOR and exergy efficiency are computed as 1.099 and 8.67%, respectively. These findings are also substantiated by Wang et al. [15].

Figure 5.4 illustrates variation of freshwater, net electricity, CGOR, and exergy efficiency at various basic NH_3 concentrations. Accordingly, the extracted thermal heat from CPC is constant with any variation in the basic NH_3 concentration, thus it is expected that any alteration in CGOR and exergy efficiency would resemble that

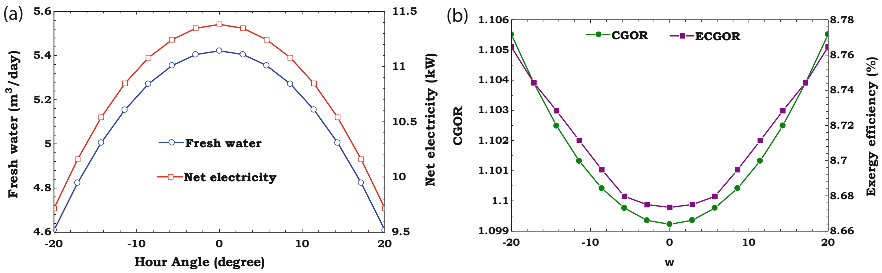


Fig. 5.3 Impact of hour angle on (**a**) freshwater rate and net electricity and (**b**) CGOR and exergy efficiency

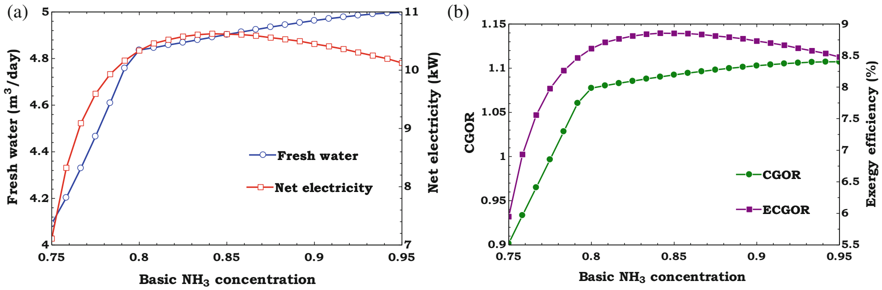


Fig. 5.4 Impact of basic NH_3 concentration on (**a**) freshwater rate and net electricity and (**b**) CGOR and exergy efficiency

of net electricity or freshwater. As Fig. 5.4 indicates, increasing basic NH_3 concentration augments the produced freshwater rate, while a maximum net electricity of 10.62 kW at $X_B = 0.85$ is observed. Since the impact of distilled water is dominant in the CGOR definition than the net electricity, thus it can be seen that the variation trend of CGOR is similar to freshwater rate. The similar concept is also true for the relation of the exergy efficiency and net electricity due to the dominant impact of net electricity in the exergy efficiency (compared to the freshwater rate). Accordingly, a maximum exergy efficiency of 8.85% at $X_B = 0.841$ is observed, while CGOR increases as X_B augments (like freshwater).

Figure 5.5 displays alteration of freshwater, net electricity, CGOR, and exergy efficiency at various generator pressures. Accordingly, the extracted thermal heat from CPC is constant with any variation in the generator pressure, since P_1 only affects the Kalina sub-cycle. Therefore, it is expected that any alteration in CGOR and exergy efficiency would resemble that of net electricity or freshwater. As pointed out in the explanation of Fig. 5.4, alteration of the distilled water dominantly affects CGOR, while variation of the net electricity substantially influences the exergy efficiency. Based on this clarification, it is observed that the freshwater is decreased as generator pressure increases, and hence CGOR will decrease through this alteration. However, the maximum net electricity of 10.72 kW at a generator pressure of 54.64 bar is seen, and hence the exergy efficiency is maximized by 8.91% at the corresponding pressure.

Figure 5.6 displays alteration of freshwater, net electricity, exergy efficiency, and CGOR at various slope angles of the aperture plane at a constant humidifier and dehumidifier effectivenesses of 0.85. As it will be demonstrated later in Fig. 5.7, the variation trend of freshwater rate, exergy efficiency, and CGOR versus of slope angle of the aperture plane is highly affected by humidifier–dehumidifier effectiveness. Overall, the extracted thermal heat from CPC is decreased substantially as slope angle of the aperture plane goes up. Consequently, less heat will be supplied to KC and less rich solution will rotate through the turbine. However, the enthalpy difference through the turbine is surged as the absorbed heat via generator decreases. A precise inspection has revealed that the increment rate of enthalpy difference through the turbine is dominant over the decrement of mass flow rate at low slope angle of the aperture plane ($\beta < 43.6$), while the trend is reversed onward. Therefore, a maximum net electricity of around 14.36 kW at $\beta = 43.6$ is seen. In terms of freshwater production (according to Figs. 5.6 and 5.7), it can be stated that the freshwater rate is continuously decreased at low humidifier–dehumidifier effectivenesses (e.g., $\varepsilon_{Hum} = \varepsilon_{Dhum} = 0.85$). However, in high humidifier–dehumidifier effectivenesses (e.g., $\varepsilon_{Hum} = \varepsilon_{Dhum} = 0.95$), it remains nearly unvaried at low slope angles and decreased thereafter more drastically. Also, as expected, more freshwater is distilled at high effectivenesses which has an exponential trend. In terms of CGOR and exergy efficiency, it can be said that CGOR is mainly affected by freshwater rate and useful thermal heat extracted from CPC, while exergy efficiency is prominently influenced by net electricity and $\dot{Q}_u$. Therefore, the alteration trend of CGOR will highly depend on humidifier–dehumidifier effectivenesses. Accordingly, at low humidifier–dehumidifier effectivenesses (Fig. 5.6b),

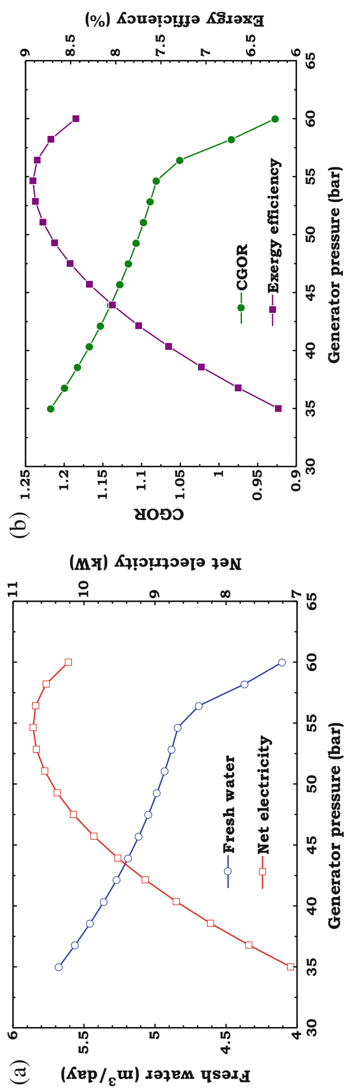


Fig. 5.5 Impact of generator pressure on **(a)** freshwater rate and net electricity and **(b)** CGOR and exergy efficiency

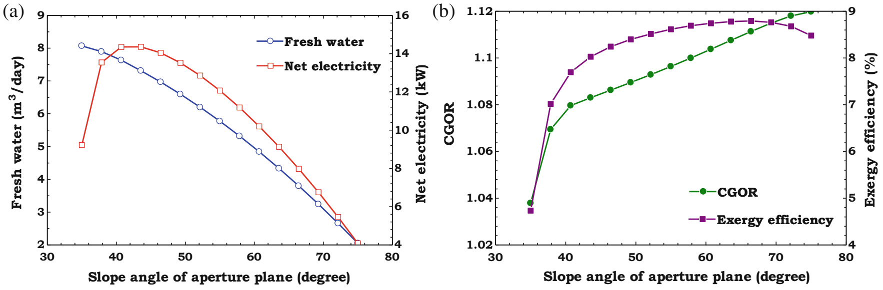


Fig. 5.6 Impact of slope angle of aperture plane on (**a**) freshwater rate and net electricity and (**b**) CGOR and exergy efficiency

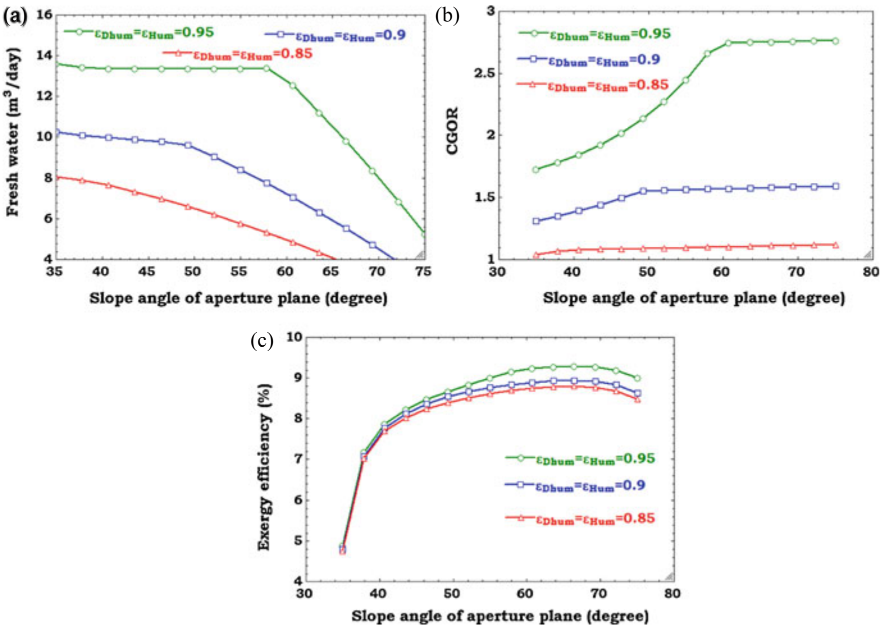


Fig. 5.7 Impact of humidifier and dehumidifier effectivenesses on (**a**) freshwater, (**b**) CGOR, and (**c**) exergy efficiency at different slope angles

CGOR is augmented, while at high humidifier–dehumidifier effectivenesses, it is remained constant at high slope angles (Fig. 5.7b). In exergy evaluation, it is discovered that the maximum exergy efficiency values of 8.79% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.85$), 8.94% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.9$), and 9.29% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.95$) at 66.5° can be attained.

Figure 5.8 displays alteration of freshwater, CGOR, and exergy efficiency at various desalination flow ratios and number of absorber tubes and a constant humidifier and dehumidifier effectivenesses of 0.95. It is worthy to pinpoint that

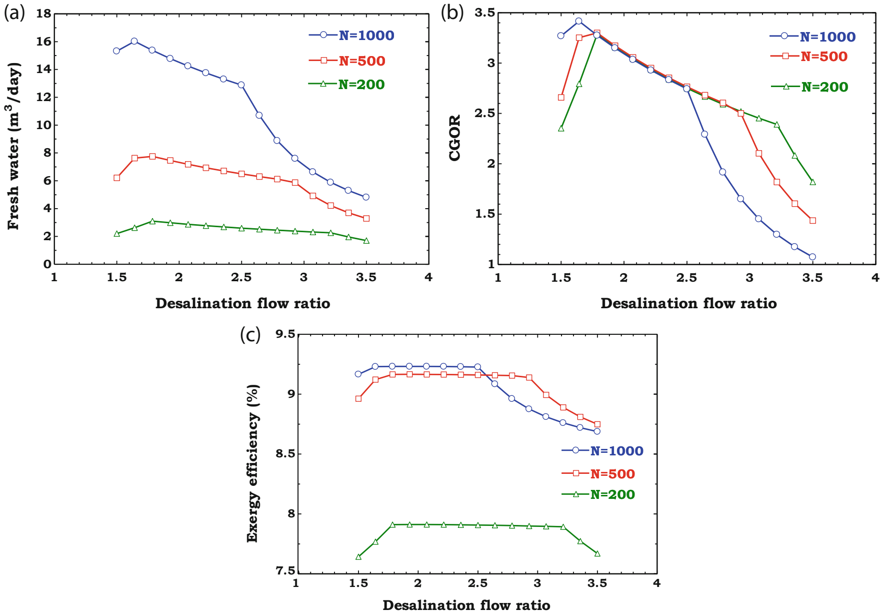


Fig. 5.8 Impact of desalination flow ratio on (**a**) freshwater, (**b**) CGOR, and (**c**) exergy efficiency at different number of solar collectors

since net electricity does not vary with m_r, thus its figure is excluded in this section. Since the extracted thermal heat from CPC is constant with desalination flow ratio, thus any variation in CGOR and exergy efficiency can be expounded with trend of distilled water rate. Regarding freshwater variation with desalination flow ratio, Fig. 5.8 illustrates that a pinnacle value is observed for the distilled water rate versus of the desalination flow ratio, where its value and location depends on number of collectors. Overall, any design of the devised CPD system with desalination flow ratio of 1.5–2 is recommended. Similarly, CGOR and exergy efficiency (especially CGOR) are peaked within in this range. As desalination flow ratio increases further from this range, the values of distilled water rate, CGOR, and exergy efficiency are decreased substantially. Deliberating CGOR variation versus of desalination flow ratio at various number of absorber tubes, the maximum value of CGOR for $N = 1000$, $N = 500$, and $N = 200$ is computed as 3.41, 3.3, and 2.79 at $m_r = 1.64$, $m_r = 1.78$, and $m_r = 1.78$, respectively.

Figure 5.9 displays simultaneous impact of number of absorber tubes and humidifier/dehumidifier effectiveness on the freshwater, net electricity, CGOR, and exergy efficiency. Since net electricity does not vary with humidifier–dehumidifier effectiveness, thus its variation with N is only plotted for $\varepsilon_{\text{Hum}} = \varepsilon_{\text{Dhum}} = 0.85$. As N increases, more heat will be extracted from CPC, leading to more power and freshwater production. However, according to variation of freshwater and net electricity versus of number of tubes, freshwater rate remains nearly constant or varies

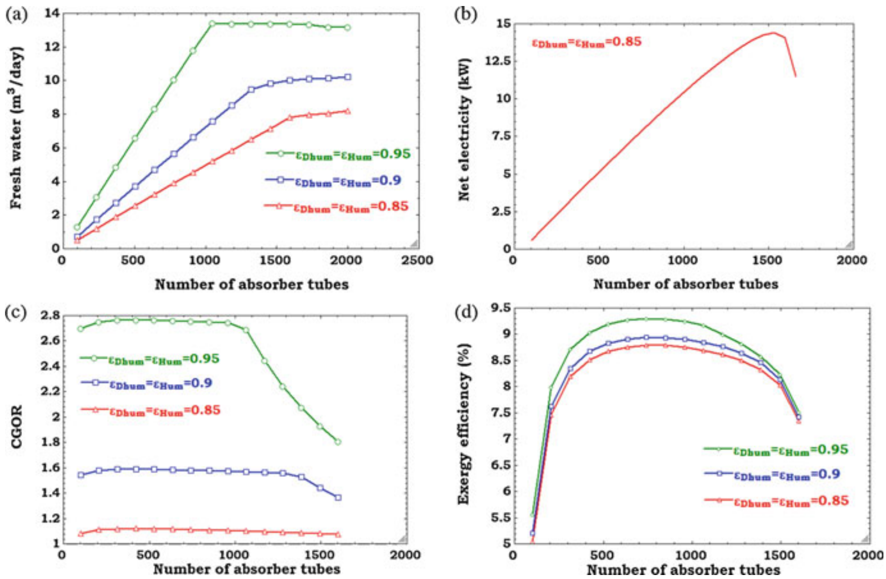
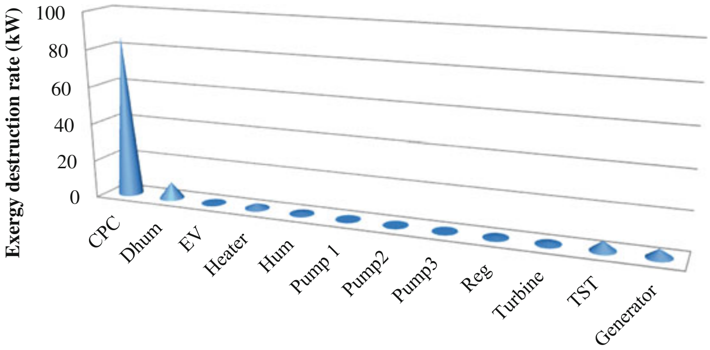


Fig. 5.9 Impact of number of tube on (**a**) freshwater, (**b**) net electricity, (**c**) CGOR, and (**d**) exergy efficiency at different humidifier and dehumidifier effectivenesses

subtly with any augmenting absorber tube, which is not economical and worthy solution. Thus, selecting appropriate and required number of absorber tubes should be accounted based on the attained results and highly depends on humidifier–dehumidifier effectiveness. As humidifier–dehumidifier effectiveness increases, efficiency of HDH unit increases and fewer number of tubes can be installed to attain the same potable water rate. In terms of power production, a peak net electricity of 14.35 kW at around $N = 1495$ is seen. The variation trend of net electricity and useful heating from solar energy results in a maximum value of exergy efficiency versus of number of tubes. According to Fig. 5.9d, the maximum exergy efficiency values of 8.75% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.85$), 8.93% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.9$), and 9.29% (in $\varepsilon_{\mathrm{Hum}} = \varepsilon_{\mathrm{Dhum}} = 0.95$) at around $N = 635$, $N = 740$, and $N = 740$ can be attained, respectively. Due to the variation trend of freshwater and useful heat of solar energy, CGOR does not vary significantly at low number of tubes and decreases onward since the extracted heat via CPC increases substantially in comparison with freshwater. Therefore, a trade-off should be considered in selection of number of tubes in CPC design which is recommended to be around 1000.

Figure 5.10 displays ascribable portion of different constituents of the devised CPD set-up. As the sketch indicates, CPC accounts for 86.3 kW out of the overall exergy destruction of 110.3 kW (approximately 78.24%). After CPC, dehumidifier has the second highest portion by 8.81 kW (around 7.98%). Therefore, any improvement in the operating condition of CPC is appreciable than other constituents in terms of improving its heat transfer rate.



	CPC	Dhum	EV	Heater	Hum	Pump1	Pump2	Pump3	Reg	Turbine	TST	Generator
Exergy destruction rate (kW)	86.3	8.812	0.227	2.79	0.957	0.039	0.018	0.086	0.778	1.167	4.84	4.31

Fig. 5.10 Portion of different equipment to overall exergy destruction rate

5.5 Concluding Comments

Solar-based combined power and desalination (CPD) systems at small-scale applications have recently been investigated numerously. Therefore, devising high-efficient solar-based CPD systems can be promising when the waste heat from various utilized constituents of the set-up is minimized. Meantime, Kalina cycle (KC) is suggested as an appropriate power generation system for low-temperature heat sources due to its zeotropic mixture characteristics. On the other side, humidification–dehumidification (HDH) desalination units profusely match with low-temperaturebased power generation systems (like KC) for waste heat capturing. HDH system is highly appropriate for low-temperature sources, and because of that the waste heat of KC is utilized as the main source of HDH unit. Also, a compound parabolic collector (CPC) is designed as a solar energy supplier of KC, where its capability for all hours of a day is investigated by designing a thermal energy storage unit as well. An extensive numerical modeling of the proposed CPD system is presented using first and second laws of thermodynamics. Following conclusions are drawn:

- The amounts of distilled water, net electricity, CGOR, and exergy efficiency were calculated as 4.96 m^3/day, 10.45 kW, 1.103, and 8.73%, respectively.
- Among all invested equipment, CPC was accounted for the highest exergy destruction by approximately 78.24%, followed by dehumidifier by around 7.98%.
- Freshwater rate and net electricity were maximized with hour angle, while CGOR and exergy efficiency were minimized with it.
- Increasing basic NH_3 concentration increased the freshwater rate and CGOR, while the maximum net electricity of 10.62 kW at $X_B = 0.85$ and exergy efficiency of 8.85% at $X_B = 0.841$ were observed.

- The freshwater and CGOR were decreased as generator pressure increases, while the maximum net electricity of 10.72 kW and exergy efficiency of 8.91% at a generator pressure of 54.64 bar were attained.
- The variation trend of freshwater rate, CGOR, and exergy efficiency versus of slope angle of the aperture plane was highly affected by value humidifier/dehumidifier effectiveness.
- Design of the devised CPD system within desalination flow ratio range of 1.5–2 was recommended.
- Selecting appropriate and required number of absorber tubes highly depended on humidifier–dehumidifier effectiveness. As humidifier–dehumidifier effectiveness increases, the efficiency of HDH unit was increased and fewer number of tubes can be installed to attain the same amount of potable water.

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Chapter 6
Biodiesel: A Sustainable Energy Source for Compression Ignition Engine

N. Kapilan

6.1 Background Information

The availability of energy resources affects the economic growth of any country. The long-term availability of energy sources may boost the economic growth. Most of the energy consumed worldwide originate from fossil fuels. The depletion and growing demand for fossil fuels has promoted the use of alternative fuels. In recent years, the conventional energy sources have been partially replaced by nonconventional energy sources such as wind energy, tidal energy, solar energy, biofuel, etc.

The world energy consumption is estimated to increase by 50% from the year 2005 to 2030 as per the International Energy Outlook Report. It is also reported that the energy demand in the Organisation for Economic Co-operation and Development (OECD) economies is estimated to increase slowly, whereas energy demand in the non-OECD countries is estimated to increase sharply. India is the fastest emerging non-OECD economy, and its energy consumption will increase sharply in the future [1].

The demand of the internal combustion engine has increased in recent years due to industrialization, increase in number of automotive vehicles, etc. The energy consumption of the world is expected to grow due to strong growth in economies and increase in populations in the developing countries. The demand of fossil fuel is increasing rapidly and researchers need to find suitable alternatives to the fossil diesel and petrol. Biodiesel is considered as an immediate replacement for the fossil diesel as the properties of biodiesel are similar to the diesel. The first-generation biodiesel is mostly produced from vegetable oils as it is easily available and also renewable.

N. Kapilan (✉)
Nagarjuna College of Engineering and Technology, Bengaluru, Karnataka, India

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6.2 Vegetable Oils

The vegetable oils are projected as one of the best replacements to the diesel. They are water-insoluble hydrophobic substances that primarily consist of fatty esters of glycerol. The variation in viscosity of the vegetable oils is due to its unsaturated bonds and interaction between the combinations longer fatty acid chain. The commonly present fatty acids in vegetable oils are myristic, palmitic, stearic, arachidic, behenic, linoceri, oleic, erucic, linoleic, and linoleinic. The molecular weight of triglyceride molecules ranges from 800 to 900 and it is four times higher than the diesel. This results in lower volatility of the vegetable oil. The vegetable oils are prone to oxidation and polymerization due to their unsaturation [2]. The vegetable oil properties such as viscosity, carbon residue, flash point, cloud, and pour points are higher than the diesel. However, calorific value and sulfur content are lower than the diesel.

The straight vegetable oil (SVO) has higher viscosity and causes incomplete combustion, carbon deposit in combustion chamber, higher engine exhaust emissions, and lower engine power. Hence it is not used as the sole fuel in the diesel engine. It is suggested that the SVO can be used as a partial substitute for the diesel in the CI engine in the form of fuel blend. The engine results show that the brake-specific fuel consumption (BSFC) for diesel and SVO diesel blends are better than the SVO and lower than the diesel. The use of the SVO diesel blend results in reduction in NOx emission as compared to the diesel. The ternary blends of SVO–diesel–alcohol reduce the engine exhaust emissions such as smoke. However, the use of SVO results in lower engine power output and higher exhaust emissions. The other problems with the use of SVO are carbon deposit in fuel nozzle injector, gum formation, filter clogging, carbon deposits at the nozzle tips and reaction with the few engine components. Hence, it is not advisable to use SVO or blends of SVO as fuel in the CI engine and the techniques such as preheating, fumigation of gaseous fuels, and application of thermal barrier coating on combustion chamber parts were tried to use blends of SVO and diesel as fuel [3]. The engine tests conducted with rubber seed oil diesel blends suggested that regular cleaning of fuel pump, fuel filter, and the combustion chamber is needed for long-term use of the blend in diesel engine [4].

The viscosity of the blend of thumba oil diesel (20% thumba oil +80% diesel) can be reduced using the engine's exhaust gases, as the heating minimizes the viscosity of the blend. It was reported that the preheated blend gives better engine performance and minimizes the engine exhaust emissions with reference to unheated thumba oil and diesel. Also optimized preheating of thumba blend causes higher brake thermal efficiency and reduces the exhaust emissions such as CO, HC, and smoke opacity emissions [5]. Increasing fuel inlet temperature increases peak cylinder pressure. It is preferred at part load and also at low speed when SVO was used as fuel in unmodified single-cylinder CI engine. Also the ignition delay was shorter for the preheated vegetable oil [6].

The thermal barrier coatings applied on the engine cylinder head, valves, and piston increase the combustion chamber temperature and result in better spray characteristics and atomization of the SVO. Also they reduce the fuel ignition delay. The thermal barrier coating results in higher thermal efficiency than the normal engine and minimizes HC, CO, and smoke emissions. However, this modification may cause lower lubrication in the combustion chamber [7]. The engine tests conducted with linseed oil–diesel blends on a CI engine which is coated with a ceramic material on engine inlet, exhaust valves, and piston show that the thermal barrier coating improves the fuel spray characteristics. The combined effect of thermal barrier coating and preheating enhances the thermal efficiency of the engine and reduces the engine smoke, CO, and HC emissions. However, it increases the NOx emission of the engine [8]. The SVO can be used in the CI with fumigation of liquefied petroleum gas (LPG), hydrogen, etc. The engine tests were carried out with mahua oil (MO) as a replacement to diesel by fumigating LPG. However, this method needs suitable modification to supply gaseous fuel to the combustion chamber. The fuel pump was used to inject the MO into the combustion chamber (CC) and LPG was fumigated with the air. The CI engine gives higher brake thermal efficiency and lower smoke emission in dual fuel mode as compared to the sole fuel mode with MO [9].

From the above discussion, we observe that the higher viscosity of vegetable oils results in poor engine performance due to pumping problem and poor spray formation which results in larger fuel droplet size. Hence, the poor fuel atomization and poor fuel air mixing results in incomplete combustion. Also it results in the formation of deposits in the CC and causes crankcase oil dilution. The long-term use of vegetable oils poses serious problems due to its higher viscosity and low volatility. Hence, vegetable oils can be converted into biodiesel to use as fuel in CI engines. This biodiesel can also be used as a partial substitute in the form of fuel blend with diesel in the CI engine without modifying the fuel injection system.

6.3 Biodiesel

According to National Biodiesel Board, USA, biodiesel is a mono-alkyl ester of long-chain fatty acids, derived from animal fats or vegetable oils, which conform to ASTMD6751 specifications for use in CI engines. The biodiesel can be obtained from any fat or vegetable oils by transesterification process. The biodiesel shall meet the biodiesel specifications in order to ensure proper performance.

The general equation shown in Fig. 6.1 explains the transesterification reaction. It contains three equivalent and consecutive reactions that are reversible. The stages of transesterification reaction are shown in Fig. 6.2, and triglyceride is converted into biodiesel with intermediate reactions such as diglyceride and monoglyceride respectively. In each reaction stage, for each molecule of methanol or ethanol consumed, one molecule of ethyl or methyl ester is formed. The base-catalyzed transesterification is most widely used [10].

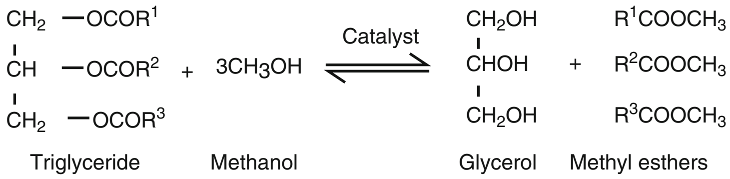

Fig. 6.1 Transesterification general equation

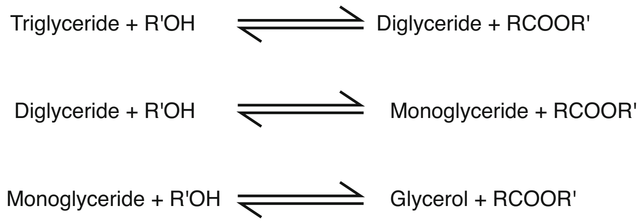

Fig. 6.2 Transesterification stages

6.3.1 Biodiesel Properties

The transesterification chemical reaction is used to produce biodiesel from vegetable oils. The long-chain fatty acids are converted into mono-alkyl esters by transesterification reaction. In transesterification reaction, the vegetable oil is heated with anhydrous methanol and suitable basic or acidic catalyst. The catalyst enhances the reaction rate and increases the product yield. Since transesterification is a reversible process, large amount of ethanol or methanol is used to shift the reaction to the product side. The process variables such as reaction temperature, reaction time, catalyst type, molar ratio of alcohol to vegetable oil, quality of the reactants, and free fatty acid (FFA) content affect the biodiesel yield [11, 12].

If the FFA content of the vegetable oil is high, then a two-step transesterification is preferred for biodiesel production. The first step is called esterification step, which is the pretreatment step used to esterify FFA present in the oil into fatty acid methyl ester. In this method, FFAs are esterified with alcohol in the presence of an acid catalyst to produce mixture of triglyceride and fatty acid methyl ester. In the second step, triglyceride is transesterified with alcohol to get biodiesel and glycerol.

The alkaline or acid-based catalysts are most widely used for the commercial production of biodiesel. The alkaline catalysts such as sodium hydroxide (NaOH), potassium hydroxide (KOH), and sodium methoxide are most widely used for the biodiesel production, and acid catalysts such as sulfuric acid, sulfonic acid, and hydrochloric acid are commonly used. The acid catalyzed is preferred when the vegetable oil contains higher amount of free fatty acids. The acid catalyst transesterification reaction is slow; however, it is preferred when low cost feedstocks are available. The homogeneous catalyst is expensive and cannot be reused. This leads to development of heterogeneous catalysts to overcome the problems faced with homogeneous catalysts. This type of catalysts can be used as substitute for strong acid catalyst to avoid corrosion problems and also environmental hazards [13, 14].

The products of transesterification are allowed to settle, to separate biodiesel and glycerol. The residual catalyst, water, and excess or unreacted alcohol present in the crude biodiesel is removed by the purification methods such as water washing, dry washing, and membrane extraction. The glycerol and alcohol are highly soluble in water and also the water can remove soaps and residual sodium salts. The distilled warm water is used for water washing and after the water wash, the biodiesel and water phases are separated by centrifuge or separating funnel. The remaining water after the water wash can be removed from the biodiesel by heating [11].

The biodiesel is highly susceptible to oxidation due to unsaturated fatty acid chains. Factors such as light, temperature, container material, and size of the surface also affect the oxidation of the biodiesel. The biodiesel properties may degrade during extended storage, and important fuel properties such as acid value, peroxide value, and insoluble impurities increase during longer storage period. The synthetic antioxidant additives such as butylated hydroxytoluene, butylated hydroxyanisole, tertiary butylhydroquinone, propyl gallate, and pyrogallol are most widely used, and these additives enhance the biodiesel stability. The selection of the antioxidant is based on number of variables. The addition of few antioxidants to the biodiesel may reduce the NOx emission of the engine. The storage condition and storage temperature affect the oxidation of the biodiesel significantly [15, 16].

6.3.2 Advantages of Biodiesel

The advantages are listed as follows:

1. Biodiesel is a renewable fuel.
2. Lower life cycle CO_2 emissions.
3. Biodiesel is an oxygenated fuel.
4. Biodiesel does not contain sulfur.
5. Biodiesel can act as a lubricity improver.
6. Biodiesel viscosity is close to diesel.
7. Biodiesel is safe to store and handle.
8. Biodiesel is biodegradable.
9. Biodiesel is nontoxic.
10. Biodiesel does not increase the greenhouse effect.

6.3.3 Disadvantages of Biodiesel

The disadvantages are as follows:

1. Costlier than the diesel.
2. Lower oxidation stability.
3. Reacts with copper and rubber materials.
4. Higher NOx emission.
5. Not suitable for lower temperature.
6. Lower volatility.

6.4 Engine Test

A significant number of engine tests were performed with and without making any modifications in the engine hardware, on single-cylinder and multi-cylinder CI engines, to find the suitability of biodiesel blends and biodiesel as a replacement for the fossil diesel. The effect of the biodiesel blends and biodiesel on the CI engine performance and emissions are discussed in the following paragraphs.

6.5 Effect of Biodiesel on Engine Performance

The engine tests were performed on a single-cylinder CI engine with mustard oil biodiesel–diesel fuel blends, such as B10, B20, and B30, at full-load conditions indicating that the designated thermal efficiency of the engine decreased by 6.8% with B10, while brake-specific fuel consumption (BSFC) increased by 4.8% with B10 and engine exhaust emissions such as CO and smoke emissions minimized as compared to diesel at full-load condition. However, oxides of nitrogen (NOx) emissions of the engine increased with mustard oil biodiesel fuel blends [17]. Also the engine tests carried out on a diesel engine with the waste cooking oil biodiesel blends such as B20, B50, B80, B100, and diesel suggest that the B20 produces lower CO for different engine speeds. However, all the biodiesel blends cause higher NO*x* for different engine speeds [18]. The engine tests conducted on a single-cylinder CI engine as per ISO 8718 standard with different operating conditions suggest the Egyptian castor biodiesel–diesel blend of B20 is preferred to get higher engine efficiency with lower emissions [19].

The engine tests conducted on a turbocharged common rail CI engine with blends of calophyllumInophyllum biodiesel and diesel show that the substation of biodiesel blends in multi-cylinder engine results in lower engine power at all engine speeds and lower engine emissions such as CO, smoke, and particulate matter (PM) emissions. It is suggested that the calophylluminophyllum biodiesel can be used as a partial substitute to the diesel in an unmodified multi-cylinder diesel engine

[20]. The hydrogen can be used to enhance the thermal efficiency of pomegranate seed oil biodiesel–fuelled diesel engine. The inlet manifold of the engine should be modified to supply hydrogen to the combustion chamber and the hydrogen enrichment study shows that hydrogen fumigation results in higher thermal efficiency and also improvement in engine exhaust emissions [21].

The engine performance parameters such as engine load, speed, compression ratio, air swirl, fuel injection pressure, and piston design affect engine performance and emissions [22]. The injection pressure and injection timing of the CI engine should be optimized to get better thermal efficiency and lower engine emissions when biodiesel or biodiesel blend is used as fuel [23].

The volatility and viscosity of the biodiesel are slightly inferior to fossil diesel, and hence it is necessary to advance the injection timing and to increase injection pressure to get better combustion and higher thermal efficiency. The increased injection pressure of the diesel engine results in improvement in the brake power, engine torque, and brake thermal efficiency and lowers the engine HC, and smoke emissions, while NOx emission is increased. It is suggested to increase injection pressure and advance the injection timing to get better combustion characteristics [24, 25]. The retard start of the injection timing with triple injection can be used to reduce NOx and smoke emission of the diesel engine [20].

The compression ratio significantly affects the performance and emissions of a multi-fuel engine, which is single cylinder variable compression ratio engine, and it is suggested that the higher thermal efficiency can be obtained with higher compression ratio, as it also reduces exhaust emissions [26]. The combustion chamber geometry can be modified to get higher thermal efficiency, better BSFC, and improvement in heat release rate, cylinder pressure, ignition delay, peak pressure, and lower engine exhaust emission such as CO, HC, smoke, NOx, and SO_2 [27]. The palm oil biodiesel results in higher wall impingement and it can be minimized by retarded injection timing, higher compression ratio, and exhaust gas recirculation (EGR). However, these techniques reduce the brake power and brake thermal efficiency [28].

6.6 NOx Emission Reduction

The biodiesel-fueled CI engine emits higher NOx emission due to slow combustion, which causes higher combustion temperature. Various techniques are used to reduce the NOx emission and among these methods selective catalytic reduction (SCR) is popular.

The engine experiments performed with B20 soybean biodiesel blend on a heavy-duty CI engine with SCR shows that the SCR minimizes the NOx and NO concentrations by 68–93% respectively, however it causes higher NH_3 emission [29].

The durability test performed on a CI engine fitted with diesel oxidation catalyst (DOC) and an SCR system and fuelled with biodiesel suggests that the engine power performance can be improved due to the running-in effect. However, the Brunauer–

Emmett–Teller analysis shows the reduction in specific surface areas of the DOC and SCR and results in increase in CO, HC, and NOx [30].

6.7 Effect of Additive Added Biodiesel

The biodiesel has lower volatility and poor oxidation stability and hence natural and synthetic additives are added to the biodiesel and biodiesel blends to enhance fuel properties. The volatile fuels such as ethanol and kerosene can be added with the biodiesel to enhance the cloud point by 10 °C with 20% ethanol and 13 °C with 20% kerosene. Also these additives minimize biodiesel's flash-and-fire points [31]. The addition of alcohol and butanol to the biodiesel may affect the biodiesel combustion characteristics. The biodiesel–ethanol blends reduce the particulate and NOx levels significantly; however, the biodiesel–n-butanol blends result in lower increase in CO and HC [32]. The addition of 5% diethyl ether to the diesel–biodiesel blend improves the performance of the engine in most of the engine loads [33].

The hydrogen addition to the biodiesel–diesel blends enhances the performance of the engine and also results in better emission parameters except NOx emissions. This is because hydrogen does not contain carbon, and hence hydrogen addition minimizes CO and CO_2 emission levels. However, it causes higher cylinder temperature and also increases NOx level [34].

It is reported in the literature that the addition of fuel additives with nano-sized particles made of metallic, nonmetallic, oxygenated, organic, and combination, with diesel–biodiesel fuel emulsion enhances the fuel properties, improvement in the heat transfer rate and also increases the stabilization of the fuel mixtures. Hence, the engine performance parameters may be improved and simultaneously there will be a reduction in the exhaust emissions based on nanofluid dosage [35].

The metal oxide additives such as titanium oxide and pentanol at nano-size can enhance the efficiency of a multi-cylinder CI engine, which is water-cooled at different engine loads, various speeds, and injection pressures. The ultrasonication process is used to add these metal oxides with the biodiesel and engine tests were carried out with the fuel blends. It is reported that the fuel blend with 5% of titanium dioxide dosage is better than other dosages and improves the BSFC. Also it reduces the NOx emission and improves the brake power of the engine at full load condition [36]. The addition of manganese oxide and cobalt oxide nano additives B20 blend of waste frying oil biodiesel shows improvement in the BSFC and the brake thermal efficiency; however, the NOx and CO levels were decreased as compared to base fuel [37].

Hence for the stabilization of fuel mixture, better fuel properties of the biodiesel and heat transfer rate improvement, different types of nano additives were added [35].

Biodiesel is composed of saturated fatty acid alkyl esters and hence it has relatively high cloud points. The cold-flow-improving additives dimethyl azelate and triacetin lower the cloud point of the biodiesel [38]. The herbal extracts have better antioxidant property due to the presence of phenolic compounds. The leaf extract of *Moringa oleifera* Lam has lower toxicity; however, it has better antioxidant property and improves oxidation stability of the biodiesel. However, it is less effective as compared to the synthetic commercial additive BHT [39].

The exhaust gas emission analysis of the biodiesel reported in the literature does not mention the environmental impacts created during biodiesel production process. Also, the effect of synthetic fuel additives and metal-based nano additives on nonregulated and regulated engine emissions is rarely reported in the literature [40].

A static immersion test carried-out with palm biodiesel on metals such as phosphorous bronze, leaded bronze, and copper shows that copper is more prone to oxidation as compared to other metals. The products of copper corrosion in biodiesel are cupric oxide and copper carbonate. However, the degradation of metal surface can be reduced significantly with the help of *tert*-butylamine and benzotriazole additives [41]. It is reported in the literature that the copper promotes the biodiesel oxidation. The metal such as Mo and Re showed an inhibitory effect on biodiesel oxidation. It is also reported that the metal oxides show similar effects on biodiesel oxidation from promotion to inhibition with oxides of Au, Cr, Cu, Ag, and Re [42]. The static immersion studies carried-out to study the palm biodiesel blends with 100 ppm *tert*-butylamine or butylated hydroxyanisole additive indicates that as the blend concentration increases the corrosion rate on copper also increases [41].

6.8 Biodiesel on Engine Vibration and Corrosion

In CI engines, vibration is produced during metallic contact developed due to combustion of the fuel and moving parts of the engine [43]. The engine tests conducted on a single-cylinder diesel engine with soyabean and rapeseed oil biodiesel show relationship between the noise produced during combustion, external noise, and heat release rate (HRR). The higher HRR causes higher external noise and combustion noise [44]. It is reported that the use of biodiesel as fuel in diesel engines lowers engine vibration. The fumigation of hydrogen to the diesel or biodiesel fueled engine decreases the engine vibration [45].

6.8.1 Effect of Biodiesel on Engine Lubrication

The wear scar diameter produced using the high-frequency reciprocating rig (HFRR) characterize the biodiesel lubricity. The low shear characteristics can be obtained by adopting a good balance between the monounsaturated–polyunsaturated and saturated–unsaturated and fatty acid methyl ester content [46]. The field tests, approximately for 800 h, conducted on a direct injection diesel engine to study the impact of the palm oil biodiesel on a multi-grade lubricating oil indicates that the lubricating system was maintained well and the lubrication system undergoes the normal wear rate, without affecting mechanical durability [47]. A long-run endurance test conducted CI engines with diesel and optimized biodiesel blend shows that the biodiesel causes lower wear as compared to diesel [48].

It is reported that the use of biodiesel blends up to 20% significantly reduces both friction coefficient and wear of the tribo-contact surfaces. Hence, the use of biodiesel will reduce environment pollution [49]. According to the lubrication trials, the biodiesel blends were compatible with various engine lubricant and also various engine gaskets [50].

The engine tests carried-out to study the impact of synthetic lubricating oil on a low heat rejection diesel engine fueled with Pongamiaoil biodiesel blends and diesel show improvement in thermal efficiency of the engine and reduction in specific fuel consumption. Also better engine exhaust emissions except NOx were observed as compared to uncoated engine [51].

6.8.2 Effect of Biodiesel on Engine Components

The engine components are affected by wear. The excellent lubricity of the biodiesel protects the engine components from both frictions and wear [52]. The tribological study was carried out to find out the effect palm oil biodiesel diluted in engine lubricants such as SAE 5W40 and SAE 10W40 suggesting that the acceptable palm oil biodiesel dilution threshold level for SAE 5W40 is up to 17.5-vol%, however for SAE 10W40 is from 28 to 34.5-vol%. If the dilution levels exceed these threshold values, then the lubrication film rupture due to higher load and higher shear rate produces material wear [53]. The tribological carried out with B20% honge oil biodiesel blend, 200 h long-endurance test shows the value of carbon residue, density, and ash content of the lubricating oil is higher with biodiesel blend as compared to fossil diesel. Also the endurance test conducted with biodiesel shows increase in oxidation and polymerization of the lubricating oil. The increase in wear trace metals such as copper, aluminum, iron, aluminum, chromium, and magnesium in the engine lubricating oil shows deterioration in properties of lubricating oil [54]. The 250 h endurance test conducted on fuel injection equipment (FIE) test rig with Karanja oil shows that the Karanja oil has lower wear as compared to the diesel [55].

Experimental results revealed that for 20% mahua biodiesel blend, the optimum EGR ratio is 15% for hot EGR and 20% for cold EGR. The series of engine tests conducted with B20 blend and at optimized EGR ratio shows lower wear rates as compared to diesel [56]. It is reported that the anticorrosion additive, IRGALUBE 349, is effective in improving engine performance. The engine tests shows that the mixture of biodiesel blend and additive [POD8A: 0.2% additive +8% palm oil biodiesel +92% diesel] and other fuel mixture [POD16A: 0.2% additive +16% palm oil biodiesel +84% diesel] results in higher brake power and higher torque as compared to biodiesel blend without additive. The fuel blends POD8A and POD16A minimizes the CO and NOx levels as compared to diesel, except HC emission. The anticorrosion additives reduce the ferrous wear debris concentration [57]. The friction and wear study carried out with biodiesel and blends of palm and calophylluminophyllum biodiesel, on the four-ball tester, at different temperatures at 40 and 80 kg loads show that the average coefficient of friction of biodiesel is lower than the diesel. Also the wear scar diameter of biodiesel and its biodiesel were lower than diesel at different loads and temperatures. The PB20 blend of palm oil biodiesel results in good lubrication characteristics and it has the ability to form highly lubricating film without damaging over a long time [58].

The immersion tests carried out in biodiesel and its blends with and without the addition of 100 ppm *tert*-butylamine or butylated hydroxyanisole additive result that copper corrosion rate increases with an increase in immersion time. However, similar copper corrosion rate was observed with diesel and B20 blend and the corrosion rate significantly does not vary with immersion time. The commercially available antioxidant, butylated hydroxyanisole, is effective in minimizing biodiesel oxidation [41].

Few nano additives improve the fuel quality and result in improved engine performance and better engine exhaust emission characteristics. The B20 blend of Pongamia biodiesel and diesel added with copper oxide nanoparticles results in higher engine brake thermal efficiency and lower the engine exhaust emissions such as smoke emission and NOx [59]. The diethyl ether (DEE) can be used as an oxygenated fuel additive to the biodiesel. The addition of 5% DEE in the diesel–biodiesel blend improves the engine performance significantly in almost all the engine loads. However, the addition of DEE does not have any impact on engine stability [33].

The compatibility carried out with biodiesel blends on five common elastomers such as ethylene propylene diene monomer or monomer ethylene–propylene diene (EPDM) acrylonitrile rubber or nitrile rubber (NBR), fluorocarbon, neoprene, and silicone. It is reported that the biodiesel results in higher swelling in NBR, neoprene, fluorocarbon, and silicone [60].

6.9 Future Challenges

The vegetable oils and fats can be converted into biodiesel and can be used as a partial replacement for the fossil diesel. However, the process variables of transesterification have to be optimized with better reusable catalyst and with proper biodiesel and glycerol separation method. The engine combustion chamber can be modified to enhance engine performance and also to reduce engine emissions. The work related to combustion chamber modification is limited in the literature and hence there is a scope in this area. The effect of adding synthetic additives and nanoparticles on the environment and human health is limited in the literature and further studies can be carried out in this area.

6.10 Further Reading

For further reading, the readers can go through the book and journal publications of SAE International or Elsevier Publications related to biodiesel and engine tests carried out with biodiesel.

6.11 Conclusions

The first-generation biodiesel is produced from vegetable oils, and the process variables should be optimized to get better biodiesel yield. The properties of the biodiesel are similar to fossil diesel. However, it has lower volatility, lower oxidation stability, and higher flashpoint. Hence, the engine process variables such as compression ratio, combustion chamber geometry, injection pressure, injection timing, etc., have to be modified to get better engine efficiency and lower engine exhaust emissions. Also biodiesel is added with different types of additives to improve its fuel properties and also to enhance the combustion characteristics of the biodiesel. The biodiesel blends up to B20 can be used in the CI engine without making any modifications in engine hardware. This work suggests that there is enough scope for further research in the area of biodiesel.

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Chapter 7
Net-Zero Energy Buildings: Modeling, Real-Time Operation, and Protection

Nasrin Kianpoor, Navid Bayati, Mojtaba Yousefi, Amin Hajizadeh, and Mohsen Soltani

7.1 Introduction

Energy consumption is proliferating in the world. In the USA, around 40% of initial energy consumption and 70% of global electricity usage is being consumed in the buildings [1]. Moreover, environmental effects related to energy usage created severe concerns among different societies such as researchers, engineers, and even politicians. Energy consumption in the buildings causes 38% of CO_2, 52% of SO_2, and 20% of NO_x emissions to the atmosphere, which results in a global climate change. Therefore, it is necessary to minimize energy consumption from the unfriendly energy resources in buildings to achieve a sustainable environment, which means maximizing the building energy efficiency without overlooking their comfort levels [2].

The existence of energy crisis and environmental effects caused European countries to make some decisions to deal with these problems. According to the EU commission target, all buildings must change to low energy buildings by 2020 to reduce greenhouse gas at least 20% compared to 1990.

In order to design zero energy buildings, several studies have been carried out on such issues as thermal insulation and home facade, size, building age, lighting systems, thermal conditions, air conditioning equipment, urban infrastructure, building orientation, and other applicable factors for reducing energy consumption.

On the other hand, due to the undesirable effects of fossil fuels on the environment and global warming, the production of green and low carbon energy is a significant priority of electric power systems. Energy production (especially electrical energy) by renewable resources is known as an efficient, reliable, and environmentally friendly option to reach sustainable development and low carbon society.

N. Kianpoor · N. Bayati (✉) · M. Yousefi · A. Hajizadeh · M. Soltani
Department of Energy Technology, Aalborg University, Esbjerg, Denmark
e-mail: nab@et.aau.dk; moy@et.aau.dk; aha@et.aau.dk; sms@et.aau.dk

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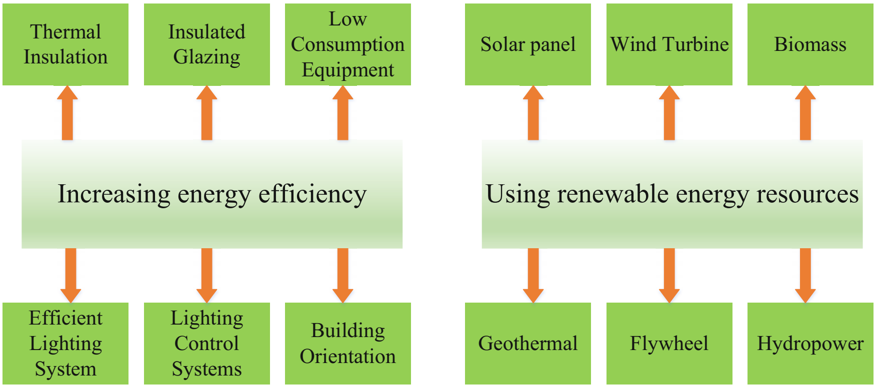


Fig. 7.1 Two fundamental features that nZEB should be including

Therefore, renewable energy systems in the buildings such as fuel cells, wind turbines, photovoltaic (PV) systems, and other renewable resources have got attention rapidly.

Accordingly, in recent years, ideal concepts such as zero energy buildings and zero-carbon buildings are presented and developed. In these buildings, two fundamental solutions have been considered to reduce energy consumption from traditional fossil fuels and greenhouse gas emissions:

1. Increasing home energy efficiency and demand-side management
2. Using renewable energy resources

Therefore, nZEB should be including two fundamental features that are presented in Fig. 7.1.

Several studies are available in order to design energy-efficient buildings. In these studies, some factors have considered reducing the energy consumption for residential homes. These factors included building envelope and thermal insulation, size, age, outdoor weather conditions, lighting systems, heat ventilation air conditioner (HVAC) equipment, urban infrastructures, building orientation, and other applicable factors [3]. In [4], the thermal insulation impacts including walls, floor, windows, and roof are investigated on the building energy performance. In some studies, the smart occupancy sensors' potential is considered to reduce building energy consumption [5, 6]. [7, 8] have considered the HVAC system management effect on the power demand of the building because HVAC system management is an undeniable concern in designing an energy-efficient building.

Some studies have considered the building as an electrical microgrid. Then based on this strategy, designing an energy management system for the buildings is necessary. A building that is modeled as a microgrid includes many local loads and resources (renewable energy resources and storage devices). Moreover, for improving the performance of the energy management system, randomness, uncertainty, and uncontrollability of these resources have to be considered because they will affect the real-time performance of the nZEB and reduce the building efficiency.

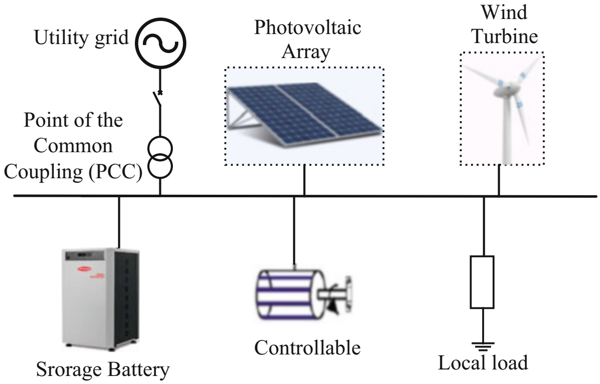


Fig. 7.2 Configuration of a microgrid that is considered in [8]

In recent years, how to design a stochastic energy management system for nZEB has attracted rapidly. The purpose of these researches is mainly to minimize energy costs and CO_2 emissions.

In [7], an energy management system is designed for an nZEB integrated with wind turbine, PV arrays, and energy storage batteries. The energy management system is in charge to minimize the cost of reliability and greenhouse gas emissions. In [8], an nZEB including PV arrays, wind turbines, energy storage devices, local loads and controllable loads is considered as a microgrid. The configuration of this microgrid is shown in Fig. 7.2, in which the optimization problem is defined to reduce the ratio between the energy cost and energy production in the nZEB.

Many types of research have been devoted to HEMS to minimize nZEB electricity energy consumption. Rule-based programming methods were developed in [9]. But the method problem is the lack of logical designing methodology. Hence, other alternatives such as mixed-integer linear programming and linear programming optimization approaches attracted more interest. These are the most common methods in smart home applications, to compute optimal control solutions [10]. But linear models were assumed for PV and EVs' battery in the mentioned literature; while in practice, the batteries models and PVs models are nonlinear [11]. Therefore, other methods like nonlinear optimizations have been getting more and more interest [12].

On the other hand, home uncertainties associated with the load demand, PV, and EV play a critical role in designing a proper HEMS. Power generation of PV fluctuates due to many factors like weather condition, air mass, day-time, etc. Similar to PV, EV state of charge (SOC) and the EV plug-in and plug-out time are very stochastic because of driving distance, traffic, EV plug-out SOC, etc. [13, 14]. Therefore, some stochastic models are found for the EV trip time model by some cutting-edge methods like Markov chain to formulate a stochastic dynamic optimization [15, 16]. In work [17], a HEMS was developed for commercial EV charging based on forecast models for home load demand and PV. Household power consumption was optimally scheduled by a HEMS for each household unit [18]. PV nonlinear model and battery energy storage are used by an MPC to minimize the cost of electricity in which artificial neural networks (ANN) are utilized to forecast the home load demand [11]. In work [14], the electricity load consumption and PV power output were predicted by the radial basis function neural network (RBFNN). RBFNN is used as it can capture the nonlinearity and models the effect of uncertainties. In addition, the electricity cost was minimized by a new SDP algorithm, while other problem requirements such as the EV charging requirement and power demand were fulfilled. In [19], a multi-stage energy management system was developed by an MPC to minimize the home energy cost. Three stages were introduced in which the PV power output and load were forecasted in the first stage, then a day-ahead off-line optimization was done, and finally, the MPC is applied to improve HEMS real-time performance by removing the forecasted data error as the real-time data reveal. In the literature, only a few works can be found like [11, 19] which developed some HEMS on the actual operation mode to make close the gap between forecast error and real-time data. Moreover, these works did not study the EV's impacts on HEMS performance.

Another important topic which is totally new in the nZEB research is the protection problem, and using a well-functioning protection scheme ensures the reliable operation of the nZEBs. As a starting point, evaluating the behavior of the existing protection devices such as fuses and current-based methods can be used. However, nZEBs uses different types of converters with current limiting capability during the fault. Moreover, an nZEB has different components which must be protected by different protection Schemes [20, 21]; for instance, electronic devices can be protected by fuses, but the suitable protection methods for long lines are current-based methods [22]. In recent years, several protection methods are proposed for microgrids [23], but the nZEB protection problems did not study yet. Therefore, in this chapter, the impact of protection devices on the operation on nZEBs is studied. In addition, one of the significant parts of the nZEBs is the grounding equipment, which is investigated in [24]. The grounding facilities of an nZEB affect the safety of personals in the system, and the selection of a suitable grounding scheme is an essential consideration for nZEBs.

7.2 nZEB Concept

A zero-energy building or net-zero energy building is a home with zero energy consumption from the grid/utilities; it means that the total amount of the used energy in the house is almost equal to the generated renewable energy on the site. These kinds of buildings reduce overall greenhouse gas emissions to the atmosphere compared with the non-ZEB.

nZEB is a new form of using renewable energy resources for the future of the cities. In the nZEB system, the building's conventional components including façade elements, roof tiles, and shading devices can be substituted by PV arrays to do the same functionality. Low installation cost, shortened energy payback time, and pleasant architectural appearance are some advantages of these replacements.

The nZEB system can be divided into two structures: grid-connected and independent systems. If it is connected to the grid, then it will be grid-connected; otherwise, it is independent (islanded mode) [25]. PV arrays and inverters (converters) are essential parts of an nZEB system. The structure of them can be mainly divided into a string, multi-string, centralized configuration, DC and AC modules based on the different compositions of PV arrays and inverters (converters). The generated DC power from the PV panels can be fed in an inverter that transforms the DC to AC power or can be stored as electricity or thermal energy in the batteries, hot water tank, and building mass. The generated electricity can be used in the building for the load demands; the extra electricity can be stored in the energy storage or exported to the grid. Nowadays, a wide variety of nZEB systems are available in the markets. Maximizing energy efficiency in nZEB is the primary first step. Generally, nZEB systems will decrease the energy demand of a building from the utility grid and generate electricity on-site.

7.2.1 nZEB Components

In the literature, an nZEB includes many different components which have to work efficiently under a proper HEMS. Typically, an nZEB has its own resources, storages (electric storage and heat storages), and loads (controllable loads, shiftable and nonshiftable loads). The main target in an nZEB is to make it independent from the grid by considering the environmental issues such as global warming, greenhouse gas, etc. Therefore, renewable resources such as biomass, geothermal, wind, and solar are using in nZEB researches. These renewable energy resources can be utilized in different ways to generate electricity, heating, and cooling for a building and it leads to less usage from utilities. Selecting what kind and how much alternative energy resources is the most crucial factor to have net-zero energy in a building. The type of renewable energy resources should be chosen according to the particular region that the building is located. A building located in the tropical region should consider solar energy, while a coastal or marine building should consider wind energy resources.

Renewable resource output varies significantly due to several factors such as air mass, day-time, seasons, etc. To stabilize the intermittent generation and improve the quality of power, the presence of energy storage systems like batteries is vital for the nZEBs [26]. Energy storages can be used to save the extra power generation as electricity or thermal energy (batteries, building space, and hot water tank) [27]. The balance of energy between the home renewable resource and demand is highly required for HEMS. Therefore, batteries and thermal storages have a high potential to coordinate discharging/charging schemes to balance the power generation. Moreover, these are able to store the electrical energy for future and emergency use, when electricity outage occurs. In the nZEB literature, EVs are considered as an energy storage system, since EVs are used for transportation only 4% of a year and they can be used for secondary function for the rest of a year [28].

7.2.1.1 Renewable Energy Resources

Nowadays, increasing energy demands and world environmental conditions have provided tremendous opportunities to use different sustainable resources. In nZEB, different kinds of renewable energy resources can be utilized, including solar panels, wind turbines, biomass, and geothermal. In the following sections, they will be explained.

7.2.1.1.1 Solar Panel

Solar energy is the most common renewable energy resource in nZEBs. It is clean and endless energy [29]. Solar energy can be used in different ways such as solar PV, solar water heater (SWH), solar cooling, and solar drying. The SWH is widely utilized in the household because of the low cost and easy installation. Hot water that is heated via solar can be used for different aspects such as washing, showering, and cooking. Solar energy can be divided into two categories: solar PV and solar thermal. The best way to convert sunlight directly to electricity is known as solar PV. The solar PV is popular in the places that the average sunshine is abundant. PVs are suitable candidates to use in nZEBs because of the easy installation and maintenance. Furthermore, ZEBs are usually equipped with an energy storage system to save energy for further uses [30, 31]. The PV module is the main part of a solar system; therefore, the PV module should be properly installed based on the slope and direction of the module. There is an irreplaceable charge controller in a stand-alone PV in order to keep the battery from overcharging or discharging.

7.2.1.1.2 Wind Turbine

Because of the natural variability of PVs, using another type of renewable energy resources such as wind energy can improve the functionality of the nZEBs. Wind energy is one of the important renewable energy resources and its usage in nZEBs is a hot topic among researchers in the past years. The device which generates electrical energy from the wind power is known as a wind turbine, that generally has a generator, blades, steering gear, safety mechanism, tower, and energy storage device [32]. In the nZEBs, the straight motion of the wind is blocked by the buildings; so, the air diverts to the sides and top of the building which results in pressure difference around the blades. This pressure difference rotates the generator and generates electricity. Generally, electricity generated by a wind turbine is employed for many applications like communication equipment, home lighting equipment, and electrical tools [33].

7.2.1.1.3 Biomass

Another renewable energy resource is biomass. Biomass is an animal or plant material used for producing electrical or thermal energy in various industrial processes. The biomass energy is widely used in nZEBs in rural areas. A lot of researches have been done on the utilization of biomass energy such as biomass energy in high rise building and the effect of biomass boilers on energy rating [34]. Nowadays, different kinds of biomass energy are used in nZEBs, such as biomass gasification generation, biomass combustion generation, and biogas power generation.

7.2.1.1.4 Geothermal

Geothermal energy is a sustainable and clean renewable energy. Geothermal energy has different resources, including shallow ground, to hot water and rock that are a few miles under the ground. In the last years, many geothermal devices have been used in nZEBs. The shallow systems do not require a remarkable geological setting and high geothermal gradients with eco-friendly and clean features [35, 36]. The shallow geothermal energy is mainly used for air conditioning in a residential home, and the heat pump methods are used to pump up the shallow underground low-temperature heat sources. The ground source heat pump is an effective air conditioning system to use surface geothermal resources for heating and cooling purposes. Geothermal energy resources development is a new emerging industry which needs high investment and has a high risk because of the geographical distribution limitations of geothermal energy [35].

7.2.1.2 Home Energy Storage

The energy storage systems are an important part of nZEBs. They have significant effects on the usage of renewable energy. The extra electricity can be stored in the home energy storage devices for different applications, or it can be fed into the grid. At the moment, selling the extra electricity is not economic since the government stops their subsidies and reduce the tariff of buying electricity from the home renewable resources. In addition, based on some research, selling the electricity to the grid affected the battery aging and cause many problem such as overload and reverse power in the district with high penetration of PVs; so, it is not economic and the idea of self-consumption nZEB is proposed which is more dependent on the energy storage for saving the electricity. Currently, different kind of energy storage devices is used in nZEBs such as flow batteries, lead-acid batteries, ultracapacitors, hot water tanks, building mass, and chemical energy storages [37]. The electricity that is produced by wind and solar energy is always volatile and fluctuant, and the amount between demand and energy supply at any time should be balanced. Therefore, coordinating charging/discharging schemes of home energy storage system (HEES) can effectively make a balance of the renewable energy resources volatility and variability and keep the power supply reliable and stable.

7.2.1.3 Building Load

Building loads can be classified into shiftable loads, non-shiftable, and controllable loads. Shiftable building loads can be switched on or switched off at any time. These kinds of loads can do a task without any manual control. Washing machine, iron, water heater, and air conditioner are some of the shiftable loads in residential buildings [38]. Shiftable loads in terms of the operation time continuity are divided into two categories: ‘non-interruptible’ and ‘interruptible’ [39].The interruptible home loads are usually more schedulable than non-interruptible ones [39]. Non-shiftable home loads are used only when the users are home; they depend on manual control to do a task. Television, light, computer, refrigerator, printer, microwave, hairdryer are some of the non-shiftable appliances. Using of non-shiftable appliances cannot be postponed because the comfortability of users relies on the timely services of non-shiftable appliances. Another important group of loads is controllable load such as EVs, HPs, HVAC, etc. Despite the fact that the time of these kinds of loads can be shifted, the rating power of them can be controlled as well. In other words, it is possible to charge a car in a range of power or use a heat pump in a specific range of power. These components increase the flexibility of the HEMS and can be used as an auxiliary service for the nZEB. The number of EVs is increasing in recent years; it helps to decrease greenhouse gas emissions and air pollutions [40, 41]. When EVs are connected to the grid, they can charge or discharge. Therefore, the electric energy that is stored in the EV battery can be transferred to the home during peak periods and charged during off-peak [28, 42].

7.2.2 Potential Impacts of Considering Uncertainties into the Models

Just a few studies in the nZEB literature considered the uncertainties related to the nZEB components and try to model them. In HEMS literature, ANN is used a lot to work with PV uncertainties and household demand to forecast power generation and consumption [19, 43]. In [44], ANN was used to model the uncertainties related to home load demand where they comprehensively studied several random parameters. Similarly, in work [45], the solar radiation uncertainties, building internal gains, and ambient temperature are considered as disturbances for the system and a discrete bi-linear space model of the building was formulated. However, EV uncertainties are not considered in their work. The main challenge of designing HEMS for an nZEB arises from the uncertainty of multiple sources, such as renewable power generation, customer's power demand, EV mobility, etc. There are only a few works that consider these challenges explicitly. In this book chapter, the interaction among various random variables is presented. Then, the stochastic behavior and uncertainties of PV, load demand, and EV are discussed and modeled to improve the energy efficiency of nZEBs. In sequence, the stochastic models for nZEB components are obtained by some well-known techniques.

7.3 Different Modeling Techniques by Incorporating Uncertainties

In this section, models of the smart home components are presented, which are obtained by different techniques, such as data-driven methods and mathematical model methods. In this study, the uncertainties and stochastic parameters of the nZEB variables are discussed and modeled. The uncertainties problems arise from different resources such as PV, EV, the household electric demand, and time-varying electricity price [15]. Therefore, well-known techniques are employed to model the building components regarding the uncertainties. Finally, the strengths and weaknesses of each technique are discussed. The proposed techniques are listed below:

- Data-driven techniques
  - ANN
  - Fuzzy Inference System
  - Adaptive Neuro-Fuzzy Inference System (ANFIS)
  - Markov chain
  - The conditional probability distribution for EVs
- Mathematical techniques
  - Sandia PV panel performance model
  - PVWatts model
  - Power temperature coefficient model
  - Simple PV array efficiency model

7.3.1 Data-Driven Methods

Data-driven expression literary means that progress in an activity is forced by data, rather than by intuition or by personal experience. Therefore, there are many techniques or algorithms, which find a solution or make a decision for a system or plan based on data analysis interpretation. In nZEB literature, some data-driven methods like ANN, fuzzy inference systems (FIS), ANFIS, time series algorithms, probability theories, and Markov chain are well-known techniques which are often utilized to find forecast models for renewable resources, EVs status, home load demand, etc. [46]. In the sequence, each method is introduced, respectively.

7.3.1.1 Artificial Neural Networks

ANNs are computing systems, which are inspired by the neural network of animal brains [47]. These kinds of systems have self-learning capability to do tasks by considering examples, usually are a free programmer. Therefore, they are outstanding candidates to utilize in the nZEB application to predict the load and power generation from renewable resources. Many various types of ANN are presented in the literature, for example, convolutional neural network (CNN), recurrent neural network (RNN), and multilayer perceptron (MLP). These methods are often employed for forecasting the home load demand and renewable resource output power (mainly PV).

7.3.1.1.1 MLP Neural Network

The MLP structure is the most popular type of ANN. Generally, the MLP consists of input layers, hidden layers, and output layers. A representative MLP structure is shown in Fig. 7.3. As can be seen, this structure has two hidden layers and two outputs. The neurons in layers share the same inputs, but they are not connected to each other. In the feed-forward structure, the inputs of a layer are the outputs of the previous layer. The equivalent model of this network is as follows [48]:

$$y_k = \sum_{j=1}^{4} \left(u_{k,j} \cdot \frac{1}{1 - \exp\left(- \sum_{i=1}^{3} W_{ji} x_i + \Theta_j \right)} \right) + \Theta_k, \tag{7.1}$$

where $W_{i,\,j}$ (connect the neuron i to the input j), $u_{k,\,j}$ are the weight matrix and Θ_k is the bias vector (it is not represented in the figure). The back-propagation algorithm is

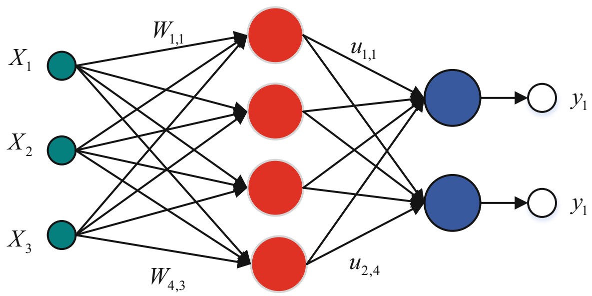


Fig. 7.3 A multi-layer feed-forward neural network architecture with two hidden layers

the most commonly used algorithm for the MLP training, which employs the steepest descent approach by computation of the loss function gradient toward the ANN parameters.

In the PV and load forecasting application, the feed-forward neural network with backpropagation algorithm is still the most widespread technique; however, there are many ANN architectures that might be suited for other applications.

7.3.1.1.2 RNN Architecture

Nowadays, deep learning algorithms have promoted rapidly compared to shadow learning algorithms [49]. Deep learning algorithms have a large number of hidden layers, which are capable to model intricate nonlinear patterns [50]. Therefore, RNN is presented as a powerful deep learning algorithm to capture the nonstationary and long-term dependencies of the forecast horizon. The mathematical expression of the RNN is presented as [50]:

$$\begin{aligned} S_t &= f(u \times x_t + W \times S_{t-1}) \\ y_t &= g(V \times S_t), \end{aligned} \tag{7.2}$$

where $f(\cdot)$ and $g(\cdot)$ are the nonlinear functions. The parameters W, u, and V are the weight matrixes for the RNN's layer. The variable S_t is the network memory at the time t. In Fig. 7.4, the RNN structure is presented.

In the RNN structures, the internal state (memory) plays vital roles. They are in charge to process the sequence of inputs, unlike the weight connection in the basic neural network [51]. In the RNN, the information at the previous time can be obtained by the hidden state, and the output is calculated based on the current time and previous memories. Due to the transmission of information from the last node to the next node, the performance of the RNN is quite good once the output is near to its related inputs. Today RNN is used in many applications like regression prediction problems, speech recognition, and text recognition.

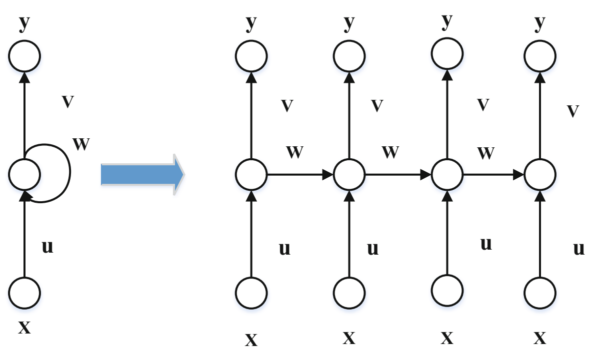


Fig. 7.4 A simple representative RNN architecture

7.3.1.1.3 CNN Architecture

Similar to RNN, CNN is another kind of deep neural network that provides better accuracy than MLP type in the serious nonlinear problems like home load forecasting. This kind of neural network got inspired by the concept of weight sharing. A typical CNN architecture with a one-dimensional convolution and one polling layer is depicted in Fig. 7.5. The lines in same colors represent the same sharing weight and the weight sets are treated as kernels. When the convolution time finished, the inputs are passed to the feature maps. In the next step, the feature map of the convolution layer will be checked out and the dimension will be decreased in the pooling layer. As can be evidenced in Fig. 7.5, the dimension of the feature map reduces to two after the pooling process.

To sum up, the MLP structure is the best popular and simplest ANN. In this architecture, the information goes in one way from the input to output nodes via the hidden layers. The RNN and CNN types are the advanced types of the neural network, which are more complicated compared with MLP, but they are more accurate than MLP architecture. In the load and supply forecast literature, there are many studies, which recommended these architectures. In [52], RNN and feed-forward were utilized to forecast the load demand. It is the only report, which claims the linear models have better performance than ANN. A novel pooling-based deep RNN was developed to predict the load demand and attained initial success [53]. In work [54], CNN was trained to develop a model for forecasting home load and its results were compared with other ANN architectures. They proved that CNN is a valuable approach in the load forecasting application.

To show the ability of the neural networks in the nZEB application, MLP neural network architecture is trained with Levenberg-Marquardt optimization, which is a famous backpropagation algorithm. As an example, for PV power and home load forecasting, the MLP inputs are months, days, day-time, ambient temperature, wind speed, and humidity, and MLP targets are the historical household demand and

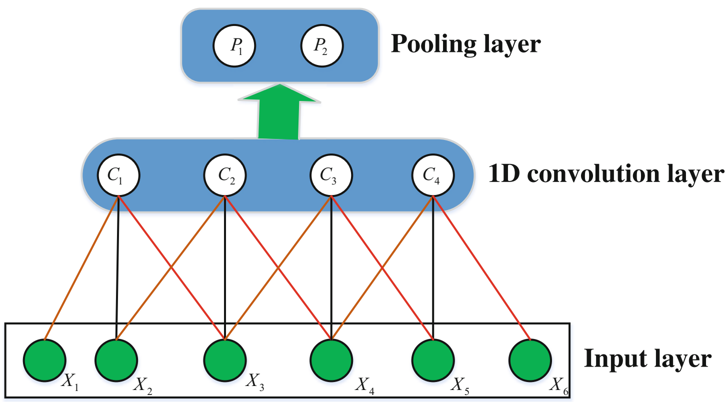


Fig. 7.5 A simple CNN structure with a one-dimensional layer

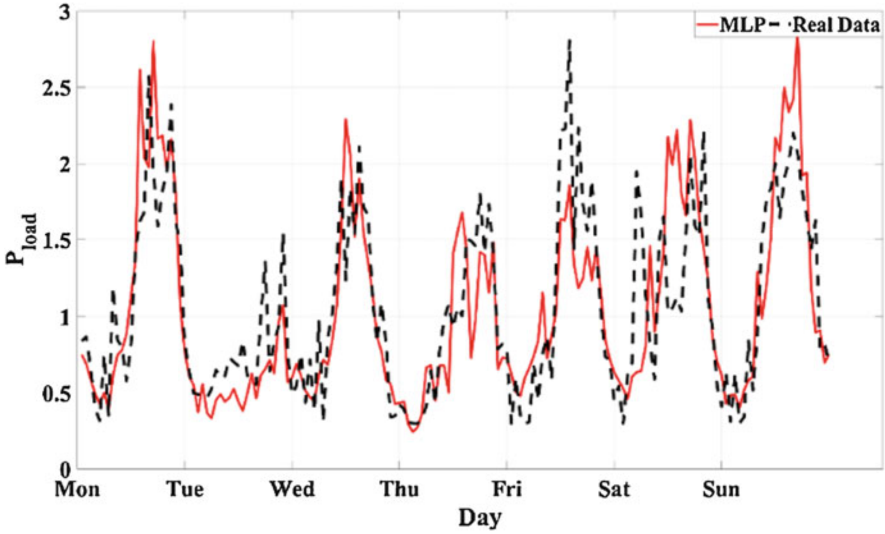


Fig. 7.6 The home load demand over a week (July 2017)

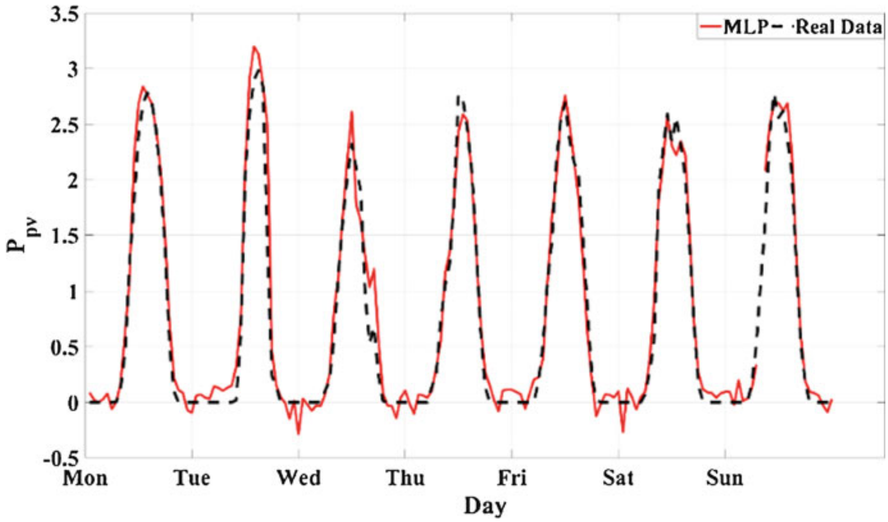


Fig. 7.7 The PV output over a week (July 2017)

historical PV power output respectively. In Figs. 7.6 and 7.7, the results of forecast models are compared to the real data. As it is exhibited, the trained MLPs can track the real data and have a strong ability in pattern recognition. The real data is obtained from a single family in Esbjerg, Demark. The data related to the weather is collected from the Esbjerg weather station, Esbjerg campus, Aalborg University, Denmark (from 1st of January 2017 to 1st of January 2018). In this work, 2/3 of the data are utilized for training the MLP and the 1/3 of them are employed to test and validate the trained MLP.

7.3.1.2 Fuzzy Inference System

Another popular research area is a fuzzy inference system, which has been successfully utilized in many applications such as process control, system identification, and pattern recognition [55]. Fuzzy inference system allows us to approximate any functions and it has the ability as ANN [56]. The benefit of the FIS to ANN is to capture reason and consequence in the inference process. In work [57], short-term load was forecasted by a designed fuzzy expert system. The fuzzy inference systems are fast approaches for uncertain problems, but these systems are highly depended on expert experiences and knowledge. In other words, when the information related to the system is insufficient, obtaining proper forecast results is very difficult. Therefore, ANFIS approach presented in the literature is to make a trade-off between ANN and FIS systems [13].

7.3.1.3 ANFIS

ANFIS is a method that can take advantage of ANN self-learning ability with the fuzzy inference linguistic expression function. It can be trained better when the data are not sufficient and do not need high computational power compared with ANN [46]. Nevertheless, this method is a data-driven method and works well as long as the quality of the provided data be appropriate. This approach was presented first in the 1990s [58]. Any nonlinear functions can be estimated by the fuzzy inference system of ANFIS which is corresponded to a set of fuzzy "if-then" rules [59]. ANFIS is a well-known technique for load and power supply forecasting [60]. In this part, the power of PV and household demand are predicted by a trained ANFIS, respectively. ANFIS is trained by about 2/3 of the data and 1/3 of data is applied for validation and testing. Similar to ANN, the ANFIS inputs are the months, days, day-time, humidity, wind speed, solar irradiance, ambient temperature, and the ANFIS outputs are historical PV power data and historical household demand to forecast the PV generation and load demand regarding the effects of random parameters respectively. The ANFIS structure for the PV system is shown in Fig. 7.8. As it is illustrated, the ANFIS is trained with 54 Gaussian membership functions. The Gaussian membership function and subtractive clustering method are selected for generating the FIS, because they have a strong performance with multiple inputs system. In addition, for proving the ANFIS accuracy, the home load forecast is compared with MLP and real data in Fig. 7.9. As it is illustrated, both methods (ANFIS and MLP) are good at pattern recognition and are able to give a practical output for short-term load forecasting and power generation forecasting, more details are available in [46].

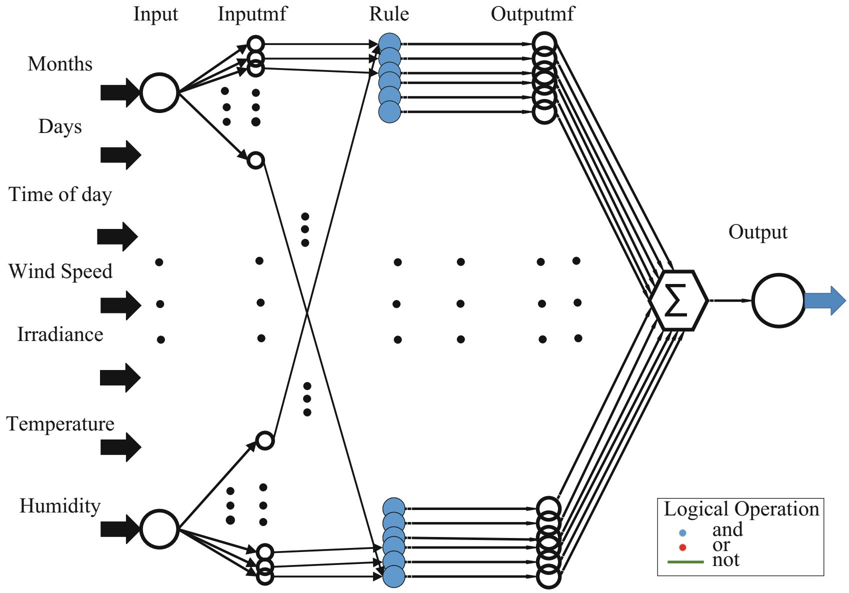


Fig. 7.8 ANFIS structure for PV power generation

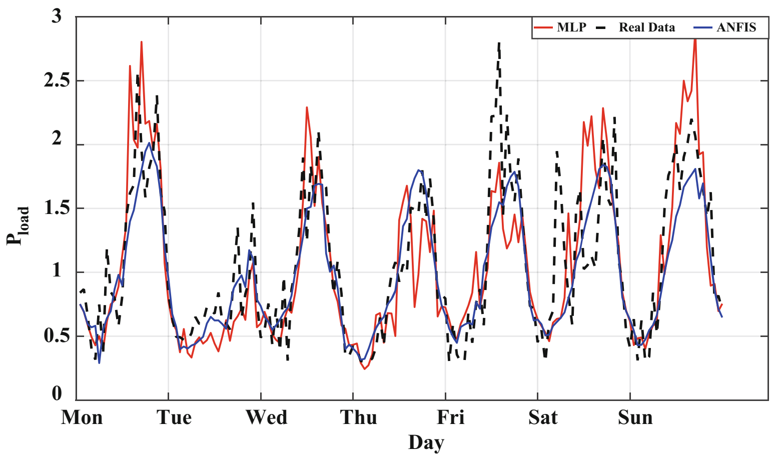


Fig. 7.9 Forecasted home load demand (July 2017)

7.3.1.4 Markov Chain

Markov model is a simple and common approach to statistically model the random processes. The Markov chain's transition matrix represents the probability distribution. If the Markov chain has two possible states ($x_k = 0$ and $x_k = 1$), the matrix will

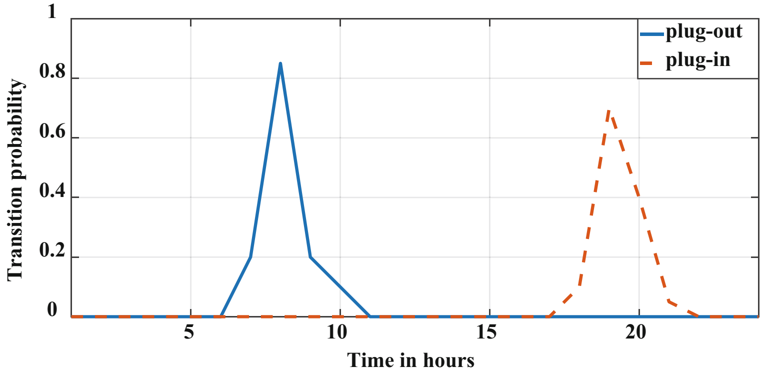


Fig. 7.10 EV plug-in/out temporal distribution [46]

be a 2 × 2 matrix. The transient matrix can be obtained, assuming the values $D(k)$ and $C(k)$ be the transition probabilities of $x_k = 1$ and $x_k = 0$ respectively.

$$\begin{cases} P_{ij,k} = \Pr[x_{k+1} = j | x_k = i, k], \quad i, j \in \{0, 1\}^2, \\ P_{ij,k} = \Pr[x_{k+1} = 0 | x_k = 1, k] = D(k), \\ P_{ij,k} = \Pr[x_{k+1} = 1 | x_k = 1, k] = 1 - D(k), \\ P_{ij,k} = \Pr[x_{k+1} = 1 | x_k = 0, k] = C(k), \\ P_{ij,k} = \Pr[x_{k+1} = 0 | x_k = 0, k] = 1 - C(k). \end{cases} \tag{7.3}$$

In the EV literature, the Markov chain technique is widespread and popular to model the EV states (plug-in $x_k = 1$ or plug-out $x_k = 0$ status) [61]. In work [15], the EV dynamic charging stations are formulated by Markov modeling techniques.

To model the EV status, a Markov chain is designed as an example in this section. Thereby, around 3197 working days of 10 individual daily driving patterns were analyzed. The people were from the Chengdu University office who started their works from 8:30 AM and ended at 5:30 PM [14]. The temporal distribution of EV plug-in/out is calculated by studying the daily driving statistical data. It is exhibited in Fig. 7.10.

As it is evident, around 7:30 the probability of plug-out status is high when the EV leave and around 19:30 plug-in probability is high, when the EV comes back. Moreover, the EV transition probability matrix is achieved for the EV state in every timeslot, and it is plotted in Fig. 7.11.

7.3.1.5 EV Conditional Probability Distribution at Plug-in Time

One of the most critical concepts in the probability theory is conditional probability. The EV plug-in battery energy (E_{in}) can be estimated by this valuable approach. In practice, the EV plug-in battery energy can influence by several factors such as the

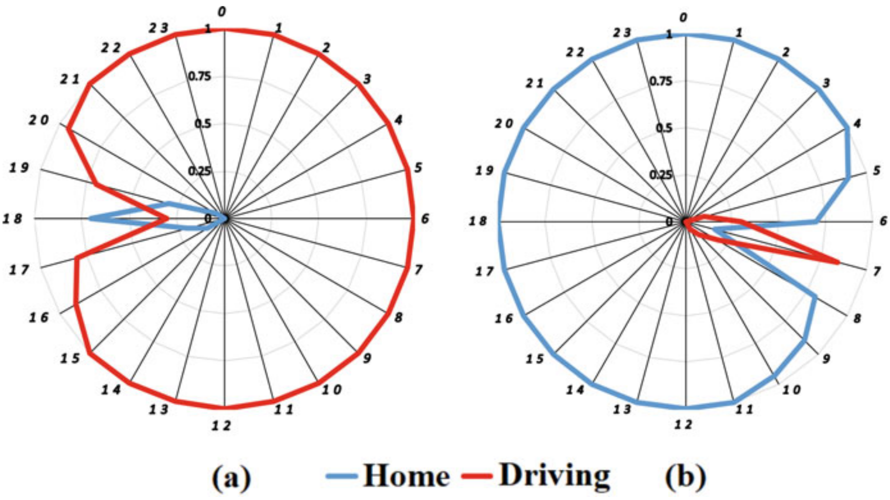


Fig. 7.11 Transition probability matrix of the EV: (**a**) driving status; (**b**) home status [46]

EV plug-out energy (E_{out}), driving distance (d), traffic, driving styles (downtown or countryside), etc. In this study, the driving distance effect is assumed only and it is calculated as follows:

$$E_{\text{in}} = \begin{cases} E^{\min}, & \text{if } E_{\text{out}} - E_{\text{cc}} \times d \leq E^{\min} \\ E_{\text{out}} - E_{\text{cc}} \times d, & \text{otherwise,} \end{cases} \tag{7.4}$$

where $E^{\min}$ is the minimum battery energy level and $E_{\text{cc}} = 0.159\,(\text{KWh/km})$ [62]. Then, by knowing the amounts of E_{out} and d, the EV conditional probability distribution is computed as below:

$$M_{A_1B_1} = \text{Pro}(E_{\text{in}} = A_1 | E_{\text{out}} = B_1), \tag{7.5}$$

where A_1 and B_1 are values from the feasible discretized set of the EV battery energy values ($A_1, B_1 \in S$). The value $M_{A_1B_1}$ is the probability amount in which the EV plug-in battery energy $E_{\text{in}} = A_1$ results in $E_{\text{out}} = B_1$.

By examining the statistical data from the 2009 US national household travel survey related to the daily driving distance [63], the conditional probability of E_{in} by given E_{out} is calculated and is presented in Fig. 7.12.

Moreover, the EV battery charging dynamic model is calculated as follows [14]:

$$\begin{aligned} E_{k+1} &= E_k + \Delta t(P_{\text{evc},K} - \eta |P_{\text{evc},K}|) \\ E_0 &= E_{\text{init}}, \end{aligned} \tag{7.6}$$

where the E_k is the energy of the EV battery at the time K, P_{evc} is the EV's charging power. The variables η and Δt are the loss efficiency and time interval, respectively.

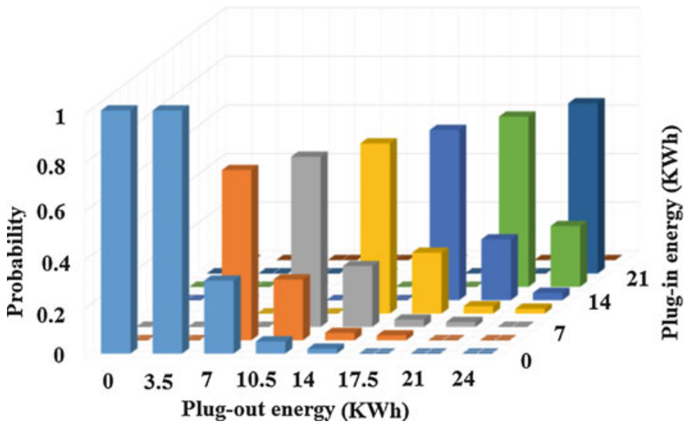


Fig. 7.12 EV battery energy probability values during the plug-in time [63]

Furthermore, E_{init} is the initial battery energy level. The charging EV's battery equation is explained above when it is available at home. The EV dynamic equation in a whole day with incorporating the random parameters is as follows [14]:

$$E_{k+1} = \begin{cases} E_k, & X_k = 0 \rightarrow X_{k+1} = 0 \\ \text{Pro}[E_{\text{in}}]_{E^{\min}}^{E^{\max}}, & X_k = 0 \rightarrow X_{k+1} = 1 \\ E_k + \Delta t(P_{\text{evc},K} - \eta|P_{\text{evc},K}|), & X_k = 1 \rightarrow X_{k+1} = 1 \\ E_k + \Delta t(P_{\text{evc},K} - \eta|P_{\text{evc},K}|), & X_k = 1 \rightarrow X_{k+1} = 0 \end{cases} \quad (7.7)$$

Here, the EV plug-in time, plug-out time simulation, and the EV charging power for a Nissan Leaf are presented in Fig. 7.13. As it is shown the blue solid line is the real EV charging power under a specific program named "pricing trial" [64]. Users got the monetary motivation to shift their electricity consumption away from peak pricing hours and move them toward low pricing hours under this program [64]. Hence, EV charging happened during the early morning when the electricity price is cheap. The black solid line is the time interval that the EV is available in the home and it is simulated by the Markov chain. Most of the time, the Markov chain estimated the plug-in time and plug-out time correctly. The red dash line shows the simulation of (7.7) with no control scheme. As it is evident, whenever the EV plugged-in, the batteries were charging, especially during serious peak pricing hours which is not economical and prove the importance of a proper HEMS for a smart home.

7.3.2 Mathematical Model

In the nZEB literature, many works can be found which proposed mathematical models for the building components such as PV, HPs, HVAC, and batteries.

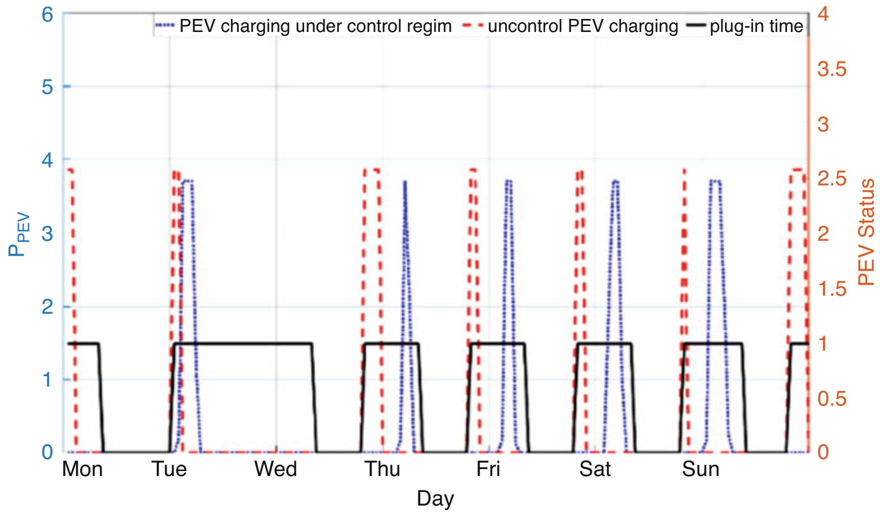


Fig. 7.13 EV charging power underpricing trial program and with no control program and Markov chain simulation for a week (July 2017) [64]

For instance, in [11], Liu-Jordan model was used to determine the effective irradiance and panel temperature of the PV as well as the PV modeled as an equivalent circuit. A nonlinear PV model was proposed in [65], which is a nonlinear function of irradiance.

In this section, different PV array mathematical model techniques are presented. The PV models have to incorporate all essential parameters associated with solar cell physics and the environment to effectively monitor and model the PV performance. Hence, researchers focused for several years and proposed empirical models based on mathematical and physics rules. In work [46], four models were presented for PV, which are introduced in details in the following part.

7.3.2.1 Simple Panel Efficiency Model (Simple Model)

In this model, a linear function of effective irradiance ρ_e is obtained to compute the PV power output, which is shown in (7.8). It is a straightforward model and can be parameterized from the PV panel datasheet, but its accuracy is not acceptable since it did not consider the environmental effects like wind speed and cell temperature of the PV performance [66]:

$$P_{\text{mp,array}}(\rho_e) = N_s \times N_p \times \left(\frac{\rho_e}{\rho_s} P_{\text{mp,s}}\right), \tag{7.8}$$

where $P_{\text{mp,s}}$ and $P_{\text{mp, array}}$ are the maximum point of the PV power for the PV array (kW), N_s and N_p are the subarray and panel numbers respectively. The variables ρ_s

and ρ_e are the solar irradiance under standard test condition (STC) (1000 w/m^2) and effective solar irradiance (w/m^2) respectively.

7.3.2.2 Power Temperature Coefficient Model

The model presents a linear function, which is depended on the effective irradiance and cell temperature. The output power relation is illustrated in (7.9). The accuracy of the model is more than the previous one because the effects of ambient temperature and wind speed are accounted for the PV model. Similar to the simple model, it can parameterize from the PV module datasheet [66].

$$P_{\mathrm{mp,array}}(\rho_e) = N_s \times N_p \times \left(\frac{\rho_e}{\rho_s} P_{\mathrm{mp,s}}[1+\gamma(T_c - T_s)]\right), \tag{7.9}$$

where the cell temperature (°C) and STC temperature (25/°C) are denoted by T_c and T_s respectively. The variable γ is the peak power normalized temperature factor (1/°C).

7.3.2.3 PVWatt Model

The national renewable energy laboratory (NREL) presents the PVWatt model in 2014 [67]. It is a nonlinear function of the effective irradiance and temperature. The power output is formulated based on the irradiance level, as follows:

$$\begin{cases} P_{\mathrm{mp,array}}(\rho_e, T_c) = N_s \times N_p \\ \times \left(P_{\mathrm{mp,s}}\left(\frac{\rho_e}{\rho_s}[1+\gamma(T_c - T_s)] - k_G \frac{\rho_s - \rho_e}{\rho_s - \rho_c}\right)\right),\ \rho_e > \rho_c = 200\ \mathrm{W/m^2} \\ P_{\mathrm{mp,array}}(\rho_e, T_c) = N_s \times N_p \\ \times \left(P_{\mathrm{mp,s}}\left(\frac{\rho_e}{\rho_s}[1+\gamma(T_c - T_s)] - k_G \left[1 - \left(1 - \frac{\rho_e}{\rho_c}\right)^4\right]\right)\right),\ \rho_e \le \rho_c = 200\ \mathrm{W/m^2}, \end{cases} \tag{7.10}$$

where

$$k_G = \frac{P_{\mathrm{mp}}(G_c, T_c) - P_{\mathrm{mp,meas}}(G_c, T_c)}{P_{\mathrm{mp,s}}}, \tag{7.11}$$

where the variable ρ_c is the solar irradiance under the low light conditions (200 W/m^2). Under the low-light conditions, it is more precise than two previous models. It is parameterized from the PV module datasheet. It can utilize to model thin-film-based PV systems.

7.3.2.4 Sandia PV Array Performance Model (Sandia)

The Solar Technologies Department at Sandia introduced the following formula to model an accurate PV array performance [68]:

$$\begin{aligned} I_{\mathrm{mp}}(\rho_{\mathrm{e}}, T_{\mathrm{c}}) &= I_{\mathrm{mp,ref}}\left(C_0\rho_{\mathrm{e}} + C_1\rho_{\mathrm{e}}^2\right)\left[1 + \widehat{\alpha}_{\mathrm{mp}}(T_{\mathrm{c}} - T_{\mathrm{s}})\right] \\ V_{\mathrm{mp}}(\rho_{\mathrm{e}}, T_{\mathrm{c}}) &= V_{\mathrm{mp,ref}} + C_2 n_{\mathrm{s}} \delta(T_{\mathrm{c}}) \ln(\rho_{\mathrm{e}}) \\ &\quad + C_3 n_{\mathrm{s}}[\delta T_{\mathrm{c}} \ln(\rho_{\mathrm{e}})]^2 + \beta_{\mathrm{mp}}(T_{\mathrm{c}} - T_{\mathrm{s}}), \end{aligned} \tag{7.12}$$

where

$$\delta(T_{\mathrm{c}}) = A_1 \frac{kT_{\mathrm{c}}}{q} = A_1.V_{\mathrm{t}} \tag{7.13}$$

where I_{mp} and, $I_{\mathrm{mp,\ ref}}$ are the PV current at peak power and reference condition (A). V_{mp} and $V_{\mathrm{mp,\ ref}}$ are the PV voltage at peak power and reference condition (V). C_0, C_1, C_2, and C_3 are the coefficients related to I_{mp} and V_{mp} to effective irradiance respectively. α_{mp} and β_{mp} are the normalized temperature factor for I_{mp} (1/°C) and the temperature factor for module V_{mp} (V/°C). n_{s} is the number of cells in series, A_1 is the diode ideality factor (dimensionless) and q is the elementary charge (C). The model accuracy is around $\pm 1\%$, which is the best among the introduced models. It can model various PV technologies. Based on a series of tests the model parameters are obtained and its public parameter databases are accessible [66]. In this chapter, to forecast the PV power generation the Sandia and Simple models are selected. These models are employed by system advisor model (SAM) as well [66]. SAM is a desktop application, which can compute the PV power output for 1 year by given the system specification data and weather file. The weather file must contain some information related to the PV array location such as latitude, longitude, time zone and elevation and weather condition include wind speed, solar irradiance and ambient temperature for 1 year. By this information, SAM can compute sun position, plane of array (POA) irradiance, PV cell temperature, and array DC loss. The data related to ambient temperature and wind speed is employed to estimate the impact of these parameters on the PV performance. SAM's PV model algorithm is depicted as a flowchart in Fig. 7.14 [66]. In addition, the forecast PV output is shown in Fig. 7.15. As you can see, the simple and Sandia result is compared with MLP and real data to show the accuracy and effectiveness of these models.

7.4 Stochastic Control Strategies

There are always mismatch between the forecast data and the real one since forecasts are never entirely accurate. Thereby, some strategies have been presented to address uncertainties. These strategies are categorized by their forecasting requirements.

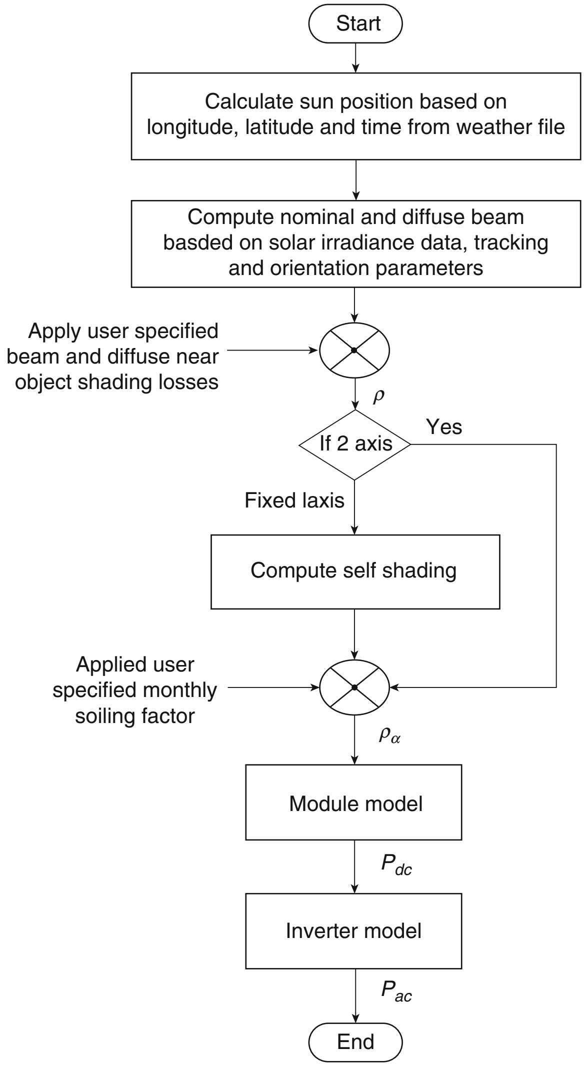


Fig. 7.14 Simple flowchart of SAM performance [66]

For example, online scheduling (not using forecasts), model predictive control (MPC) (using point forecasts), and stochastic dynamic programming (SDP) (incorporating the uncertainties into the model). Among the introduced methods, MPC is the most famous approach to address the forecast errors [69]. In addition, some works incorporate uncertainties within the model, like SDP. The prominent feature of these works under uncertainties is presented in [70]. However, we briefly introduce them as follows.

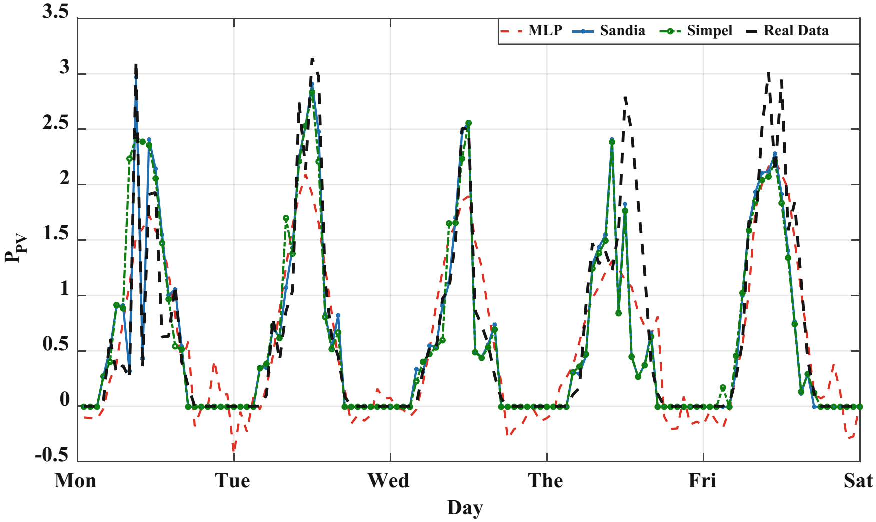


Fig. 7.15 Forecast of PV power generation

7.4.1 Stochastic Dynamic Programming

It is a well-known technique for solving the optimization problem under uncertainties. It is a method, which combines the stochastic programming, and dynamic programming approaches with the primary aim to compute an optimal decision in the face of uncertainties. This method depends on finite state-space models to minimize the cost function and relies on the cost of memoryless state transitions. It has the ability to be solved from the final time step and recursively computes the optimal pathway back to the first state. Generally, the SDP is a Markov chain generalization, which in some articles is named as a Markov decision process [69]. Sometimes it can turn to an NP-hard problem, due to the size of the problem raise with respect to the state numbers. However, this problem can be approximated in polynomial time, that is presented for HEMS [71].

7.4.2 Online Scheduling Approaches

The concept of online scheduling or online optimization is a little unclear, and in many research, these methods referred to MPC; while, they can represent a different class of scheduling problems, described in [72]. This is a method, which is a suite for some optimization problems that have incomplete knowledge of the future. In other words, these algorithms process inputs sequentially with no prior data of future inputs. When each input revealed, the online scheduler has to find the optimal solution to feed it into the plan. In this method, the scheduler has to find a way to add new items, which appear in queue, because the uncertainties are not modeled. A famous classical online optimization is Tetris, which has upcoming unknown inputs and the programmer may develop some suboptimal programs. Online scheduling approaches are used in many applications. For example in [73], it is employed HEMS application to minimize the peak loads. In reality, to evaluate these methods, their worst-case performance is compared to the offline optimal schedules by regret function or competitive ratio. Although online scheduling and MPC have this ability to add new data to their optimization algorithms, it is necessary to distinguish them.

7.4.3 Model Predictive Control

MPC is a well-known advance controlling approach of the process control which is used to control a plan while fulfilling a set of constraints. It has been widely used in many industries such as process, chemical, oil refineries, power electronics, and power systems industries since the 1980s. This method intensively relays on the dynamic models of the process, which often are empirical models obtained by system identification techniques. The main superiority of the MPC is that it optimizes the present timeslot while considering the future timeslots. It is done by optimizing a finite time horizon, but only applying the present timeslot and repeat it again for the next timeslots. In addition, it is able to predict future events and can take control actions accordingly. MPC is utilized to make a short-term decision during a time horizon consecutively. For instance, it optimizes the state-of-charge (SOC) of a power storage system in a building integrated with PV [15]. Although the MPC relies on the deterministic point-forecasts, it works well in connection with stochastic optimization problems as well. MPC has this ability to update periodically its schedules and adds new data when solving the optimization problem. In order to avoid myopic optimization, it is an essential concern to ensure that the planning horizon is long adequately because MPC is a greedy algorithm and tents to find a locally optimal solution at every stage with the aim to find a global optimal solution at the end.

The MPC performance and its result are typically compared with results of a complete offline optimization, that all future inputs are known for evaluating the effectiveness of the MPC. Thereby, the best-case scenario is represented by offline scheduling problem. When the MPC scheme is employing, the problem complexity raises by a rate of $O(T(n + m)^3)$ instead of $O(T^3(n + m)^3)$. Therefore, MPC is still an effective approach compared with offline scheduling problems with complete knowledge of all next inputs, because the excessive computational burden is required to solve the offline problem due to the enhancing in time horizon T.

In this section, an MPC is developed for minimizing the cost of electricity for nZEB with EV and PV while satisfying the battery charging and load demand requirements. The following model is presented for nZEB to design the MPC:

$$x_{k+1} = f(x_k, u_k, d_k), \quad y_k = g(x_k, u_k, d_k), \tag{7.14}$$

where the variables d_k, u_k, x_k, and y_k are the disturbance, control action, state, and system output, which $u_k = p_{\mathrm{ev}}$, $y_k = p_{\mathrm{grid},k}$, $x_k = E$, and $d_k = \left[\widehat{p}_{\mathrm{dem},k}, \widehat{p}_{\mathrm{pv},k}, \ \widehat{E}_{\mathrm{in}} \text{ and } \widehat{X}_k\right]^{\mathrm{T}}$, the variables $\widehat{E}_{\mathrm{in}}, \widehat{X}_k, \widehat{p}_{\mathrm{dem},k},$ and $\widehat{p}_{\mathrm{pv},k}$ are the battery energy forecast at the plug-in time of the EV, EV status forecast, demand, and the PV power generation forecast, respectively. In Fig. 7.16, the MPC structure is shown. It stands to reason that the MPC by coordinating the discharging/charging of the P_{ev} minimizes the cost of electricity as well as fulfilling the household load demand and EV charging requirements.

For minimizing the electricity cost, the following objective function is formulated:

$$\min_{P_{\mathrm{ev},k}, E_k, x_k} \sum_{k=0}^{N-1} C_k y_k^2, \tag{7.15}$$

where the variable C_k is the electricity price [$/kWh]. Here, the dynamic optimization method is used for solving the nonlinear constrained optimization problem, because of the nonlinearities in the EV and PV models (PVWatt model is used for simulation). The optimization problem is constrained by Eqs. (7.1, 7.3, 7.4, 7.5, 7.7, 7.10, 7.11, 7.14).

In this study, a 4 (kW) PV system is installed in a residential home located in Esbjerg, Denmark. In the PV system, 16 series panels are connected in two subarrays with a Solar-Edge inverter with maximum rated power 4000 (VA). Moreover, the EV battery pack is T-shaped lithium from Nissan leaf (24 kWh). In addition, weather forecasting service is available everywhere and by using this

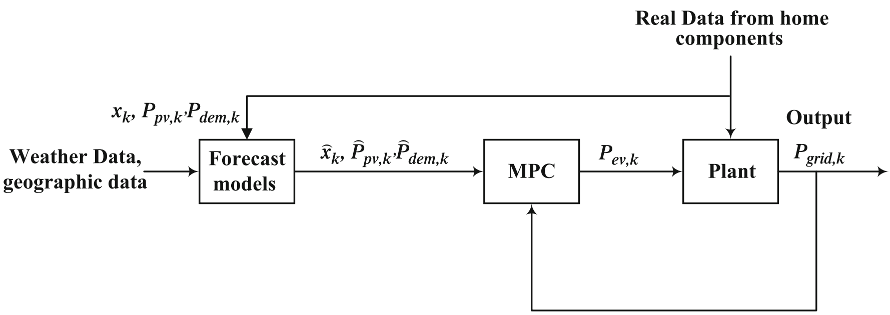


Fig. 7.16 MPC process structure [61]

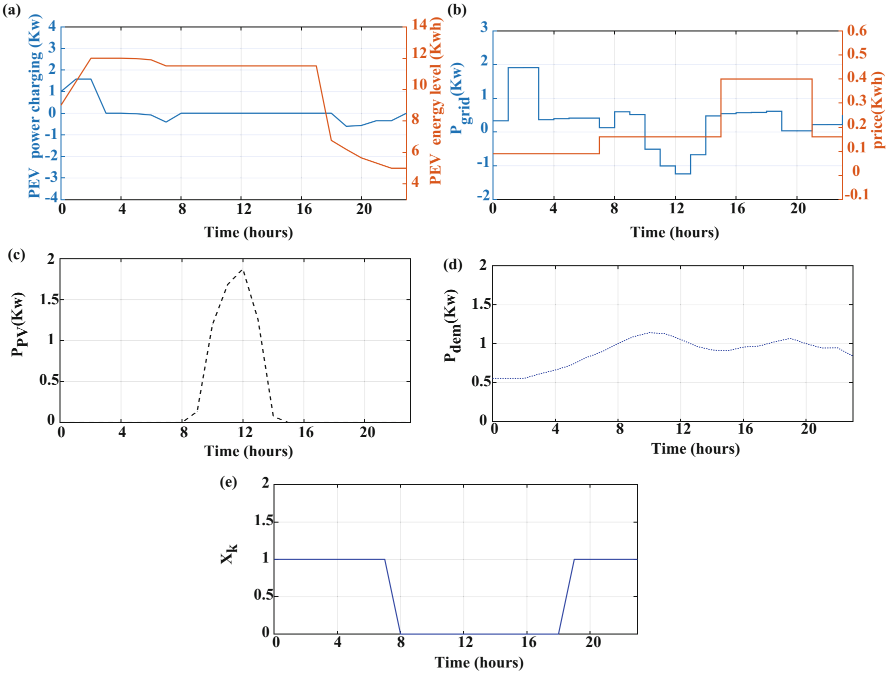


Fig. 7.17 Energy management results: (**a**) optimal energy level of the EV battery and power charging of the EV under MPC control operation; (**b**) the optimal power of the grid and tariff of used electricity price; (**c**) power generation from the PV; (**d**) household consumption; (**e**) EV states

data in the solar cell temperature and effective irradiance model, the forecast of ρ_e and T_c is obtained [66]. Thereby, the PV power output is forecasted by (7.10) and (7.11) when the forecasted amount of ρ_e and T_c known already. Then, the MPC used the forecasted data to make an optimal decision and determine the control signals. In each time step, the MPC updates its control action as new real measured data reveal. This process will continuously repeat to the end of time horizon. For this example, the time step is set to 1 hour and the operation period is 24 hours, which is from 01:00 to 24:00. Moreover, the control horizon length of the MPC is set to 24 hours.

The energy management results during 1 day are depicted in Fig. 7.17. The PEV energy level and charging power are shown in Fig. 7.17a. It can be seen in Fig. 7.17a that the EV is charged when the electricity price is not high and discharged when the electricity price is expensive to minimize the cost of the electricity. Moreover, in Fig. 7.17b, the grid power and the electricity price are shown. Since PV power generation is more significant than the power consumption, the power of the grid is negative between 10:00 and 14:00. The PV power generation is shown in Fig. 7.17c that follows a diurnal cycle. The household profile consumption is illustrated in Fig. 7.17d and also the EV states are depicted in Fig. 7.17e.

7.5 Protection Methods

One of the considerable challenges in the nZEBs is the protection of them with the presence of different sources while nZEB is operated as the islanded mode. High penetration of the inverter-based PVs in these systems leads to a bidirectional power and current. Differently, due to the limitation in the current tolerant of inverters during fault, over-current-based protection methods cannot be used in these systems under the islanded mode. Moreover, the function and setting of the protection systems must take into account the different grounding schemes of the building, for example, multi-grounding, uni-grounding, and un-grounding systems. nZEBs usually have PVs and DC loads, which increase the penetration of inverters. Under the islanded operation of these systems, the generated and consumed power must be almost the same; therefore, the generated power of PVs in these systems has an effect on the fault current level. The protection methods are divided into the unit and non-unit protection approaches [74]. The unit protection method protects a specific zone, and in the majority of protection schemes, this is a backup of the primary protection scheme, especially, in the complex electrical networks [75]. The non-unit protection method operates and trips the fault if electrical variables violate the thresholds. To evaluate and review available fault protection methods applied to the nZEBs, this section investigates communication-based, source, load, and line protection methods of these systems. In the first stage, the challenges of the protection of nZEBs are investigated. And finally, the grounding systems and human safety of Net-zero energy buildings are evaluated.

7.5.1 Protection Challenges on Net-Zero Energy Buildings

In this section, challenges of the fault protection, grounding, and coordination of protection devices in the nZEBs will be analyzed to understand the importance of the protection system for these systems. More clearly, the primary concerns and challenges of the protection studies in the nZEBs are as follows:

Under the island operation of the nZEBs, due to the penetration of inverter-based PVs, the fault current amplitude is limited; therefore, the overcurrent-based protection devices (PDs), which are implemented to the system based on the grid-connected mode cannot be active during the fault. Thus, the protection schemes must be designed based on the island operation of these systems.

Considering two characteristics, for example, central storage unit or master controller, is essential for the operation of the standalone net-zero energy buildings, and PV and battery system can be installed in any place of the nZEB. Thus, in the standalone nZEB fault current is bidirectional, which leads to mal-operation of PDs.

During the pole to ground faults, the voltage balance between positive and negative poles will be eliminated, and due to the discharge of the capacitors to the ground, the voltage of the healthy line will increase. Therefore, this type of electrical system requires an appropriate grounding system.

Therefore, a study on the protection of the net-zero buildings is an essential part of this system. Based on the characteristics of each electrical system, the grounding system and fault detection should be selected based on the performances of the fault current and requirement of the system.

7.5.2 Evaluating Different Protection Methods of Net-Zero Energy Buildings

Each protection scheme is divided into four different sections, fault detection, location, classification, and isolation. In the nZEBs, the main aims of the protection schemes are fault detection and isolation. In these systems, three different components can be faulted: loads, lines, and sources, in which the majority of faults in the electrical systems happen in lines. In addition, two different protection methods are proposed in recent years, communication-based [76] and local protection [77] schemes, which based on the characteristics of the system, the suitable protection scheme can be selected. In this section, the presented protection methods for different components are discussed.

Selective protection approaches based on the communication links provide a smart and intelligent protection system by which relays will be selective, predictive, and coordinated with other PDs. Figure 7.18 depicted the structure of an nZEB protection scheme with communication systems. The performance of the PVs is monitored by adaptivity and communication system, and the relay settings are updated during topology changes in the system. And also, after fault detecting, the relay sends the trip signal to the circuit breakers (CBs) [78].

The main communication-based PD in the net-zero energy buildings is overcurrent PD (OCPD). The OCPD detects the faults in the system by considering the variation of the fault current. In this case, if the current exceeds from a specific threshold, the OCPD will send the trip signal to the responsible breaker to isolate the faulty zone [79]. By installing communication facilities in the electrical system, the OCPDs can be connected to each other and increase the reliability of the protection method [80]. In addition, OCPDs and measurement units are connected to a Central Protection Unit (CPU) to monitor the currents and voltage of different nodes of the nZEB. In this method, CPU analyzes the data of the measurement units and also, another evaluation method can be linked to OCPDs for improving the protection method. For example, in [81], machine learning is linked to OCPDs to consider uncertainties and adaptivity for the protection scheme.

In Fig. 7.19, a net-zero energy building consisting of PV, battery, and several loads is shown. The rated voltage of the studied system is 110 V, and it is assumed that system is working on islanded mode. In addition, three different load clusters consisting of different customers are connected to the system.

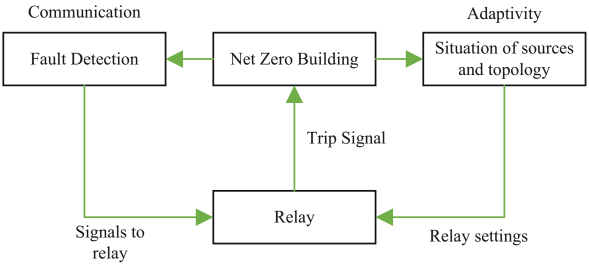


Fig. 7.18 Structure of a communication base net-zero energy building protection scheme

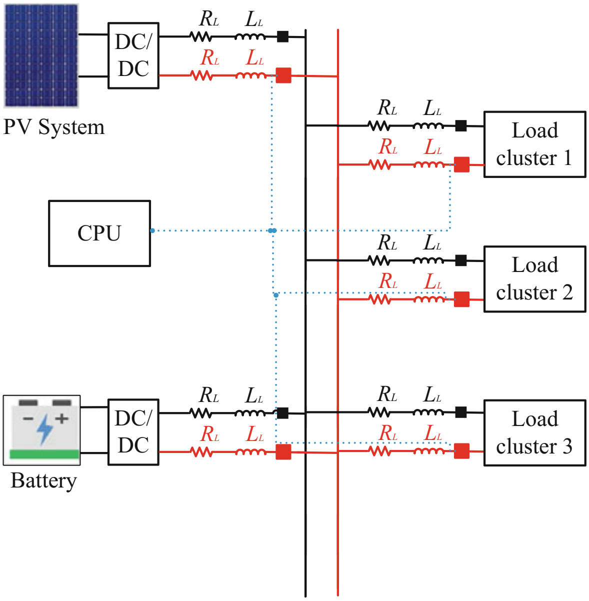


Fig. 7.19 Net-zero energy building with load clusters

All breakers and measurement units are connected to a CPU, which can be operated by an overcurrent characteristic. During the fault on $t = 1$ at the main bus, the fault current is shown in Fig. 7.20. The first stage of the fault current, which the current increases almost 20 times higher than the nominal current is capacitor-discharge stage. At this stage, after fault, the capacitors begin to discharge and inject a high rise current to the system. However, after this stage, the fault is supplied by battery and PV system.

The nominal current of the main bus of this system is 19 A, but, at the capacitor discharge stage, it increases to 423 A, and then it reaches to 63 A. Increasing the fault current to an extremely high value in buildings can make an arc which can cause a fire in the buildings. Therefore, detecting the fault and isolating the fault zone is an important task. Thus, a communication-based method uses a backup strategy for each breaker to increase reliability. OCPDs are defined by an equation for determining the operation time and coordinate with other PDs; this equation is [82]:

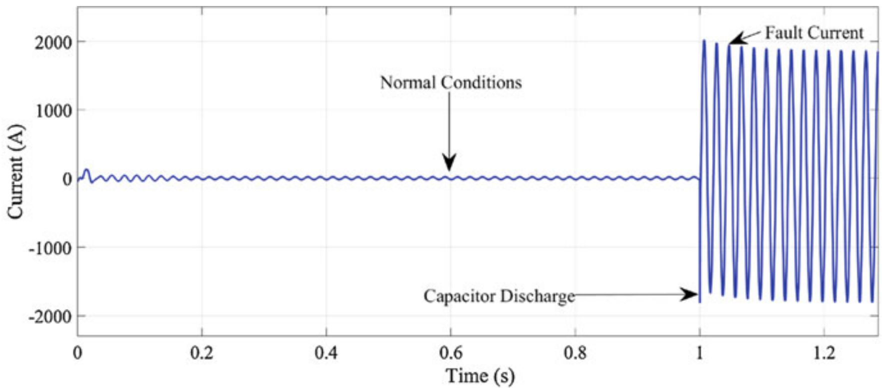


Fig. 7.20 Fault current for fault at the main bus

$$t_i = \frac{A}{\left(\frac{I_{SC_i}}{I_{P_i}}\right)^B - 1} \text{TMS}_i \tag{7.16}$$

where t_i and TMS_i are the operation time and time multiplier setting of *i*th OCPD, respectively. I_{P_i} is the pickup current of the *i*th OCPD, and I_{SC_i} is the fault current. The values of *A* and *B* depend on the used standard, for instance, based on the IEC 255-3, the value of *A* is 0.14 and *B* is 0.02. Moreover, the coordination of tripping time of two different breakers or OCPDs in different locations is defined by:

$$t_j - t_i \geq \text{CTI} \tag{7.17}$$

where the t_j and t_i are the operation time of the *j*th and *i*th OCPDs, respectively, and CTI is the coordination time interval. By minimizing the operation time and the constraint, the value of the settings of OCPDs will be evaluated. For example, if a backup OCPD is installed in the main bus, the OCPD operation times will be defined by previous equations. The value of settings for OCPDs and fault current is depicted in Fig. 7.21. Therefore, the fault is clear after 0.0863 s and the bus is divided into two different sections, and the fault will be isolated. The values of the TMS of PV relay and bus relay are 0.05 s and 0.2 s, respectively. And also, the values of pick up current of the PV and bus relay are selected as 40 and 57 A, respectively. Therefore, for the fault at the main bus, the bus relay is the main relay which operates 0.0863 s after fault, and the backup relay is PV relay which operates 0.3863 s after a fault in case of misoperation of the main relay. The current of the main bus is shown in Fig. 7.21.

On the other hand, the main local PD in net-zero energy buildings is a fuse. Also, the fuse is a component protector which is suitable for battery, PV, and load cluster protection. To protect the modern electrical systems, for instance, net-zero energy buildings, fuses are made up with a ceramic cartridge and a fuse link [83]. The ceramic cartridge contains silica sand, which is put out transient arc

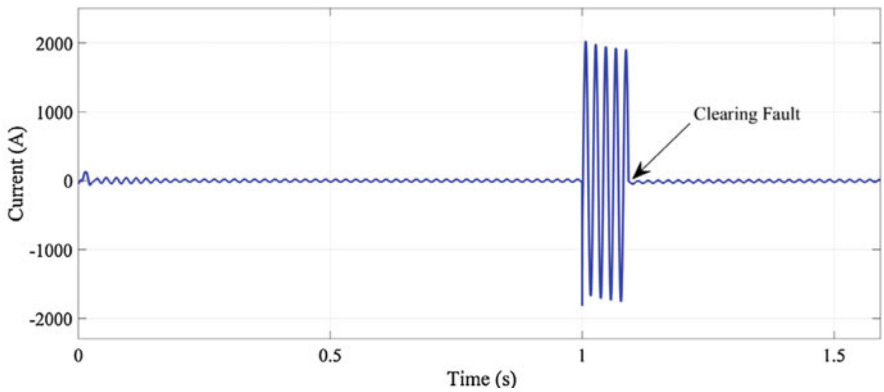
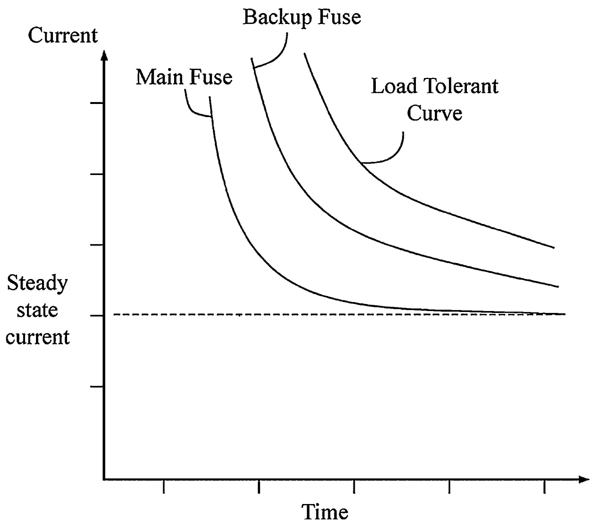


Fig. 7.21 The fault is occurred at $t = 1$ s and cleared by OCPDs at $t = 1.0863$ s

Fig. 7.22 The time-current curve of the fuse



heats. In addition, the fuse link is silver or copper, that is selected based on the current and voltage ratings of the system. Another important factor for determining the fuse characteristics is the time constant of the system because it depends on the current rise time. By increasing the value of the time constant, the ability of the ceramic cartridge for quenching the arc will decrease.

Traditionally, loads and components in the net-zero energy buildings are protected by small fuses. Commonly, for a 208 V system, the current ratings of the fuses are 32 A, 16 A, and 6 A. Also, due to that the fault current contribution of the PVs is large to active fuses in approximately 5 cycles after fault, there is no requirement to replace fuses [84]. In Fig. 7.22, the time-current curve of two fuses and tolerant curve of a load are shown. For selecting the correct model of a fuse, the fuse time-current curve must be down of the component tolerant curve, because,

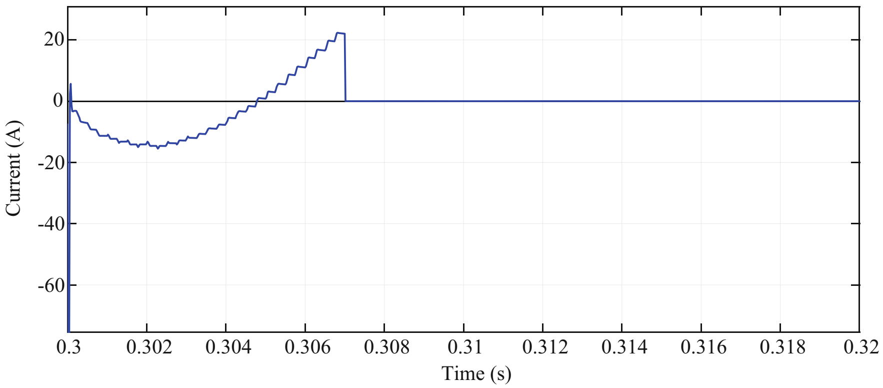


Fig. 7.23 Clearing of the fault current by a fuse

the fuse must cut the current before of tolerance of the component. In addition, the time-current curve of the backup fuse must be selected in the up of the main fuse.

One of the main roles of the fuses is the protection of components, for example, battery protection. For this purpose, a fuse can be used in series with a switch and battery. In this case, fuses are operated same to a switch, and when fault current exceeds a threshold, which is specified based on the battery tolerant curve, fuse cuts the current. Figure 7.23 depicts the fault current is cleared by fuse after 0.007 s, and the fault occurs at $t = 0.3$ s. In this case, in this case, the fuse selection is suitable for battery protection. However, the decision on the installation of fuse depends on the cost, system characteristics, and responsiveness. For protecting sensitive and critical components, for instance, PV, fuse, and circuit breaker can be serried to increase the reliability of the protection method. But the selection of the PDs is affected by the cost and requirements of the system. Circuit breakers are more robust than fuses, but, the cost of fuses is much lower than circuit breakers. In addition, the response time of the fuses is shorter than circuit breakers.

7.5.3 Grounding and Human Safety in Net-Zero Energy Buildings

Generally, designing a safe AC grounding system dissipates the fault current into the earth without exceeding any equipment and operation limits. Also, it must ensure that humans in the proximity of the grounded components are safe during the fault conditions. During the fault, by touching grounded facilities by personals, their bodies affected by fault voltage, and this voltage depends on the parameters of the nZEBs at the point of touch. Also, the value of the current depends on the resistance of the body. In the normal condition, by touching a grounded component, the duration and magnitude of the current conducted in the body are less than the value which can cause ventricular fibrillation. Therefore, to limit this current to a safe range, installing a system with effective connections between all metallic components of the nZEB with the earth. Evaluation of the effect of current through the body in the net-zero energy buildings is very important, because, in these systems, the only available energy source is electricity. Based on [85], several parameters must be calculated to minimize the duration and magnitude of the damage to the human body. Also, the standard body resistance is approximately 1000 Ohms, and on the other hand, the threshold of the feeling of current is 1 mA, and let go current for women is 6–14 mA and for men is 9–22 mA. Therefore, a maximum voltage of 6 V is appropriate for human safety during the fault. And in practice, it is very difficult to reach this voltage during the fault. Thus, minimizing the duration of fault current and value of fault voltage increases the human safety of the system. The fault amplitude is obtained by fault voltage and impedance of the fault path. During the electrify of the human body, the body impedance, based on the which part of the body is contacted to the electricity, limits the current.

The grounding system of a building generally consists of different parts as follows:

- The covering surface layer
- The ground grid with buried conductors
- The ground rods
- The soil beneath

Also, due to the following reasons, an nZEB must be equipped with a system grounding:

1. Limit of lightning voltage
2. Limit voltage during touching lines
3. Limit voltage during line surges
4. Stabling voltage during normal conditions

Unintended contact of human with the electrify line provides a path from the ground of the body place and the ground of the system; therefore, the current will flow in the human body and then back to the system via the ground to the source of the system. In this case, the grounding of the building cannot minimize the magnitude and duration of the fault, because, the fault current is almost equal to the system voltage divided by the impedance of the body. Therefore, because the resistance of the human body is higher than the system impedance and ground resistance to limit the fault current. Fault current is lower than 1 A for 277 V system, and it cannot activate the OCPDs [85]. In a building with a grounded source and grounded load, the fault voltage at the load place, when the phase is touched by a person, with respect to the local ground is calculated by:

$$V_{\text{fault}} = \frac{V_{\text{source}} Z_{\text{return}}}{Z_{\text{phase}} + Z_{\text{return}}} \tag{7.18}$$

where the V_{source} is the voltage of the source, Z_{return} is the impedance of the return path, including ground and body, and Z_{phase} is the impedance of the phase line.

7.6 Conclusion

In this chapter, the concept of nZEB was explained, and the different components of the nZEB were introduced and discussed. The data-driven methods and model-based design approaches were discussed for nZEB variables. The various NN structures, FIS, ANFIS, Markov Chain, and conditional probability, were discussed in the data-driven section. These techniques were employed to find a forecast model for nZEB components such as PV, load demand, and EV. Moreover, some model-based design approaches (power temperature coefficient, PVWatt, and Sandia PV array performance, and simple PV model) were introduced for PV modeling regarding its uncertainties. Afterward, these models were validated and compared with the real measured data and data-driven approach results. In the next step, the different stochastic control approaches, which are common in the nZEB literature under uncertainties condition, are introduced. The concepts of MPC, online scheduling and SDP were explained, and their difference was distinguished. Then, an MPC was designed to optimize the cost of electrical energy while fulfilling the load and battery charging requirements. In addition, in this chapter, a fault study for the nZEBs is presented. And, different types of PDs are evaluated for implementing in this system. The results show that using both current based protection methods and fuses improves the reliability of the nZEB. Moreover, the impact of the grounding on human safety in the nZEBs is investigated. In addition, for future work, the following works still need to be discussed and addressed:

- Zero-emission buildings will be studied in future works, and it will include the emissions and embodied energy analyses during the operation of the nZEB.
- Developing and integrating of the ANN for predicting the PV generation and load demand.
- Developing the optimization problem by adding more physical constraints, such as nZEB maximum energy consumption, and cost of PV and storage.
- Developing a new collaborative controller for optimizations of nZEB building group-level performance. In addition, the most important factors which have a significant effect on nZEB collaboration effectiveness will be evaluated.
- The study does not consider the losses in the discharging and charging process of batteries. In real situations, this value of energy losses is large; then, a more comprehensive model of the battery will be used to evaluate the energy losses in the system.
- By increasing the energy reduction stages in the nZEBs, the density of electronic devices is increased. Therefore, the next step in this issue could be investigating the effect of the dynamic of power electronic components on the control schemes.
- Exploring the implication of other technologies such as combined power and heat on the management of energy demand.
- Developing a control method for generation resources of storage systems to reduce the energy use severity.
- Using a machine learning method to deeply compare the datasets of optimized design.

- Developing a protection method to coordinate the fuses and other protection schemes and increase the number of zones in the nZEB to reduce the extent of the isolated area.

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Chapter 8
Data Analysis Model for Solar Energy System Design in Different Climatic Regions

Figen Balo and Lutfu S. Sua

8.1 Introduction

Solar power has the largest potential among other renewable power sources with regard to implementation areas [1]. The sustainable resources' yearly potential and all recoverable reserves for the fossil sources are given in Fig. 8.1 [2].

Figure 8.2 displays the global longwave sun radiation map. In the twenty-first century, solar power is becoming more and more appealing as a result of the intensity of the environmental pollution caused by fossil-based energy sources. The other important cause for valuing sun power is the extreme depletion of the fossil-based energy sources with limited reserve. The fossil-based energy sources' scantiness is a cosmic long-term opportunity that requires us struggling for sustainable and renewable power sources [4]. Irradiation data is inevitable for assessing and designing sun power systems. These are also important for the PV system operation and designs based on solar energy; thus a great number of models exist in the literature to predict irradiation values [5]. Some of the models are compact mathematical formulas, which are called empirical models and convenient for engineering applications. For approximately accurate prediction, these models are used commonly.

In order to predict average daily worldwide irradiation, Rajesh et al. studied many papers using artificial neural network (ANN) and linear empirical models. They conclude that the regression models are worse than the artificial neural network models [6]. Many papers also indicated that the methodology of ANNs is better than empirical models [7–9]. Katiyar et al. used annual data of four cities in India to search for linear, cubic, and quadratic models to predict average monthly radiation. The values changed between 0.8 and 0.43 MJ/m^{2}day [10]. In China, Li et al. appraised eight fractional sunlight duration models of four stations. Data covering a span of 11 years are utilized for calibration. The 4-year validation of the

F. Balo (✉) · L. S. Sua
Department of Industrial Engineering, Firat University, Elazığ, Turkey

S. Asadi, B. Mohammadi-Ivatloo (eds.), *Food-Energy-Water Nexus Resilience and Sustainable Development*, https://doi.org/10.1007/978-3-030-40052-1_8

Fig. 8.1 Comparing renewable and finite world power reserves (TWyears) [2]

Solar	23000
Wind	25-70
Natural Gas	215
Petroleum	240
Uranium	90-300
Tides	0,3
Geothermal	0,3-2
Hydro	3.0 - 4.0
OTEC	3.0-11.0
Coal	900
World Energy Use	**16 TW**

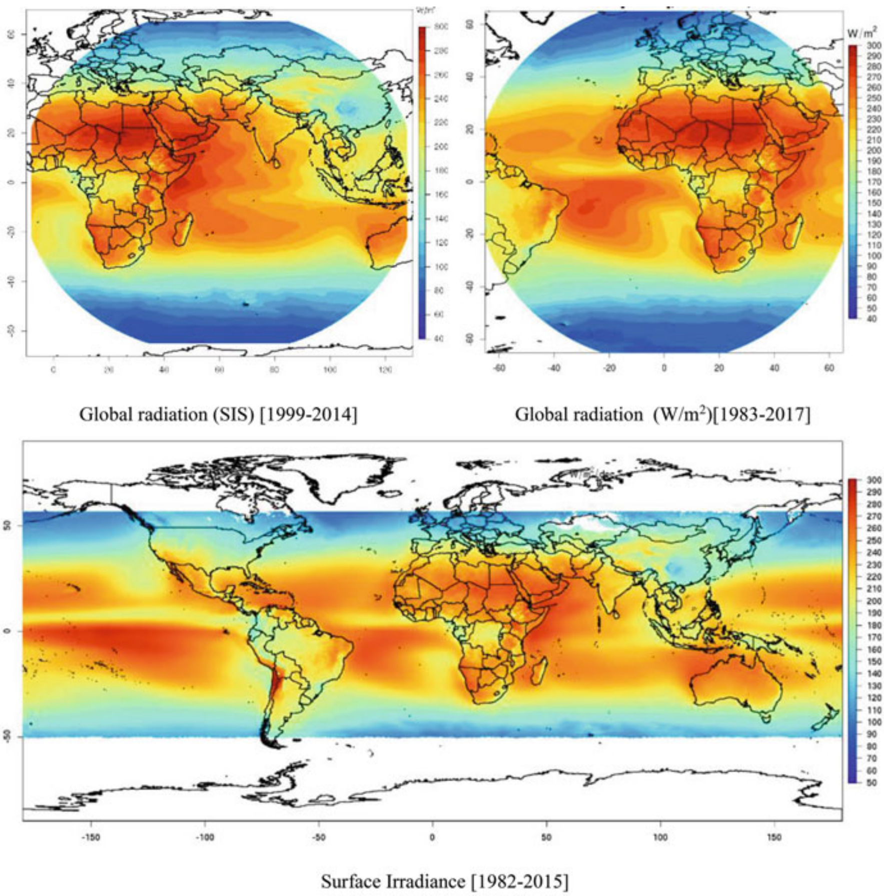

Fig. 8.2 The global longwave solar radiation map [3]

information is used. As a statistical indicator, the root mean square error (RMSE) is used. The linear model's RMSE altered from 1.26 to 0.72 MJ/(m^2day). The eight models' RMSE changed from 1.33 to 0.7 MJ/m^2day [11]. Amit et al. studied a large number of papers using ANN to predict sun irradiation into three reviews and estimate horizontal solar energy radiation. They indicated there were preferable artificial neural network models than empirical models [12]. Seventy-eight empirical models were studied by Fariba et al. They divided them into four groups, namely, sun-sourced, cloud-sourced, weather-sourced, and other temperature-sourced models. In Iran, they used a couple of models from each class to develop one case study. A sun-sourced model with exponential expression determines the highest output [13]. With data from 18 different places, Kadir researched seven separate fractional sunshine duration models. He used different models to forecast the long-term monthly mean global sun irradiation with the inclusion of linear, quadratic, exponential, and logarithmic equations. With slight differences for the identical locations, the applied models' efficiency is accomplished [14]. For 25 locations in Spain, Manzano et al. evaluated the linearly related model of Prescott–Angstrom. For the calibration purposes, 10 years of data were used in RMSE. The results changed from 0.8 to 0.36 MJ/m^2day [15]. Eighty-nine monthly mean radiation models are assessed for Shanghai in China by Yao et al. The identical mathematical statements are implemented in many models by using different coefficients. They obtained fresh fitting coefficients to the five sunlight fraction models in Shanghai [16]. To predict monthly mean worldwide solar radiation, El-Sebaii et al. applied three average fractional sunlight, three fractional sunlight, and one non-sunlight duration models in Saudi Arabia. Cloud cover, relative humidity, and temperature were the features grouped into mean sunshine duration fraction models. Nine-year data were used to obtain novel empirical coefficient values. Various models' RMSE values changed from 0.02 to 0.15 MJ/m^2day [17, 18].

To predict monthly average sun irradiation, Zhou et al. evaluated six fractional sunlight duration models for 69 locations in China. As parameters, the latitude and altitude in altered models are added. The coefficient's values were obtained individually. The proportion of the sunshine length was between 1.634 and 1.636 MJ/m^2day [19]. To predict long-term monthly average sun irradiation model, six non-sunlight duration models were searched by Adaramola in Nigeria. Precipitation, ambient temperature, and relative humidity were utilized in non-sunshine duration models. For the linear model, the RMSE altered between 8.25 and 4.78 MJ/m^2day [20]. By utilizing the balance of energy between soil and neighboring atmosphere layer, Antonio et al. developed a linear equation to develop a correlation between sunlight with the product of daily change in sunlight duration and temperature [21]. For the entry layer, Ozgoren et al. utilized the multi-nonlinear-regression model of ANNs for Turkey to acquire the most appropriate independent features. To this end, they chose ten features. These features were altitude, soil temperature, month, length of sunlight, cloudiness, minimum–maximum–mean temperature of the atmosphere, wind speed, and latitude. Marquardt–Levenberg optimization algorithm is utilized to train ANNs [22]. In order to estimate monthly mean clearness valuations, 16 non-sunlight duration models were researched by Iranna et al. The features associated with wind speed, moisture, relative humidity, longitude, altitude, and five different temperatures were used as inputs. Analyzing the models involves evaluation of data for 875 sites [23]. To show the clearness index distribution, a function was applied in 1 year by Ayodele et al. by utilizing 7 years, daily sun irradiation information was determined by the coefficient values. The efficacy of all months was achieved, with the exception of October. The RMSE ranged from 0.221 MJ/m^{2}day to 0.213 [24].

To select the appropriate input features, Jiang et al. conducted Pearson correlation coefficients and prior association rules. Parameters were selected for wind speed, complete average opaque skies cover precipitation, correlative humidity, minimal daylight, average temperature, heating–cooling degree–days [25]. Yadav et al. conducted the Waikato Environment simulation program to achieve the most effective entry features for prediction. As input features, they obtained the minimal–maximal temperature, length of sunlight, average temperature, and altitude, while the least efficient features were longitude and latitude. However, the forecast was for worldwide sun irradiation on a monthly average. The maximal average absolute error in proportion achieved by ANNs is 6.89% [26, 27]. Marquardt–Levenberg algorithm was applied with entities, including difference in field temperature from night to day, average field temperature, air pressure, monthly precipitation, and flora index by Qin et al. For Tibetan plateau, the 7 years of data from 22 locations were utilized to train ANNs [28]. The average percentage total error ranged between 15.43% and 4.00% when the RMSE changed from 1.03 to 1.83 MJ/m^{2}day. Zang et al. investigated the identical models for 35 locations in China by decreasing two coefficients [5].For 79 China locations with 10-year data, a mixed model (sine and cosine functions) was implemented by Li et al. [29]. One satellite model was studied for four locations in Thailand and five areas in Cambodia by Janjai et al. The RMSE was calculated as 1.13 MJ/m^{2}day [30]. For the 35 sites, the RMSE and average percentage total error ranged from 16.22 to 4.33%and from 1.88 to 1.10 MJ/m^{2}day, respectively. Khorasanizadeh et al. [31, 32] evaluated six models for four provinces in Iran. The initial model was exponential, the secondary was polynomial, and the other four were cosine- and sine-based models. The RMSE of these six designs ranged from 1.26 to 0.72 MJ/m^{2}day, and the average percentage total error ranged between 5.72% and 3.38%.

8.2 Solar, Electricity, and Climate Potential in Istanbul and Izmir

The scarcity and maintenance costs of the equipment have restricted the number of stations measuring solar irradiation, so it is prevalent for meteorological factors to calculate sun radiation [7–9]. The duration of sunlight and soil are of great significance for establishing installations depending on solar power. Therefore, extensive study on solar power potential, present installations, and environment needs to be

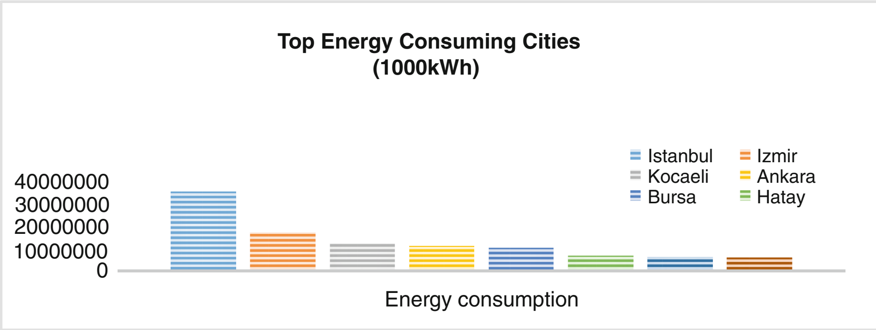

Fig. 8.3 Energy consumption of top eight cities

Table 8.1 The radiation data

Province	FGI (MJ/m^{2}day)	Iort (MJ/m^{2}day)	Latitude	FKI
Istanbul	7.84	12.0	40.58	5.67
Izmir	6.48	11.4	38.24	3.50

conducted. In terms of energy consumption, Istanbul and Izmir are the top two towns in the nation (Fig. 8.3).

Izmir is situated within the first climatic region in terms of solar energy capacity, while Istanbul is situated in the second region. The phase shift values for radiation function, average solar radiation, latitude, and radiation function for both towns are shown in Table 8.1.

In the next chapter, a comprehensive assessment is carried out for both towns, on Matlab platform, to show their sun irradiation potential and features.

8.2.1 Calculation of Intensity of Solar Radiation

The sun energy intercepted during a day is the daily sun radiation by the unit field of the horizontal surface (MJ/m^{2}day). The daily radiation's mean value over a month is daily radiation on a monthly average. The sun irradiation shift demonstrates complete annual values in a year divided by 365 values. These radiation values can reflect the efficiency of the sun in the area under investigation and are used for studies of sketchy design. The model chosen to be utilized to calculate the sun irradiation concentrations also depends on the horizontal or inclined superficies. Thus, in the sections below, the most suitable models are selected for each case, and the required computations are made on the Matlab simulation program.

8.2.2 Horizontal Area

8.2.2.1 Total Daily Sun Irradiation

Total sun irradiation on a certain day can be calculated on a horizontal layer using the formula below [19]:

$$I = I_{\text{ort}} - \text{FGI}\cos\left[\frac{2\pi}{365}(n + \text{FKI})\right] \tag{8.1}$$

where

FKI: stage change of the radiation feature
FGI: frequency of radiation function
I_{ort}: total annual average daily radiation
n: days

8.2.2.2 Daily Sun Irradiation Diffusion

The daily complete diffuse sun irradiation can be achieved on a horizontal layer utilizing formulation 8.2 [20]:

$$Iy = I(1 - B)^2\left(1 + 3B^2\right) \tag{8.2}$$

where:

I_{o}: Radiation out of the atmosphere
B: Index of transparency

8.2.2.3 Total Instantaneous Solar Radiation

Using Formula 8.3, the current complete solar radiation can be achieved on a horizontal layer [21, 22] by:

$$I_o = \frac{24}{\pi} I_{\text{s}}(\text{Cos}(e)\text{Cos}(d)\text{Sin}(w_{\text{s}}) + w_{\text{s}}\text{Sin}(e)\sin(d))f \tag{8.3}$$

where:

I_{s}: perpetual constant (W/m^2)
e: latitude’s angle
w_{s}: sunrise hour’s angle
d: declination’s angle
f: factor for steady sun correction

The associated formulas and tables can obtain these values. Radiation from the atmosphere can be determined using Formula 8.4 [20]:

$$I_{\mathrm{ts}} = A_{\mathrm{ts}} \mathrm{Cos} \left[\frac{\pi}{t_{\mathrm{gi}}} (t - 12) \right] \tag{8.4}$$

where:

A_{ts}: sun irradiation
t_{gi}: the day's imaginary duration

8.2.2.4 Diffuse and Direct Momentary Sun Irradiation

Using formulas 8.5 and 8.6, it is possible to obtain temporary direct and diffuse sun irradiation on horizontal superficies [21, 22]. Here, A_{ys} is a frequency of function.

$$I_{\mathrm{ys}} = A_{\mathrm{ys}} \mathrm{Cos} \left[\frac{\pi}{t_{\mathrm{g}}} (t - 12) \right] \tag{8.5}$$

$$I_{\mathrm{ds}} = I_{\mathrm{ts}} = I_{\mathrm{ys}} \tag{8.6}$$

8.2.3 The Sun Irradiation Intensity's Determination on Inclined Superficies

8.2.3.1 Direct Sun Irradiation as the Momentary

The momentary direct sun irradiation can be determined on inclined superficies (30°–60°–90° angles) utilizing the formula below [22]:

$$I_{\mathrm{be}} = I_{\mathrm{b}} R_{\mathrm{b}} \tag{8.7}$$

$$R_{\mathrm{b}} = \frac{\mathrm{Cos}\,\theta}{\mathrm{Cos}\,\theta_z} \tag{8.8}$$

$$\cos\,\theta_z = \sin d\,\sin e + \cos d\,\cos e\,\cos w \tag{8.9}$$

$$\cos\,\theta = \sin d\,\sin (e - \beta) + \cos d\cos (e - \beta)\cos w \tag{8.10}$$

8.2.3.2 The Diffusion of Solar Radiation (Momentary)

On inclined superficies, the momentary value of diffuse irradiation can be determined by the formulation below [22]:

$$I_{ye} = R_y I_{ys} \tag{8.11}$$

R_y (the Conversion factor) for diffuse radiation can be obtained by the equation below [22]:

$$R_y = \frac{1 + \cos(a)}{2} \tag{8.12}$$

R_y parameter ensures the layer's slope. For vertical superficies ($a = 90°$), R_y is exactly 0.5. Thus, the momentary values of the diffuse irradiation on inclined layers (30°, 60°, 90° angles) for 24 h can be obtained.

8.2.3.3 Reflecting Sun Irradiation (Momentary)

On inclined superficies, the reflecting irradiation [22] can be obtained using the formulation below:

$$I_{ya} = I_{ts} p \frac{1 + \cos(a)}{2} \tag{8.13}$$

The ecologic reflection rate is given with ρ characteristic and utilized as about $\rho = 0.2$ in computations.

8.2.3.4 Total Sun Irradiation (Momentary)

On inclined superficies, the momentary total irradiation [22] can be obtained by the formulation below:

$$I_t = I_{de} + I_{ye} + I_{ya} \tag{8.14}$$

8.3 Method

Figure 8.4 shows the following values:

(a) For 24 hours, alteration in the current yearly complete value of sun irradiation.
(b) Per hour, change in the current yearly diffuse values of solar radiation.
(c) For 24 h, change in the current annual horizontal value of direct sun irradiation.

Figure 8.5 guarantees daily alterations:

(a) The sun irradiation's total values per day
(b) The declination angle

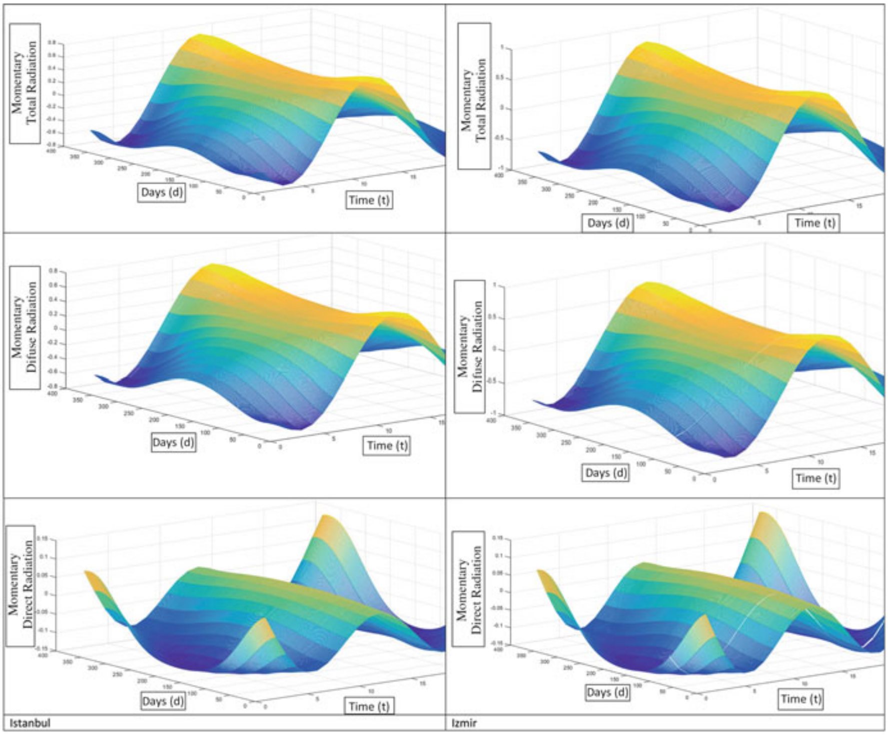

Fig. 8.4 Change in annual sun irradiation values on a horizontal layer for 24 h

(c) Hourly angle for sunrise
(d) For a factor of correction, sun constant
(e) The sun values of radiation out-of-atmosphere
(f) function periodicity graph (A_{ys})
(g) Diffuse irradiation from the sun (A_{ts}), and
(h) Index of accountability on the horizontal surface

The solar radiation's route duration from the atmosphere's top to a specified location on the superficies of the Earth, by turns, will be a function of the Sun's zenith angle and the location's geographic altitude, such as the angle between the line to the Sun and the Earth's normal superficies. It can concretize the relationship as follows: if it is 0°, such as if the Sun is at the zenith angle, the sunlight beam must move within the atmosphere of Earth as little as necessary until it hits the superficies. By comparison, the route within the atmosphere will be too long if the Sun is close to the horizon. With respect to this, the atmospheric mass' comparative measure can be defined by which beam irradiation goes to the superficies of the Earth. If the Sun is in the zenith, the light must travel through the minimum mass of atmosphere. This atmosphere's mass is given the value one, if consideration is given to a location at sea level. This minimal value will be associated with all other feasible values.

The current direct irradiation values with three different corners (30°, 60°, and 90°) are provided in Fig. 8.4 for a 24-h period. The maximum values are set at 12:00

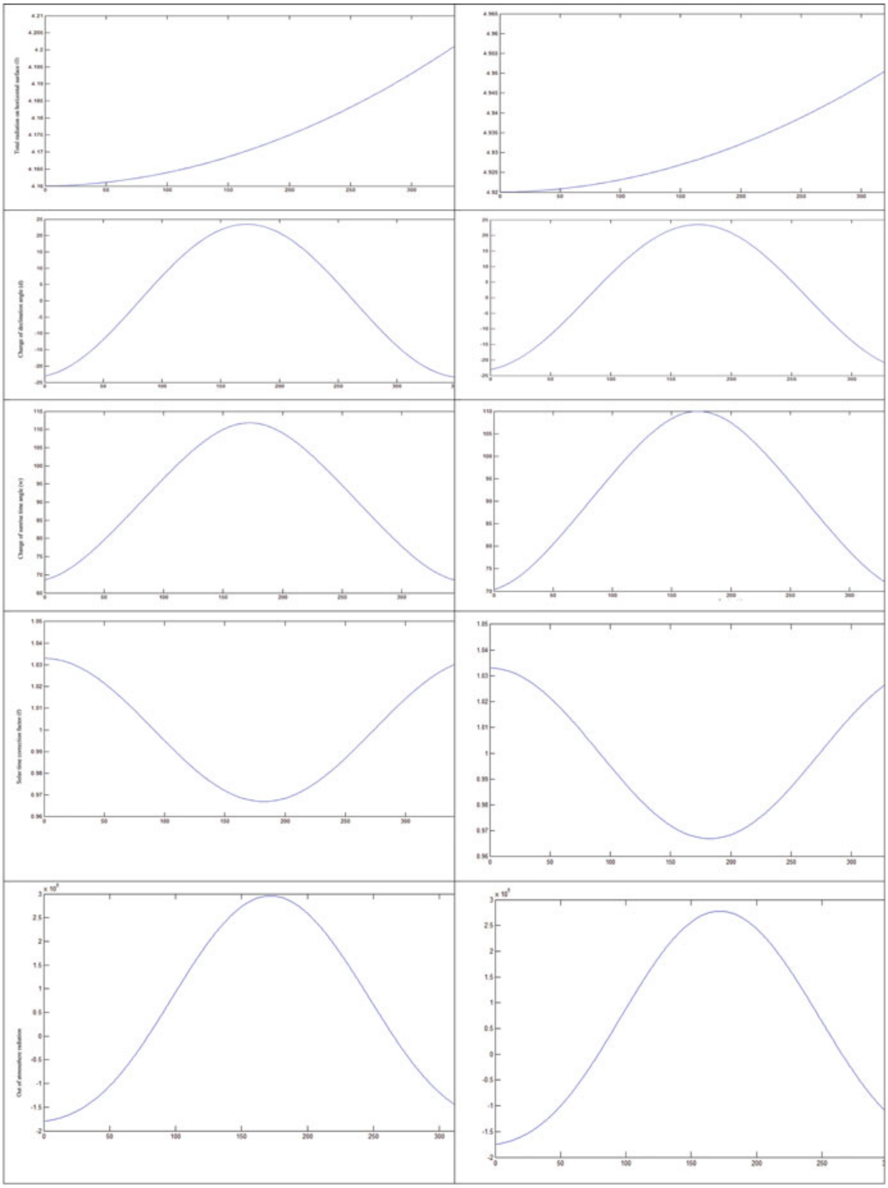

Fig. 8.5 Horizontal sun irradiation

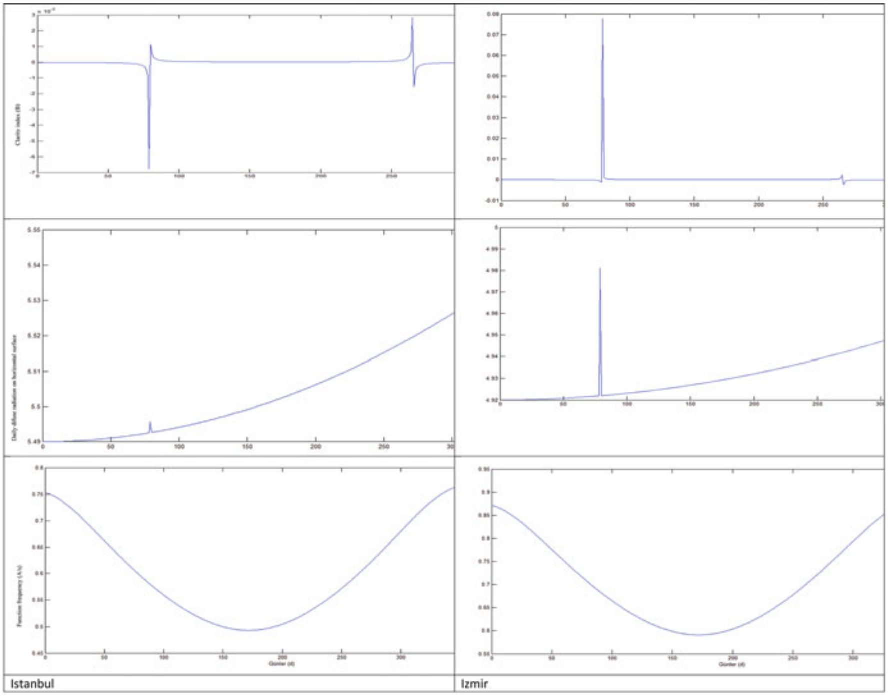

Fig. 8.5 (continued)

on the 355th day for all three corners, while the minimum values are set at 03:00 on an identical day (Fig. 8.6).

Total sun irradiation on a horizontal surface, which is worldwide radiation, is the sum of diffuse incident irradiation and the direct normal irradiation designed on the horizontal superficies. If the superficies under research is shifted horizontally, the complete solar irradiation is the amount of diffuse incident irradiation, the direct ordinary radiation designed onto the tilted superficies, and ground reflected radiation that occurs on the tilted superficies. The mixture of diffused and direct solar event at the Earth's surface on a horizontal plane and all three volumes (especially their irradiance or speed) is referred to as global sun energy. In this research, the highest total solar irradiation values are obtained in Izmir city. These values are determined as 4.9694 and 4.92 W/m^2 for Izmir city.

The angle of declination is the angle between the sun's direction and the equator's plane. For both cities, it is 23.4498°. The angle of the hour is the angle the Earth has been rotating since solar noon. Because Earth is rotating at 360°/24 h = 15°/h, the angle of the hour is positive at night and negative in the morning. The highest sunrise hour angles are determined in Istanbul city. The maximum and minimum sunrise hour angle values are obtained as 112.0186 and 63.9814, respectively, in Istanbul.

The irradiance value attained at a specified place of the Earth's surface depends on two primary variables, namely, the irradiance values outside the atmosphere also

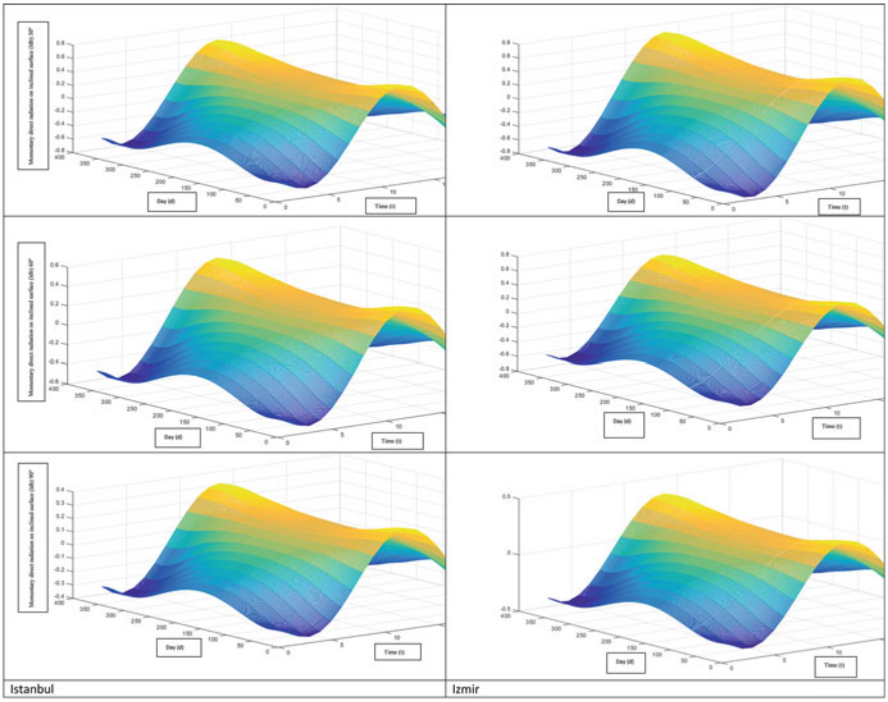

Fig. 8.6 The annual momentary values of direct irradiation for 24 h on inclined layers. (**a**) Momentary values of direct irradiation on an inclined layer of 30°. (**b**) Momentary values of direct irradiation on an inclined layer of 60°. (**c**) Momentary values of direct irradiation on an inclined layer of 90°

taking into consideration the Sun's position relative to the evaluated site place, as well as the Earth's atmosphere's attenuation impacts. Outside the Earth's atmosphere, the irradiance obtained from the Sun is almost continuous at any stage in space. The highest out-of-atmosphere irradiation value is obtained as 298,010 W/m^2 in Istanbul. The transparency clarity value is the fraction of that transferred by the sun irradiation by the atmosphere to strike the Earth's surface. It is a dimensionless number between 0 and 1, characterized through the extraterrestrial irradiation as the groundwork irradiation split. The most elevated transparency clarity values are defined in Izmir city (maximum 0.078 W/m^2). The diffuse irradiation is dispersed by molecules, aerosols, and clouds from the direct beam. The maximal diffuse irradiation is calculated as 49,522 in İzmir city. The flux density emitted as a function of wavelength frequency exceeding 1 cm divides the curve into two instances recognized as "quiet sun" and "troubled sun." The first is described by ordinary operation of the Sun while the second is dependent on operation of the sunspots. The lowest function frequency is obtained as 0.4731 in Istanbul city.

The momentary diffuse irradiation depicts the sunlight that was momenarily dispersed in the atmosphere through particles and molecules but still made it down to the earth's superficies. The momentary direct irradiation is called "momentary beam irradiation" or "momentary direct beam irradiation." It is utilized to portray sun irradiation traveling from the sun down to the earth's ground in a straight row. The proportion of diffuse sky radiation is much greater in higher latitude, cloudier places than in lesser latitude, and sunnier locations. In these greater latitudes, cloudier locations, the percentage of complete irradiation, that is diffuse irradiation, tends to be greater in winter than in summer. By comparison, the sunniest locations tend to have less seasonal variation in the diffuse–direct radiation proportion. The diffuse irradiance also relies on the procedures of extinction. The presence of diffuse radiation, apart from the attenuation of direct radiation, is just another consequence of these procedures. There are, however, two extra parameters to be considered in determining diffuse irradiance. Since diffuse radiation is partly generated by procedures of reflection between the surface of the Sun and the Earth, diffuse radiation also relies on the ground albedo and the atmospheric atmosphere albedo. Albedo is the proportion of incident radiation to diffusely reflected radiation. It ranges from 0.1 to more than 0.9 for new snow in dark, moist lands, or forests. The typical values are between 0.3 and 0.2 for many locations (without circumstances that are liable for extreme albedo values, such as ice and snow). Once again, we assume that the reflected irradiance is isotropic at a given place and time. This means that it is equal from the half-space below the horizontal plane in all directions. The radiation that the Earth's surface reflects may be backscattered or reflected back to Earth, thus contributing to the diffuse radiation. Hence, it is necessary to take into account reflective procedures for determining ground irradiance. In this research, momentary diffuse irradiation, momentary direct irradiation, and momentary total irradiation values are determined as in Izmir city.

The yearly momentary values of diffuse irradiation for three angles (30°, 60°, and 90°), are shown in Fig. 8.7. In Fig. 8.8, the total momentary sun irradiation's yearly values for 24-h periods are shown. For annual angle and hours, the total momentary sun radiation values are presented in Fig. 8.9.

Reflected radiation, which describes sunlight reflected from non-atmospheric stuff, such as the floor. PV panels, however, tends to be tilted away from where the reflected light goes, and reflected irradiation rarely accounts for a substantial portion of the sunlight that strikes their superficies. The global solar irradiation is the complete insolation: diffuse + direct + reflected light. Total solar irradiation occurs on a horizontal surface, and if the total surface radiation occurs at a specific angle, they'll represent something like "total $X+Y+Z°$ tilt irradiation," etc. Normal radiation describes the radiation that affects a surface at an angle of 90° to the rays of the sun. Taking into consideration the different impacts of solar radiation (e.g., intermittence, absorption, dispersion, tilting, and excentricity), it is possible to optimize solar energy converters, facilities, and yield forecasts.

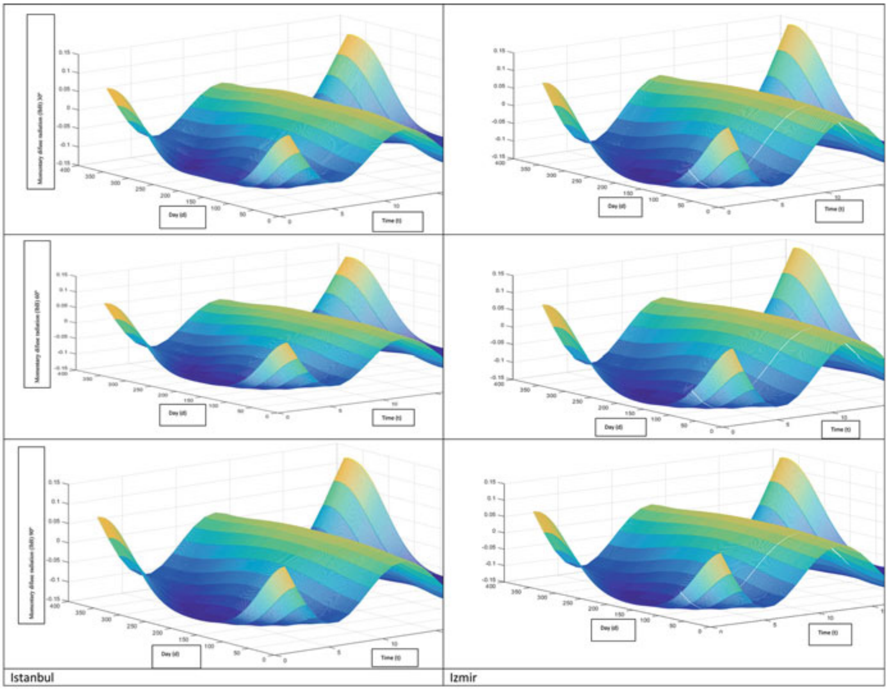

Fig. 8.7 For inclined surfaces, the momentary annual diffuse radiation values. (**a**) Momentary values of diffuse irradiation on an inclined layer of 30°. (**b**) Momentary values of diffuse irradiation on an inclined layer of 60°. (**c**) Momentary values of diffuse irradiation on an inclined layer of 90°

8.4 Results and Findings

The technology behind the solar energy relies on receiving energy from the Sun.The energy emitted by the Sun is, in fact, the radiation energy produced by fusion that takes place inside the Sun's core. The data related to the solar radiation constitutes the major input in designing solar systems and evaluation of their feasibilities. For this reason, it is significantly important to determine the solar radiation levels of various geographic regions with different characteristics in order to obtain the best performance from any given solar system.

Given the high initial costs to install solar systems, analyzing the data on solar radiation levels is vital as part of any feasibility study being conducted for solar systems to be installed in a given geographic location.

The initial investment requirement is to ensure the efficient use of economic resources and extensive planning. Data to be obtained from Meteorology constitutes the most important part of such a plan. Although the data on radiation levels have such an important role in determining the potential of a given solar farm, measurements are not readily available. This is why mathematical models in a wide range

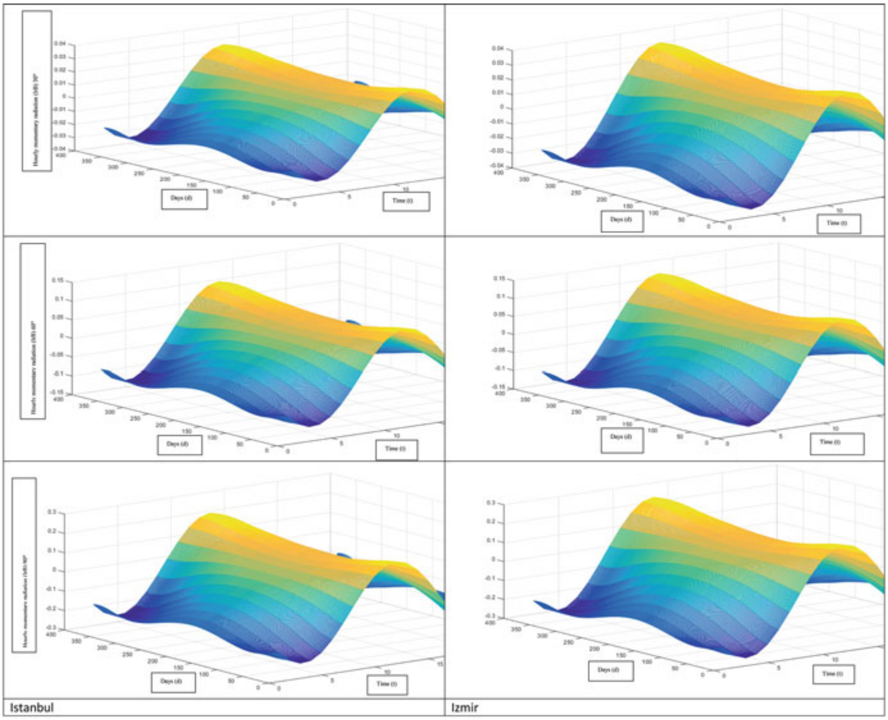

Fig. 8.8 For inclined superficies, the yearly complete momentary irradiation values. (**a**) Total momentary irradiation values on an inclined superficies 30°. (**b**) Total momentary irradiation values on an inclined superficies 60°. (**c**) Total momentary irradiation values on an inclined superficies 90°

have been proposed in the related literature. Underlying reason behind the development of these models is to be able to obtain the parameter values that are not available. However, such models are location-specific and need to be developed primarily for the region that is under investigation.

The data on sunlight is important for assessing and designing the PV energy industries. About sun irradiation, estimation methods are too significant to obtain the change characteristics. It is usually recognized that heat efficiency assessments of eco-responsive renewable system design are extremely susceptible to preliminary solar/climatic factor estimates. For this reason, reliable formulas shall be used efficiently to analyze the solar design potential for presimulation.

This chapter reflects on the research that is undertaken to establish itself as a reference for the feasibility studies conducted to design the optimum solar farms with efficient components. Within the scope of this study, models used to forecast total daily-diffuse sun irradiation and momentary direct-diffuse total horizontal sun irradiation are evaluated, categorized, and contrasted for two of the major cities in Turkey, namely Istanbul and Izmir. Both cities are categorized with high solar potential, Istanbul being one of the most populated cities in the world.

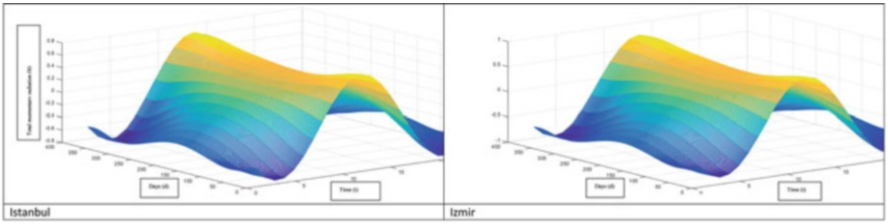

Fig. 8.9 Total momentary annual angle and hours of radiation

To obtain the sun irradiation's intensity on inclined surfaces, momentary direct-diffuse-reflecting-total sun radiation values are determined. To illustrate their performances, the corresponding results are collected through the models presented in the study. Based on the above assessment, it is possible to assess the real potential of both cities through the calculations of solar features given in Table 8.2.

Adding a meteorogical profile to the site information makes it possible to calculate formula-based the diurnal incident radiation on a tracking surface. Calculations are typically accompanied by mainly city climatic data for determining the range of basic solar benefits obtained by the region for the available solar values. Analogously, these results would profile climate conditions and solar access potential in such a manner that a preliminary assessment of promising design strategies could be make for a PV system feasibility.

8.5 Conclusions

Solar power is the most promising source of sustainable power to provide a major portion of the world's power requisition. Precise understanding of solar irradiation is regarded the first stage in assessing the accessibility of solar energy and serves as the main input for solar energy's various applications. Due to the elevated cost and machinery maintenance and calibration requirements, the sun irradiation measurements are not always accessible, various solar radiation models have been created to estimate solar radiation. The sun irradiation models are proposed to estimate solar irradiation using diverse data types, including time series methods, geographical and meteorological data, neural networks, geostationary satellite images, models of physical radiation transfer, and stochastic weather methods. For several engineering applications, the forecast of global solar radiation is of utmost significance. During the development stage of few techniques, for example, flat plates and concentration collectors, solar heaters and energy storage equipments, and solar energy stations, to name a few, solar irradiation predictions are essential. In addition, solar radiation estimates are essential in building power research, as is the case for air-conditioning systems during the cooling load's calculation.

Table 8.2 Attributes of sun irradiation

Attributes		Izmir	Istanbul	Attributes		Izmir	Istanbul
Total irradiation	Imax W/m^2	4.9694	4.2094	**Mom. dir. irrad.**	Idbmax (30°)	1.3299	0.7699
	Imin W/m^2	4.92	4.16		Idbmin (30°)	−1.3216	−0.7816
Declination angle	D_{max}	23.4498°	23.4498°		Idbmax (60°)	1.069	0.569
	d_{min}	23.4498°	23.4498°		Idbmin (60°)	−1.0624	−0.0634
Sunrise hour angle	w_{max}	110.019	112.0186		Idbmax (90°)	0.7127	0.3527
	w_{min}	60.9814	63.9814		Idbmin (90°)	−0.7082	−0.4382
Out-of-atmosphere irradiation	I_o(max) W/m^2	278010	298010	**Mom. Dif. irrad.**	IbBmax (30°)	0.2457	0.1257
	Io(min) W/m^2	−176900	−186900		IbBmin (30°)	−0.2545	−0.1545
Transp. index	Bmax	0.078	0.003		IbBmax (60°)	0.2461	0.1461
	Bmin	−0.0044	−0.0064		IbBmin (60°)	−0.2549	−0.1592
Total diffuse irradiation	Iy(max) W/m^2	4.9522	4.2022		IbBmax (90°)	0.2458	0.1458
	Iy(min) W/m^2	4.92	4.16		IbBmin (90°)	−0.2545	−0.1545
Function freq.	Ats (max)	0.9575	0.7712				
	Ats (min)	0.5904	0.4731	**Mom. reflecting irrad.**	IrBmax (30°)	0.0346	0.2806
Mom. Tot. irrad.	It(max)	0.8075	0.7075		IrBmin (30°)	−0.0405	−0.0405
	It(min)	1.4044	−0.8344		IrBmax (60°)	0.1461	0.1361
Mom. Dif. irrad.	$(Ays)_{max}$	0.84	0.732		IrBmin (60°)	−0.1571	−0.1557
	$(Ays)_{min}$	0.53	0.437		IrBmax (90°)	0.2622	0.1922
	Id(max)	0.5653	0.6853		IrBmin (90°)	−0.3513	−0.3131
	Id(min)	−1.1465	−0.8665				
Mom. direct irrad.	Ib(max)	0.2463	0.1363				
	Ib(min)	−0.2551	−0.1551				

Using Matlab software, solar irradiation is calculated on the values of inclined and horizontal surfaces. The indicator values indicate that, based on the calculations, the potential for PV systems in both provinces matches the anticipated concentrations, in this study. An important aspect of planning the PV systems is to compare the expected values with the real ones. System efficiency relies on different parameters. It is very important to use realistic radiation values to design the optimum system. The objective of this article is to obtain a mathematical reference model for selecting the best efficient solar panel by depending on the real sun irradiation values determined for the best efficient design of the PV system. To design a PV system, the sun irradiation values are assessed to be at an acceptable level of effectiveness. The sun energy parameters and a chosen region's potential is primarily assessed depending on the available data. In the second step, the sun irradiation analysis is determined on Matlab simulation program. To plan a PV system, the values of solar radiation in Istanbul and Izmir cases are assessed to achieve an acceptable level of effectiveness, model verification. Part of the total incoming radiation, direct beam and diffuse, is reflected by the surrounding ground and, to the extent that the plane is tilted into partial view of the ground plane, is also incident upon the inclined surface. In this study, most performance formulae were used to calculate the three primary parts of the solar radiation incident on a specified surface (reflected ground, diffuse sky, and direct beam). The most evident benefit of this use is the relative independence it gives the designer of the construction, who typically evaluates the consistency and analyzes the applicability of accessible climate information. In this regard, formula-based application of radiation models can be used to assess possible solar radiation potential for anywhere on the globe scheduled PV system.

Additionally, the proposed mathematical model is significant both in terms of the number of variables that are used and the wide range of models included within the resulting model. Simulation of the proposed model for the two specific cities approximate the real conditions, thus minimizing the margin for error before installing costly solar systems.

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Chapter 9
The Necessity of a Food–Energy–Water Nexus Approach for Lake Urmia Basin Under the Risks of Climate Change and Environment Degradation

Mohsen Zare, Behnam Mohammadi-Ivatloo, Mehdi Abapour, Somayeh Asadi, and Gholamhasan Mohammadi

9.1 Introduction

Food, energy, and water, considered as the most basic human needs, have complex linkages with each other in a particular cycle, and the food–energy–water (FEW or WEF) nexus perspectives highlights this interdependence to manage them under an integrated system to respond to the national sustainability and security challenges [1]. Furthermore, the increasing demand for food, energy, and water from population growth and urbanization under resource constraints increases the importance of studying the linkages. Meanwhile, climate change along with environmental degradation is one of the issues, directly or indirectly disturbing the cycle, causing significant challenges in the sustainability and security of food, energy, and water [2, 3].

Estimates show that about 2 billion people around the world suffer from a lack of sufficient energy and nutrients and are malnourished [4, 5]. Whereas resources do not respond to the current population's demand for food, energy, and water, demand for them is increasing. Already agriculture is the largest consumer of water, accounting for about 70% of overall freshwater use. Apart from agriculture, water is used in

M. Zare (✉) · B. Mohammadi-Ivatloo · M. Abapour
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: m.zare95@ms.tabrizu.ac.ir; mohamadi@ieee.org; abapour@tabrizu.ac.ir

S. Asadi
Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA
e-mail: asadi@engr.psu.edu

G. Mohammadi
Faculty of Planning and Environmental Sciences, University of Tabriz, Tabriz, Iran
e-mail: gh.mohammadi88@gmail.com

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the industry sector and the production of many energy forms. At the same time, 30% of the world's total energy production is consumed in the food production and supply chain [6]. This situation is expected to intensify in the near future, as it is estimated that demand for food, energy, and water will increase by 40, 50, and 35%, respectively, by 2030. Furthermore, whereas today almost 54% of the world's population is living in urban areas, this ratio is likely to reach 66% by 2030 [7].

Concerns and tensions in the sustainable supply of food, energy, and water are not limited to the above-mentioned issues. Climate change, causing changes in weather patterns and cycles, and environmental degradation by humans are factors subsequently affecting the availability of food, water, and land resources. Change of weather patterns and cycles means longer and more severe drought periods, unusually large and destructive storms, more devastating and frequent floods, rise of dust concentration and events, greater natural firefighting, and other complications, such as drying the rivers and lakes, no-snow winters with reducing of the frozen period and dry summers, no timely raining, and decreasing infertility of soil, each of which can occur on both regional and global scales and be vulnerable to the sustainability and security of food, energy, and water [3]. Moreover, other destructive human activities have caused extensive environmental changes, such as the construction of dams, mining activities for industrial mining, deforestation for arable land, habitat conversion, expanding settlements for housing, diffusion of toxic materials generated from chemical farming, and increase in groundwater consumption leading to land subsidence, which have doubled the challenges rate [2].

With the increasing pressure on resources and assuming the complex relationship between them, the need for a new approach in the identification and analysis of the relationships on the sustainability of food, energy, and water resources is undeniable. The FEW nexus is an approach that gives us this capability [8]. The first report on the need for the development of the FEW nexus concepts was presented at the Bonn Conference in 2011, which emphasized this approach as a comprehensive solution to the green economy growth [9]. After that, the UN Rio+20 Summit in Brazil (2012), highlighting the relationship between water, sustainable agriculture, food security, health, biodiversity, and desertification, emphasized the FEW nexus approach as a global security issue [10]. In 2015, the US National Science Foundation announced US$50 million in funding for research on interactions between food, energy, and water [11]. Within 2011–2015, 291 different organizations, from political institutions to scientific research to commercial enterprises, dealt in FEW nexus security activities [7].

The framework of a FEW nexus study can vary depending on the focus of the study, which ranges from local, provincial, national [12], regional [13] to global scales, at which its goals are largely achieved through legislation and regulations. Local, provincial, and regional scale legislation and regulations are heavily dependent on local food, energy, and water systems, while national and international principles are impressed by national politics and diplomatic relations between the countries [14].

This study assesses and tests a feasibility framework for the application of the FEW nexus at Lake Urmia basin (a basin scale study), similar to what's done for River Duero basin in Spain and the River Colorado basin in the southwestern United

States [15, 16]. Lake Urmia basin is located in the northwest of Iran, mainly in the two provinces of East Azerbaijan and West Azerbaijan. Hundreds of papers have been published in an attempt to evaluate and better understand the factors influencing the environmental dynamics of the basin. A common feature of many of these papers has been to focus on three actors of water, agriculture (for food), and climate situations of the region. Due to low-cost access to energy in Iran, this actor has not been highly considered for the basin. As the resources are limited and polluting the environment, renewable energy expansion is highly supported by government policies. In this chapter, each of the actors of the nexus and their interdependencies on each other will be examined. It is hoped that this study will present the basis for providing a comprehensive nexus model for informed decision-making about the challenges ahead of the basin. Subsequently, in Sect. 9.2, we will briefly review the effects of climate change in Iran and the Middle East and North Africa (MENA) region. Section 9.3 examines environmental problems in the Lake Urmia Basin. The interdependencies of FEW components in the Basin and Iran is studied in Sect. 9.4. Section 9.5, ends the with a conclusion.

9.2 Climate Change Impact on Iran

The main contributor to climate change is considered to be the high levels of greenhouse gases in the atmosphere, as a consequence of more than 150 years of burning fossil fuels by humans. Greenhouse gasses capture and absorb some of the sunlight reflected by the Earth's surface, and when the concentration of them exceeds a certain amount, the global mean surface temperature increases dangerously which can cause unwanted change on the distribution of weather cycles.

Studies show that Iran is at the forefront of the countries that will be affected by the destructive impact of climate change. Although climatology is a complex knowledge composed of a multitude of uncertain components and propositions [17, 18], the idea of aridity of Iran is the absolute opinion of climate experts. What follows in the next paragraph refers to the reasons for the expert consensus on the continuing persistent drought in Iran [19].

It can easily be verified that Iran has continuously significantly become more drought-prone and warmer in the past 3 decades. The Islamic Republic of Iran Meteorological Organization (IRIMO) website (http://irimo.ir/far/wd/2703) has provided monthly statistics of temperature and rainfall for different parts of Iran for more than 60-year period. An examination of this data suggests that Iran has warmed between 1 and 2 °C [20, 21], and almost an average of 20% has been exposed to reduced rainfall [22, 23]. Many papers, given at the first and second national Iranian climate conferences, acknowledged the climate change in Iran as a continuous drought [24, 25]. Different articles, published in a variety of journals, declared the aridity of the Middle East during the past three decades and, of course, the continuation of this process in the coming decades [26]. Finally, the most documented source for the study of the climatic trends of a given region is the official

Intergovernmental Panel on Climate Change (IPCC) reports [27, 28]. Briefly, the reports state that the impact of global warming on low-latitude regions would be twice greater than its impact on high latitudes. That is, if Europe gets 2° warmer by the end of this century, the Middle East will be warmed up by 4°. One evidence is that while the rise in average temperature under the influence of global warming in the whole world is about 1°, this is a faster rise and estimated to be between 1.5° to 2° for most Middle Eastern countries [29]. For this reason, the effects of climate change in the Middle East and North Africa have been more pronounced than elsewhere in the world, and concern for the region's future is greater than in other parts of the world [30].

Sometimes, both drought and aridity are not distinguished and treated in the same way. In principle, drought is a temporary, normal, and periodic phenomenon, occurring in virtually all climatic zones when the amount of rainfall is below normal, which is a climatic feature of a particular region (e.g., drought, normal, and wet) [31]. But, aridity is permanent low average rainfall, bringing about deserts [32, 33]. Every drought is temporary and definitely ends, but if the Middle East is thought to be warmer and drier, and this process will still continue, it can no longer be considered a drought. This is an abnormal situation, which is not according to the conventional and expected cyclic nature of a climate processes [34], and as it is irreversible, it cannot be a normal reversible phenomenon as drought [35]. Basically, the climate type of each region can be identified by averaging its 30-year climatic trends [36]. If a region has been exposed to temperature rise and rainfall reduction for 30 years, it can be claimed that the region has undergone climate change, and its climate type must be redefined [37]. Aridity means a state of unusual and irreversible dryness and warming of the climate [35]. That is, the region does not temporarily suffer from drought, but it has constantly been warmer and drier. Figures 9.1 and 9.2 illustrate average rainfall and reference evapotranspiration of the Middle East and North Africa countries for current and future decades [38]. We know that Iran has more or less faced drought over the past 3 decades. These two figures show that such a process will also continue "at least" until 2050, which means that lower average rainfall and more reference evapotranspiration will intensify in Iran [19].

Because an absolute consensus of scientific research reports that Iran is drying, it is necessary to explain the truth that "Iran's main problem is aridity" [19]. Iranian authorities must have the ability to design and develop a comprehensive and integrated national program, setting it as a foundation (or masterplan) for all future plans, to curb the climate crisis and adapt the country to the realities of climate change [22].

9.3 Environmental Crisis in the Lake Urmia Basin

Lake Urmia basin, covering an area of 51,876 km^2, located in the northwest of Iran with an area of approximately 52,000 km^2, is one of the six main basins in Iran. Lake Urmia, occupying about one-tenth of the basin area, is the largest inland lake in Iran

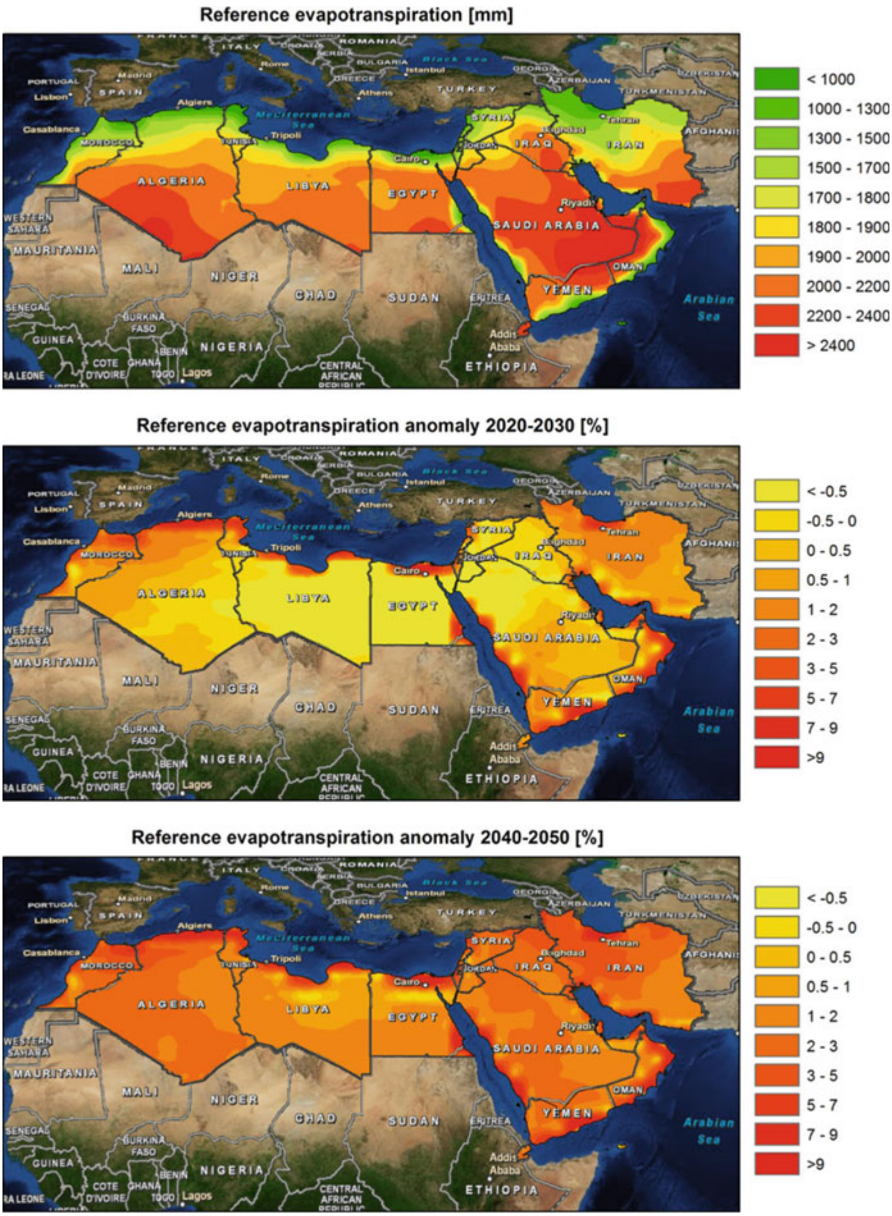

Fig. 9.1 Reference evapotranspiration for the Middle East and North Africa until 2050 [38]

and the second largest hypersaline lake in the world (before September 2010) [39]. The ecosystem of this lake is a prominent example of a closed basin where all rivers of the basin are discharged into. The exact boundary of the Lake Urmia

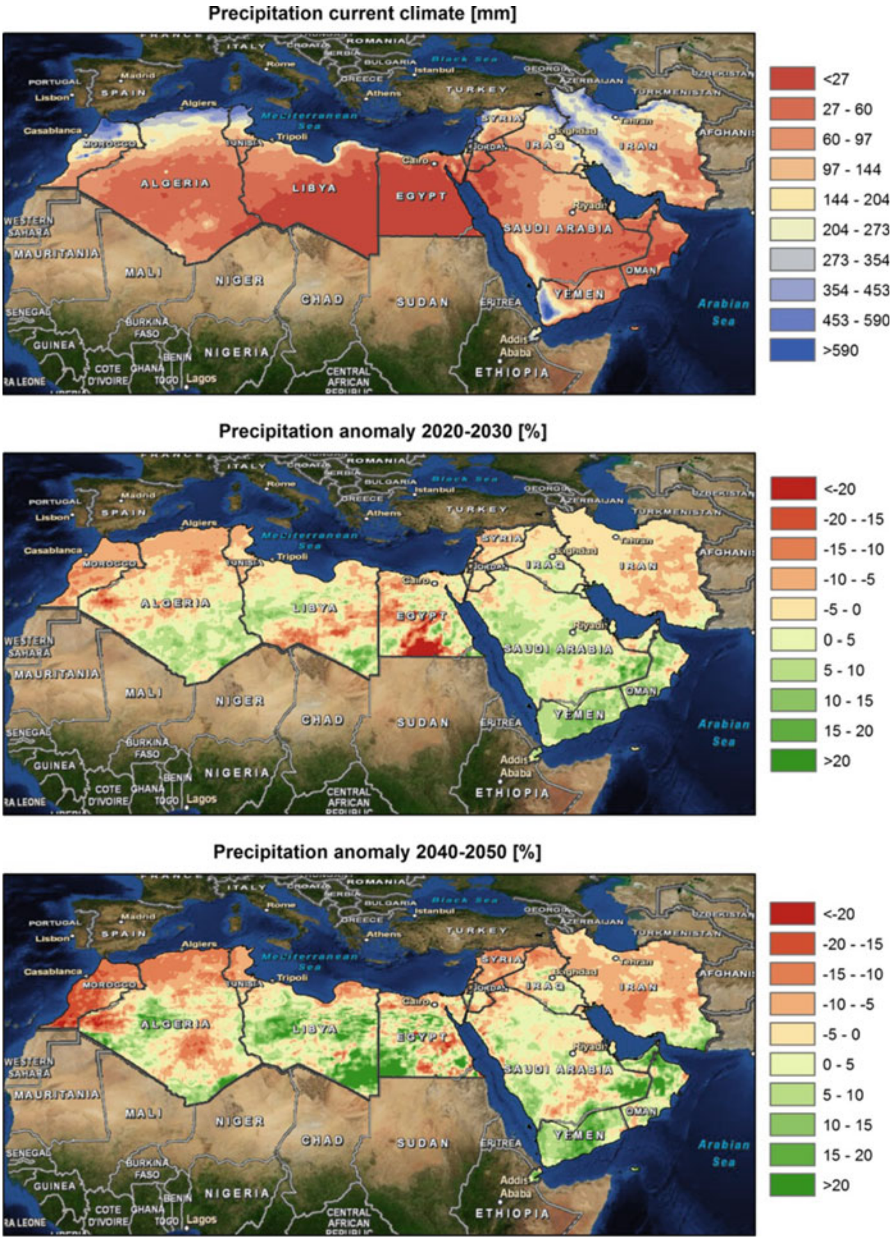

Fig. 9.2 Precipitation for the Middle East and North Africa until 2050 [38]

Fig. 9.3 The geographical location of the Lake Urmia basin and other Iranian major basins

basin has created a precise area for the management of factors affecting the lake and important habitats in the basin. Figures 9.3 and 9.4 depict the geographical location of the Lake Urmia basin along with other major basins of the country and its topographic features, respectively.

The surface area of Lake Urmia, containing about 30 billion m^3 of water on the high-watery period in 1995, was about 5200 km^2 and containing about 14 billion m^3 of water at the ecological level, was approximately 4500 km^2. Before the significant decline in the lake's water level in recent years, the salt density in the water of the lake was 220 g L^{-1}, but at present, it is close to 400 g L^{-1} [40]. The process of changes in the level of Lake Urmia over the last century has been plotted in the diagram presented in Fig. 9.5. Although the lake level has undergone repeated fluctuations over the last century, its changes have not been as strong as the changes over the recent 25 years. As indicated in the chart, the lake's downward trend began after its high-water period in 1995, and over the next years, its level dropped by more than 8 m, and its water volume decreased from about 30 to 1 billion m^3, due to evaporation and lack of sufficient water supply to it.

Considering the location of Lake Urmia in a closed basin, only direct rainfall and surface and subsurface runoff and streams are considered as the sources of water entering the lake and evaporation from the lake's surface as the major part of the

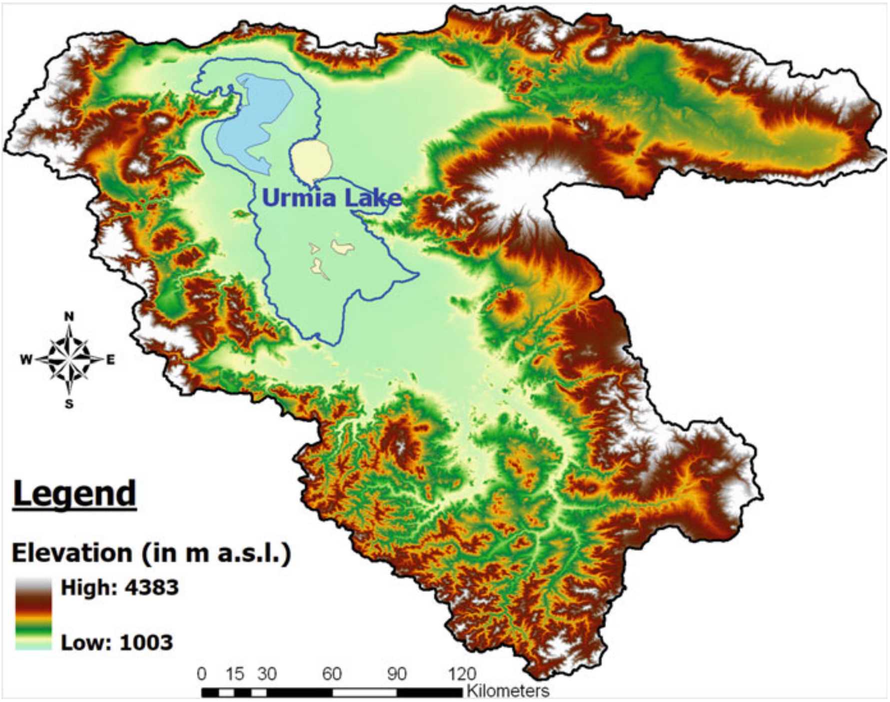

Fig. 9.4 Topographic features of the Lake Urmia basin

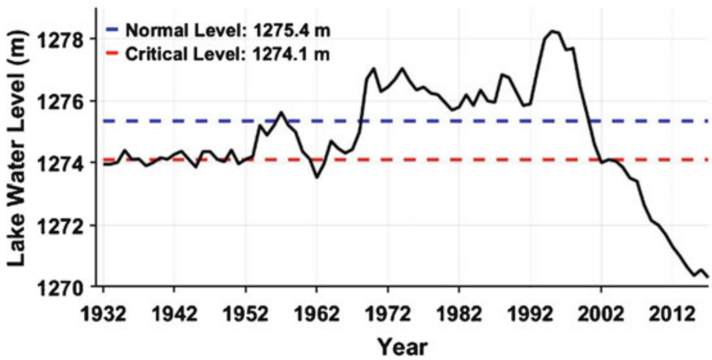

Fig. 9.5 Changes in surface and water level of Lake Urmia over the recent century

lake's water loss. Therefore, continuous extreme reduction of lake water volume due to evaporation and lack of access to sufficient runoff and streams to enter the lake to compensate and maintain its water balance are debated as the main causes of the dryness of the lake [41]. Contrary to many climatic disasters, the dryness of the Lake Urmia was mainly due to mismanagement and intensive activities in the agricultural

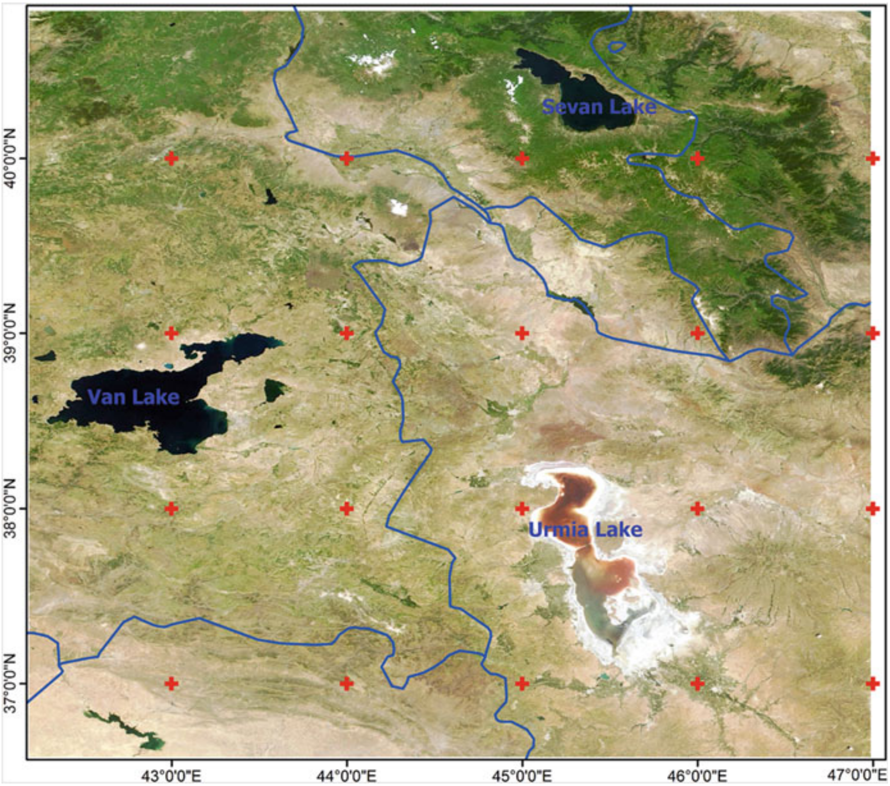

Fig. 9.6 Comparison of the current situations of Lake Urmia with its nearby lakes, Lake Van in Turkey and Lake Sevan in Armenia. (Source: https://worldview.earthdata.nasa.gov, 2018)

sector, upstream competition over water, and aggressive regional water resources development plans [42], while the contributions of climate change and increase in the frequency and intensity of droughts are relatively small [43, 44]. The higher water level from the ecological level of Lake Van, which is located in eastern Turkey 150 km away from Lake Urmia, can be evidence of this claim (Fig. 9.6). Even, the issue of water transfer from Lake Van to Urmia has recently been proposed to overcome the water scarcity problem, which is possible considering the adjacency and the similarity of the ecology of the two lakes. Also, Lake Sevan in Armenia, like Lake Van, has a better water balance (Fig. 9.6).

The excessive consumption of the basin's natural renewable water resource has been carried out by constructing more than 120 small and large dams and diversion structures [42, 45]. Fifty-six of the dams with large reservoirs are under the supervision of the Ministry of Energy and the rest were built by the Ministry of Agricultural Jihad. According to the United Nations Economic and Social Council (UN ECOSOC, 1997) report, the acceptable rate of surface water harvesting is between 20% and 40%, and a rate of more than 40% is highly risky [46], while

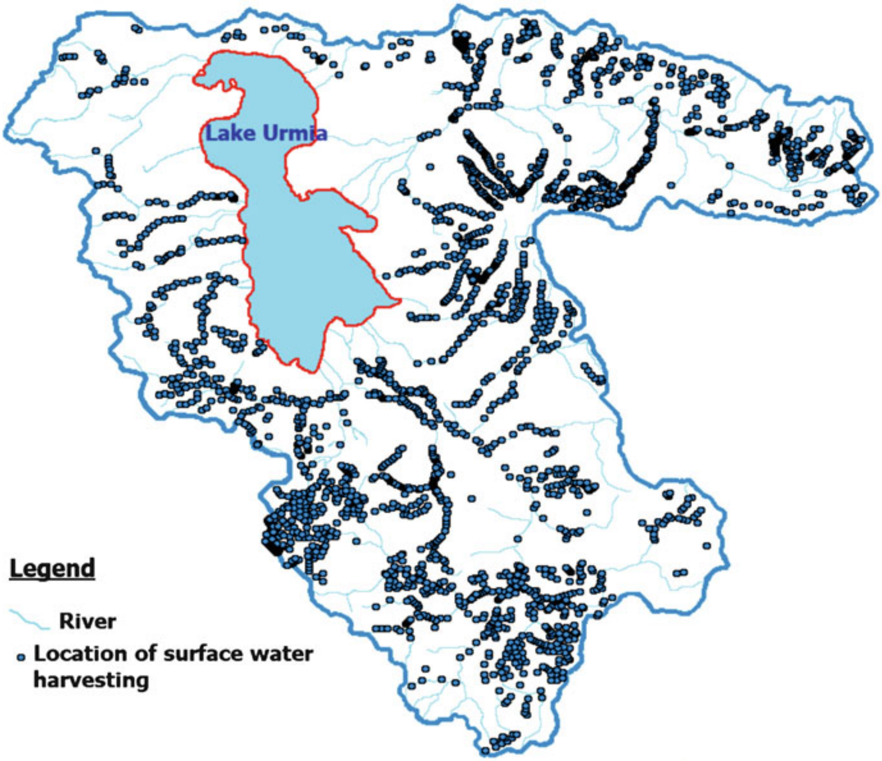

Fig. 9.7 Spreading of the locations of surface water harvesting in Urmia watersheds. (Source data: Urmia Lake Restoration Program committee, 2015)

this rate for Lake Urmia basin has been about 70% [47]. The expansion of points and areas of water harvesting of the Urmia watersheds is identified in Fig. 9.7.

Overuse of water from Lake Urmia Basin has not been limited to the surface water. An evaluation of the effect of human anthropogenic activities on groundwater quality of the basin indicated significant groundwater contamination in urban and suburban areas [48]. According to the statistics of Urmia Lake Restoration Program committee, digging about 88,000 deep and semi-deep wells for groundwater extraction and many qanats across the basin [49] have led to land subsidence in many areas and had a direct and/or indirect impact on the river flows, resulting in a significant decrease in the input water to the lake [50]. Unfortunately, about half of these wells are illegal [51]. Figure 9.8 shows the extensiveness of the wells for water pumping across the Lake Urmia Basin and the forbidden areas for any new well construction.

Actually, the current condition of Lake Urmia is the result of the implementation of harvesting 70% of the renewable water resources of the basin and lack of the allocation of required lake ecological water [52]. If the United Nations Commission on Sustainable Development (CSD) index in the water resource management was followed, which does not allow harvesting more than 40% of the renewable surface

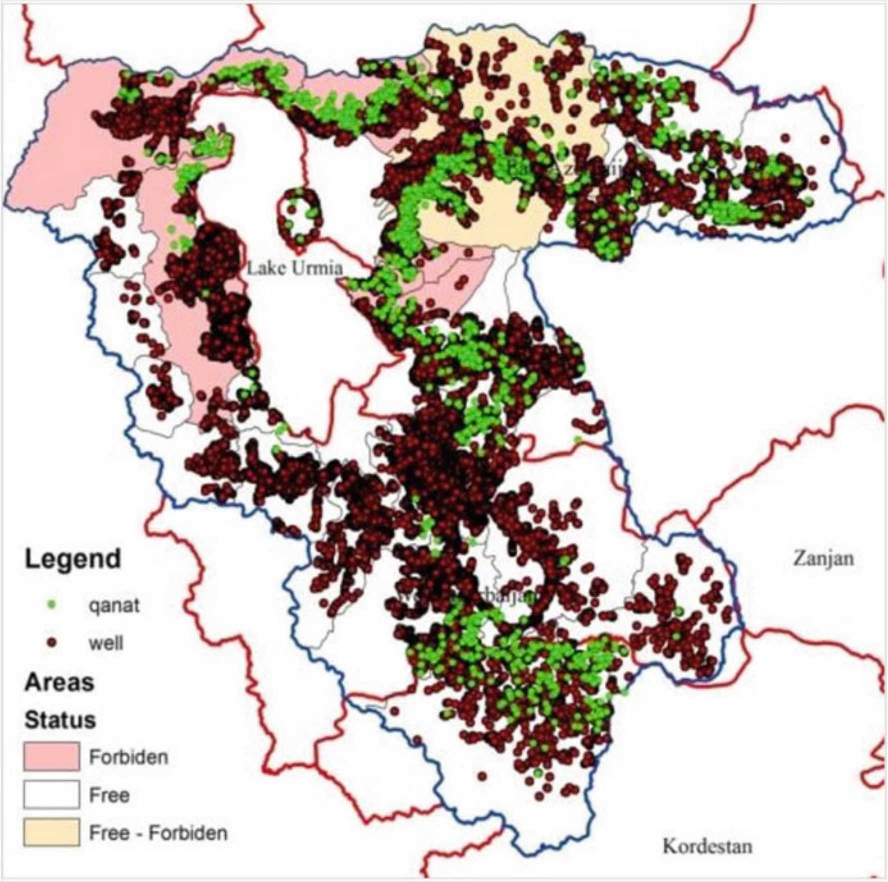

Fig. 9.8 Spreading of the qanats and 88,000 deep and semi-deep wells for groundwater withdrawals across Lake Urmia basin. All the wells located in the forbidden area (pink) and some in yellow are illegal [51]

water resources, the level of the lake was about 1273 m in the current situation of drought, which is far better than the 1270 m. In Fig. 9.9, the probable process of changes in the level of Lake Urmia from 2001 to 2014 has been shown in different water harvesting scenarios of renewable surface water resources in the basin.

Another environmental problem in Lake Urmia Basin is Shahid Kalantari causeway, a dike-type that divides the lake into northern and southern parts. This causeway, with a length of 15 km and a 1.2-km culvert, has caused disruption of the natural pattern of the lake-water circulation (the north–south and south–north flows) and division of the lakebed into two separate water parts [45, 54]. Several studies have shown that the causeway has played a significant role in increasing the evaporation of water and the disturbance of the lake ecosystem [55, 56]. For this reason, several suggestions have been made to reform or completely destroy the causeway [56, 57]. In Fig. 9.10, different colors of the lake water are visible on the

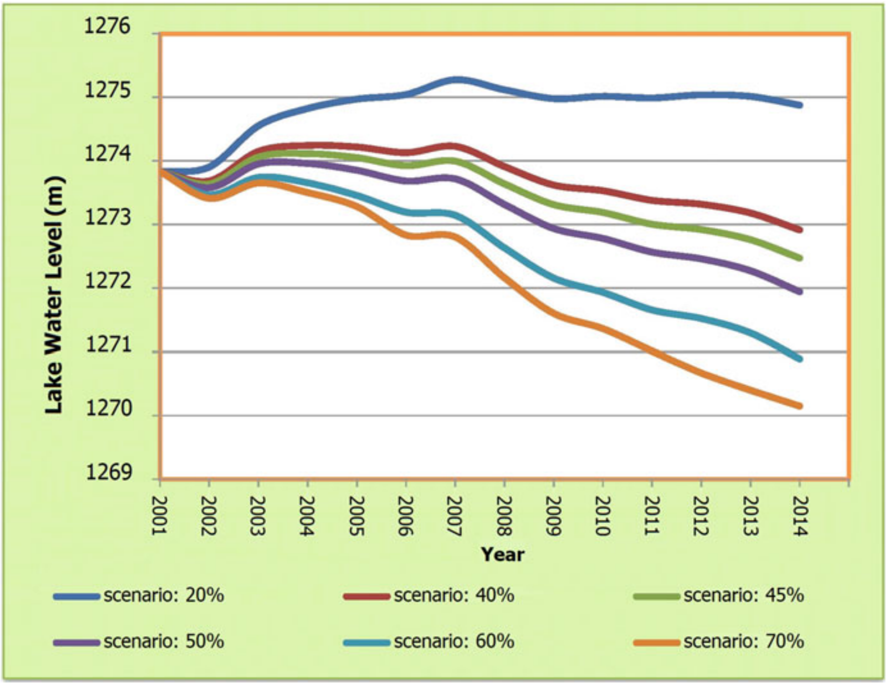

Fig. 9.9 Probable level of the Lake Urmia water based on the different scenarios of surface water harvesting, 2001–2014 [53]

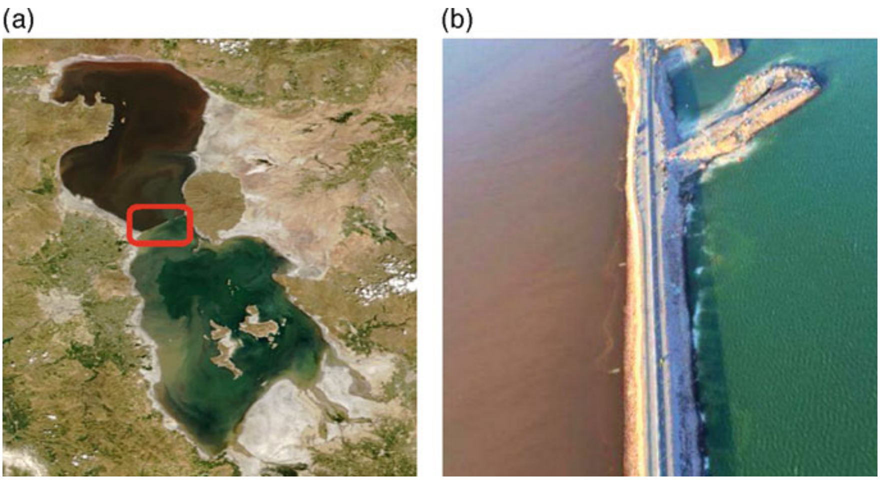

Fig. 9.10 Different colors of lake water on the two sides of the anti-environmental road constructed on Lake Urmia bed. (Sources of (**a**) and (**b**): Terra MODIS satellite data and Iranian news agencies, respectively, June 1, 2019)

two sides of the anti-environmental road, which is due to the high temperature and salt density in the northern part.

According to international experience, the continuation of the present conditions and drying of Lake Urmia will undoubtedly cause irreparable damage to the ecosystem [58], agricultural lands and gardens, and the health of residents of the basin [59]. The creation and exacerbation of salt dust storms from dry areas of the lakebed are one of the direct consequences of dryness of the Lake and threaten the health of the people residing in the area, the effect of which can reach hundreds of kilometers away, similar to what happened to the Aral Lake in the former Soviet Union, namely the tragedy of the Aral Sea [60, 61]. Lake Aral, located in Central Asia, on the territory of Uzbekistan and Kazakhstan, was supplied by water from Amu Darya and Syr Darya rivers. Within I960 and 1980, by the order of Khrushchev, widespread construction of dams and irrigation projects were carried out on both the rivers for the development of agriculture, mainly for cotton production, which caused the great Aral Lake to decline gradually to less than 10% of its original size [62]. This resulted in the loss of 60,000 fishing jobs, destruction of part of the agricultural land, and especially development of salt dust storms, which led to the people of the region being affected by a variety of respiratory diseases and skin and lung cancers, whose consequences still persist [63, 64].

What is certain is that the current crisis in Lake Urmia Basin will eventually lead to its complete destruction. Though the government has taken measures to stop the process, these measures do not seem adequate, because things go slowly, mainly due to the lack of efficient management and reduced resources caused by economic sanctions. Therefore, the government should be able to design and implement a more comprehensive and integrated strategy to deal with the threats.

9.4 Interactions Among FEW Actors at the Lake Urmia Basin

In practical terms, FEW nexus is an approach from local to regional scales for integrated management of natural resources to achieve multiple benefits toward a more sustainable and resilient world and mitigate and adapt to climate change. What is said in the previous sections about Lake Urmia basin reveals the need for studies to evaluate the implementation of a comprehensive and integrated strategy for critical resource management, such as the FEW nexus framework. In this section, we examined the interactions between each of the components of FEW nexus for the basin. Limited research and data regarding FEW nexus concepts exist across Iran, including within the Lake Urmia basin, despite having 5 million population living within the basin, active agriculture, and sensitive ecosystem. One of the studies for increasing simultaneously the efficiencies of water, energy, and production is presented for grape gardens of West Azerbaijan, located in the western part of the basin [65].

9.4.1 *Water for Energy*

Most of the electricity required in the basin is supplied through gas, steam and combined cycle power plants, which are mainly fed from gas, and the share of other power plants is negligible. There are six such plants, with a total generation capacity of 2914 megawatts (MW). The number and total generation capacity will reached 7 and 4394 MW, respectively with completion of the under-construction power plants. Some specifications of these conventional units, including type, capacity, operating capacity, and the amount of water use, are presented in Table 9.1. The volume of water used by each power plant in terms of liters per MW-hour (MWh) is shown in the chart in Fig. 9.11. The high water consumption of Combined Cycle Power Plant of Tabriz is due to its aging and wet cooling tower. Half of this water is

Table 9.1 Some specifications of the power plants located in the Lake Urmia Basin

No.	Power plant	Type	Capacity (MW)	Operating capacity (MW)	Water use (L/MWh)
1	**Urmia**	Combined cycle	1434	950	420
2	**Urmia**	Natural gas	60	60	700
3	**Tabriz**	Combined cycle	800	800	2250
4	**Sahand**	Steam	650	650	22
5	**Khoy**	Natural gas	350	350	920
6	**Sofian**	Natural gas	100	100	480
7	**Heris**	Combined cycle	1000	0	–
Total			**4394**	**2914**	**–**

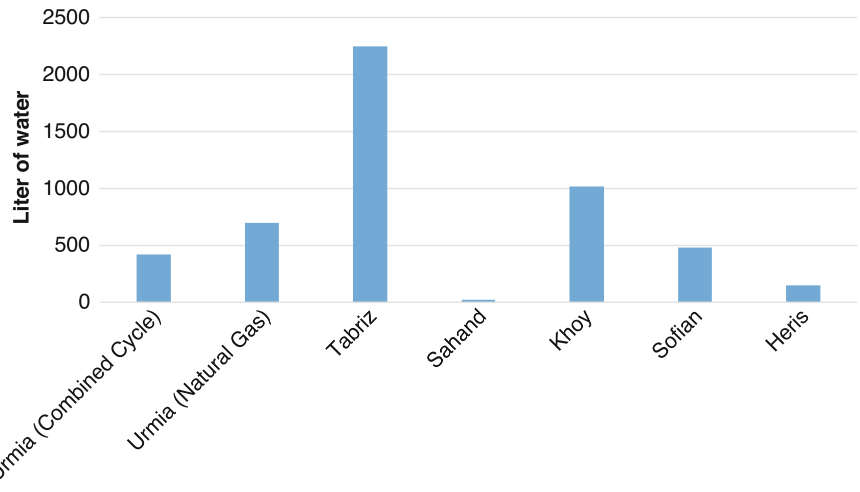

Fig. 9.11 Amount of water used by each power plant in the basin (L/MWh)

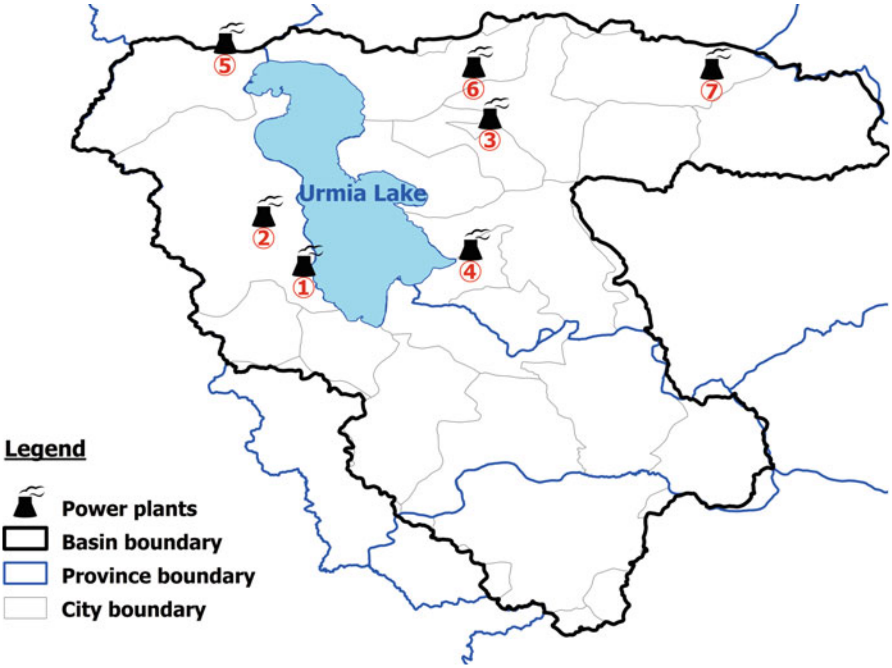

Fig. 9.12 Location of power plants within the basin

Table 9.2 Number and generation capacity of hydropower plants under operation, construction, and study

Hydropower plant	Number	Capacity (MW)	Annual generation (GWh)
Under operation	1	6	17
Under construction	2	11	49
Under study	19	143	297

supplied through groundwater and the rest from the surface water sources. The total annual water use of the plants is about 18 million cubic meters, 26% of the water used in the industrial sector of the basin. The spread of the power plants within the basin is shown in Fig. 9.12.

The share of renewable energy sources in the total energy supply of the basin is almost zero. Among the 56 large dams under the supervision of the Ministry of Energy, only one of them is equipped to generate electricity, with a generation capacity of 6 MW. The total capacity of the under-construction and under-operation wind farm and solar panel units within the basin is less than 100 MW. Currently, other dams and hydropower plant projects are under construction or study. Their generation capacity and average annual electricity generation are listed in Table 9.2. Even, with the construction and completion of the projects, hydropower's share of electricity generation will still be small.

9.4.2 Water for Energy

Agriculture for food, as the largest user of water resources, consumes about 70% of the total freshwater withdrawals in the world [66], but unfortunately, this value is approximately 89% for the Urmia Lake basin (Table 9.3). The agriculture sector consists mainly of four subsectors, namely crop and horticulture, breeding and hunting, forestry and fishing. Based on the results of surveys, conducted by Ministry of Energy (Iran) regarding water consumption in Lake Urmia basin, the total volume of water use in different sectors is about 4825 million cubic meters per year, which is supplied from two sources of ground and surface sources. In Table 9.3, the water consumption of different sectors from each of the two sources is listed along with their percentages (in parentheses), in which the agricultural and industry have the highest and lowest consumption, respectively. As can be recognized from the table, about 57% of water consumption in the agricultural sector of the basin is provided by surface water and the rest from groundwater sources.

The main destructive factor in water resource development projects is related to land irrigation [67, 68]. According to the studies, the irrigated land area over Lake Urmia basin increased from 1265 km^2 in 1975 to 5525 km^2 in 2011, while the surface area of the lake dropped from 5982 km^2 in 1995 to 586 km^2 in 2014 [69]. This irrigated land area increase has been much greater in recent years, leading to the extension of salinization and desertification [70]. It can be said that there is a direct and significant relationship between the aggressive hydro-economic development plans and the degradation of the lake ecosystem [71]. In addition to the increase in irrigated land area, other factors have contributed to the unbalanced and unsustainable development of the agricultural sector of the basin, including additional cultivation of water-intensive crops, such as sugar beet and apples (instead of grapes) [72], and a 30% increase in the irrigated gardening areas [73]. Water consumption for agriculture is the main cause of dryness of Lake Urmia and many of Iran's wetlands.

In general, the aggressive hydro-economic development policy of the government of Iran, especially in Lake Urmia Basin, in order to realize the dream of food self-sufficiency, which has been carried out by providing cheap water and energy, has led to the ecological unsustainable agricultural systems and lack of the allocation of required Lake Urmia ecological water [74, 75]. If the water and energy prices reflect the true value of consumption, production costs will rise considerably, and farmers will seek more resilience behavior in the face of water scarcity [76] and more

Table 9.3 Water harvesting volume from surface and groundwater resources in different sectors in Lake Urmia basin (million cubic meters per year)

Water source/consumption sector	Agriculture	Domestic	Industry	Over
Groundwater	2424 (50.2)	276 (5.7)	33 (0.7)	2733 (56.6)
Surface water	1867 (38.7)	190 (3.9)	35 (0.7)	2092 (43.4)
Over	4291 (88.9)	466 (9.7)	68 (1.4)	4825 (100)

affordable consumption patterns, in which cultivation of water-intensive crops will not be economically justified [77]. Rising production costs and, consequently, rising sales prices will decrease the demand for products that reduce the pressure on resources and can also change the culture of food consumption in the community. This will also cause a significant reduction in both food losses and food waste, which is one of the sustainable solutions to increase future food availability [78, 79].

9.4.3 Energy for Water

Energy is required in all stages of water production, distribution, use, and refinement, which plays a key role in the development and sustainability of urban and rural water supply systems. The consumption of energy in water supply sectors can be summarized as (i) primary supply of water by local sources or imports; (ii) treatment of raw water and distribution in service areas; (iii) pumping and local purification of water, and heating and cooling inputs before consumption at end use; and (iv) collection, pumping, and treatment of wastewater [80, 81]. The importance of each stage is significantly influenced by changes in the geographical location of the service area, the availability of water, the local climate, the culture and customs of the region, and the economic status of the area [82]. Some energy-consuming processes in various stages of the water life cycle are shown for the municipal sector in Fig. 9.13.

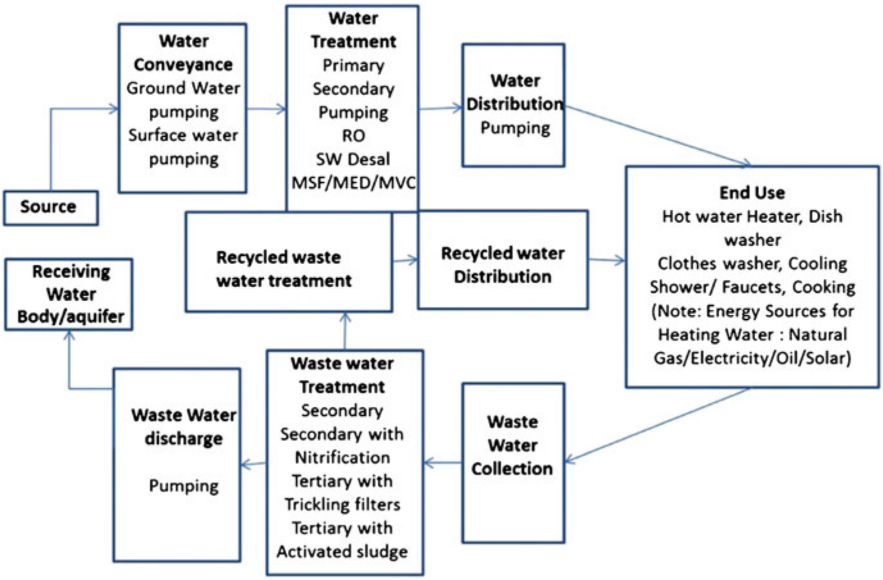

Fig. 9.13 Some of the energy-consuming processes of the water life cycle through the municipal sector [83, 84]

The intensity of energy consumption (kWh/m^3) is different in each step of the water cycle. Also, depending on the technology used, the intensity of energy required at each stage varies widely. The energy intensity of residential end use is very high compared to other parts of the water cycle due to water heating, cooking activities, and washing clothes and dishes [85]. Wastewater treatment, when done with advanced methods, will be the most expensive part of the water cycle, and, depending on the gotten water that is used for particular purpose(s), can include different stages that require various energy intensities [86]. Wastewater treatment processes consume more energy if the effluents are treated to potable water quality [87]. In the two graphs in Fig. 9.14, the intensity of energy consumption required for two different wastewater treatment plants is shown. As can be seen, the advanced method has more treatment stages that require more energy intensity.

Considering the requirement of at least 3 billion cubic meters water to compensate for annual evaporation and sustain the ecology of Lake Urmia [88, 89], treated wastewater of the basin is one of the sources to provide part of this water, which can be done at a lower cost because wastewater treatment is costly. For other purposes, such as drinking water supply, as shown in Fig. 9.14, the government plans to provide about 10% of the annual water requirement for the lake health through discharging about 300 million cubic meters of treated wastewater directly to the lake body. However, a member of Iran's parliament recently expressed that the country's environmental organization has not been functioning well in treatment processes and preventing untreated wastewater to the lake. The person claimed that about half of the sewage goes to the lake without primary treatment, and when it is rainy, the water treatment plants are turned off and all the factories' sewage and untreated industrial wastewater pour into the lake. Repetition of this process will undoubtedly result in the creation of a new ecosystem with a high potential for environmental degradation and new environmental challenges for the lake and overall basin.

Energy consumption in the agricultural sector, which is mainly related to irrigation pumping, generally has less intensity than urban wastewater treatment or consumption at end use. In Lake Urmia basin, where crop production is rarely mechanized, a significant amount of the energy consumption for agricultural water use is spent on water extraction from wells, in which some of them are powered by electricity and some by a diesel engine. There is an essential linear relationship between electricity required for pumping 1 m^3 of water and the depth from which it is pumped at a particular pressure (Fig. 9.15). Due to a large volume of water extraction at Lake Urmia basin within recent decades, the current operations are carried out from greater depths, resulting in an increase in the energy required for pumping.

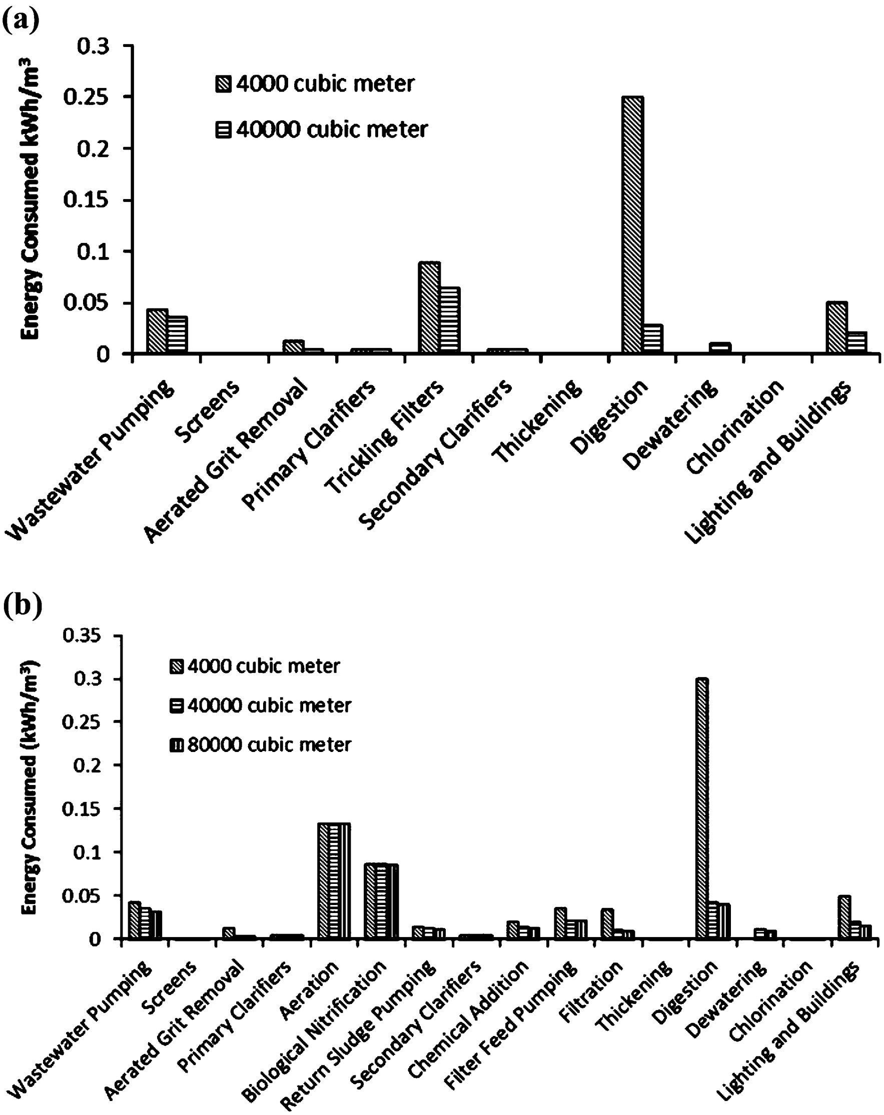

Fig. 9.14 Energy use for (**a**) trickling filters and (**b**) advanced wastewater plants [83]

9.4.4 Energy for Food

Like other economic sectors, the food sector has a close relationship with energy in order to produce, supply, and distribute the products. The demand for energy carriers in the food sector is mainly used to provide the required driving force for irrigation

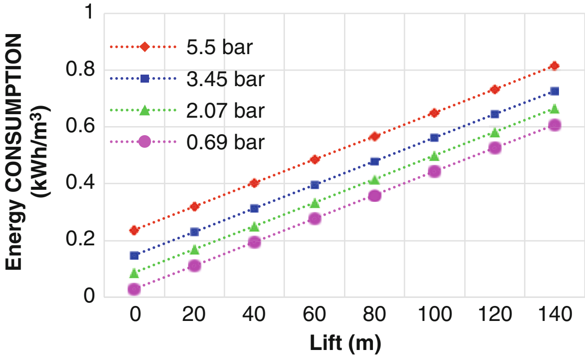

Fig. 9.15 Relationship between electricity required for pumping 1 m^3 of water and the lift with different discharge pressure requirements [83, 90]

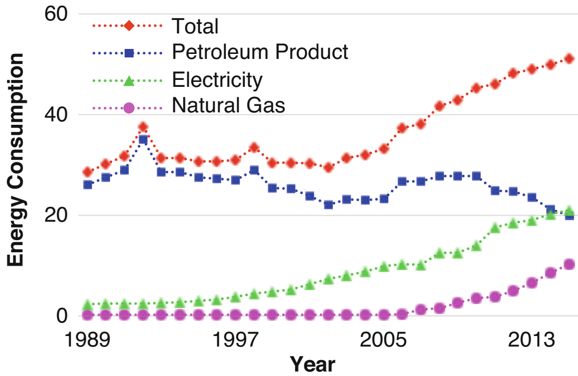

Fig. 9.16 Average consumption of each energy carrier used in the agriculture sector in Iran (unit: million barrels of crude oil equivalent), 1989–2015 [52]

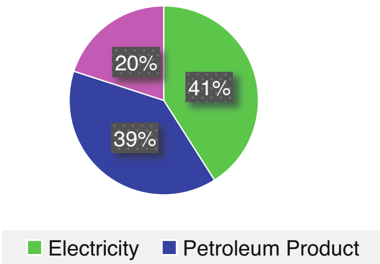

Fig. 9.17 Share of each energy carrier used in the agricultural sector in Iran, 2015

pumps, machinery, and equipment, respectively. This sector now accounts for about 30% of the world's total energy consumption.

In Iran, petroleum products (mainly gasoline), electricity, and natural gas are used in the agricultural sector as the most important energy carriers. A survey on the consumption of energy in the agricultural sector over the years 1989–2015 indicates that consumption of petroleum products has been decreasing, but consumptions of electricity and natural gas carriers have had upward trends (Fig. 9.16). According to the energy balance sheet in 2015, the share of each energy carrier in the agricultural sector is shown in Fig. 9.17 [52].

Table 9.4 Average energy use in Iran and share of the agricultural sector during five development programs of the country (unit: million barrels of crude oil equivalent per year)

Period	Average consumption of the country	Agriculture sector		
		Consumption	Growth rate (%)	Share from the total consumption of the country (%)
1989–1993[1*]	618.8	31.6	3.9	5.1
1995–1999[2*]	646.14	31	−0.2	4.8
2000–2004[3*]	744.56	30.9	1.3	4.2
2005–2009[4*]	1053.1	38.6	5.6	3.7
2011–2015[5*]	1247	48.9	2.5	3.9

[1–5*]First to Fifth Iran Development Plans (Source: Iran Ministry of Energy, Energy Balance Sheet)

While about 30% of the world's total energy production is consumed for food, unfortunately in Iran, it was 4% in 2015. Energy consumption in Iran majorly occurs in transportation, commerce, and household sectors, respectively, and the share of agriculture has remained negligible since 1967. The energy consumption growth has also taken place in the above-mentioned sectors, and agriculture has a marginal share. During 1989–2015, although the mean energy consumption in agriculture has increased from 31.6 to 48.9 million barrels of crude oil equivalent, its contribution from total average energy consumption of the country has dropped from 5.1% to 3.9% as shown in Table 9.4. Therefore, the growth of energy consumption in the transportation sector was not due to the growth of consumption of energy carriers in the agricultural sector [52].

In recent decades, agriculture in Iran has rarely been industrialized and still operates in the traditional way. Agricultural industrialization mainly appears in the application of modern equipment, machinery, and methods. Therefore, an increase in the growth of industrial agriculture level results in an increase in energy consumption level. As agriculture is not mechanized in Iran, its energy consumption is negligible. Such inefficient agriculture and, on the other hand, the dream of self-sufficiency in the food supply have destroyed many valuable and nonrenewable water resources of the country, only one of which is the water resource of Lake Urmia basin. The government not only has not prevented some improper development but also has provided financial assistance for the projects, such as the provision of cheap or free electricity for agricultural wells that leads to water harvesting more than is needed and probably reduced the desire to mechanize cultivation. In Table 9.5, electricity tariffs from 2005 to 2015 have been presented for different consumer categories of the country, in which the tariff for unmechanized agriculture is the lowest.

The gradual increase of energy tariffs combined with demand response programs in power markets can be considered as essential techniques for reducing water and energy consumption in the Lake Urmia Basin. The most difficult or socially, politically, and technically acceptable scenarios for electricity tariffs for groundwater pumping have been studied and presented for the Mexica [91].

Table 9.5 Electricity tariffs for different sectors in Iran, 2005–2015 (Unit: Iranian Rials/kWh) [52]

Year	Household	Public	Agriculture	Industry	Others
2005	102.7	176.8	21.6	201.6	539.7
2006	102.9	181.7	21.3	200.4	541.2
2007	124.7	159.6	21	205.9	508
2008	119.3	228.9	22	204.6	552.4
2009	129	152	21	206	501
2010	142.3	226.5	46.8	263.6	599.1
2011	334.8	501.6	125.7	441.9	1275.3
2012	337.5	491	131.1	427.5	1339.5
2013	346.7	516.3	133.4	442.6	1342.2
2014	439.4	617.6	177.9	542.6	1664
2015	504.7	717.6	195.5	633.2	2046.8

9.4.5 Energy for Water

The use of food for energy production is recognized as bioenergy or biomass, a renewable form of energy used to produce both heat and electricity from non-fossil biological materials and one of the most important indicators of sustainable development for countries. Biomass power plants provide a significant amount of energy and are effective in controlling the serious crisis caused by urban waste and environmental pollutants [92]. However, these plants are one of the most water-intensive energy sources [93]. No biomass power plants have been built in Urmia Lake basin, and there are only five biomass power plants in the whole country with a total capacity of 11 MW electricity generation. Electricity produced by the biomass power plants is about twice as expensive as other renewable energy sources, such as wind and solar. Electricity produced by the biomass power plants is about twice as expensive as other renewable energy sources, such as wind and solar, so the government needs to provide the funding to support them. Of course, as in many other parts, the main problem of Iran is the limited financial resources and foreign investment due to the heavy economic sanctions.

9.5 Conclusion

Nexus thinking is an effective framework that helps connect, coordinate, and strengthen individual food, energy, and water management policies which permit synergies in order to create coherent strategies. This thinking can be applied to all spheres of society, where resource management and optimization is required within political spheres, including regional, national, provincial, or local scales, for a business or even at a domestic scale.

Generally, the importance of the FEW nexus and gaining a deep understanding of it from a political perspective have only recently been cleared. In the case of the Lake

Urmia Basin, up-to-date food, energy, and water policies have rarely been checked together when planning.

Primary issues derived from FEW interdependencies for the Lake Urmia Basin contain extreme consumption of water for food, especially for water-based products, low efficiency in the food sector due to the absence of mechanized modern systems which has appeared in low energy consumption, and low energy prices, especially for water pumping, which leads to overuse of water and energy. Secondary issues are (i) the water used for power plant cooling at the Tabriz conventional unit is much higher than the other plants of the basin and global standard. Due to its aging, its water use should be limited in replacing it with new technology. (ii) Renewable energy sources do not have a significant share of the basin's energy supply, as an important indicator for a sustainable society and environment. (iii) Wastewater transported to the lake body should have a proper treatment standard to prevent a new challenge against the lake ecosystem. (iv) The huge volume of industrial and municipal waste materials will be challenging for the basin environment if not properly managed. The construction of biomass plants is a proper way to manage them, however, it should be noted that these plants are water intensive.

Disturbed ecosystem and low level of water of the lake have created an unstable environment, rooted in intensive agricultural activities, mismanagement, and wrong decision-making. Most likely, in the coming years, the lake ecosystem and the basin environment will collapse in the crisis with increasing destructive effect of climate change. In order to cope with these threats, proceedings such as the creation of NGOs to increase social awareness about the dimensions of the crisis, reforming consumption pattern, adapting society to the climate change realities, and comprehensive and integrated planning for critical resource management are very necessary.

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Chapter 10
Enabling Technology for Water Smart Agriculture: A Test Bed for Water and Energy Efficiency for Developing Nations

Syed Muhammad Raza Kazmi

10.1 Introduction

Water constitutes the very heart of Food–Energy–Water (FEW) nexus as depicted in Fig. 10.1. This is paramount in significance for the developing nations like Pakistan where the water resource not only is the major fuel for energy but also the backbone for the primarily agrarian economy. Most of these countries are briskly falling from the water-stressed status to water scarce. This is not only because of climate change and water pollution but also due to the poor management and wastage of water—the most of which happens in the agricultural irrigation. Agriculture is not only the major consumer of country's water resource but also the major cause of water depletion due to inefficient irrigation. The irrigation efficiency is defined as the percentage of water in the field that is actually used by the crops. In Pakistan, unfortunately, this efficiency is reported to be as low as 40%, and hence it is indeed a major cause of water loss [1]. Therefore, agriculture irrigation is the area which direly needs immediate efficiency improvement to make an impact on water conservation.

10.1.1 Socioeconomic Impact of Water Crisis

Pakistan is among the highly water-stressed countries, the severity of which is growing every day. An article published by World Resource Institute (WRI) has rated Pakistan in the category of "extremely high stress" [2]. With the current

S. M. R. Kazmi (✉)
Head of Department of Electrical Engineering, University of Lahore, Islamabad, Pakistan
e-mail: raza.kazmi@ieee.org

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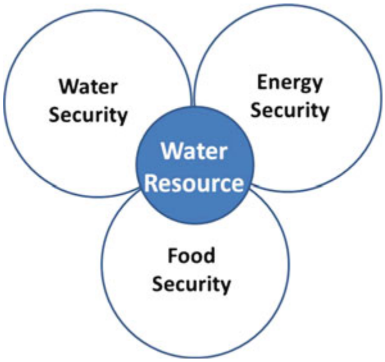

Fig. 10.1 Water in the heart of FEW Nexus

projections, it reports that the country will deteriorate to "water scarce" by 2040 if no immediate, large–scale, and sustainable action for water conservation is taken.

There is a direct and dreadful impact of water crisis on country's economy, energy, and the quality of life. The agriculture sector in particular is to suffer the most major hit which can adversely affect the energy and food security. According to a report published by Pakistan's Ministry of Finance, the agriculture sector is the largest employer in the country which absorbs 45% of the total labor force and has a mammoth contribution of over 21% to country's GDP [3]. Hence, the far-reaching impact of water crisis extends to food and job security, leading to quite a significant socioeconomic impact.

10.1.2 Review of Existing Solutions for Water Efficiency

The modern world has realized the importance of the stated problem early on and has developed several solutions for water smart irrigation. However, these solutions may not be feasible for the direct use in developing countries like Pakistan due to several factors such as cost, energy crisis, less educated farmers, and also nonexistent water tariffs which leads to lack of motivation for water conservation. Table 10.1 shows the list of the existing methods with their strengths and, more interestingly, their weakness in the context of their implementation in Pakistan. None of these is either readily available or accessible for the local farmers of Pakistan. This gap analysis provides a motivation for designing a low cost, easy to use, and low maintenance system to assist in scheduling the crop irrigation.

Table 10.1 Comparison of existing solutions

Companies	Countries of operation	Strengths	Weakness (particular to developing nations)
CropX	Israel, USA	Water-efficient irrigation, data-driven farming	Installation has to be done by farmer, no energy harvesting
PlantCare AG	Switzerland, India	Minimized pesticide, fertilizer, and water usage	Technical interface, extensive wiring, expensive
Agronom	Israel, China	Automatic drip irrigation with above benefits	Local maintenance, extensive wiring for PLC
The Climate Corporation	USA, acquired by Monsanto	Colored map to show moisture distributions for optimization	Interface has to be learned, Pro and Prime versions required to improve accuracy which are expensive
Crop Metrics	USA	Full virtual agronomist on tablet	Interface learning curve is high and aimed toward researchers
AquaSpy	Australia	Automated weather and sensor-based irrigation	Radio network used requires lot of energy
E4 Technologies	Pakistan	Yield and crop parameter analysis	No system installed yet to assesses
FarmersLab	Pakistan	Cloud and real-time monitoring	Stagnant progress
Sentek, Stevens Hydra Probe, UMS Germany, Decagon Devices	USA, Germany, UK	Accurate sensor line for moisture, salinity, etc.	Expensive, stand-alone sensors

10.2 The Enabling Technology

This section illustrates the components from modern technology that can contribute to form an integrated solution for water smart irrigation. The aim is to have low cost, low energy consumption, self-sustained, and flexible solution.

10.2.1 Real-Time Soil Moisture Measurement Methods

In order to automate and optimize the crop irrigation, the first requirement is of the condition monitoring of soil moisture. There can be two approaches here. One is to develop mathematical models which can evaluate the soil infiltration function of water during an irrigation event [4, 5]. With such mathematical formulation, the water propagation through soil can be estimated and a dynamic simulation model can be created for computer-based simulations. This can lead to the optimal decision-making for water actuation and cut-off timings as well as for dynamically adjusting the inflow rate to achieve better efficiency in the irrigation. This requires expertise in irrigation modeling, agriculture informatics, and nonlinear dynamic modeling. The other approach is to develop and deploy sensors which can measure, record, and transmit data in real time [6]. This chapter focuses on the latter approach and presents the core concepts behind the various moisture sensing techniques available in literature.

There are several techniques available for the measurement of soil moisture [7, 8]. An understanding of their working principles can provide the basis of judicious selection as per the design constraints. A rudimentary version of some of these sensors can be constructed with an inexpensive lab setup. The signal conditioning and interfacing circuit is beyond the scope of discussion here as lots of literature and application notes are easily available on that.

10.2.1.1 Principles of Soil Moisture Measurement Techniques

10.2.1.1.1 Soil Moisture Tension Method

Soil moisture tension is the measure of suction stress that a plant needs to experience in order to extract water from the soil it is situated in [9]. The measure of this tension is directly related to the availability of water to the plant. Hence, this method has become a benchmark in modern methods of irrigation [10]. A tensiometer construction usually comprises an airtight tube with a porous ceramic material at one end and a vacuum meter at the other [11]. The porous tip is buried in the soil and can suck the water in if the soil is moist and out if the soil dries. This changes the vacuum in the tube whose measure is captured by the vacuum gauge at the other end. So the reading by vacuum meter can give the measure of water tension. However, this method gives the measurement only as a visual display. In a control system, however, we need an electrical transducer, which can be made through the methods described below.

10.2.1.1.2 Resistive Method

Soil resistance changes with the water content. This principle can be employed to construct a very simple soil resistance meter that can be calibrated against a benchmark tensiometer [12, 13]. One way to construct this resistive transducer is similar to tensiometer, using a porous material with embedded electrodes. Gypsum is the most suitable candidate as the porous material not only because it is quite inexpensive but also because it can mask the effect of salinity in the soil which can otherwise bias the reading. The porous gypsum allows water to permeate in and out when the soil wets and dries. It consequently changes the electrical resistance which can easily be monitored by passing current through the electrodes.

10.2.1.1.3 Capacitive Method

Employing the underlying principle that the dielectric constant of soil is a function of its water content, the soil moisture can fairly be determined by measuring the fringing fields of capacitive probes with soil as dielectric [14, 15]. It is reported in literature that the dry soil exhibits a dielectric of 4 and pure water a dielectric of 80; therefore, calibrating dielectric against moisture gives a useful metric for soil moisture measurement.

10.2.1.1.4 Time-Domain Reflectometry (TDR)

It uses the concept that an electromagnetic wave travels faster in dry soil than in wet soil. So measuring the propagation time delay of the reflected wave gives a measure of the soil's dielectric constant, which in turns determines the moisture content [16, 17].

10.2.1.1.5 Frequency-Domain Reflectometry (FDR)

The concept behind FDR is that since the moisture changes the dielectric constant of the soil leading to change in capacitance, so it means that the resonant frequency of the soil changes with moisture [17, 18]. Resonant frequency is the one at which the maximum current is drawn for a given voltage. So by calibrating the resonant frequency of soil against moisture and then measuring the frequency at which the current value peaks, the moisture can be determined as per the calibration.

10.2.1.1.6 Neutron Scattering Method

This is the most accurate method which uses a radioactive isotope to emit high energy neutrons into the soil [19]. These fast-moving neutrons slow down as they collide with the hydrogen nuclei in the soil water molecules. These slow neutrons diffuse back into the probe generating an electrical impulse which can be counted. The more the water content, the more will be the count.

10.2.1.2 The Low-Cost Solution

The methods above are listed in the ascending order of accuracy and cost. So for a low-budget project, the resistance block or capacitance probe can be the most viable solutions. For instance, Fig. 10.2a shows an inexpensive sensor based on resistive principle, whereas Fig. 10.2b shows a very simple capacitive probe fabricated in lab.

Fig. 10.2 (**a**) Resistive moisture sensor. (**b**) Lab-made capacitive probe

Fig. 10.3 Sensor calibration

The method for measurement through the resistive sensor of Fig. 10.2a is the same as described in the subsection above, though it does not require gypsum block [12, 13]. Another advantage is that it can be directly interfaced with a microcontroller. However, it has very low life as the electrodes erode due to the soil salinity.

The measurement method for the capacitive probe of Fig. 10.2b requires a setup to determine the *RC* time constant with respect to a constant resistance *R* placed in series with the probe whose capacitance *C* can therefore be calculated.

Calibration of these probes against the soil moisture can be done by placing those side by side with a direct measurement sensor such as a tensiometer, shown in Fig. 10.3. Readings are taken at steady state while adding water to the soil.

10.2.2 Energy-Efficient Communication for Wireless Sensor Network (WSN)

A two-dimensional mesh of soil moisture sensor probes is required in order to cover a crop field. The sensor nodes must be wireless so that they do not hinder the farming activities. The cost constraint demands that the number of sensor nodes needs to be kept as less as possible. The communication system plays a very important role in this regard. The effective range at which the wireless communication system can transmit the data between two nodes and the energy consumption during the send/receive operation are the critical parameters. Ref. [20, 21] provide good reviews of various WSN systems.

There are lots of communication standards and technologies available for deploying a low-powered radio network depending on range, data rate, and power requirements. A quick reference is tabulated in Fig. 10.4.

In order to develop a wireless system, it is necessary to abide by the frequency band constraint imposed by the regulatory authority on a country. Pakistan lies in Region 3 in Industrial Scientific and Medical (ISM) radio band allocation where only 433–434 MHz, 2.45 GHz, and 24 GHz bands are open for private network deployment [22].

There is considerable amount of research available in protocols for Low Power Networks (LPN) which can be employed to further reduce the power consumption of the wireless sensor nodes. An overview of some of these protocols is given below to encourage the reader for further research and development.

- TEEN (Threshold-Sensitive Energy-Efficient Sensor Network protocol) is for saving transmission energy and reducing packet size if a variable did not cross a certain threshold [23].
- PW-MAC (Predictive Wakeup MAC) is for pseudo-random seeding and random number generation to transmit packet with least collision probability [24].
- PEDAMACS (Power-Efficient and Delay-Aware Medium Access Control Protocol) is for intelligent transmission power throttling [25].
- LEACH (Low-Energy Adaptive Clustering Hierarchy) uses TDMA-based MAC policy. It forms clusters and chooses heads randomly. Heads are responsible to transmit data of the whole cluster in TDMA fashion [26].

Fig. 10.4 Wireless communication technologies and their respective frequency bands

10.2.2.1 The Low Cost and Low Energy Solution

Usually, a wireless communication system is meant for high data rate with little or no regard to the power consumption. A system with higher data rate would consequently consume more power. For the subject application, the lower power consumption and longer range are the preferred attributes over high bandwidth because the application does not require a high data rate due to intermittency of measurements. LoRa, shown in Fig. 10.4, is therefore a good candidate that offers long range at low data rate. The range of the module can be tested for line-of-sight communication between the points marked on the Google Map from where the distance can easily be calculated. For instance, Fig. 10.5 shows the transceiver points at the ends of the solid line. The range measured via the digital map is 780 m.

In Pakistan, "acre" is used as the units to represent the area of an agricultural field which is equivalent to about 4050 m^2. This implies that one such WSN can cover a field of more than 400 acres. However, another important constraint here is the resolution of data at each point in time. One WSN corresponds to a single data point, which in practice is too coarse to make an optimal control decision for the whole field. Therefore, in practice, multiple nodes per acre are employed which are strategically placed through the visual inspection and investigation of field terrain. In addition, two sets of nodes can be placed at two different depths in order to get even better resolution of water propagation through soil.

Fig. 10.5 LoRa range measurement

10.2.3 Energy Harvesting for Stand-Alone Sensor Nodes and Gateway

Since the WSNs need to be stand-alone and self-sustained, therefore, a low maintenance energy source is essential to power up the sensing and communication circuitry. This rules out the conventional batteries alone as those are not feasible option due to their limited life and need of maintenance. There are several long-life batteries available which are known as maintenance-free batteries [27]; however, those have high cost effect. Therefore, in order to power up the WSNs cheaply and indefinitely, the energy harvesting techniques are employed [28]. Energy harvesting refers to the scavenging of energy from the in situ environment where the WSN is placed. Popular methods to harvest energy from the environment involve solar cells that can convert photons into electricity through photoelectric effect [29, 30], Peltier cells that generate electricity due to temperature difference on either sides of the cell through thermoelectric effect [31], ambient radio frequency (RF) energy harvesting using rectenna [32], and piezoelectric crystals that harness mechanical energy from vibrations and generate electrical energy [33]. Among these, for the outdoor usage and power consumption of more than 1 W, solar cell is a preferred choice.

Gateways have a significant power budget due to GSM module and higher processing power. This opens up avenue for research in multiplexing multiple power paths from rechargeable and primary batteries for backup and supercapacitors to support impulsive loads especially during RF transmissions [34].

Recently, there has been a thrust among the various manufacturers to develop such application-specific technologies [35]. For instance, Texas Instruments has introduced autonomous power multiplexor and ultralow energy harvester Power Management Integrated Circuits (PMICs) especially for WSNs with moderate energy budgets. Linear technology and analog devices have also introduced highly efficient nano-power management DC/DC converters especially targeted toward WSNs. Cost of supercapacitors per watt-second has also decreased with board mountable capacitors from Vishay Intertechnology, Maxwell Technologies, and Murata Manufacturing.

10.2.4 Integrating Weather Information

Another dimension to this framework is the use of available weather information since weather can have great influence on irrigation pattern. Knowing the incoming weather beforehand at the site of interest can greatly help in optimizing the scheduling of crop irrigation. For instance, if it is recorded that a rain system is traveling from remote to nearby destination, then the irrigation can be seized to wait for the rain. This scenario is very practical and frequent in some seasons in Pakistan, where overflow of water due to uncontrolled irrigation followed by the rain can cause flooding and severe destruction of crops. This has been witnessed by the team of researchers associated with the author who visited and surveyed an agriculture site in the city of Sargodha.

There are three ways to fetch the weather data input. One is by incorporating the weather forecast available for free through various mobile applications or online websites. Second is to tap into the already existing weather stations owned by the country's meteorological department, and third is through the purchase and deployment of a low price device such as AcuRite. The raw data through sensors would require some level of data science to automatically extract the incoming weather patterns of interest. Here lies the application of artificial intelligence and machine learning. The information about rain or draught can be sent as a text message to the mobile phones of the farmers so that they can make preemptive measures to save water.

10.2.5 Internet of Things (IoT) and Cloud Computing

IoT and cloud computing are the zeitgeist of enabling technology for many applications that require the storage and processing of big data. In literature, there are many standards of layered and hierarchical structures for Internet of things. Most notable however are:

- IEEE Standard for an Architectural Framework for the Internet of Things, working group (IEEE P2413). It defines a three-tiered architecture for IoT—sensing as tier 1, network and data communication as tier 2, and application as tier 3.
- Cisco Internet of Things Architecture offers a more comprehensive seven-tier architecture. This is more suitable against the IEEE architecture which has lots of hidden processes. Cisco IoT architecture is shown in Fig. 10.6.

In the subject application, the WSNs are the *thing* in the IoT, constituting tier 1. Tier 2 connectivity is achieved using low-powered radio network. Gateway serves as tier 3 device. Tier 4 to 7 are implemented in cloud which deals with data storage, processing, and visualization.

3G in Pakistan does not cover all rural areas where farms are situated but EDGE and 2G connectivity have been observed in rural areas. MQTT and HTTP 1.1 protocols are suitable for gateway to cloud communication as they provide low throughput but at lower power. Amazon Web Services (AWS) also support these protocols through its software development kit for Internet of things. AWS can also serve as data accumulation platform and to apply various tools to sift through data. Data can be displayed on ThingSpeak cloud as it provides APIs to quickly setup display as if in MATLAB environment. Sierra Wireless HL modules support low energy modes and provides embedded solution for gateway to cloud communication. However, Adafruit FONA is suitable to quickly set up for 3G connectivity as other modules require extensive PCB development.

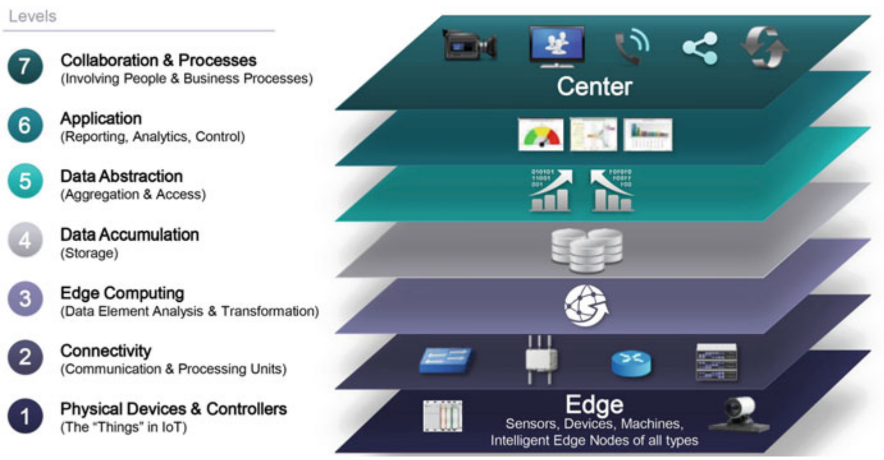

Fig. 10.6 CISCO IoT architecture (source: IoT World Forum)

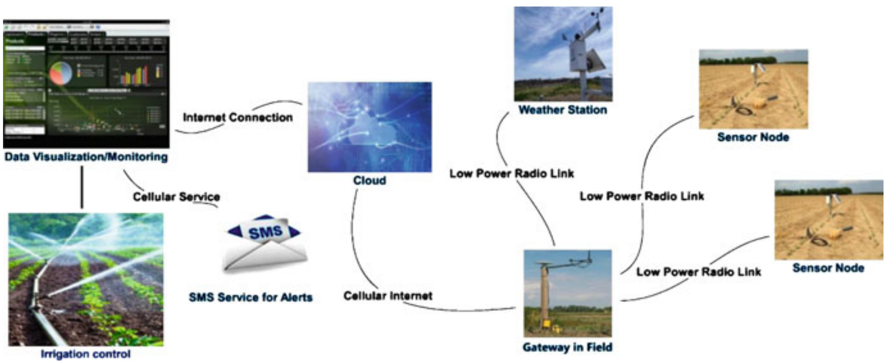

Fig. 10.7 The proposed framework for water smart irrigation system

10.3 The Proposed Framework

With the thorough explanation of each of the constituent modules in the previous section, an integrated framework is proposed in Fig. 10.7. The gateway collects the data from the field sensor nodes and the nearby weather station. The data are pushed into the cloud for storage and processing. The data can be visualized on a local computer through web link, and decisions about the irrigation actuation and text alerts can be made.

A simple high abstraction level algorithm to control the actuation of water smart irrigation is proposed in Fig. 10.8. It starts by setting appropriate thresholds for the moisture readings from the sensor nodes and also for the likelihood of rain from the weather stations. These thresholds set the limits to actuate the irrigation. These limits are non-generic in nature and have to be tuned for a particular site. However, a

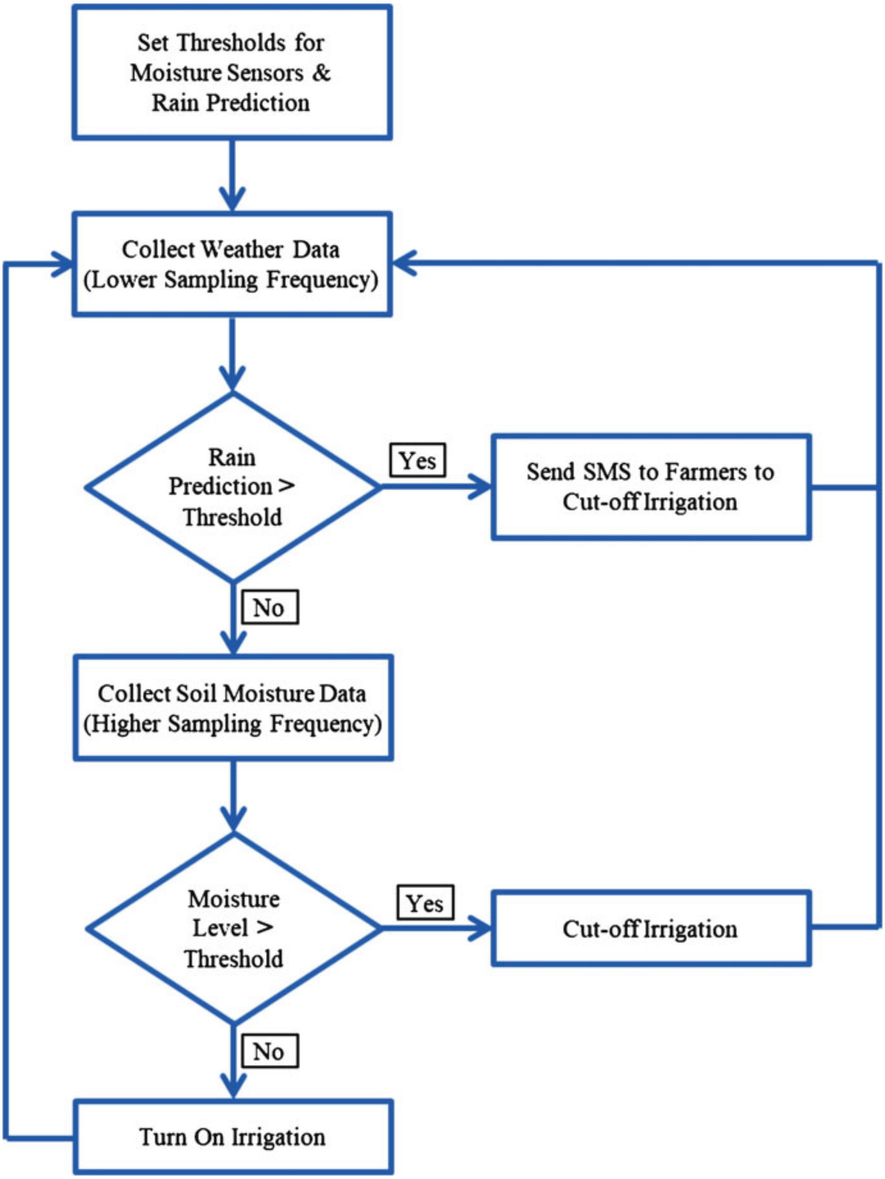

Fig. 10.8 Flowchart of the proposed control algorithm

general guideline to determine the appropriate thresholds would partially involve hit and trial in addition to more educated decision through visual inspection of terrain and slope of the field, average weather conditions, experimentation, and fine-tuning. Weather data are then fetched from the nearby weather stations. If the data analysis predicts a fair chance of rain sometime soon, then a mobile SMS message is sent to all the registered farmers to suggest them for curtailing irrigation and wait for the rain. Otherwise, data from on-field WSNs are fetched and irrigation is actuated according to the threshold settings of the WSNs. Since the weather change is a slow event, therefore the sampling rate of weather stations can be kept lower than the sampling rate of the WSNs installed in the field. This can save the bandwidth and processing time.

Figure 10.8 can also have an update loop to improve upon the threshold settings by analyzing the outcomes such as crop condition and savings in water plus energy once the system is up and running.

10.4 Conclusion

This chapter has laid down a comprehensive framework for achieving water smart irrigation through the integration of various technologies. It is a system of systems in which each module is an area of research of its own, as evident from the given references. This chapter has contributed a concise account of these enabling technologies, their working principles, as well as the framework to integrate them as one system to achieve high irrigation efficiency.

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Chapter 11
Dealing with Trade-offs in Sustainable Energy Planning: Insight for Indonesia

Maral Mahlooji, Firra Ghassani Gumilar, and Kaveh Madani

11.1 Introduction

The energy industry is accountable for two-third of the total anthropogenic greenhouse gas (GHG) emissions [1]. Consequently, without immediate action, climate change impacts will aggravate rapidly. This has led to an international movement toward increased share of renewable contribution, an effort to decarbonize portfolios and lower total emissions [1].

Indonesia is of particular interest for this study as the country was among the top global CO_2 emitters in 2010 and 2012, ranked globally at 10th and 11th, respectively [2]. In parallel, the country has demonstrated the will to contribute to the global movement regarding climate change mitigations. It was among the first nations to ratify the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 [3] and has since participated in the global movement of climate change mitigations, by continuously submitting and updating its commitments. Indonesia has ratified the Paris agreement [4] and has made an international pledge to cut its carbon emission unconditionally by 26% and by 41% given the provision of international support (conditionally) by the year 2020 [5].

The National Energy Policy of Indonesia focuses on energy independence and energy security. Emphasis is placed on the utilization of domestic resources in a sustainable manner to secure long-term supply and access for the nation at an

M. Mahlooji (✉) · F. G. Gumilar
Centre for Environmental Policy, Imperial College London, London, UK
e-mail: maral.mahlooji12@ic.ac.uk

K. Madani
The Macmillan Center for International and Area Studies, Yale University, New Haven, CT, USA

Department of Physical Geography, Stockholm University, Stockholm, Sweden
e-mail: kaveh.madani@yale.edu

S. Asadi, B. Mohammadi-Ivatloo (eds.), *Food-Energy-Water Nexus Resilience and Sustainable Development*, https://doi.org/10.1007/978-3-030-40052-1_11

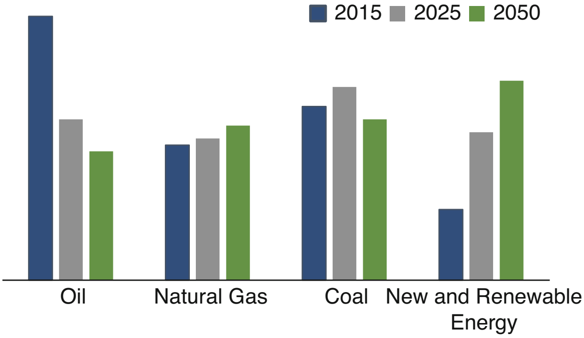

Fig. 11.1 Indonesia's energy goals according to the National Energy Planning. (The energy mix of 2015 has been reproduced from [7], and the 2025 and 2050 energy targets have been reproduced from [6])

affordable price, without aggravating environmental harm. The power sector has three major objectives in its national plan: (1) to obtain an installed capacity of 115 GW and 430 GW by 2025 and 2050, respectively, in its power generation; (2) to accomplish electricity use of 2.5 MWh per capita by 2025 and 7 MWh by 2050; and (3) to obtain an electrification of almost 100% by 2020 [6].

To satisfy the aforementioned goals, Indonesia delegated an energy mix target portrayed in Fig. 11.1. In 2015, renewables contributed to a total share of 11% in Indonesia, with 7% contribution from biofuels, 3% from hydropower, and 2% from geothermal. The renewable share is projected to increase to at least 23% by 2025 and 31% by 2050 [7], where the majority of this share is projected to come from geothermal and hydropower [8]. On the other hand, the dominant role of fossil fuels in the future portfolio of the region is apparent as coal's contribution is projected to increase to 30% by 2025 and reduce slightly by 2050 to 25%. Contribution from oil and natural gas will remain more or less the same. The heavy reliance on fossil fuels is due to abundant availability of resources and the consequent cheaper associated costs. According to Sugiyono et al. [9], Indonesia benefits from sufficient oil and coal reserves for an estimated period of 70 and 12 years, respectively. In addition, these alternatives, specifically coal-fired power plants, are readily available and can provide cheap electricity [10, 11].

Indonesia's electrification rate is lower than that of its neighboring countries. The average electrification rate in 2016 was 91.16%. However, this rate can plunge down to 47.78% in West Papua and rise up to 99.97% in Bangka Belitung [12]. This portrays the existing disparity between the east and the west of the nation. The nation is recognized as the fourth most populated nation in the world with over 255.5 million individuals residing in a 7.8 million km^2 area. Thus, it has witnessed rapid growth in its electricity demand [13, 14]. The archipelago nature of the country creates a challenge for electricity and power coverage.

East Java and West Java, along with South Sumatra and West Sumatra, are recognized as economically productive zones and are acknowledged to be among the most vulnerable regions of Southeast Asia to climate change impacts, including floods, landslides, droughts, and rising sea levels [15]. In addition, Jakarta is geographically placed at a juncture point of climate-related threats, highly unprotected and vulnerable to regular flooding because of its highly dense population.

Consequently, climate change and natural degradation is projected to reduce the predicted 7% GDP growth per year to around 2–3.5% by 2050 [16]. Coastal GDP can also be impacted by 39% [17]. Thus, climate change is deemed as a serious threat to Indonesia and is in immediate need of attention.

Indonesia is not actually recognized as a water-scarce nation; however, its water resources are not free of challenges. Though 6% of the global water reserves (26% of Asia Pacific) are found in Indonesia [18], the unequal distribution of water across the country is the main problem. Java Island is home to 60% of the total population of the country, but yet it possesses less than 10% of the nation's water reserves [19]. In parallel, only 13% of the population reside in Kalimantan and Papua, yet it holds 70% of the nation's water reserves [18]. This has led to poor water access and sanitation, where in 2013 only 68% and 60% of the population had access to clean water and sanitation, respectively [20]. In addition, the energy sector claims 2825 million cubic meters of the total water used annually, with hydropower being responsible for close to 40% of this share, and biodiesel and solar energies responsible for another 23% [19].

Indonesia's target to increase its biofuel production, through the allocation of 100,000 ha of forests to be used for production across Kalimantan, Sumatra, and Papua, poses a serious threat to land conservation and biodiversity [21]. The 312 potential sites of geothermal resources in the country present an 18% overlap with conservation forests, and another 31% are located within protected forests [22]. In the past, geothermal assessments were prohibited in conservation forests, a law that is now invalid. The country has witnessed distressing rate of productive land conversion as well as large deforestation. From 2008 to 2010, only in 2 years, the country lost 200,000 hectares of its exceedingly productive wetlands. Fifty percent of these lands are now acknowledged as critical land [23]. In just over a decade from 2000 to 2012, 16 million hectares of forest area was lost [24]. The drive to expand areas used for food production and biofuel feedstocks have led to rapid plummet of Indonesia's low rain forest land. This, in turn, leads to imbalance of natural ecology and substantial greenhouse gas emissions as a result of excessive logging, blazing, and draining peatlands which are carbon-intensive [25].

This study highlights the need to promote sustainable electricity options for Indonesia through a nexus approach that determines the desirability of different energy options across the country with respect to local availability conditions. The study reviews desirability of alternatives at both national and subnational levels to highlight the impact local resource limitations can have on the sustainability of alternatives.

11.2 Method

This chapter determines the Relative Aggregated Footprint (RAF) of ten energy alternatives in Indonesia. Developed by Hadian and Madani [26] and Ristic et al. [27], RAF is an index with a value between 0 and 100, reflecting the overall impact (footprint) of an alternative on various through consideration of uncertainty, trade-offs, and local resource availability conditions. The higher the value of this index, the higher its aggregate impact and conversely the lower its desirability. An RAF score of 0 demonstrated an ultimate best (desirable) alternative, while a score of 100 demonstrated the ultimate worse (undesirable) energy alternative.

The National Energy Planning and the National Sustainable Development Planning's promoted energy–environment–economy nexus approach [6, 28] was applied here and as proposed by Hadian and Madani [26], four sustainability indicators, namely, water footprint, carbon footprint, land footprint, and cost, are utilized. An extensive literature review was conducted to collect the life-cycle performance values of the ten energy alternatives under these sustainability criteria, illustrated in Table 11.1. Ideally, only the data that are specific to Indonesia should be used to create a more realistic context; however, where data availability was limited or withheld from the public, global data were used. Some performance values are presented in a range, which portrays the uncertainty across performance due to technological, geographical, and other variations across countries.

The RAF index value is determined using a Monte Carlo multi-criteria decision-making (MC-MCDM) framework [26, 36–38]. MC-MCDM used five MCDM techniques, namely, minimax [39], lexicographic [40], Simple Additive Weighting (SAW) [41], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [42], and dominance [43]. This, in turn, lowers the bias of results to specific optimality notions [26, 44]. The uncertainty introduced by the performance value ranges is addressed through Mote Carlo selections. In every 500,000 iterations, random performance values are selected from the given range and ranks are determined. Following Ristic et al. [27] and Mahlooji et al. [45], in this study, a truncated normal (if median is close to the mean) or lognormal probability (when significant difference is seen between mean and median) distribution is used. Once energy alternatives are ranked across each MCDM, the aggregated performance value, otherwise denoted as Relative Aggregated Footprint (RAF), is determined using the following equation [26]:

$$\mathrm{RAF}_i = 100\left[1 - \left(\frac{CN - B_i}{N(C-1)}\right)\right] \tag{11.1}$$

where C illustrates the quantity of technologies, N is the number of optimality notions, and B_i is the sum of individual ranks given to technology i by each MCDM approach.

The desirability of energy alternatives is determined by the availability and limitations of resources within a country. For example, in a small geographical country with high population, land-intensive technologies have lower desirability. Thus, to perform RAF calculations that are specific to Indonesia and its individual islands, the impact indicators were weighted using their subsequent position in a global benchmark ranking of resource condition as done based on the approach proposed by Ristic et al. [27]. These resource conditions are reflected by

Table 11.1 Life-cycle performance value of energy alternatives

Energy alternative	Carbon footprint (gCO_2eq/kWh)			Water footprint (m^3/GJ)			Land footprint (m^2/GWh)			Cost (USD_{2010}/MWh)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Coal	740.0[a]	820[a]	910[a]	0.0790[c]		2.1000[c]	0.24[e]	0.64[e]	1.51[e]	30[a]	78.00[a]	120.00[a]
Oil	657.0[b]	–	866[b]	0.2140[c]	–	1.1900[c]	2.86[e]	–	2.860[e]	266.00[f]	–	665.00[f]
Natural gas	410.0[a]	490	650[a]	0.0760[c]	–	1.2400[c]	2.86[e]	–	2.860[e]	34.00[a]	79.00[a]	150.00[a]
Geothermal	6.0[a]	38[a]	79[a]	0.0070[c]	–	0.7590[c]	2.14[e]	5.14[e]	10.960[e]	41.18[g]	74.51[g]	164.71[g]
Hydropower	1.0[a]	24[a]	2200[a]	0.3000[c]	–	850.0000[c]	6.45[e]	16.86[e]	86.950[e]	23.53[g]	74.51[g]	280.39[g]
Bioenergy	130.0[a]	230[a]	420[a]	46.0000[d]	–	396.0000[d]	557.93[e]	809.74[e]	1254.028[e]	58.82[g]	141.18[g]	392.16[g]
Solar photovoltaic	18.0[a]	48[a]	180[a]	0.0060[c]	–	0.3030[c]	12.30[e]	15.01[e]	16.97[e]	127.45[g]	200.00[g]	427.45[g]
Wind (Onshore)	7.0[a]	11[a]	56[a]	0.0002	–	0.0012[c]	126.92[e]	–	126.920[e]	53.00[g]	92.16[g]	209.80[g]
Wind (Offshore)	8.0[a]	12[a]	35[a]	0.0002[c]	–	0.0012[c]	126.92[e]	–	126.920[e]	110.00[a]	170.00[a]	250.00[a]
Nuclear	3.7[a]	12[a]	110[a]	0.0180[c]	–	1.4500[c]	0.02[e]	0.13[e]	0.240[e]	45.00[a]	99.00[a]	150.00[a]

[a] S. Schlömer et al. [29]– global data
[b] World Energy Council [30]– global data
[c] Mekonnen et al. [31]– global data
[d] Gerbens-Leenes et al. [32]– global data
[e] Trainor and Mcdonald [33]– USA data
[f] Blum et al. [34]– Indonesia data
[g] IRENA [35]– Indonesia data

Indonesia's emission per capita [2], land availability per capita [46, 47], freshwater withdrawal (as a percentage of renewable water resources) [48], and economic power (presented as GDP PPP per capita) [49]. Similarly, weights are determined for the island-specific analysis using the data on resource limitations and availability of Indonesia's seven major islands; these include Java, Papua, Kalimantan, Sumatera Sulawesi, Bali and Nusa Tenggara, and Maluku. The same indices were used: carbon emission [50], freshwater withdrawal [51], available land area [52], and economic power [53].

11.3 Results

11.3.1 Country-Specific Weighting of Energy Alternatives

Figure 11.2 reflects Indonesia's relative resource availability/limitation and positions on the global ranking are presented. Due to its high population density, Indonesia's biggest relative limitation at the national level is its available land per capita, which has been assigned the highest weight (0.31). Water availability, economic capacity, and carbon emissions all follow with the same assigned weight (0.23), reflecting equal importance of these three resources following land availability. Based on the calculated weights, land-intensive energy technologies are not generally desirable for Indonesia.

Figure 11.3 shows the RAF scores of energy alternatives, based on the national resource availability conditions of Indonesia (Fig. 11.2) and life-cycle performance value of energy alternatives (Table 11.1). According to this figure, there are no strictly dominant energy alternatives, i.e., alternatives with RAF = 0 that were ranked first for Indonesia across the range MCDM approaches, respectively. There is general desirability for low-carbon-emitting technologies. However, when the energy–economy–environment nexus is considered, hydropower and bioenergy

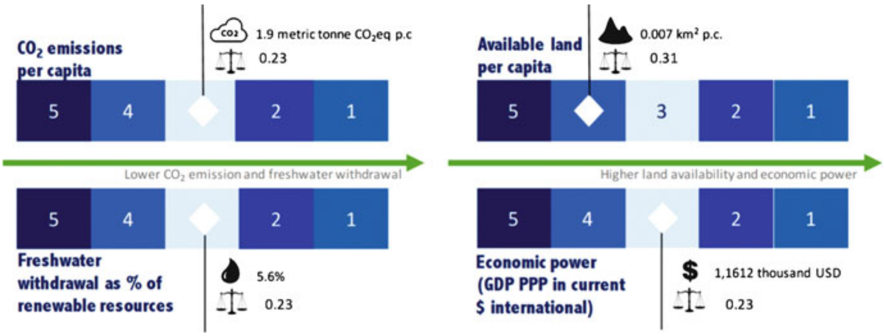

Fig. 11.2 Indonesia's country-specific weighting of the impact indicators

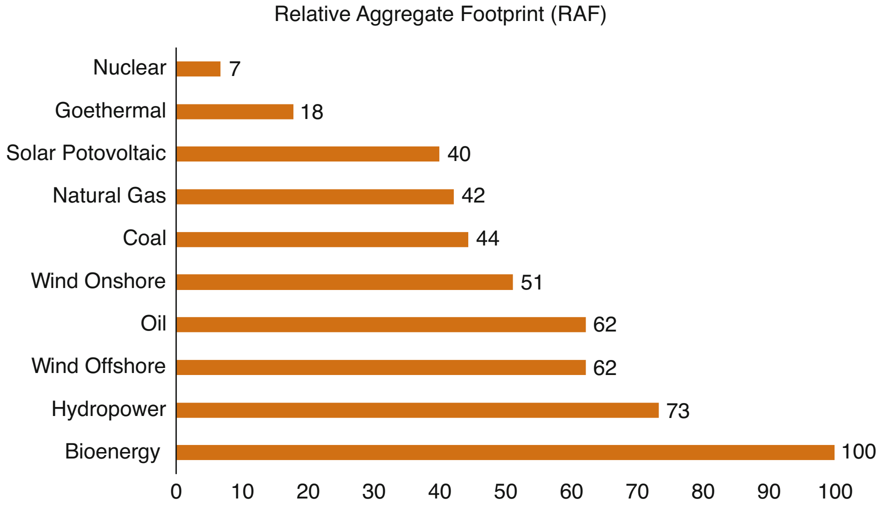

Fig. 11.3 Relative Aggregated Footprint (RAF) values of Indonesia's energy alternatives using country-specific weights

are among the most undesirable alternatives, with bioenergy being the strictly dominated energy alternative (ranked as the worst option under all MCDM method) with a score of RAF of 100. While hydropower benefits from lower economic costs, it portrays the highest water footprint across the technologies considered. This energy also suffers from the relatively high land (ecologic) footprint. Bioenergy is the least desirable alternative due to poor performances across all four indicators. Even if it has a lower carbon emission than fossil fuels, its enormous land and water footprint make this energy undesirable in regions with limited land and water availability. Thus, relying on decarbonization as the sole objective can lead to selection of alternatives such as hydropower and bioenergy which place additional burden on other valuable resources.

With the lowest carbon emission among fossil fuels, natural gas shows medium desirability. This energy option outperforms wind, hydropower, and bioenergy in Indonesia. This suggests that this energy alternative might be used in transition toward higher share of renewables, instead of investing in popular resource-intensive renewables such as hydropower and bioenergy.

Onshore wind is outperformed by natural gas and coal, mainly due to its significant land footprint. However, it has higher desirability in comparison to that of offshore wind due to lower capital cost [29]. Offshore wind tends to be more expensive due to lower exploitation rates and higher associated cost of installation and maintenance. Nuclear and geothermal present the best energy alternatives due to lower land use and emissions. Solar Photovoltaic (PV) is also among the desirable alternatives, while its higher associated cost has led to its slightly lower RAF in comparison to nuclear and geothermal.

11.3.2 Island-Specific Desirability Energy Alternatives

The uneven distribution of resources across Indonesia further analyzes at the subnational scale. Thus, resource conditions of islands are considered individually to assign weights to the performance indicators to perform the analysis at the island's level. Figure 11.4 illustrates the calculated weight assigned to each criterion for the seven main islands of Indonesia.

The variances across the weights highlight the heterogeneity of resource distribution within Indonesia. An optimal alternative in one island might be suboptimal in another due to different resource availability conditions in each island. This highlights the need for consideration of local resource conditions in energy planning for the country. For example, with a high rate of CO_2 emission per capita, Papua has the highest resource availability weight assigned to CO_3 across the islands. This reflects the island's need to steer away from carbon-intensive energy options, while it might be able to afford to implement some water-intensive alternatives due to the lower weight of water resources in this island as a result of a lower rate of water use. On the other hand, Java has the lowest carbon emission rates in the country, which means a smaller weight is assigned to carbon. Thus, Java might be able to some nonrenewable resources to alleviate pressure on its most burdened resources which are water and land.

Sections 11.3.2.1, 11.3.2.2, 11.3.2.3, 11.3.2.4, 11.3.2.5, 11.3.2.6, and 11.3.2.7 illustrate the RAF/desirability of energy alternatives across the seven major islands of Indonesia. The desirability of an energy alternative is the opposite of RAF, i.e., the greater the RAF, the lower the desirability of an alternative. The desirability of an alternative increases from maximum RAF (red in the following figures) to minimum RAF (blue in the following figures).

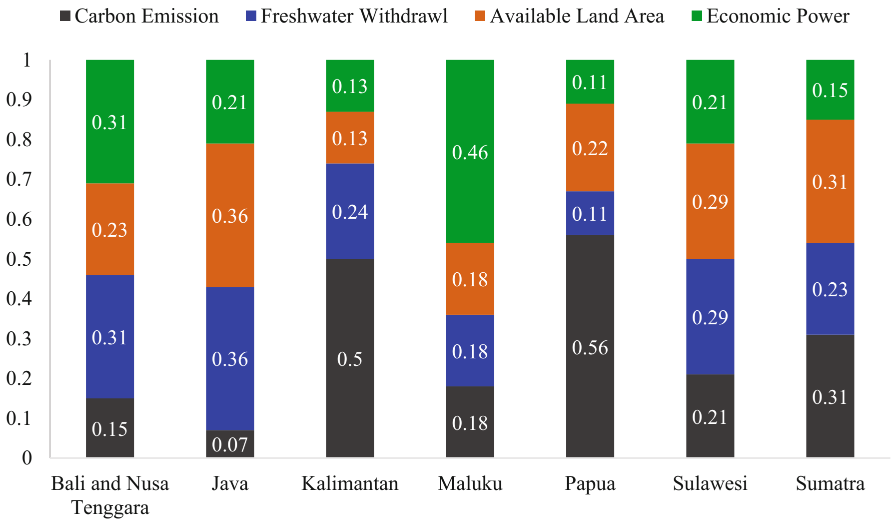

Fig. 11.4 Island-specific weightings of the impact indicators

Fig. 11.5 Nuclear's RAF across Indonesia. The figure also shows the location of preferred sites for the implementation of this energy (based on the data from BATAN [53])

11.3.2.1 Nuclear

Figure 11.5 indicates the island-specific desirability of nuclear energy. Nuclear reflects high desirability across the seven islands, with a RAF score of 2 across Kalimantan, Papua, and Sumatra, and a score of 7 for Java and Sulawesi. Its desirability decreases slightly in Bali and Nusa Tenggara (RAF = 27) and Maluku (RAF = 29). This is due to the technology's higher associated cost combined with the low economic capacity of these islands.

The government of Indonesia has identified eight potential sites for the implementation of nuclear energy. Given the domestic availability of uranium [55], nuclear can be a highly desirable option to support the increase in electrification rate and energy security of the country. So far, the nuclear projects in the Muria Peninsula with the capacity of 7 GW [56] and in Bangka with the capacity of 10 GWe [57] have not received the required support for implementation. A major obstacle to energy production from nuclear is the associated safety concerns of the public regarding operation safety, security, and supervision of radioactive waste [58]. The 2011 accident in Fukushima, combined with the high vulnerability of the country to earthquakes, has created sociopolitical oppositions to nuclear energy. The associated safety measures would also add to the cost of this alternative, which in turn can decrease its desirability. These important factors must be carefully investigated before increasing the share of this source across the country.

11.3.2.2 Geothermal

Geothermal is generally highly desirable across Indonesia with an RAF value of 18 at the national level (Fig. 11.3). At the island level, geothermal's RAF varies from 4 in Bali and Nusa Tenggara and Maluku to 22 in Kalimantan and Papua (Fig. 11.6). In islands such as Maluku and Bali and Nusa Tenggara with the lowest GDP per capita, geothermal's high desirability is directly related to its low associated costs.

Fig. 11.6 Geothermal's RAF across Indonesia

The carbon footprint has a high weight in Kalimantan and Papua. Thus, the relative desirability of geothermal in comparison to other renewables such as solar and wind decreases in these islands.

Table 11.2. demonstrates the distribution and capacity of this type of energy across Indonesia. Nevertheless, the geothermal sites identified by the country are frequently located in the borderlines of conservation areas or confined forestry zones, and implementing geothermal in these sites can result in deforestation [22].

According to Indonesia's national energy plans, an ambitious target has been set for geothermal to expand its installed capacity to 4.85 GW in the near future [8]. Over half of the targeted capacity is planned to be installed at Sumatra and 40% of it in Java. The results of this study (RAF of 16 and 20 in Sumatra and Java, respectively) justify these installations. Geothermal also has a low RAF [4] and a generation potential of 1.6 GW. Nevertheless, its current capacity stands at 12.5 MW and is projected to only increase to 105 MW. Maluku with the same low RAF value and potential of 1.45 GW does not have any power plants installed and no plans to exploit geothermal in the future. This could be the result of an imbalance between potential and proven reserves which call for further investigation. Additionally, geothermal expansion is often restricted by financing, conflict among central and local government bodies, and lack of interest in investment in this option which is generally perceived as a high-risk energy option [59]. Yet, Indonesia has set a target to become the number one nation with the highest installed capacity of geothermal [60] in the world. To achieve this target, several policies have been formed in support of geothermal power plants.

11.3.2.3 Solar Photovoltaic

At the national level, solar PV has medium desirability with a RAF score of 40 (Fig. 11.3). The desirability of this alternative across the islands is presented in Fig. 11.7a. The highest desirability of PV is seen in Sulawesi (RAF = 38), Papua (RAF = 42), Sumatra (RAF = 42), Java (RAF = 44), and Kalimantan (RAF = 44). The lowest desirability of PV is seen in Bali and Nusa Tenggara (RAF = 56) and Maluku (RAF = 65).

Table 11.2 Installed capacity and potential for geothermal in Indonesia

Island	No. of location	Potential					Total (MWe)	Installed capacity (MWe)
		Resource		Reserve				
		Speculative	Hypothetic	Presumed	Possible	Proven		
Bali	6	70	22	262	–	–	354	0
Java	73	1560	1739	4023	658	1815	9795	1224
Kalimantan	14	152.5	30	–	–	–	182.5	0
Maluku	33	560	91	800	–	–	1451	0
Nusa Tenggara	27	225	409	917	–	15	1566	12.5
Papua	3	75	–	–	–	–	75	0
Sulawesi	77	1221	318	1441		120	3208	120
Sumatera	97	3191	2334	6992	15	380	12,912	287
Total	330	7054.5	4943	14,435	781	2330	29,543.5	1643.5

Reproduced from [55]

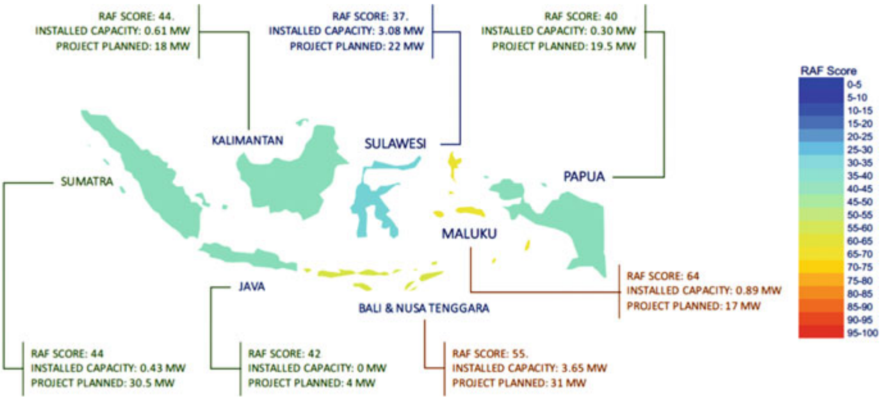

Fig. 11.7 Solar PV's RAF across Indonesia. (Installed capacity and additional capacity data are from PLN [61] and ESDM [22], respectively)

The high associated cost of solar PV and its moderate land and water footprint lowers its desirability in the islands with lower economic resources and limited water and land availability such as Maluku and Bali and Nusa Tenggara (RAF = 11.5). Solar PV is outperformed by other renewables in these islands when the aggregate footprints of these energies are considered. However, the exposure of these areas to persistently high solar irradiance is the main motivation behind developments [62, 63] of solar (on-grid, 3.65 MW) in comparison to other regions (Fig. 11.7).

At the end of 2015, Kupang of East Nusa Tenggara commissioned the largest on-grid solar power plant of Indonesia, with the total capacity of 5 MW [64]. The biggest installed capacity of solar PV at 2 MW is available in Sulawesi [65], with the highest desirability for solar PV among all islands based on the results (Fig. 11.7). It is noteworthy that several PV development projects are implemented with the objective of advancing the electrification rate of remote and rural villages of Eastern Indonesia, which includes Nusa Tenggara and Maluku [66–68]. This strategy is significant considering the fact that the lowest electrification rate across Indonesia was observed in East Nusa Tenggara. In 2015, solar PV's installed capacity was 71 MW across Indonesia [22]. This capacity is expected to grow to 12–21 GW by 2050 providing for less than 6% of the overall national electricity production [61]. Solar PV's cost is still the main burden in Indonesia but with the decreasing cost of this energy, its desirability in Indonesia is on the rise.

11.3.2.4 Wind

Wind's desirability varies across Indonesian as illustrated in Fig. 11.8. Onshore wind's RAF varies from 18 in Kalimantan to 47 in Java. Offshore wind has a generally higher RAF with a smaller variance from 33 in Kalimantan and Papua to 58 in Java and Maluku.

Fig. 11.8 RAF of across Indonesia onshore wind (above) and offshore wind (bottom) across Indonesia

Wind generation potential is very site-specific. Indonesia's general wind speed is usually under 4 m/s (measured from 100 m height) [69]. Wind energy has limited potential production sites in Indonesia that are mainly located in coastal areas where the wind speed is higher. Overall, the potential capacity of wind energy at the national level is estimated to be 60 GW [70].

Sumba in Nusa Tenggara, southern Sumatra, Papua, and the outer coastal regions of Kalimantan are identified as good locations for this alternative. These areas have the lowest RAF score for wind and the highest wind speed (3–4 m/s) [69]. These areas experience the lowest electrification rates [71], and a decentralized wind power system can be a great support to increase the electrification rate of the region. But these regions have a relatively low population density which makes them less attractive for energy development investments.

Java is one of the windiest islands in Indonesia [72]. However, it has limited land availability for wind power infrastructure. On the other hand, Maluku has a limited economic power (GDP per capita) to accommodate the cost associated with wind energy. Similarly, Sulawesi's potential for exploiting win energy is affected by moderate limitation in economic resources and land availability.

The large land footprint of wind technologies comes from the wide spacing needed between the wind turbines. If future research and development focused on the reduction of this space, land footprints can be much smaller [33], making this alternative competitive with fossil fuels with regard to its land footprint and more desirable overall. The lower land footprint for wind can be achieved through reduction of the diameter of turbines, consideration of the wake effect in construction of farm layout, and co-use of land for turbine and cropland (biomass use) [33, 73].

Offshore wind is more expensive but has a higher energy output due to higher wind speeds over the sea [74]. Thus, further commercialization and cost reduction of offshore wind can be beneficial for the region.

11.3.2.5 Fossil Fuels

Figure 11.9a–c demonstrates the desirability of fossil fuel resources across the islands of Indonesia. In accordance to the RAF scores obtained, the highest desirability for natural gas (RAF = 27) and coal (RAF = 38) is achieved in Java, while the island scored the lowest desirability for oil (RAF = 73) across Indonesia. This is mainly because Java's lower weight assigned to CO_2 emission, meaning that this island can afford to implement higher shares of carbon-intensive alternatives. However, its low water and land availability lead to lower attractivity of land- and water-intensive oil.

Bali and Nusa Tenggara has low water availability (Fig. 11.4) making oil and particularly coal (which has the highest water use) undesirable in this island. But natural gas becomes more desirable across the island as it has a lower water use. Fossil fuel resources are not recommended for use in the highly polluted islands of Sumatra, Kalimantan, and Papua, due to the carbon-intensive nature of fossil fuels (Fig. 11.4). Oil presents the highest economic burden among fossil fuels. Therefore, Sulawesi and Maluku might be more inclined toward shares of natural gas and coal due to lower associated costs and existing high economic stress in the region (Fig. 11.4).

Currently, Indonesia presents a strong dependency on fossil fuels in its energy planning and as its primary source of export revenues [75]. In 2015, 72% of the country's energy portfolio was sourced from fossil fuels [56]. Diesel, which is made from oil, is a popular electricity source in remote locations and small islands which are disconnected from the main grid, while coal is recognized as a cheap, easy, and fast pledge to decreasing the existing gap amid power demand and supply. Natural gas capacity had to be increased that previously proposed to compromise for the 25% renewable contribution that will not be met by 2025 [8]. As advised earlier, natural gas's low resource-intensive nature makes it an attractive alternative to some renewables in transition to low-carbon portfolios.

Though fossil fuels are high carbon-emitting energy sources, they have the lowest Levelized Cost of Energy (LCOE) in comparison to other alternatives. This is due to the maturity of these technologies and economies of scale. Natural gas and coal demonstrate higher desirability due to their low land and water footprint when compared to renewables such as hydropower, bioenergy, and wind. The low land footprints of these sources are highly valued in a country with serious land limitations.

Oil's higher cost and carbon emissions make this energy undesirable. This has been recognized by the government which has planned to decrease the contribution of oil from 45% in 2015 to 20% by 2020. This is supposed to be achieved through eliminating fuel subsidies [75] and endorsing renewables such as solar PV [64].

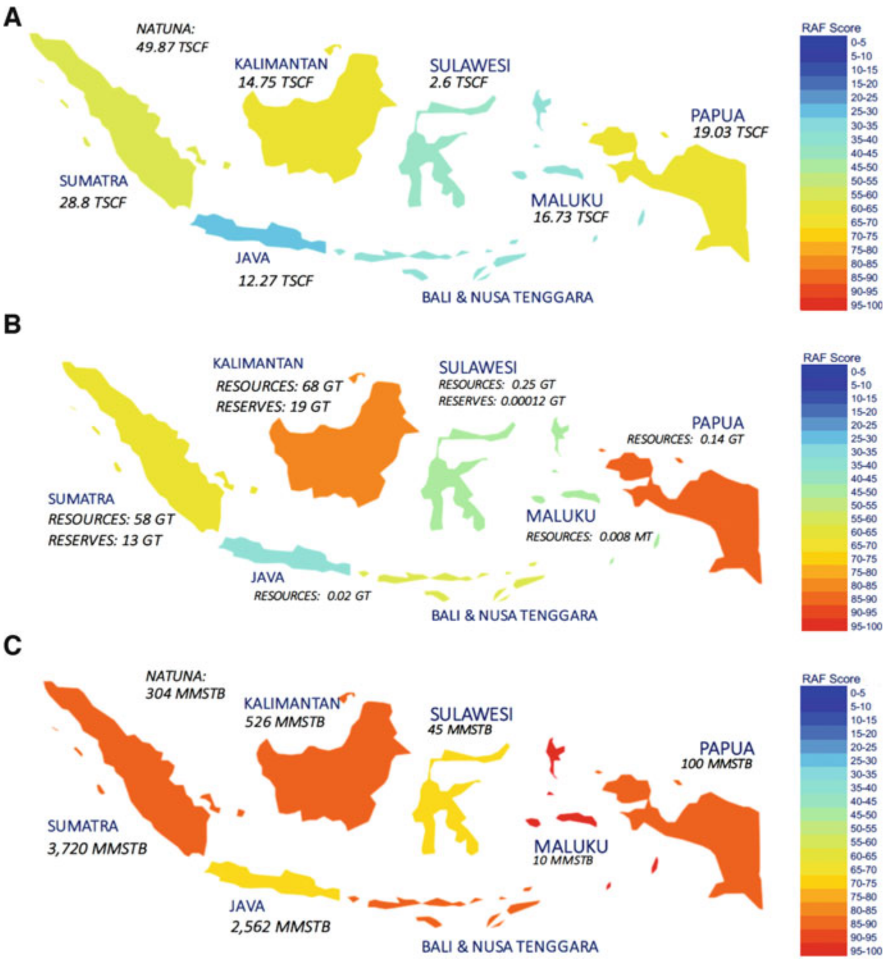

Fig. 11.9 (**A**) Natural gas's RAF and potential. (Based on data from Ditjen Migas [76]) across Indonesia, presented in units of trillions of standard cubic feet of gas (TSCF). (**B**) Coal's RAF and potential. (Based on data from ESDM [77]) across Indonesia, presented in units of gigatons (GT) and million tons (MT). (**C**) Oil's RAF and potential. (Based on data from Ditjen Migas [78]) across Indonesia, presented in units of Million Stock Tank Barrels (MMSTB)

11.3.2.6 Hydropower

The RAF of hydropower is highly dependent on resource availability and limitations in each island as shown in Fig. 11.10. Hydropower's RAF is as low as 7 (competitive with nuclear) in Bali and Nusa Tenggara and can reach 87 in Java. The main reason behind the large depreciation of its desirability is its immense water footprint, combined with its large land footprint. Hydropower has the highest desirability (lowest RAF) in Bali with a high available land per capita, a medium water

Fig. 11.10 Hydropower's RAF across Indonesia

availability, and low carbon emissions. Hydropower has medium desirability in Maluku (RAF = 47), because of the island's greater water availability and lower carbon emissions. Meanwhile, large-scale hydropower is not encouraged for the other three islands: Papua (RAF = 51), Kalimantan (RAF = 56), and Sumatra (RAF = 69).

Most of the country's installed hydropower plants are located in Sumatra and Sulawesi and Java. Large-scale hydropower plants do not exist in Bali and Nusa Tenggara [61]. This is probably relevant to the distribution of hydropower potential across the country [55]. Further expansion of large-scale hydropower is not desirable across the nation. The large footprint of hydropower on the environment together with its cost should not be overlooked simply because the potential production capacity is high. This is not to say that hydropower should be fully eliminated. Instead, it is suggested that the share of this alternative is adjusted based on resource availability conditions on each island.

11.3.2.7 Bioenergy

Biomass is generally highly undesirable across Indonesia (Fig. 11.11). Bioenergy is identified as the ultimate worst energy alternative with RAF of 100 in both Sulawesi and Java mainly due to its large land use. This alternative has an RAF score of 98 and 96 in Sumatra, and Bali and Nusa Tenggara, respectively. The RAF slightly decreases for Kalimantan, Maluku, and Papua, to 87, 84, and 82, respectively, as they have a slightly higher land availability compared to the rest of the islands.

In terms of availability of bioenergy, this source can be found across every region in Indonesia with sufficient potential (32.6 GW) to operate a large-scale power plant. The highest potential is recorded in Sumatra and Java [79]. The LCOE for bioenergy is higher than that of natural gas and oil. Even though it has a cheaper median cost than solar PV and offshore wind, its significantly higher water and land use lead to lower desirability. Bioenergy is an attractive option to the government due to its flexibility, scalability, and the wide ranges of available feedstocks. However, once its impacts are viewed through an MCDM perspective, this energy option's negative impacts might outweigh its benefits. Thus, further

Fig. 11.11 Bioenergy's RAF across Indonesia

expansion of this alternative can result in adverse impacts on economic and environmental sustainability. Across Indonesia, land exploitation is viewed to be compliant with the dynamic needs of the market. In other words, as long as the farmers benefit from higher economic returns, any plantation for bioenergy feedstock can be justified. This way of thinking is itself a serious threat to water and land resources and can lead to serious competition between food supply and energy production [21, 80]. However, given the high availability of resources in Java and Sumatra [79], complete elimination of this alternative may not be practical, but a diversified portfolio can be a way forward. Therefore, careful assessment of the trade-offs is needed to determine the contribution of this alternative.

11.4 Policy Implications

This chapter investigated the sustainability performance of energy alternatives beyond their carbon emissions to indicate the sole purpose of energy decarbonization does not lead to sustainable outcomes. Once the impacts on other valuable resources such as water and land as well as economic burdens are considered, some renewable alternatives perceived to be green become undesirable. The variability across desirability performance of energy alternatives demonstrated the importance of considering local resource conditions. Due to the lack of international dimension to Indonesia's transmission grid, it is crucial for the country to optimize its electricity mix to secure a continuous supply while minimizing its adverse impacts with respect to the obtained RAF information in this study.

Electrification and carbon emission reduction initiatives should not become the sole focus of future energy development. To achieve a balance between meeting the country's growing energy and perseveration of its natural resources, reforms are needed in the current energy development paradigm of Indonesia that lead to appreciating the nexus of energy–environment–economy. Although the issues of energy, water, and land security are recognized alongside climate change mitigation in National Development Planning, the existing agendas reflect the lack of

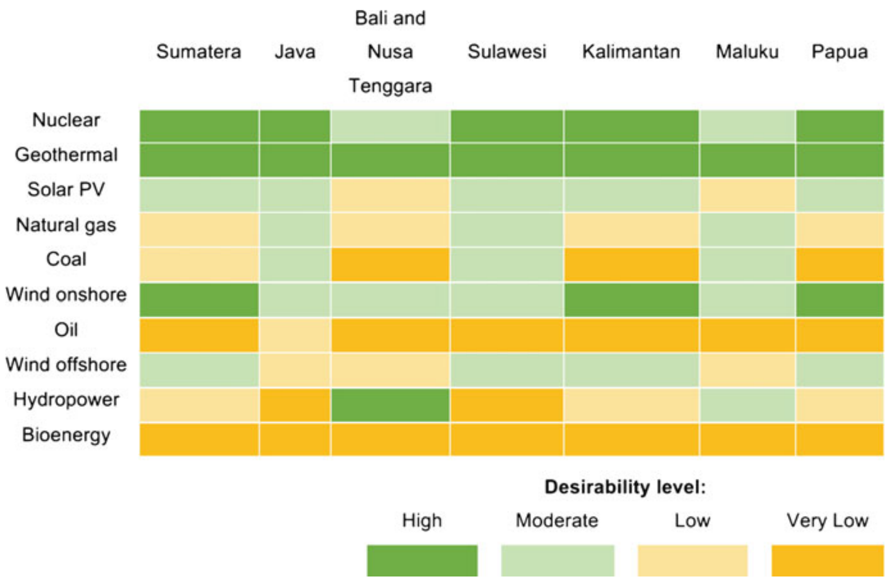

Fig. 11.12 Desirability of energy alternatives in the Indonesian islands

understanding of the important interrelationships of these issues. Tackling each problem individually without thinking of other systems can result in ineffective efforts as well as unintended impacts on other sectors.

It must be noted that the feasibility of implementing different energy options was not considered in this study. Nevertheless, the qualitative data about the potential generation capacity of different energy options across the region together with the calculated RAFs can lead to the following general conclusions about the desirability of different options across Indonesia (Fig. 11.12):

1. Nuclear energy is highly desirable nationally and at the island level. Nevertheless, technical safety concerns and social issues around this alternative might make its rapid expansion unlikely.
2. Geothermal has a strong potential across the country and can be a good substitution to hydropower which is highly undesirable at both the national and island levels.
3. Coal might seem like a desirable option at the national level due to its low economic burden and land use. However, at island-specific levels, this alternative is mostly unacceptable. The existing high emissions in Bali and Nusa Tenggara, Sumatra, Kalimantan, and Papua means that carbon-intensive coal is undesirable. Yet, coal-fired power is among the favorable options in Java, Maluku, and Sulawesi due to the existence of ideal sites for coal energy production in these islands. The shift from fossil fuels is inevitable due to the depleting nature of these resources. Thus, the desirability of coal in some locations must not justify the dominance of this energy in the national energy supply mix. This means that

although coal can be a part of the country's diversified energy portfolio in the short run, this energy must not be considered as a sustainable energy source for Indonesia.

4. The anticipated role for hydropower in the national electricity mix needs to be re-examined due to its high RAF. Further increase in the share of hydropower to mitigate the impacts of climate change is not necessarily sustainable as it can severely impact environmental (land and water) resources. This study only considered large-scale hydropower and found it to be highly undesirable. However, small-scale hydropower production can be more desirable due to lower aggregated impacts and their practical benefits in the electrification of remote rural areas.
5. Bioenergy was found to be highly undesirable across the country and in the islands due to significantly high land and water use of this energy. Substantial areas of land have already been lost to bioenergy feedstock and considering the land availability limitations in Indonesia, more attention must be paid to land use of energy resources. Results do not justify the expansion of bioenergy across the nation and in the islands unless the aggregated footprints are lowered through technological advancement and applying alternative methods for bioenergy generation.
6. Wind energy has variable desirability across the region. Improvement in its land footprint and cost (specifically for offshore wind) can lead to the improved performance of this alternative.
7. Solar PV has medium desirability across most of the region, except for Bali and Nusa Tenggara and Maluku. These islands have limited economic resources and might not afford energy options that require substantial capital investments. Nevertheless, the decreasing cost of this energy is making it more viable across the country in the near future.

11.5 Conclusions

The study results show how the consideration of multiple criteria, trade-offs, impacts on other resources, and uncertainty can decrease the perceived desirability of some renewable energies. Additionally, the results show how by taking the local resource availability restrictions into account can lead to changes in the desirability of energy sources across regions.

Decarbonization of Indonesia's energy portfolio cannot be done without considering the pressing issues the country is facing in other sectors, including economy, agriculture, and environment. The country can pursue its plans to increase the electrification rate by diversifying its energy supply portfolio without negative impacts on other sectors. This requires some reforms in the current practices and frameworks for national energy planning in the country.

The analysis framework used in this chapter does not attempt in any way to provide a specific portfolio to be used for developing mitigation pathways for Indonesia. The purpose of this study was to provide suggestions and guidelines for the need to assess energy alternatives based on a system of systems perspective that considers nexus, trade-offs, and uncertainty. Much like any other computational modeling study, many assumptions were made in this study to simplify real conditions. These simplifications (extensively reviewed by Hadian and Madani [26], Mahlooji et al, [45]. and Ristic et al. [27]) must be considered in interpreting the study results.

This study demonstrates the needs for a multi-criteria assessment in energy planning; however, the framework here is limited to four fundamental sustainability indicators. To create a more robust result, future studies should expand these sustainability indicators. The wider the range of indicators considered, the more robust the results and recommendations would be. Energy conservation and security are two aspects known to be crucial to Indonesia which can be converted into an index for future studies.

Caveat Parts of this chapter have been reproduced from a master's dissertation report of Firra Ghassani Gumilar at Imperial College London.

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Chapter 12
An Updated Review on Net-Zero Energy and Water Buildings: Design and Operation

Somayeh Asadi, Morteza Nazari-Heris, Sajad Rezaei Nasab, Hossein Torabi, and Melika Sharifironizi

12.1 Introduction

Population growth, human activities, and excessive use of water and energy resources have caused some challenges including climate changes, resource scarcity, and pollution of the environment. Among different environmental problems associated with consumption of energy and water carriers, the issue of interconnection between energy and water has attracted a lot of attention [1], which is referred to as water–energy nexus. A comprehensive investigation of the water and energy consumptions of various types of consumers was developed by utilizing data collection and an extended environmental-based framework by Fan et al. in China [2]. They also identified the types of consumers with most powerful energy–water nexus. Meng, F., et al. conducted a review of the progression in urban energy–water–carbon nexus investigations. The observations in this reference showed that almost 94% of the research performed in the area of energy–water–carbon concentrate on the two-aspect nexus, where the water–energy type represents the main subject [3].

Many kinds of research provide information on energy and water interrelationship and identified backgrounds on energy for treatment appliances and delivering water to consumers and wastewater discharge [4–12]. Several investigations aim at identifying the key interrelationship on energy–water and environmental impacts. Climate changes, depletion of natural resources, pollution of the environment,

S. Asadi (✉) · M. Nazari-Heris
Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA
e-mail: asadi@engr.psu.edu

S. R. Nasab · H. Torabi
Department of Civil Engineering, Qazvin Azad University, Qazvin, Iran

M. Sharifironizi
Department of Architectural Engineering, 204 Engineering Unit A, University Park, PA, USA

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energy and water resources security, and emissions of carbon dioxide are the most attractive cases among different environmental issues coupled with these topics as studied in [12–24]. Furthermore, it should be mentioned that improvement of the water sources sustainability is critical for the present and future generations [25]. The unequal geographic dispatch of freshwater reserves coupled with density of population of each continent severely jeopardizes the deprivation of water and its quality. Such inequality will deteriorate over the next few decades by growing the urban population that is expected to make up 66% of the world's population by 2050 [25].

Despite many large-scale research in the field of energy and water nexus, including mining, fuel supply, hydro-based power plants, cooling of power plants, and the energy required for pumping, treatment, collection and water dispatch, treatment, and discharge of wastewater, only a few research have been carried out in the commercial and residential building sectors. Buildings allocate 40% of universal consumption of energy as reported in [26, 27]. The building type is one of the sectors most affected by the consumption of energy of industrialized countries. Specifically, the European Union reported 40% energy consumption for the buildings and 36% emission of pollutants gases [28, 29]. Furthermore, with living standard enhanced and increasing the need of the people for comfort, buildings' energy usage is forecasted to grow consecutively [30]. Energy consumption in buildings is a major problem at the world level. Other reports highlighted that buildings allocate around 40% to 45% of primary energy and 36% of pollutant gas emissions [31, 32]. Buildings are known as the most significant energy users in the world [31].

The aim of this review is to investigate studies around ZEBs and ZWBs and analyze approaches adopted in the design and operation of such buildings. Accordingly, both net ZEBs and net ZWBs will be investigated in the next sections from different points of view.

12.2 Definition of Net-Zero Building

Most definitions of zero building are around the energy issue while in addition to energy there are other resources such as water and waste that their optimal consumption should be considered. Zero energy is one of the highest aspirations in energy efficiency in the constructed environment worldwide. The international living future institute has established a certification for commercial and residential parts to allow projects to demonstrate zero energy performance [33]. The world green building council commenced a project in 2016 concentrating on NZB certification and training to attain net-zero carbon buildings by 2050 for reducing emis sions from the buildings [34]. NZB is beneficial in terms of generating clean energy and producing no emissions. The Department of Energy (DOE) has introduced ZEB as "*an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy*" [35]. In DOE, federal buildings that were addressed the buildings that occupants are federal government employee, the net-zero efforts go beyond ZEBs for including net-zero energy, water, and waste buildings [36]. In the following, we will discuss net ZEBs, and then we will focus more on the topic of water efficiency measures in buildings since significant research has not been performed on the topic of net ZWB.

12.2.1 Net-Zero Energy Building

Awareness of the global increase in population has increased challenges on the necessity of energy-saving measures [37]. The first concepts of the net energy can be traced back to Podolinsky, who was trying to analyze society aspects and merchandises production, especially associated with agriculture, in terms of energy [38]. In the constructed environment, the term "net energy" is mostly utilized for portraying the balance between building energy consumption and its inhabitants and systems, and renewable energy outputs [26]. A ZEB should have the capability of reducing its energy need in line with developing efficiency measures [39]. A high efficient building is required to include renewable energy sources including locally or in the vicinity [40]. The NZEB can balance the primary consumption of energy so that the primary energy supply of the network or another energy grid is equal to the primary energy supplied by the energy grids to the NZEB [41]. An annual 0 kWh/m^2 early energy consumption usually results in a significant part of the on-site power supply being interchanged with the power network. Therefore, an NZEB generates energy when the situation is appropriate and it consumes the delivered energy for the remainder time interval [41, 42]. ZEB influences the method that a building can attain this target, as several design options are conceivable, depending on how the basics of ZEB clarifies the efficiency, energy resources, and fuel options of building [43, 44].

Different aspects of ZEB have been investigated in the past decade [45–47]. As one of the definitions, within the International Energy Agency (IEA), the aim was to propose a common definition for the ZEB, which highlighted "on the way to zero-energy solar buildings" [40, 48]. Conforming to some researchers, net ZEBs signify buildings integrated into the energy system for energy transfer and reach a net-zero objective through the network [49]. In the latest definitions of the ZEB and the NZEB, the local use of renewable resources control the consumption of energy resources will be maximized such buildings using intelligent controls to optimize the building system. The interactions between high-performance buildings, renewable energy technologies available for building requirements, and the energy supply network are becoming increasingly critical [40, 50, 51]. For instance, one of the compliments of ZEBs is as follows [43]: Initial energy means energy produced and imported energy subtracting exports and storage changes, and the secondary energy is the carrier of the building, which is generated by conversion from a primary energy source. End users use different forms of energy to satisfy the requirements such as cooling, heating, lighting, power, water, and so on [37].

Recently, the subject of low-energy buildings has met with broad enthusiastic considering the policies associated with the energy saving of the industrialized countries. Energy-saving measurements and power supply of renewable sources are effective in the planning of a low-energy house. However, the appropriate evaluation of the phenomena happening in a building typically needs dynamic simulations and the analysis of several case studies to achieve an optimal outcome [29]. In net-zero buildings, global energy needs should be reduced, and their drawing can greatly benefit from the evaluation of energy usage and their impact on the environment throughout the life cycle, even with a simple way [29, 52, 53]. An approach recognized by EU countries for reducing this share of energy needs is the near-ZEB, which was included in the 2010 recast of the energy performance of buildings directive as a building with very high energy efficiency. Almost zero or very low energy needs must be met to a considerable extent by renewable energy sources, including renewable energy produced locally or in the vicinity [29, 54]. So, in general, near-ZEBs should be designed to meet the energy needs of active energy generation technologies and renewable systems for reach NZEB goal [55–58].

The treatment and transport of water and wastewater account for about 4% of US electricity consumption, with 80% being utilized for transport. Nearly/net-zero water (NZW) buildings would reduce the demand for some of this energy, for water and after the treatment of drinking water for pesticides and the release of toxic chemicals in water resources, although household sewage contains nitrogen loads that are much larger than the ecosystems of cities/suburbs can normally absorb [1, 59].

12.2.1.1 Design of ZEBs

Buildings are one of the most energy-consuming sectors in countries worldwide. Pushed by this fact and some regulations and legal arrangement, academics and designers based on various definitions, categories, and limitations of an energy-efficient building developed various design criteria for efficient buildings. In according to most generic consensus on the ZEB definition, a net ZEB exchange energy with the main energy network to achieve an annual zero balance between received and transferred energy during this time [60]. Although, there may be other definition on NZEB such that a building is independent of surrounding energy networks via utilization of an adequate storage system [31, 47]. A Net ZEB needs to be operated to achieve zero, and good operations begin with design. Several rules of the design strategy mentioned by Montana et al. [29] are as follows:

- Reduction of building's thermal load by reducing envelop transmittance
- Utilizing passive measures
- Employment of high-performance HVAC systems
- Adopting renewable energy generation technologies to cover building energy differences.

Designers must choose the best solution among the various measures to achieve the best configuration of abovementioned strategies to gain the correct design of a net ZEB. Thus, designers should combine building simulation tools and mathematical methods in order to find an optimal solution.

Some review papers have aimed at identifying different optimization algorithms, objective functions and variables, different approaches and methods toward the optimal design of buildings, challenges and problems and uncertainties [61–69]. In common, the objective function considers the building as a black box balancing between energies exported and imported to the building [30]. This approach only considers the building energy consumption during the use phase, and it does not account energy embodied in a life cycle perspective during construction, use phase, and demolishing. The authors in [70] define life cycle energy building as a building with annual life cycle energy usage equal to zero. In a more detailed perspective, the authors in [41] consider the annual initial embodied energy, annual recurring energy, and annual demolishing energy in energy calculations. Cost optimization is another approach adopted by several researchers. They usually consider investment cost only, both investment and operating cost or life cycle cost occurring during the life of a building [41]. EU cost-optimal methodology [50] and EN 15459 standard [51] are two legislative frameworks that describe the concept of cost optimality and life cycle assessment, respectively. In-depth search of relevant strategies and performance indicators, the researchers announced that no standard fundamentals for NZEBs design exist, or no special design methods exist in arriving NZEBs design; however, based on research done by Yeung et al. [71], several similar design elements have defined for NZEBs design [55, 72–74]. In general, there are three main approaches to NZEB design. The first design technique is inactive technique, which focuses on reduction of energy load. The second attitude is the usage of an efficient structure for the building, and the final attitude is the use of renewable energy that heavily compensates for energy load. The integration of these three design approaches can be effective in achieving NZEB's optimal performance [55, 72, 75] .

Another design objective used by researchers is CO_2 emissions balancing due to building energy consumption. So, the use of renewable sources in buildings is a feasible way against global warming and pollution [55–58]. Studies suggest that the significant penetration of NZEBs through designing and operation can potentially influence the current index of power load by decreasing the power purchased from the power network and increasing the export of power into the grid during peak periods [76]. Due to the rapid growth of renewable energies, the net ZEB concept was seen as one of the means to reduce the consumption of electrical energy and increase energy efficiency in buildings [76, 77].

12.2.1.2 Application of Renewable Energy Sources in ZEBs

One of the main elements of ZEBs is penetration of renewable energy sources such as photovoltaic cells and wind turbines. The authors in [78] have investigated the role of renewable sources with various configurations of photovoltaic systems and wind turbines integrated with hourly building power demands to assess the practicality of near-ZEBs. In this reference, future weather data from the Global Climate Models have been utilized for forecasting the performance of renewable energy sources for satisfying load demand of the buildings in 10 various climate zones in the

U.S. In [79], the application of photovoltaic thermal technology in line with heat pump in a ZEB is investigated as a real case study in Canada performed in 2007. In this reference, a geothermal heat pump is utilized in the studied ZEB for supplying domestic hot water and air heating required in the building. The authors in [80] have proposed a multi-criterion design of renewable sources for net ZEBs considering uncertain parameters of the system. Monte Carlo simulation is employed for predicting annual energy balance and grid stress that is appeared because of power mismatch. Photovoltaic cells, CHP units, and batteries are considered as the main elements of power and heat load supply for a micro-grid including several buildings in [81], where a heat storage technology is considered for managing the on-peak load demands by storing the heat in low-demand time intervals and discharge it in times with high load. A penalty cost in design process of renewable energy sources is proposed in [82] that aims at ensuring the cost-effective design of the net ZEBs verifying a net-zero/positive energy building. In [1], the photovoltaic system is studied as basic for heating, cooling, and power supply in investigating the operation of residential buildings in Cyprus. In this reference, electrolyzer uses the extra power output of the photovoltaic system for producing hydrogen that is used in natural gas supply of generation plants. A combined power and heat network with integration of photovoltaic system and electrolyzer is proposed in [2], where fuel cell is considered for satisfying power load. The authors in [3] have proposed design criteria for ZEBs with penetration of renewable energy resources by employing genetic algorithm as a heuristic optimization approach, where the interactions between renewable source and building energy networks in optimization have been studied. An optimization framework for evaluation of renewable systems with energy storage technologies in zero/near-zero buildings has been presented in [4] investigating the optimal configuration of the building. The proposed scheme in this reference considered the availability of rooftop for installation of photovoltaic and mini wind turbines as well as energy storage units. Various kinds of vertical wind turbines and their installment capability in buildings have been evaluated in [5], where the profits of such integration to buildings are compared with photovoltaic cells. In [6], the authors have implemented genetic algorithm for searching optimal sizes of net ZEBs as well as performing sensitivity analysis for system with photovoltaic cells and wind turbines for investigating the effects of variations of design input on the performance of ZEBs. A simulation-based optimization method, which obtains optimal sizing of a renewable-based building, is studied in [7] for maximizing the ratio of buildings' renewable energy and minimizing the whole net present cost and pollutant gas emissions.

12.2.1.3 Operation of ZEBs

Operation of a net ZEB basically means that the building generates as much energy as it needs annually. The evident challenge with net-zero energy is that it is required to generate enough energy to reach a net-zero, and solar panels, heat pump, wind turbines, fuel cells, equipment for the recycling of rainwater and gray water, etc.

require substantial capital to procure them. The included renewable energy sources are multiple. More than half of the buildings use photovoltaic systems and solar thermal modules. Different energy sources including geothermal energy, biomass, and district heating with a high proportion of renewable energies are used in a lot of buildings [78]. To start the operation and to gain zero energy, the first step is to avoid wasting energy. In net ZEB, design and implementation of details allocate a high proportion of the building's energy casualty, underscoring the importance of carefully planning these details. Also, the savings achieved over time can be invested in a building to reach the next wave of energy efficiency. A review of net ZEBs prepares a basic knowledge for contractors and designers to growth NZEBs approach at the design step for development of buildings [55].

Considering the abovementioned descriptions, we aim to briefly outline the projects that have been implemented in different countries with the NZE target. The examples are presented in a structured manner in the report. These include residential and nonresidential buildings, office space, new buildings, and renovations on the NZEB level. In the following, some of the case studies are briefly described to show quite different approaches. In addition to all the above, we need to point out the largest planned "net-zero energy" community in the United States that included 662 apartments, 343 single-family homes, 42,500 square feet of commercial space, 60,000 square feet Community College as shown in Table 12.1.

12.2.2 Net-Zero Water Buildings

NZW is a novel perspective for managing urban water that does not import or export significant water into the supply area, such as local water independence. On the other hand, it is expected that distributed NZW systems will achieve a high recycling rate, which can lead to a positive energy operation, reducing more domestic hot water energy less than the energy needed for treatment [83]. Almost net ZEB requirements must be satisfied by considerable renewable sources, including power supply of such resources locally or in the vicinity [41] such as solar heating and recycling rainwater and gray water. The recycling of rainwater and gray water technologies decrease buildings energy usage by augmenting the system efficiency and recycling wastewater from buildings [75]. Study on rainwater and gray water has been conducted around the world to promote drinking water savings. There is insignificant research on the integration of rainwater and gray water for promoting drinking water savings [84]. It is reported that the rainwater usage in residential areas of Brazil is able to promote drinking water savings of between 48% in the southeast area and 100% in the northern area [84, 85].

The objective of net ZWB is conserving the quality and amount of natural water sources with minimum degeneration, evacuation, and diversion according to the water consumption of the building. Such objective can be attained by using alternative sources and efficiency measurements of water for minimizing the freshwater usage. Ultimately, a ZWB will balance the water consumption completely. The

Table 12.1 Different projects of the net ZEBs projects in the world [78–82]

Num.	Country	Building type	Building service system					
			Heating	Ventilation	Hot water	Cooling	Lighting	Heat pump and gas boiler
1	United States of America	Housing, office space, and college	Heat pump	Fresh air mechanical ventilation	Central high-performance water and heater	Heat pump	Photovoltaic panel	
2	Austria	Residential (single-family house as well as a small combined office)	Wood pellet stove	Mechanical ventilation system with 86% heat recovery	Wood pellets and solar thermal technology	0.0 kWh/m^2. year	Electrical appliances	–
3	Austria	Residential (multi-family apartment building)	District heating and solar thermal panels	Mechanical ventilation system	Solar thermal panels on the roof	0.0 kWh/m^2. year	Unknown	A heat pump is utilized to pre-heat incoming air of the mechanical ventilation unit.
4	Belgium Flemish region	Residential (seven individual apartments with a small private garden)	Gas boiler with underfloor heating in the kitchen and living area	Mechanical, fresh air supply in dry room, exhaust air in humid rooms, with heat recovery	Gas boiler	Part of the architectural design to reach cooling	All common lighting complies with **BREEAM**[a] standards	–

5	Belgium Flemish region	Nonresidential (office building)	Usage of a delivery system for heating, and usage of concrete core activation	–	–	A delivery system for cooling, concrete core activation is used	The lighting is worked by presence detection and daylight-dependent control and photovoltaic panels	Borehole thermal energy storage in composition with a heat pump. For heating and cooling load
6	Bulgaria	Nonresidential (University research center building)	Flow heat pump	Heat pump and heat recovery system to ambient air	Local electricity-based heaters	VRF[b]-based system	Energy-saving lighting technology	Ambient-based heat pump and heat recovery
7	Croatia	Residential (multi-family house)	The underfloor system, a compact heat pump with **COP**[c] or by boilers using natural gas	The exhaust air heat is absorbed by a high-performance energy recovery unit	Solar thermal collectors and in necessity gas boilers	The underfloor system using the same pipes for both heating and cooling	Part of comes from solar panels	Heating and cooling are provided by a heat pump
8	Denmark	Residential (dormitory)	Central heating system	Balanced mechanical ventilation unit	Solar thermal collectors	0.00 kWh/m^2. year	Unknown	–
9	Estonia	Nonresidential (office building)	Local district heating network	Mechanical ventilation systems with heat recovery	District heating	A passive high-temperature cooling system based on open energy piles connected to the groundwater	Photovoltaic system	–
10	Finland	Residential (a home for elderly people)	Solar thermal collectors and geothermal heating	Mechanical ventilation unit with heat recovery	The ground source heating was originally used for domestic hot water	0 kWh/m^2.year	Solar electricity and low-energy lighting	Installation of a heat pump

(continued)

Table 12.1 (continued)

Num.	Country	Building type	Building service system					
			Heating	Ventilation	Hot water	Cooling	Lighting	Heat pump and gas boiler
11	Finland	Residential (A two- single-family house)	A ground source heat pump and distributed by a floor-heating network. Solar heat can also supply part of the heating	Mechanical ventilation unit with heat recovery unit	A ground source heat pump and Solar heat	Insignificant	LED lighting system is designed, and all appliances are classified with the best energy label A++	Geothermal heat pump as well as solar heating system
12	France	Residential (single-family house)	Gas-condensing boiler distributed by a floor-heating network	A single-flow ventilation unit	Solar thermal collectors supporting by a boiler	0.00 kWh/m^2. year	A little bit with solar panels	–
13	France	Complex residential	Heating by individual condensing gas boiler	Installation of humidity-sensitive mechanical ventilation	DHW production by the gas boiler	0.00 kWh/m^2. year	–	–
14	France	Residential (collective housing—Private)	Heating by individual condensing gas boiler	Installation of humidity-sensitive mechanical ventilation	By a solar solution composed and an 800-liter flask	0.00 kWh/m^2. year	–	–
15	France	Residential (collective housing—Social)	Individual gas-condensing boilers	Installation of humidity-sensitive mechanical ventilation	DHW production by the gas boiler	0.00 kWh/m^2. year	Photovoltaic installation in multi-crystalline silicon	–

16	France-Périers	Residential (individual grouped houses—Social)	A dual-service heat pump that provides heating production	Installation of humidity-sensitive mechanical ventilation	A dual-service heat pump that provides DHW production	–	–	Dual-function air/water thermodynamic heat pump
17	France-Wintzenheim	Residential (collective housing—Social)	Individual condensing gas boiler heating	Installation of humidity-sensitive mechanical ventilation	HW production by the individual boiler	–	–	–
18	France	Residential (single-family house)	Gas-condensing boiler	A single-flow ventilation unit	The boiler supports solar thermal collectors	0.00 kWh/m^2. year	Solar thermal collectors	The boiler supports solar thermal collectors, which are the major source of domestic hot water
19	Germany	Residential (single-family house with two floors)	A central heating unit with an air-to-water heat pump and floor heating	A balanced mechanical ventilation unit and a building energy management system with touch pads	Heat pump	0.00 kWh/m^2. year	A photovoltaic system	The air-to-water heat pump utilizes ambient energy from the outside air
20	Germany	Nonresidential (public, school)	A district heating system	A central ventilating system with a heat recovery system	Renewable energy	0.00 kWh/m^2. year	Photovoltaic modules	–

(continued)

Table 12.1 (continued)

Num.	Country	Building type	Building service system					
			Heating	Ventilation	Hot water	Cooling	Lighting	Heat pump and gas boiler
21	Ireland	Residential (single-family house)	Weather-compensated gas boiler with floor heating	Ventilation system with 91% heat recovery and temperature control and timer	Solar thermal collector	0.00 kWh/m^2. year	Solar thermal collector	–
22	Ireland	Public, post-primary school	Biomass boiler and cogeneration unit	Auto ventilation with airtight automatic shutdown and connection to CO_2 sensors	Biomass boiler and cogeneration unit	0.00 kWh/m^2. year	Photovoltaic electricity production and LED-based outdoor lights with improved control	–
23	Italy	Residential (single-family house with two storeys)	Usage a condensing boiler fueled by natural gas and radiant wall panels	Mechanical ventilation unit with heat recovery	Usage of a condensing boiler fueled by natural gas	0.00 kWh/m^2. year	The solar thermal system	–

24	Italy	Residential (single-family house with three storeys)	Geothermal heat pump with the ability of reverse for heating, solar thermal panels, a ventilation unit with heat recovery and combined with Electricity-based heaters	Ventilation system with heat recovery	Usage geothermal heat pump	Reversible geothermal heat pump for cooling	Unknown	Geothermal heat pump
25	Lithuania	Residential (double house)	District heating system	Mechanical ventilation system with heat recovery	District heating system	No cooling equipment	–	–
26	Lithuania	Residential (double house)	Stand-alone wood boiler	Mechanical ventilation unit with heat recovery	Wood boiler, solar thermal collectors, composite electrical heater	No cooling equipment	Photovoltaic panels of 10 m^2	–
27	Luxembourg	Residential (single-family house)	Air-to-air heat pump with additional usage of exhaust air, ventilation unit with heat recovery	Ground heat exchanger for ventilation	Heat pump	0.00 kWh/m^2. year	Unknown	Usage of air-to-air heat pump
28	Luxembourg	Nonresidential (office building)	Usage of biomass (pellet) boiler	CO_2 sensors are installed in each point for regulating healthy airflow	Biomass (pellet) boiler	A scroll compressor with a combined hybrid water chiller	The roof is fully covered with photovoltaic	Biomass (pellet) boiler

(continued)

Table 12.1 (continued)

Num.	Country	Building type	Building service system					
			Heating	Ventilation	Hot water	Cooling	Lighting	Heat pump and gas boiler
29	Malta	Residential (single-family house)	Inverter split-type air conditioning systems	0.00 kWh/m^2. year	Usage of a flat-plate solar water collector	Inverter split-type air conditioning systems	Photovoltaic system	–
30	The Netherlands	Residential (27 single-family houses)	Heat pump to heat the house in combination with solar thermal panels	Ventilation system	Heat pump to provide hot water in integration with solar thermal panels	0.0 kWh/m^2. year	Photovoltaic panels are placed on the roof	A heat pump uses the exhaust air of the ventilation system to heat the house in combination with solar thermal panels
31	The Netherlands	Residential (21 single-family houses)	Ground source heat pump and heat recovery from the exhaust air and solar thermal collectors	Ventilation unit and heat recovery from the exhaust air	Photovoltaic panels and solar thermal collectors for DHW and ground source heat pump	Ground source heat pump	Photovoltaic panels are placed on the roof	Ground source heat pump
32	Norway	Nonresidential (office building)	Geothermal heat pumps	Ventilation unit with very low pressure drop and ventilation ducts	Geothermal heat pumps	Geothermal heat pumps	Solar panels on roof	Geothermal heat pumps plus 10 wells
33	Norway	Nonresidential (office building)	Air-to-water reversible heat pumps	The building uses heat recovery from cooling	Air-to-water heat pumps	Air-to-water reversible heat pumps	Automatic solar system	Air-to-water heat pumps

34	Poland	Residential (single-family house)	Wooden fireplace	Ventilation unit with heat recovery	Solar thermal collectors and wood fireplace	0.00 kWh/m^2. year	Unknown	–
35	Portugal	Nonresidential (office building)	Solar thermal collector system in the ceiling with ground strong system and with natural gas boiler	Natural ventilation due to the entry of cool air	Solar thermal collector system in the ceiling with ground strong system and with natural gas boiler	Adjustable sun visor curtains and cooling system with ground source and use of buried pipes	–	Natural gas boiler
36	Sweden	Nonresidential (office building)	Ground source heat pump	Ventilation (fans)	Ground source heat pump	Ground source heat pump and free cooling	Photovoltaic panels and energy-efficient light fixtures	A ground source heat pump and free cooling
37	Sweden	Residential (single-family house)	Central pellet boiler and solar thermal collectors and circulating hot water system for used space heating	Exhaust air ventilation system with a rotating heat exchanger	Central pellet boiler and solar thermal collectors and circulating hot water system used for both hot tap water	0.00 kWh/m^2. year	Unknown	–
38	United Kingdom	Public (university library)	Low-temperature hot water (LTHW) via radiators supply from a gas boiler	Ventilation with air handling units		Cooling with air handling units and heat recovery and use demand control via CO_2 sensors	Photovoltaic panels	–

[a]Building Research Establishment Environmental Assessment Method
[b]Coefficient of Performance
[c]Variable refrigerant flow

returning maximum alternative water plus water to the original water source [36] can be formulated considering this fact that the total annual water use is equal to the sum of total annual alternative water use and total annual water returned/discharged to the original source. On the other hand, in a ZWB, the alternative water usage and the water returned to the principal water source match the water usage of the building. The principal water source consists of sources within the same position catchment area and aquifer of the building's water supply [36].

One more of the United Nations Millennium Development Goals involves implementing a sustainable development policy and reversing the loss of natural water sources [86, 87]. In this way, water resources must be conserved, considering their importance for living on this earth [71, 88]. Many research in several countries have investigated the rainwater consumption and gray water as another source of water to enhance water supply and minimize this difficulty [70, 88]. This procedure is easily adaptable to various areas and can help decision-makers in improving the performance of current and novel hybrid rainwater–gray water technologies [71]. Given the scarcity of water, it is necessary to pay attention to net ZWB. A net ZWB concept must attain maximum water efficiency while attaining minimum load by encompassing a comprehensive set of water-efficient elements, including all water-consuming devices in the building and out-of-door water use [36, 89, 90].

12.2.2.1 Design of ZWBs

Net ZWB according to a definition by [36] as net ZWB is a building with special boundary that operates in its minimal water consumption, maximum alternative water resources, minimal discharge, and finally water returned to the original water source.

In a net ZWB, annualized water usage is equal to the sum of alternative water and water returned to original resource annually. The net ZWB boundary consists of water use (i.e., potable and non-potable) of building systems and outdoor features, on-site alternative water resources (i.e., rainwater, gray water, reclaimed water), freshwater, and alternative water supply and returned water to the original water source.

During this review, the authors realized that no scientific literature was available for net ZWB, although many research aimed at investigating some special aspects of net ZWB. In these papers, following aspects are described:

- Water-efficient fixtures
- Rainwater harvesting system
- Gray water reuse

Water-saving strategy has been considered in building water fixture aiming at reducing water demand and plumbing leakage [91–93]. Such a strategy in rainwater harvesting system [94–96] and gray water reuse [92, 97, 98] is observable. Financial consideration in water-efficient fixture has been mentioned by [99]. A comparative appraisal of the consumption of rainwater harvesting system can be observed in

[100–103]. Cost–benefit evaluation of residential gray water reuse was investigated financially by [104, 105]. From environmental and life cycle assessment perspective and water conservation strategies, works done by [106–108] can be mentioned in rainwater harvesting system and [109] in gray water reuse.

12.2.2.2 Operation of ZWBs

Proper operation and maintenance for satisfying the designed performance of a net ZWB is very important [36]. There are some elements to call a building net ZWB, including

- Developing a building operation plan including a description of the actions, frequency of actions and responsibilities.
- Measuring water consumption and monitoring for leaks.
- Implementing training programs to change overusing behavior to encourage water conservation and engage occupants.
- Inspecting and reporting building water use annually.

Previous articles that report real case studies in water-saving measures before and after adoption are [110–113] in water-efficient fixture, [114, 115] in rainwater harvesting system, and [116, 117] in gray water reuse. Vitor souse et al. investigated various solutions in the Colombo shopping center. They changed restroom fixtures by more efficient models and used rainwater harvesting systems to supply cogeneration plant. They also introduced a gray water reuse system to supply toilets. The methodology included collecting data from water meters' records and archived bills, water-saving assessment evaluating life cycle costs. They concluded that gray water reuse has the shortest payback period and has annual water saving similar to rainwater harvesting system [25]. Nor Hafizi et al. evaluated the cost–benefit of installing and retrofitted RWHS on commercial buildings in Malaysia. They used daily rainfall data for simulation. They concluded that installing new rainwater harvesting system has more economic benefits in comparison with retrofitted [118]. Rezaul Karim et al. investigated rainwater harvested system in the residential buildings in Bangladesh. They use reliability and economic approach to evaluate possibility of partially offset daily water demand through RWHS. They recommended optimal roof catchment size and storage tank volumes under stochastic condition [119]. In a similar work, Vitoria et al. based on a stochastic approach, investigated the efficiency of RWHS. They concluded that RWHS is more efficient with smaller demand–roof area ratio [101]. Santosh et al. provided a life cycle assessment for commercial building's RWHS and compared it to the municipal water supply system (MWS) in Washington, D.C. They provided information about 11 life cycle assessment indicators including acidification, load, eutrophication, fossil depletion, freshwater removal, global warming, human health, metal depletion, ozone depletion, smog, and evaporative water consumption [107]. They concluded that except ozone depletion, remaining categories in RWHS performed better than MWS system. Environmental and economical optimization of a residential building's rainwater harvesting system and wastewater was performed by Mariana Garcia-Montoya et al. in Mexico. They considered total annual cost, freshwater consumption, and environmental impact in their investigation [109]. Similarly, Rashidi Mehrabadi et al. investigated the performance and applicability of buildings' RWHS in three different climates of Iran [95]. Caleb Christian Amos et al. developed an economic tool to perform a life cycle cost evaluation on daily performance of RWHS. The result highlighted that the economic feasibility of such system depends on regional freshwater cost [120]. Economic performance of RWHS was investigated by lani et al. in Malaysia [121], where the authors developed a stochastic approach in relation to tank size and water consumption in commercial building. They showed that RWHS is more efficient in large building compared to small buildings. In a review performed by Campisano et al. three priority challenges in design of RWHS were addressed consisting of adequate empirical data of system operation, maintenance aspects, and institutional and sociopolitical supports [122]. Foo et al. used analytical and computational fluid dynamic modeling to investigate a wall-mounted RWHS. They highlighted that the proposed model can be integrated well into urban stormwater system [123]. Similarly, Palla et al. proposed a hydraulic–hydrologic model to integrate domestic RWHS into urban stormwater runoff control in a residential building in Genova, Italy [124]. De Gois et al. studied the viability of gray water reuse integrated into RWHS in a shopping mall in Brazil. In this study, a simulation method was used to consider proper volume of rainwater in order to use in water supply system [125].

12.3 Discussion and Conclusion

In this chapter, recent research on various models of buildings with zero energy and water were investigated and definitions related to these concepts have been analyzed. Also, the solutions that previous researchers have taken to design and operation of these buildings are described. The result shows that an insignificant number of highly efficient buildings exist meeting net-zero condition [126]. In the case of energy, European countries are the pioneer, and a number of real case studies that implemented net ZEB strategies are higher in European countries than other countries, and it seems that EU energy-saving policy is one of the main reasons for this. Although other countries in the world are increasingly interested in the topic, in the case of water, there are numerous strategies adopted to decrease water consumption and increase water saving in buildings, but rarely real cases are found for net ZWBs. It is claimed that Silicon Valley—a global center for high technology, innovation, and social media in California—is the first net-zero campus [127]. One of the main reasons for little welcoming to net ZWBs can return to boundaries. The net-zero water boundary includes potable and non-potable water consumption, alternative water sources on the site, freshwater supply, alternative water supplement, and water returned to the original water resource like watershed or aquifer. If the building is not within the watershed or aquifer, then returning water to the original water source will not be plausible.

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Chapter 13
Food, Water and Energy Nexus a Pulpit for Implementing the Sustainable Future

Ali Asghar, Muhammad Shafqat Rasool, Talha Younas, Muhammad Basit, and Anwaarul Haq

13.1 Introduction

The water, energy and food nexus in accordance with the Food and Agriculture Organization (FAO), is an approach in which water, energy and food security are closely interdependent on each other, meaning that the outcomes of actions taken in one particular area can be easily seen in another particular area. All of these three areas (water, energy and food security) play a vital role in the benefit of humankind, for opposing poverty, and for the promise of a better future ahead. As the world's population is increasing, the demands and the basic needs of the population is also increasing. The competition for vital resources is becoming apparent and relatively urgent [1].

13.2 Food Waste

Food waste has become a major problem in this modern era of scientific developments,which has resulted in far more critical consequences. These consequences lead to food insecurity and environmental crisis. Their impact on environmental quality and social rights depict many inefficiencies and side effects on many levels. Food waste pertaining to food insecurity is a complex issue. The solution to this problem would require a technical approach, public intervention, and an incentive structure study. These approaches can be made effective at three levels: first, educating relevant individuals about incentives along with motivation for proper

A. Asghar (✉) · M. S. Rasool · T. Younas · M. Basit · A. Haq
National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan
e-mail: Ali.asghar@uaf.edu.pk

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waste behaviours; second, by focusing local governance mechanisms on the problem; third, making large-scale investments for technological advancement to prevent wastage and establish alternatives to useful energy and material. It is difficult to completely eliminate food wastes but a proper understanding of what should be disposed and what should be utilized can be made [2].

Food waste comprises materials that, after human consumption, are intentionally discarded, wasted, deteriorated or contaminated. The issue concerning food waste is skewed every year, which sets negative stress on major sectors including waste management, food supply chain management, agricultural and industrial bodies, as well as consumers and retailers. Many solutions can be formulated to cope with this problem including appropriate waste management relevant to food; avoiding donation of edible fractions to social services; utilization of food waste for production of biofuels in industries; by composting, landfilling and incineration [3].

13.3 Food Waste Management

The key sustainability challenge for developing better services in the food industry is reduction of food waste. Using new ideas and innovations can play a significant role in reducing waste in the food service industry [4].

The proper use of these wastes is necessary so that resources can be used effectively. Day by day, the population is increasing and it will be 9 billion by the year 2050.This increasing population poses major challenges to humans; one of them is scarce resources. Food for everyone is a major challenge. In order to provide safe and secure food to this expanding population, there is a need to use our resources sensibly. Food, energy and water insufficiencies are critical issues that our society faces. There is less land to produce food, and freshwater is becoming insecure. Meeting these imminent needs will require secure supplies of food, which is interdependent on energy and water. A newly designed food, energy and water nexus approach and appropriate use of limited resources can help in food security management [5].

13.3.1 Water Crisis

Water is a resource that follows the principle of natural circulation. Although natural and artificial reserves of water are useful for meeting the demands of human communities, the use of these resources must be efficient. The speed of circulation of renewable freshwater resources (RFWR) is limited by climatic effects. Despite this limitation, approximately two billion people are facing water problems because the RFWR is uneven in space. Climate change may have an effect on the water cycle, thereby indirectly increasing RFWR. This will delay water problems being faced by people living in areas where water is a scarce resource [6].

The increasing demand for water for production of food and other human demands puts a dramatic stress on various water supplies. In many areas where there is a shortage of water, approximately one billion people are facing water insecurity. Moreover, 90% of diseases are the result of water pollution. About 70% of freshwater reserves are being utilized by agriculture. For example, about 264.172 G of water is required for the production of 1000 g of grains [7].

Water insecurity is prevailing in most developing countries. Water extraction has increased with the increase in population, industrialization, land use for residence and wastage of water in agricultural practices, which have caused different water problems. Scarcity of water and inadequacy have increased in many countries. In twenty underdeveloped countries, unavailability of water is being faced by 1.2 billion people. Problems regarding water uncertainty can be divided into three main areas: availability, access and use [8].

For human survival, water is the key element. However, freshwater is not freely available. Unnecessary wastage from industries and surface runoff are major hurdles to freshwater availability. One out of six people faces water insecurity because the supply of water is too short to meet the demands for drinking water. Here, communities can play an important role in sustainable development and promotion of environmentally friendly behaviour by asking the government to make changes that are urgent and necessary. Water loss starts with humans themselves due to irresponsible behaviour; most of the behaviour is not adaptive and psychology plays an important role in overcoming this problem [9].

Fast growing population and migration to urban areas in developing countries have created an urgent need to create a centralized water system that distributes drinking water to the population. Protected water sources and well maintained modern drinking water treatment plants can supply water which is suitable for human consumption. However, an inadequate system of aging, stress, or distribution can cause a decrease in the quality of drinking water to an unacceptable level and pose a serious health concern. The shortcomings of the distribution system in developing countries are caused by unsuccessful disinfection of water or maintenance of suitable disinfectant residues; low pipe pressure, routine care, excessive network leakage, corroded sections; inadequate sanitation and uneven pricing and use of water. By increasing research, monitoring and control, a better understanding of the lack of a distribution system can be obtained. This will channel limited resources to key areas to improve community health status and reduce disease globally [10].

In areas that have high water pressure and large aquifers, additional supply is met by groundwater. However, if groundwater usage is excessive, it will lead to more unresolved water problems [11].

13.3.2 Food Crisis

Food safety is a growing global problem. It has been estimated that more than 1 billion people do not have enough nutritional energy and at least twice as many suffer from lack of food. With indicators stressing the need for action, many recent studies have aimed to improve the measurement of food insecurity. However, estimates of prevalence rates and patterns remain weak, because measures of food security, concepts that are difficult to understand, remain difficult [12].

Combating climate change or climate change in the future with its varying complex structure and patterns must be understood comprehensively [13].

The food system also contributes significantly towards the emission of greenhouse gases during the stages of food production and food processing, supply to retailers and wastage. Additionally, large-scale food production leads to loss of biodiversity and water pollution. Policymakers are increasingly aware of the need to address this problem; however, at the same time, they face an increasing burden on the issue of food and nutrition security and need to ensure that sufficient food is available to fulfil the demands of the rising population. In other words, more people need better nutrition with fewer environmental impacts. How can this be achieved? In general, three main aspects ("takes") or perspectives on this issue and their interactions can be outlined. The problem can be seen as a production challenge. In this case, the way food is produced must be made more efficient. Processing chellege involve to mke the food safe and challenges for consumption require changes in the drivers of nutrition [14].

By estimation, one-fourth of British-made food is wasted between the time it leaves the factory and until it is served to consumers on a plate. Osner considers the energy gap unstable when and where food loss occurs and discusses ways to reduce and restore waste [15].

An international literature study has shown that there is very less information on food wastage and estimations on it vary greatly. For example, post-harvest losses in under-developed countries can be overvalued. This is because most of the information on post-harvest losses in underdeveloped countries has been collected approximately 30 years ago. Moreover, current worldwide losses are not measurable. Post-harvest losses in underdeveloped countries are greater compared to those in developed countries which are also represented by limited data. For rich economies, the biggest loss is food waste after consumption. To consolidate the fragmentary picture and views on food wastage, a study was conducted through interviews by internationally recognized FSC (Food Security Center) experts. This analysis highlights the extent of the problem, the potential to improve efficiency, and the major challenges associated with behaviour change in order to reduce waste after consumption by rich population [16] (Table 13.1).

Table 13.1 Possible wastes from food water and energy sources

	Resources	Possible wastage
Food	Natural: Fruits, vegetables, meat, milk, etc. Synthetic: Industries; fruit juices, jam, jelly, snacks, cereal-based food, dairy products	Post-harvest losses of fruit and vegetables due to mishandling Mishandling of food products during distribution Useful fruit peels are discarded like banana peel that has important phenolic contents Milk wastage due to mishandling Meat oxidation and wastage due to low quality Decreased shelf life of food products packed poorly Useful material being discarded to get desired food products.
Water	Natural: Lakes, ponds, oceans, etc. Synthetic: Industries	Industrial wastes and spill being thrown into water. Unnecessary use of water for bathing, handwashing. Wastage of water at industries to wash fruit and vegetable Sewage water is mixed with fresh water without treatment
Energy	Solar Nuclear Wind Water Artificially available	More food and water wastage mean more energy wastage.

13.3.3 Energy Crisis

The task of significantly increasing energy availability to three billion people in developing countries who consume energy besides those in developed countries has become a major global problem. Different perspectives are presented, starting with a global and shared view on how to obtain energy resources and how to use them; this will determine the extent of the problem. This is followed by national profiles from Asia, Africa, and Latin America. Energy from the two most populous countries in the world (China and India) and the largest country in Latin America (Brazil) is under consideration [17].

Millions of people around the world have no access to a clean and modernized energy system, which leads to bad health, and sometimes death. However, as lack of energy has less influence on the health and well-being of the people and their productive capacity and education, coping with this problem is a low priority for governments and donors. This hidden energy crisis shows why we fail to expand access to energy for the poor in the world and offer business models that have greater potential to make a difference. It has been argued that meeting global basic needs for energy poverty would not cause significant differences in global CO_2 emissions.

However, international donors, multinational companies and national governments will need significant effort and funding to dramatically increase the number of pilot projects that are successful and significantly impact the poor. The hidden energy crisis is a call to action against the energy crisis. It must be answered by politicians in government and donor organizations and academics, students and program managers [18].

13.4 Water, Food and Energy Interdependencies

Policies made for energy, water and food have many links to ongoing problems relevant to price volatility. These problems manifest themselves in different "zones". Identification of these relationships from the start is very important to control synergistic effects and avoid possible undesirable outcomes. A systematic approach is needed in order to deal with the many possibilities of potential problems. For this purpose, the water, food and energy nexus would be an effective approach to build and upgrade policies along with regulations. Although environmental problems usually follow the principle of cohesion by looking at different areas together. Large inequalities due to insecurity indicate that solving problems to adequate access to food water and energy can be a stronger driver of change. Finally, the consideration of complex interactions requires new institutional capacity in developed and developing countries [19].

In the twenty-first century, world food production will be doubled in response to the doubling of the population. However, this benefit of food production sacrifices the ecosystem and leaves a significant ecological footprint. Use of excessive fossil fuel along with the depletition of water resources is also causing significant environment related impacts. Information from the literature represented by *Nature*, *Science*, *PNAS* along with other scientific journals are given to detail the problems relevant to water and energy insecurities in world food production. Ecological footprint is very important, locally and nationally and have an impact on world food security and the health status and efficiency of the productivity of ecosystems. Publications are almost all in accord that the different systems of food production result in significant impacts, and this situation tends to be alarming because the world population will increase by 50% by 2050. At present, investment is needed to eliminate the damaging effects of food being produced in the environment. Investing in increasing water production along with increasing energy production efficiency for crop production may be two ways to decrease the ecological footprint [20].

13.5 Remedies for Food, Energy and Water Problems

The increasing population and higher expectations for everyday comforts will cause a consistently increasing request for good quality metropolitan water and regularly expanding sewage streams. At the same time, increasingly more water will be needed to fulfil the expanding need for food for the developing population. Likewise, increasingly more water will be required for environmental concerns, for example, amphibian life, natural life shelters, human recreation, aesthetics, and riparian living spaces. Therefore, an increased water challenge can be expected. To face this challenge, the broad and universal participation of the whole world is required [21]. Every single relevant factor should be considered in the basic water supply process. Such an all-encompassing methodology requires not just supply management but also demand management (water protection, utilization of water with higher economic returns, and so forth), water quality administration, reusing and reuse of water, economics, climate adjustment, etc.

The following factors can help minimize water problems.

13.5.1 Administration to Oversee Water Usage

There is a growing awareness that the administration of water assets and water administration works all the more successfully with an open social structure which empowers more extensive cooperation between the public, private undertakings and the media, and all systems administrative bodies of the government. Besides, analyzing the job of systems or dispersed administration conquers the sterile discussion about private versus open water administration conveyance and the job of the network. The objective of making an appropriate administrative framework gives the discussion a progressively common-sense core interest. The job of the public and non-governmental organizations (NGOs) will become clearer as government guidelines encourage neighbourhood self-administration. It is significant that in structuring powerful administration frameworks, exchange expenses are not unduly increased and industry is not smothered. There will consistently be trade-offs and it is essential to get the optimal solution for every circumstance as opposed to looking for the perfect framework. In developing countries, administration frameworks must not force an excessive number of limitations on industrial activity, which untimatley can hinder the financial development and the provision of fundamental requirements for the poor. Time and again, well-meaning suggestions to improve water administration have been a hindrance to development. Thus, the monetary and social expenses of administration may be very huge, and care ought to be taken to guarantee that they are practical and they ought to be painstakingly observed. There is no single model of successful water administration; in reality, to be viable, administration frameworks must fit the social, financial and social particularities of every nation. With time, we hope that some fundamental standards or principles that may be viewed as basis for viable water governance set up [22].

13.5.2 The Worldwide Population and Water Supply

The present total population of around six billion is anticipated to practically multiply twofold in the second half of this century. The majority of this population increase will be in the underdeveloped countries, where there are, as of now, a lot of water and sanitation issues and where around 1400 individuals die every hour because of waterborne infections [23].

Moreover, there will be increasingly more relocation of individuals from rural areas to urban communities, leading to uber urban communities with an excess of 20 million individuals that will have super water needs, that will require super sewage streams, and that will have super health issues. As of now, there is a suggestion that individuals in these super urban areas ought to have little gardens where they can develop their very own food and reuse their own waste. There would then be little distinction between uber urban areas with their little nursery type cultivation and rural regions with thick population, particularly like those in the rural edges of urban areas. Every one of these individuals and other creatures that co-habit with them could display genuine medical issues like infections, and different pathogens that typically affect just creatures may move to people. In the event that the creatures are given ordinary dosages of anti-microbials to advance quicker development, immune strains of pathogens could be created which could cause serious human pandemics [21].

13.5.3 Water Reuse

All water is reused through the global hydrologic cycle. Be that as it may, arranged neighbourhood water reuse may prove progressively significant for two reasons [24]. One is the release of sewage effluent into surface water which is becoming more troublesome and costly as treatment pre-requisites become increasingly more stringent to secure the nature of the accepting water for amphibian life, entertainment and downstream clients. The expense of the stringent treatment might be high to such an extent that it turns out to be monetarily appealing for districts to treat their water for neighbourhood reuse as opposed to release the effluent into surface water.

The best water treatment plants are essential for unintruppted non-consumable recyled water, and optional treatment followed by tertiary treatment comprising flocculation, sand filtration and purification (with bright light or chlorination) to ensure that the water is free from pathogens (infections, microbes and parasites). Such tertiary treated water can be utilized for irrigation purpose to enhance the yield of crops, urban water system of parks, play areas, sports fields, fairways, street plantings, and so on., urban lakes, putting out fires, can flushing, modern uses, and others. The tertiary treatment prerequisite was created in California and is followed by most industrialized nations [24].

13.6 Virtual Water

Water-scarce regions can limit their water utilization by introducing crops that consume less amount of water to fulfil thier requirement and they can import electric power from different regions or nations that are abdudant in water resources. The accepting regions at that point get the products and additionally the water that was important to deliver them. Since this water is for all purposes and added in the product, it is called virtual water [25].

The following factors are used to overcome problems related to food.

13.6.1 Global Guidelines on Sanitation and Quality

On a worldwide level, specifically, the Food and Agricultural Organization (FAO), the World Health Organization (WHO), both UN associations and the World Trade Organization (WTO) manage sanitation issues. The point of the Codex Alimentarius (Food Code) is to ensure general well-being and help to improve overall quality. For this reason, gauges are created. The Codex Alimentarius nourishment standard issues run from quality of explicit crude and handled materials to food cleanliness, pesticides deposits, contaminants and marking, to investigation and testing strategies [26].

13.6.2 Open and Private Benchmarks to Defeat Wastage

Giovannucci [27] characterizes models as "characterized parameters that isolate comparable items into classifications and portray them with reliable phrasing that can be regularly comprehended by market members". Models, along these lines, improve the proficiency of business sectors. Benchmarks can be established for any of the procedures in the natural pecking order. In this article, we focus on sustenance principles, in an expansive sense, including social and natural aspects, and their application by different groups in the evolved way of life.

Since the 1990s, there has been a huge interest in establishing sustenance principles. Organizations around the globe are utilizing quality confirmation frameworks to improve their products and generation of products. There is a move from the previous end-of-line item investigation way to a quality confirmation approach where the firms in the natural pecking order accept accountability for the well-being of the end-of-line item through control of their procedures. This implies that quality confirmation is required at each progression in the nourishment generation chain to guarantee safe sustenance and to conform with administrative and client prerequisites. Enactment at global (for example, Codex Alimentarius), international and national levels may provide the fundamental structure and strategic direction for quality affirmation frameworks.

13.6.3 Eurep-GAP

Eurep is an association of more than twenty huge European retailers and buyers associations (for example, Tight, TESCO). Good agricultural practice (GAP) is a bundle of standards that ensure equitable trade and top-notch items. Eurep-GAP gives real consideration to sanitation, human resource and ensures that actual benefit goes to the primary producers. The Eurep-GAP declaration is created to make business firms straightforward. The standards of the Eurep-GAP retailers are more rigid than (EU) administrative requests. Burdens of Eurep-GAP are that it takes the enactment of the nation where it is actualized as a beginning stage and that there is still no uniform affirmation plot. This clarifies why Eurep-GAP executions can vary from nation to nation [28].

13.6.4 Control the Microorganisms

Probiotics are characterized as live microorganisms which when managed in satisfactory sums present a medical advantage to the host [29]. There is a growing collection of clinical proof that these microscopic organisms can decidedly influence certain human well-being conditions, assuming a significant role in the control of irritable bowel syndrome and other intestinal maladies, concealment of endogenous/exogenous pathogens by standardization of the intestinal microbial organization, mitigation of ill nourishment manifestations in newborn children by immunomodulation, bringing down serum cholesterol, improving lactose resilience, and lessening the danger factors for malignant growth in the colon by metabolic impacts [30]. Although explicit numbers are not referenced in the definition, abnormal amounts of these microorganisms are needed in probiotic items [31], given that a significant number of the clinical investigations consider day-by-day dosages of more than 109 cfu/day. Thus, the maintenance of high feasibility during drying presents specific problems in the business of probiotic development. This is especially the situation for "mechanically delicate" strains (for instance, most Bifidobacterium species) with the outcome that most effectively advertised probiotics are typically vigorous in nature. As a general proposal and without "portion reaction" information for some strains, it is recommended that probiotic items ought to contain 107 cfu/g (ml) of bacteria [32]. Most fluid/solidified probiotic societies require refrigeration for capacity and conveyance, adding cost and burden to their limitations. However, these limitations can be eliminated using dry powders, which are conceivably better than the fluid/solidified state of probiotics in their sterility and stability [32].

13.7 Remedies for the Energy Crisis

Significant changes are occurring around the world that have sweeping ramifications on the current equilibria or disequilibria in the water, food and energy interface. The expanded interest of vitality worldwide will ponder legitimately and in a roundabout way the water-subordinate framework. Direct ramifications will originate from higher vitality costs, which make extraction and transport of water all the more expensive. Roundabout ramifications will be an interest in alternative energy sources. These efforts triggers interest in hydropower and remains a noteworthy driver to other natural approaches for biofuel extension. The key question is the manner in which these alternative methods may change water requirement and impact nourishment security, nation needs, and ecological supportability. This paper sets the foundation and setting of this extraordinary issue by featuring a portion of the significant water-related strategy issues identified with the subject and gives an outline and amalgamation of the papers in this unique issue. Other than offering knowledge into how these papers address these inquiries in the useful setting of few chose nations and bowls, this paper likewise shows some key territories for future research on the subject [33, 34].

13.7.1 Wind Energy

The cost reduction of wind energy is a result of immense advances in turbines, gear boxes, industrial apparatus and development in the height of breeze towers. The greatest breeze turbine produces energy up to 7.5 MW; however, most turbines produce 1.5–2 MW of energy [35].

13.7.2 Nuclear Energy

Nuclear power can play a noteworthy role in undertakings to decarbonize the age of energy. Around the globe, nuclear plants produced about 14% of the total electrical power made in 2009 [36]; however, in 2011, this rate dropped to about 12%, with a loss of 180 TWh of energy from Germany and 5.72 TWh in Japan. This loss could be the fallout of the 2011 Fukushima nuclear disaster. A couple of countries that have nuclear reactors are proceeding with caution, although others continue to show interest in setting up a nuclear power programme. A couple of countries have put their nuclear energy plans on hold. Some have chosen to pivot their decision on nuclear power or start orchestrated stage outs. Nuclear energy now provides about 10% of the world's electricity from about 440 power reactors. Nuclear is the world's second largest source of low-carbon power (29% of the total in 2017). Over 50 countries utilise nuclear energy in about 225 research reactors.

13.7.3 Solar Energy

Most sun-controlled cells manufactured today are made of crystalline silicon and have shown efficiencies as high as 23%; however, most cells produce energy within the 17–19% domain. Sun-controlled cells could be more popular if the cost could be decreased and profitability increased. In any case, solar energy is just a single philosophy, fighting with other rapidly emergent systems [37].

By utilizing sun-based energy, we can spare our different resources like water, fossil fuels and so forth. The principal advantage of sunlight-based energy is that we can control the contamination; numerous modern machinery can be kept running on sun-based cells rather than different sources. It is conservative and better for new ventures and forestalls any contamination.

13.8 Conclusion

The world is facing a major problem regarding food and environmental security due to several reasons which are unavoidable. It is very important to understand the role of the food, energy and water (FEW) nexus. Our planet's population is rising at an alarming speed especially in the developing countries and this is also a threat to the resources of food and environment. All these challenges require out-of-the-box solutions using technology and science to sustain and renew the rapidly depleting resources. There is a need to reduce gaps and bring the use of modern scientific knowledge and techniques to grassroot levels so that the public can be made aware about this menace and learn to use natural and renewable resources in order to give this planet in a better shape to our future generations.

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Chapter 14
Security Interactions of Food, Water, and Energy Systems: A Stochastic Modeling

Alireza Akbari-Dibavar and Behnam Mohammadi-Ivatloo

14.1 Introduction

According to the last reports of the Food and Agriculture Organization of the United Nations, on average, more than 70% of the world's fresh water is used in the agriculture industry. It is also reported by the United Nations that 1.2 billion people do not have safe water; however, the population in 2050 is estimated to increase up to more than 9 billion people and it can be predicted that the global water demand will rise, and most people of the world will live difficult lives because of water shortage. On the other hand, about 30% of the global energy consumption is dedicated to the food supply chain (including food production, land irrigation, fertilization, packaging, and food storing); at the same time, around 8% of the total energy is used for water lifting and transportation process [1]. Usually, energy and water are the inputs and food is the output of the food supply chain [2].

The main energy generation units are nonrenewable; they use fossil fuels such as coal or natural gas that produce environmental pollution, in particular, CO_2, which contributes to greenhouse gases (GHGs) production [3]. Moreover, the agriculture sector contributes about 30% to GHG pollution and its contribution increases 1% every year [4, 5]. For example, India's agriculture system produces about 6% of the national emission from lifting water for irrigation [6]. Hence, food, energy, and water (FEW) are interdependent sectors and this interdependence creates the concept of a FEW nexus. Resource limitations, population growth, climate change, and the GHG emission boom are serious grounds for reliable, sustainable, and resilient planning of water and energy resources to meet the socio-economic demands on these scarce resources [7].

A. Akbari-Dibavar (✉) · B. Mohammadi-Ivatloo
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: a.dibavar96@ms.tabrizu.ac.ir

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The optimal integrated planning of a nexus is very complicated task because of the interdependency of the food, energy, and water sectors and various other economic, political, technical, climate, cultural and social factors [8, 9]. A nexus management model should be able to consider a trade-off between the three sectors and the cost of operation to demonstrate the optimal pattern of supply and consumption of water, energy, and food. The results of the studies can be analyzed by politicians, decision-makers, and governments who would then guarantee the security of the FEW nexus by establishing forward-looking policies. In the context of nexus management, future strategies of utilizing different sources, the uncertainties of demand forecasts in energy, food, or water sections, and allowable emission production should be investigated. This can be accomplished by qualitative or quantitative methods. Qualitative studies are generally ontological surveys to answer fundamental questions, while quantitative researches are ideal for optimization, cost-benefit studies, and management of the FEW nexus [10].

Quantitative studies of nexus management are suitable for decision-making because they present numerical results that are useful for analysts, and these results show the interconnectivity of water, energy, and food sectors by quantities and their dynamics. For instance, in an effort to measure the sustainability of a FEW nexus, Karan and Asadi [14] introduced the concept of an integrated FEW nexus sustainability index to see how the interconnection and cooperation of the components of a nexus can affect the system's sustainability. However, the important point is managing of existing resources in a sustainable and secure way. An integrated modeling of FEW nexus is proposed by Tian et al. [15], which uses the economic, ecosystem, and climate models to investigate the trades-off between FEW nexus benefits and economical and environmental costs. A deterministic linear optimization framework is proposed by Zhang and Vesselinov [16] to integrate the three sectors and also considering the control of GHG pollution. The presented optimization finds the optimal trajectory of the nexus system and provides an excellent insight into future planning. A game theory-based linear programming is proposed by Namany et al. [17], it considers the technology selection and resource allocation of a FEW nexus, where the first problem investigates the best combination of technologies considering environmental issues, and the second problem considers the availability of the resources, prices, and competitions. The optimal planning of a small-scale FEW nexus (about an average family) is investigated by Karan et al. [18]. The considered FEW nexus is relatively autonomous, in which the water can be recycled and energy is generated through domestic solar systems. The dynamics of the three sectors are modeled in detail and the cost of the system is optimized for two climate conditions, that is, a cloudy and humid scenario and a sunny and arid scenario. Wanjiru proposed and compared [19] an open-loop optimal control and a closed-loop model predictive control for the water-energy nexus in buildings; the aim was to minimize the operational costs of the water pumps for urban building end-users. As water plays essential roles in the FEW nexus, water forecasting is a vital task, which can be done by using a rainfall runoff (RR) hydrological model, for example, and the accuracy of water simulation can be affected by the model. Kan et al. [20] propose an optimization method to solve the water quantity simulation and forecasting in a FEW nexus. For water production and consumption, the concepts of “virtual water” and “water footprint” have been proposed, respectively, to analyze the economic aspects [11, 12]. Integrated water resource management is proposed by Ringler et al. [13] in order to investigate the whole life cycle of the water sector. The effects of hydropower generation projects on the FEW security (i.e., electricity generation and water resource development) is studied by Amjath-Babu et al. [21] using an integrated optimization model.

Regarding the whole systems optimization, using a data-driven technique and considering the historical data of the UK consumers, an input-output method is employed by Owen et al. [22] to investigate the interconnection between the water, energy, and food sectors. A comprehensive, holistic platform for urban energy system and FEW nexus is presented by Bieber et al. [23], who use a mixed-integer optimization framework to determine the optimal allocation and investments in technologies of water and energy production tools, while considering the food production costs and CO_2 emission. A fuzzy cognitive mapping approach has been proposed by Ziv et al. [24] in order to model a FEW nexus’s sectors, individually and seamlessly. Considering renewable-based energy sources, Bouadila and Ben Ali [25] propose a fuzzy controller to adjust the ambient temperature of a greenhouse, which directly affects the quality of the produced foods. The minimization of costs of additional energy and water usage for food procurement is assessed by Karnib [26], considering the coefficients of water, energy, and food and their relation to each other. Finally, a detailed review on various quantitative evaluation of FEW nexus is presented by Namany et al. [27], including instructions of algorithms, models, and decision-making tools.

There are many works regarding the subject of FEW nexus elaboration and planning but they mainly discuss the model of interconnection of FEW nexus components, their interactions with each other, and the relationship between different sectors, or they try to optimize the system for small-scales usages, short-term planning while constructing a deterministic formulation to investigate the planning without considering the associated uncertainties (or just by considering two scenarios). However, in this chapter, the aim is to provide a scenario-based stochastic optimization framework to investigate the optimal planning of a FEW nexus. The considered planning is done for a 15-year horizon, which is divided into three five-horizon eras in order to make a tractable problem, in which the sectors (i.e., water and energy) availability and demands are assumed to be equal in each three sub-horizons. The model is solved using General Algebraic Modeling System (GAMS) optimization software [28], and due to the linearity of the utilized formulation, the CONOPT [29] solver is used to solve the optimization problem. In fact, the presented work extends the integrated modeling of the FEW nexus, which was proposed with deterministic formulation by Zhang and Vesselinov [16] to consider the uncertainties more efficiently with a mathematical structure. Figure 14.1 shows the interactions of the considered FEW nexus’s sectors. According to the uncertain characteristics of available resources, the socio-economic demands and production costs, ten scenarios for each one of the sub-horizons are produced using a uniform distribution function, while the amounts of the mean and deviations are collected

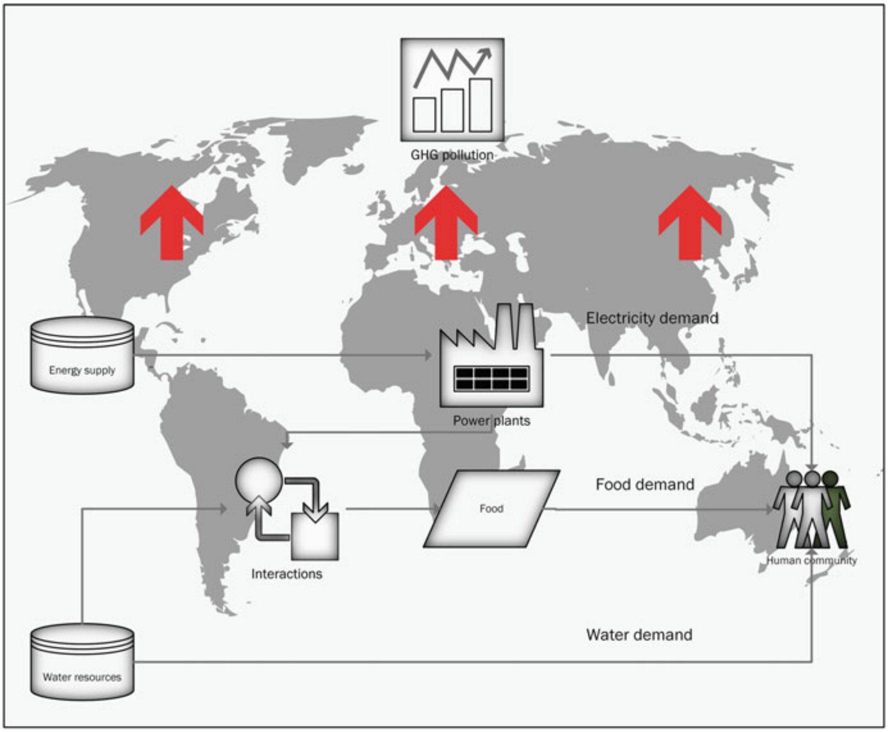


Fig. 14.1 The interactions between FEW sectors

from Zhang and Vesselinov [16]. However, in some cases, in order to increase the robustness of the proposed model, deviations are selected larger than what was reported. The proposed stochastic planning is able to manage the FEW's resources optimally with a robust security margin against undesired uncertainty of costs, demands, and availability.

14.2 Modeling

In this section, the proposed stochastic programming is presented. The objective is to minimize the system's cost during the planning horizon; the total cost consists of five terms: costs of energy and water supply, energy generation, food production, and CO_2 emission reduction as Eq. (14.1) shows.

$$\text{Total Cost} = C_{\text{energy}} + C_{\text{electricity}} + C_{\text{water}} + C_{\text{food}} + C_{CO_2} \tag{14.1}$$

where Total Cost is the objective function of the optimization and consists of five terms: the costs of consumed energy to produce electricity, total electricity production by power plants, required water for electrical and food demands, food production, and finally, GHG (mainly caused by CO_2) abatement cost. In the following equations, Eqs. (14.2, 14.3, 14.4, 14.5, and 14.6), each term is defined in detail.

$$C_{\text{energy}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} \rho(s) \times (\text{AC}_{es}(t,i,s) \times E(t,i)) \tag{14.2}$$

$$C_{\text{electricity}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} \rho(s) \times \left(\text{AC}_{\text{operation}}(t,i,s) \times P(t,i)\right) + \sum_{i=1}^{n} C_{\text{fixed}}(i) \tag{14.3}$$

$$C_{\text{water}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \rho(s) \times \left(W_f^g(t) \times CW_f^g(t,s) + W_f^s(t) \times \text{CW}_f^s(t,s)\right) + \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} \rho(s) \times \left(W_e^g(t,i) \times \text{CW}_e^g(t,i,s) + W_e^s(t,i) \times \text{CW}_e^s(t,i,s) + W_e^r(t,i) \times \text{CW}_e^r(t,i,s)\right) \tag{14.4}$$

$$C_{\text{food}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \rho(s) \times \left(C_{fp}(t,s) \times F(t)\right) \tag{14.5}$$

$$C_{CO_2} = \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} \rho(s) \times \left(\text{CA}_e^{CO_2}(t,s) \times \text{UC}_e(t,i) \times P(t,i) + \text{CA}_f^{CO_2}(t,s) \times \text{UC}_f(t) \times F(t)\right) \tag{14.6}$$

In the aforementioned equations, $\rho(s)$ is the probability of a particular scenario occurring. The decision variables are $E(t,i)$, $P(t,i)$, $F(t)$, $W_f^g(t)$, $W_f^s(t)$, $W_e^g(t,i)$, $W_e^s(t,i)$, $W_e^r(t,i)$, which are the consumed energy in the power plant i(PJ), the produced electrical power by the power plants, which consumes fuel i(PJ), the amount of consumed ground and surface water for food production and the consumed ground water, surface water and recycled water by the power plants with energy supply of i in (gal), respectively, for each sub-horizon t. As mentioned by Zhang and Vesselinov [16], recycled water resources are not utilized by food industries due to the hygienic issues. Other symbols are constant or uncertain parameters. $\text{AC}_{es}(t,i,s)$ is the average cost of the fuel i at horizon t in M$/PJ units; $\text{AC}_{\text{operation}}(t,i,s)$ is the operational cost of the power plants with fuel i at horizon t in M$/PJ; $C_{\text{fixed}}(i)$ is the fixed cost of the generation unit with the fuel i in M$; $\text{CW}_f^g(t,s)$ and $\text{CW}_f^s(t,s)$ are the costs related to the ground and surface water resources consumption in \$/gal; $CW_e^g(t,i,s)$, $CW_e^s(t,i,s)$, and $CW_e^r(t,i,s)$ are the costs related to the consumption of ground water, surface water, and recycled water for electrical power generation in \$/gal. $C_{fp}(t,s)$is the cost of food production for each horizon t(M\$/ton). $CA_e^{CO_2}(t,s)$ and $CA_f^{CO_2}(t,s)$ are the costs of CO_2 abatement that is produced during electricity generation and food production processes; they are expressed in \$/kg and \$/ton, respectively. $UC_e(t,i)$ and $UC_f(t)$ are the unit emission production by the power plants and food industries and are measured in Mkg/PJ and ton/ton, respectively. The parameters, which include the index s, are treated as uncertain parameters in this chapter.

The constraints that create interactions between the energy, water, and food sectors are defined by Eqs. (14.7, 14.8, 14.9, 14.10, 14.11, 14.12, 14.13, 14.14, 14.15, 14.16, 14.17, and 14.18).

$$P(t,i) \times EC(t,i) \leq E(t,i) \tag{14.7}$$

$$E(t,i) \leq A_{en}(t,i,s) \tag{14.8}$$

$$ED_f(t) \times F(\mathrm{t}) \leq A_f^e(t) \tag{14.9}$$

$$ED_w(t) \times \left(W_f^g(t) + W_f^s(t) + \sum_{i=1}^{n} \left(W_e^g(t,i) + W_e^s(t,i) + W_e^r(t,i) \right) \right) \leq A_w^e(t) \tag{14.10}$$

$$\begin{aligned} &\sum_{i=1}^{n} P(t,i) - ED_f(t) \times F(t) - ED_w(t) \\ &\quad \times \left(W_f^g(t) + W_f^s(t) + \sum_{i=1}^{n} \left(W_e^g(t,i) + W_e^s(t,i) + W_e^r(t,i) \right) \right) \\ &\geq D_e(t,s) \end{aligned} \tag{14.11}$$

$$(1-\alpha) \times \left(W_f^g(t) + W_f^s(t) \right) \geq WD_f(t) \times F(t) \tag{14.12}$$

$$(1-\beta(i)) \times \left(W_e^g(t,i) + W_e^s(t,i) + W_e^r(t,i) \right) \geq WD_e(i) \times P(t,i) \tag{14.13}$$

$$W_f^g(t) + \sum_{i=1}^{n} W_e^g(t,i) \leq A^g \tag{14.14}$$

$$W_f^s(t) + \sum_{i=1}^{n} W_e^s(t,i) \leq A^s \tag{14.15}$$

$$\sum_{i=1}^{n} W_e^r(t,i) \leq A^r \tag{14.16}$$

$$F(t) \geq D_f(t,s) \tag{14.17}$$

$$\sum_{t=1}^{T}\sum_{i=1}^{n}\left(P(t,i)\times \mathrm{EP}_e^{\mathrm{CO}_2}(t,i)\times\left(1-\eta^{\mathrm{CO}_2}(i)\right)\right)+\sum_{t=1}^{T}\left(F(t)\times \mathrm{EP}_f^{\mathrm{CO}_2}(t)\right) \leq A^{\mathrm{CO}_2}(s) \tag{14.18}$$

Equation (14.7) shows that the produced electricity is proportioned to the consumed fuel and cannot be larger than that; moreover, the equality is held by the parameter $\mathrm{EC}(t,i)$, which is related to the power plant's technology and is a conversion coefficient. Two kinds of fossil fuels are considered in this system, that is, coal and natural gas. Equation (14.8) shows that the consumed energy must be less than its available amount and $A_{en}(t,i,s)$ shows the maximum amount of available energy source in PJ, which is considered as an uncertain parameter. There is also a limit on the consumed energy for food production, which is forced by Eq. (14.9). $\mathrm{ED}_f(t)$ is the energy demand for producing one unit of food (PJ/ton) and $A_f^e(t)$ is the maximum amount of the energy source allocated for food production (PJ). Equation (14.10) limits the energy consumption for water-related operations, including lifting, gathering, pumping, etc. Similarly, $A_w^e(t)$ is the maximum allocated energy resource for water treatment (PJ). $\mathrm{ED}_w(t)$ is the consumed energy for one-gallon water collecting and delivery (PJ/gal). The generated electricity should meet electric demands, as well as, water and food sectors' energy demands that is considered by Eq. (14.11), and $D_e(t,s)$ is the electrical demand of the nexus in (PJ) which is considered to be an uncertain parameter. Equation (14.12) illustrates the interactions between water consumption and food production. α is a loss constant for water delivery and $\mathrm{WD}_f(t)$ is the water demand for producing one ton of food (gal/ton).

On the other hand, for electricity generation, Eq. (14.13) shows the amount of demanded water. $\beta(i)$ is a loss constant for water delivery to the generation unit i and $\mathrm{WD}_e(i)$ is the water demand for generating one PJ electricity (gal/PJ). Equations (14.14, 14.15, and 14.16) show the limits on available water resources, that is, ground water, surface water, and recycled water. Equation (14.17) guarantees the availability of food for each scenario during the planning time, while $D_f(t,s)$ is the uncertain food demand (ton). Finally, Eq. (14.18) restricts the total CO_2 emission production. In the last constraint, $\eta^{\mathrm{CO}_2}(i)$ is the efficiency factor of the power plant i and shows its ability in emission abatement. $\mathrm{EP}_e^{\mathrm{CO}_2}(t,i)$ is the amount of CO_2 production for generating one PJ electricity (Mkg/PJ); similarly, $\mathrm{EP}_f^{\mathrm{CO}_2}(t)$ is the amount of CO_2 production for producing one ton of food (ton/ton) and $A^{\mathrm{CO}_2}(s)$ is the stochastic maximum allowable amount of CO_2 pollution for all planning times in (Mton).

14.3 Data

The data used in this chapter are real-world information taken from the research conducted by Zhang and Vesselinov [16]. It should be noted that three 5-year horizons are considered consequently in order to simulate a 15-year planning. For each sub horizon, the information of costs, demands, and availability of each resource have been presented in Tables 14.1 and 14.2. Two kinds of electricity generation units, that is, the charcoal and the natural gas power plants are considered; therefore, n is equal to 2. Table 14.1 contains deterministic parameters of the optimization, while the scenarios of the uncertain parameters are presented in Table 14.2. The allowable CO_2 emission production is assumed to be the same for all periods, however, it is an uncertain parameter which is modeled by the scenarios that are shown in Fig. 14.2.

Table 14.1 Required information of constant parameters

Parameter	**Value**		
The fixed cost of the charcoal plant (M$)	65		
The fixed cost of the natural gas plant (M$)	75		
CO_2 abatement efficiency for charcoal power plant	0.8		
CO_2 abatement efficiency for natural gas power plant	0.85		
Water demand in electricity generation by the charcoal power plant (gal/kWh)	0.33		
Water demand in electricity generation by the natural gas power plant (gal/kWh)	0.44		
The loss factor of water distribution for the charcoal power plant	0.1		
The loss factor of water distribution for natural gas power plant	0.15		
The loss factor of water delivery for food production	0.15		
The probability of each scenario	0.1		
Time-related parameters			
	$t = 1$	$t = 2$	$t = 3$
Unit emission production by the charcoal power plant (Mkg/PJ)	261.03	254.89	247.08
Unit emission production by the natural gas power plant (Mkg/PJ)	152.58	149.98	146.19
Unit emission production in food industries (ton/ton)	0.48	0.48	0.48
Water consumption for food production (gal/ton)	659,000	676,000	694,000
Energy consumption for food production (10^{-6} PJ/ton)	2.52	2.64	2.75
Energy demand for water-related operations (kWh/10^3 gal)	3.56	3.79	3.91
Available energy (or electricity) source for food production (PJ)	0.23	0.25	0.27
Available energy (or electricity) source for water-related operations (PJ)	1.00	1.15	1.25
The coefficient of energy conversion to electricity in the charcoal power plant (PJ/PJ)	3.2	3.0	2.8
The coefficient of energy conversion to electricity in the natural gas power plant (PJ/PJ)	2.6	2.4	2.3

Table 14.2 The uncertain parameters' scenarios for each planning time

Parameter	Time	Scenarios 1	2	3	4	5	6	7	8	9	10
The cost of consumed ground water for food production ($\$/10^3$ gal)	1	2.17	1.82	1.81	2.26	2.38	2.12	1.84	2.30	2.01	1.99
	2	2.56	1.84	2.00	2.50	2.46	2.42	2.55	2.53	2.59	2.27
	3	2.97	2.87	2.76	2.39	3.05	2.71	2.91	3.01	2.47	2.51
The cost of consumed surface water for food production ($\$/10^3$ gal)	1	2.26	2.22	2.5	2.42	2.37	1.87	1.91	1.93	2.42	2.58
	2	2.68	2.27	2.71	2.25	2.26	2.65	2.45	2.66	2.73	2.61
	3	3.6	3.14	3.59	4.02	3.76	2.92	3.26	3.27	3.54	3.46
The cost of food production ($/ton)	1	174.38	129.13	131.25	133.90	135.48	154.62	152.79	125.62	172.27	159.13
	2	175.51	139.81	182.86	189.91	200.55	182.75	178.05	165.55	149.75	160.76
	3	160.06	146.38	207.86	170.63	170.33	172.23	178.51	186.85	144.79	198.06
The cost of CO_2 reduction in electricity generation ($/Mkg)	1	12,381	13,486	11,723	12,034	10,242	11,070	12,713	11,666	13,753	10,755
	2	17,179	14,141	14,762	18,600	13,216	13,698	13,876	15,007	15,272	12,208
	3	14,524	15,425	13,467	16,088	15,322	14,509	14,704	18,098	16,728	15,873
The cost of CO_2 reduction for food production ($/ton)	1	12.49	9.62	11.73	11.71	11.17	10.01	11.27	10.42	9.78	10.12
	2	13.51	10.24	11.16	10.07	11.82	9.34	13.52	10.98	10.42	11.40
	3	12.86	11.35	16.38	12.44	12.31	11.00	12.31	10.81	13.02	13.92
Electricity demand (PJ)	1	103.72	104.05	103.65	104.97	104.09	106.32	103.65	103.21	105.15	105.78
	2	114.44	113.94	114.52	114.07	115.03	116.52	115.38	113.54	114.68	113.16
	3	126.00	125.78	126.55	127.00	125.95	125.58	124.62	125.65	126.84	125.75
Food demand (ton)	1	67,076	67,040	66,946	67,000	66,846	67,082	67,050	66,900	66,965	67,090
	2	71,100	70,935	71,019	71,089	71,018	70,938	71,043	70,949	71,099	70,969
	3	74,997	75,076	75,100	74,933	74,148	75,096	74,632	74,722	74,945	75,063
Available surface water (billion gal)	1	33.81	32.96	31.71	32.87	31.32	32.97	33.01	30.09	31.18	31.16
	2	30.93	29.62	30.39	30.11	30.37	29.68	30.91	29.93	30.09	29.35
	3	26.95	28.02	27.19	27.83	27.66	26.73	27.55	28.05	27.01	26.13

(continued)

Table 14.2 (continued)

Parameter	Time	Scenarios									
		1	2	3	4	5	6	7	8	9	10
Available ground water (billion gal)	1	50.9	48.92	51.17	48.69	49.52	50.24	50.22	50.43	50.38	49.83
	2	46.96	48.65	47.33	48.37	49.03	46.68	49.84	46.21	48.94	48.94
	3	45.49	46.11	47.46	45.57	46.8	46.24	46.74	46.77	45.48	45.47
Available recycled water (billion gal)	1	30.26	33.00	31.67	30.95	30.69	29.99	32.99	29.98	31.63	32.89
	2	29.53	29.87	29.95	29.66	29.06	30.65	29.07	30.60	30.90	29.34
	3	27.98	26.94	26.78	27.10	27.70	28.00	26.86	26.62	27.89	26.04
The operational cost of the charcoal power plant (M $/PJ)	1	0.21	0.25	0.20	0.20	0.22	0.19	0.21	0.23	0.21	0.22
	2	0.21	0.23	0.19	0.21	0.17	0.21	0.21	0.21	0.22	0.24
	3	0.27	0.26	0.29	0.26	0.21	0.22	0.28	0.25	0.28	0.23
The operational cost of the natural gas power plant (M$/PJ)	1	0.56	0.57	0.45	0.57	0.53	0.46	0.55	0.51	0.49	0.50
	2	0.49	0.51	0.46	0.57	0.52	0.56	0.58	0.55	0.55	0.54
	3	0.49	0.55	0.61	0.61	0.52	0.51	0.56	0.57	0.54	0.53
Average cost of coal supplies (M$/PJ)	1	4.80	1.06	3.8	3.76	3.08	1.57	3.21	2.11	1.28	1.72
	2	4.99	2.82	2.00	2.65	2.84	2.33	5.01	1.76	1.04	2.30
	3	3.04	1.17	7.41	2.52	2.36	0.74	2.37	1.51	3.24	4.36
Average cost of natural gas supplies (M$/PJ)	1	5.52	1.56	1.42	6.53	7.83	4.93	1.82	6.95	3.74	3.45
	2	6.56	4.77	4.84	6.01	5.58	5.09	6.44	6.27	6.84	3.55
	3	6.58	5.63	4.57	1.21	7.29	4.16	5.98	6.96	1.96	2.27
The cost of consumed ground water for electrical power generation in the charcoal power plant ($\$/10^3$ gal)	1	2.24	2	1.9	1.79	2.22	1.9	2.01	2.1	1.92	2.15
	2	2.48	2.23	2.68	2.17	2.36	2.31	2.51	2.16	2.43	2.18
	3	2.62	3.21	2.82	3.06	3.52	2.93	3.13	3.19	2.93	3.1
The cost of consumed ground water for electrical power generation in the gas power plant ($\$/10^3$ gal)	1	1.54	2.01	1.59	1.64	1.9	1.74	1.88	1.7	1.64	1.44
	2	2.29	2.15	2.16	2.25	1.85	2.09	2.35	2.3	1.94	1.94
	3	2.27	1.99	2.57	2.72	2.77	2.64	2.3	2.71	2.32	2.33

The cost of consumed surface water for electrical power generation in the charcoal power plant ($/$10^3$ gal)	1	1.59	1.63	1.65	1.66	1.73	1.73	1.68	1.7	2.05	1.92
	2	2.22	1.99	2.01	1.88	2.49	2.31	2.22	2.08	1.98	2.26
	3	3.15	2.33	2.4	2.5	2.2	2.69	2.51	3.11	2.51	2.65
The cost of consumed surface water for electrical power generation in the gas power plant ($/$10^3$ gal)	1	1.96	2.11	1.96	2.33	2.43	2.1	2.29	2.06	2.2	2.39
	2	2.74	2.56	2.53	2.64	2.62	2.57	2.71	2.84	2.62	2.62
	3	2.79	2.53	2.98	3	3.27	3.69	3.63	3.12	2.93	3.38
The cost of consumed recycled water for electrical power generation in the charcoal power plant ($/$10^3$ gal)	1	4.44	4.42	4.42	3.63	4.35	4.11	3.82	3.61	4.54	3.76
	2	3.94	4.56	4.92	4.39	4.6	3.92	5.1	4.41	4.57	3.59
	3	4.92	4.82	3.99	4.55	4.32	4.57	4.4	4.42	4.11	4.22
The cost of consumed recycled water for electrical power generation in the gas power plant ($/$10^3$ gal)	1	3.44	4.94	4.49	4.97	3.9	4.93	4.68	4.4	4.25	4.04
	2	4.78	4.15	3.8	4.81	4.68	4.73	4.64	4.39	4.36	4.88
	3	4.44	5.08	5.03	5.15	4.67	4.82	5.43	4.59	3.94	5.18
Availability of coal (PJ)	1	283	287.85	288.04	290.11	284.92	282.8	282.86	282.26	287.03	283.88
	2	264.74	265.95	268.68	262.38	266.51	265.52	264.55	268.17	264.28	262.56
	3	240.82	240.76	238.93	242.05	247.87	244.98	237.26	238.24	235.24	240.65
Availability of natural gas (PJ)	1	128.49	127.66	129.28	128.18	126.81	129.89	128.1	128.81	129.63	128.53
	2	117.74	116.69	117.56	117.63	116.83	114.59	116.49	116.78	116.28	116
	3	105.97	104.81	106.28	104.71	105.77	104.73	105.92	105.73	104.67	104.18

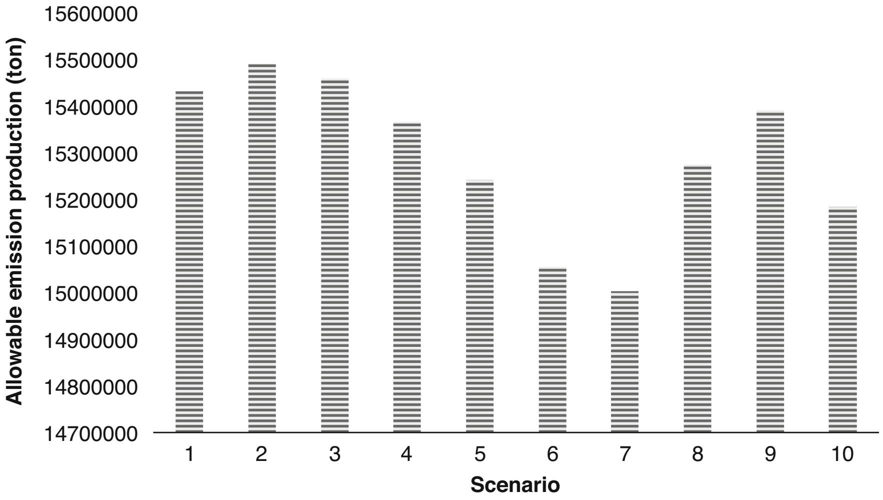
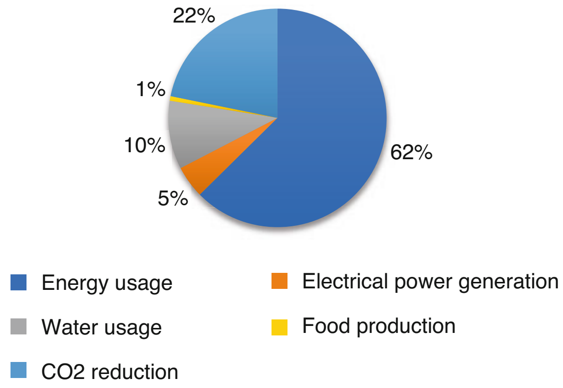


Fig. 14.2 Scenarios of the allowable GHG emission production in all periods

Fig. 14.3 The share of each sector from the total cost



14.4 Numerical Results

The proposed linear stochastic programming, including Eqs. (14.1, 14.2, 14.3, 14.4, 14.5, 14.6, 14.7, 14.8, 14.9, 14.10, 14.11, 14.12, 14.13, 14.14, 14.15, 14.16, 14.17, and 14.18) are solved via the GAMS optimization package, and the obtained results are presented in this section. The total expected cost of the nexus over 15 years is estimated at around 5.2 billion dollars. Figure 14.3 illustrates the detailed costs. As can be seen from Fig. 14.3, the cost of energy supply for electricity generation and the cost related to the food production have the highest and the lowest shares of the total cost, respectively. After energy supply cost, the emission reduction cost has the highest contribution.

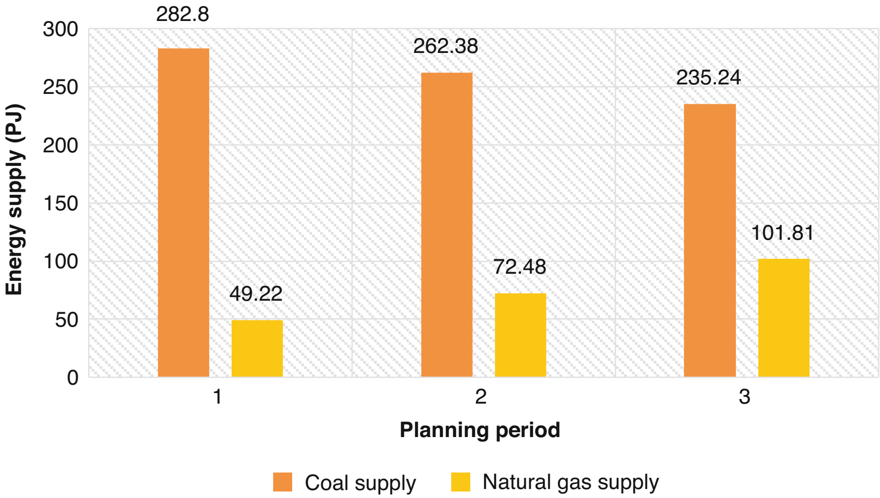


Fig. 14.4 The consumed energy for electricity generation

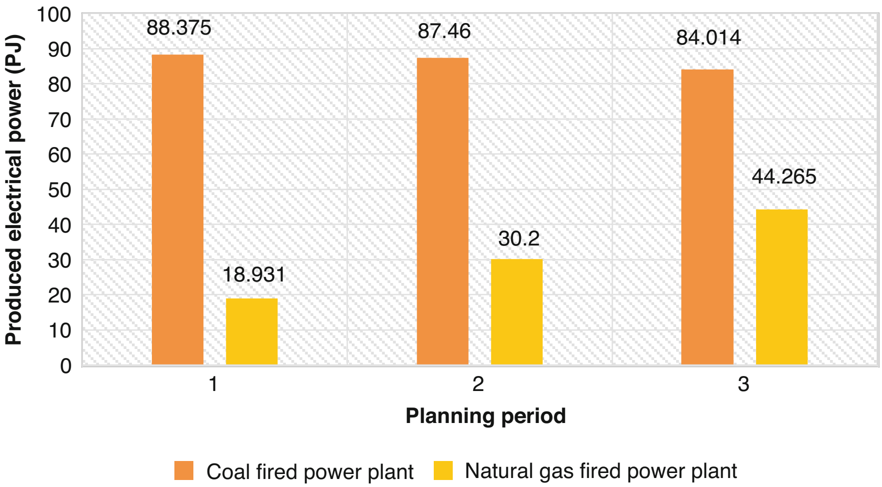


Fig. 14.5 The generated electricity by each power plant

Conservative conditions are determined by constraints Eqs. (14.11) and (14.17) for electricity and food demands; as a result, the produced electricity and food is the maximum according to the scenarios. The electricity generation should meet the electrical demands and other demands related to water and food operations. Hence, the total generated electricity is determined as 107.306, 117.66, and 128.28 PJ for each planning time. On the other hand, the food optimal production amounts are 67,090, 71,100, and 75,100 tons for each sub horizon. Figures 14.4 and 14.5 show the consumed energy for electrical power generation and the generated electrical

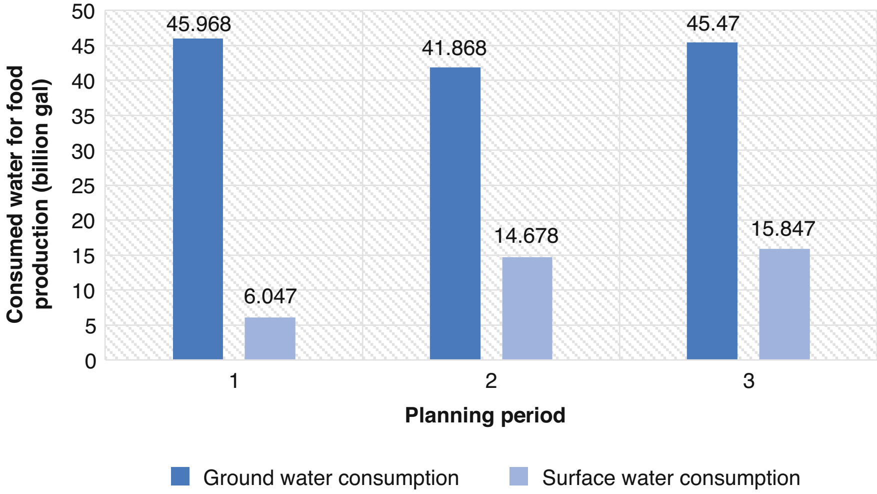


Fig. 14.6 Water consumption for food production

power from the charcoal and natural gas plants for three planning times, respectively. Due to the lower cost of the coal, the charcoal power plant has the main contribution. However, over time, the production of the natural gas plant increases gradually.

Figure 14.6 depicts the consumed water for food production. The figure shows that the ground water resources are utilized more than surface resources for food production. Finally, Fig. 14.7a, b display the consumption of different water resources for electricity generation by the charcoal and natural gas power plants. For electricity generation, different water resources are used according to the type of power plants. From the comparison between the consumed water in food and power industries, it is clear that food production needs about six times more water resources than electricity generation. In the electricity generation side, due to the variety of scenarios regarding water availability, the emission reduction, and energy sources availability, various patterns have appeared.

14.5 Conclusion

In this chapter, a stochastic programming approach is proposed to solve the integrated FEW nexus planning problem. The uncertainties of energy and water resource availability, related costs, demands, and allowable emission production are modeled by scenarios that are generated based on real-world data using a uniform distribution function. The proposed optimization framework is formulated as a linear programming (LP) problem, which gives optimal solutions. The planning is considered for a 15-year horizon, in which each sequence of 5 years is treated as a single planning period. The objective is to minimize the total expected cost of the system over the planning time and includes the costs of energy consumption for electricity

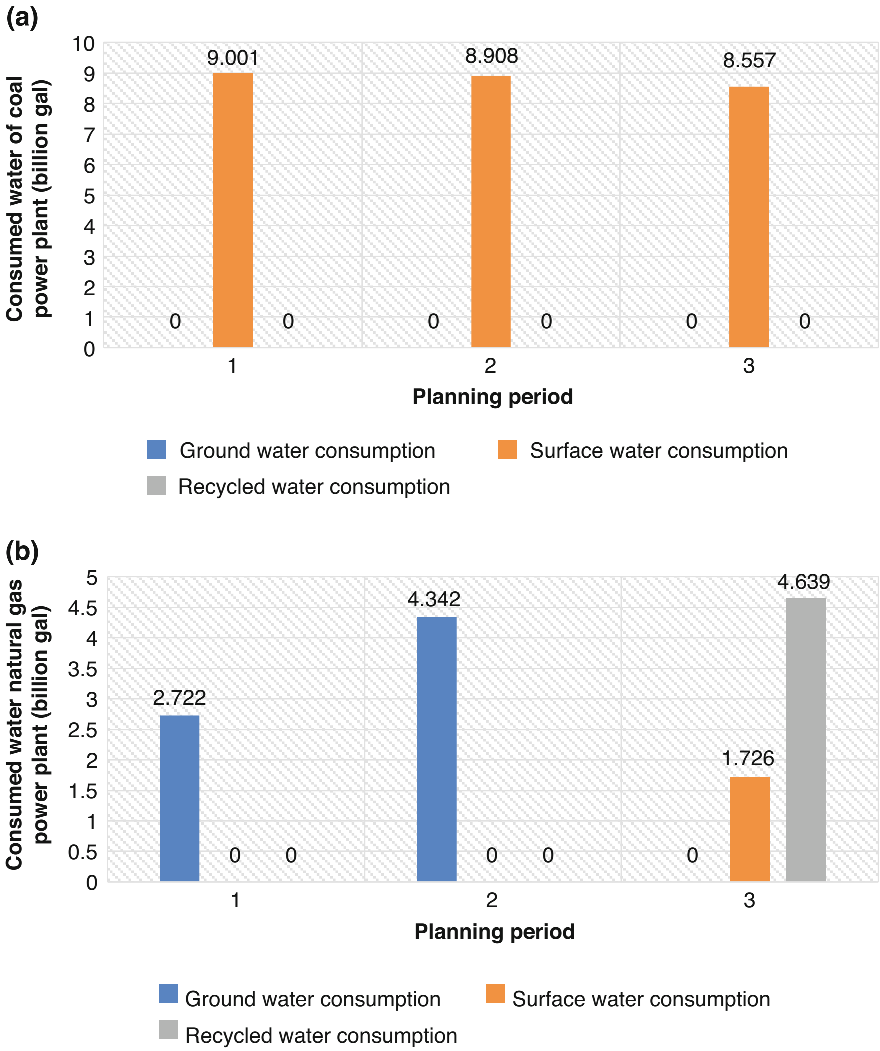


Fig. 14.7 The consumed water in the power plants: coal (**a**) and natural gas (**b**)

generation, power plants operation and fixed costs, water consumption, food production, and CO_2 emission reduction. By solving the proposed stochastic optimization, the optimal values of energy consumption, electrical power generation by each power plant, water resources utilization pattern, and optimal food production are obtained considering the environmental effects, simultaneously. According to the current and future demand scenarios for the electricity and food sectors, and considering the limited resources of energy and water, the presented integrated stochastic model will guide policy-makers to schedule different nexus resources to keep the nexus interactions secure, which will consequently lead to reduction of GHG emissions.

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Chapter 15
Beyond Carbon Emissions: A System of Systems Approach to Sustainable Energy Development in East Africa

Amanda Kahunzire, Maral Mahlooji, and Kaveh Madani

15.1 Introduction

The global warming tragedy is largely attributed to the prolonged use of cheap but highly carbon-intensive fossil fuels to generate energy. Consequently, mitigation actions in recent years have prioritized the investment in 'clean' low-carbon renewable technologies to satisfy the energy demand of the world's expanding population. Some countries have already increased the share of renewables in their energy mix, registering substantial drops in greenhouse gas (GHG) emissions. For example, EU's 20-20-20 strategy aims at advancing the contribution of renewables in the region to 20% and increasing energy efficiency by 20% in order to lower GHG emissions by 20% by the year 2020 from 1990 levels. This initiative has been highly successful with a 23% reduction in GHG emissions already reported in 2015 [18].

While the benefits of renewables to the atmosphere and emission reduction have been proven, very little has been said about their impact on other vital natural resources. In the past, blind focus on cost efficiency favored cheap fossil fuels, and this in turn had grave results for the climate. As today's decision makers focus on fighting climate change, it is imperative to learn from past mistakes and avoid causing unintended consequences [25] in other vital sectors while fixing one aspect.

A. Kahunzire
Energy Futures Lab, Imperial College London, London, UK

M. Mahlooji
Centre for Environmental Policy, Imperial College London, London, UK
e-mail: maral.mahlooji12@ic.ac.uk

K. Madani (✉)
Centre for Environmental Policy, Imperial College London, London, UK

The Macmillan Center for International and Area Studies, Yale University, New Haven, CT, USA
e-mail: kaveh.madani@yale.edu

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To achieve sustainable energy production, decisions about decarbonization of energy mixes should take into account the short- and long-term implications of various energy sources on a holistic suite of critical resources.

Energy production does not only interact with the climate but is also highly intertwined with other systems such as water and land. These systems impact each other through complex and dynamic relationships [74]. With the current global population of 7.7 billion [98] which is expected to rise by over 30% to 9.7 billion by 2050 [80], the pressure on water and land resources will increase. Decisions made today in the energy sector can either reduce or exacerbate these stresses owing to the Climate-Land-Energy-Water (CLEW) nexus. Therefore, overlooking such implications during energy planning processes may lead to disastrous consequences in the long term, causing unintended crises that may threaten human survival.

In order to avoid such negative future scenarios, this chapter applies a System of Systems (SoS) analysis, that considers the aggregated system implications of different energy options and the trade-offs involved in the energy decision-making process [20, 21]. This will support planning for sustainable development, as decision makers gain insight on the implications of today's decisions on future resources. Previous scholars have implemented SoS analysis of different nations and regions such as the U.S. [22], Morocco [75], the Middle East and North Africa (MENA) [44, 57], Persian Gulf [43], and the European Union [69]. All these studies found that the desirability of some popular renewable energies can be lowered when their impacts on other resources are considered. For example, biomass was shown to have severe impacts on land and water systems, thus raising questions over its long-term impacts in areas with limited water and land resources.

This chapter seeks to enrich this area of research by carrying out a detailed assessment of East Africa. The approach, established by Hadian and Madani [20] and improved by Ristic et al. [69], is extended to East Africa by using updated footprint data as well as Africa-specific energy costs.

The desirability of different energy sources for East Africa is assessed through establishing their impact on locally existing resources in the region. The applied analysis framework evaluates energy performance past a series of relevant economic and environmental indicators, namely, carbon, cost, land, and water footprints. These are believed to be the most crucial to the region. It also considers the desirability of energy resources with respect to the resource availability conditions in different countries.

The chapter is structured as follows: Sect. 15.2 provides an introduction to the state of the East African region. Section 15.4 introduces the method applied. In Sect. 15.4, the results are discussed in-depth and Sect. 15.5 concludes the study.

15.2 East Africa

15.2.1 Background

East Africa has a total population of 347 million [6]. Eleven countries reside in the region, namely Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania, and Uganda. It is one of the regions with the lowest income in the world, with over 55 million people living in extreme poverty (under $1.9 a day) in Kenya, Tanzania, and Uganda alone [61]. Despite this, the region is the fastest-growing region in Africa, registering an estimated GDP growth rate of 5.6% in 2017 – well above the continental average of 3.6%, and estimated at 5.9% in 2018, and 6.1% in 2019 [7].

The electricity access rate in the East is only 26% [93], consequently over 250 million people lack access to power. The region also has one of the lowest rates for electricity consumption around the globe. For example, the energy access rate in South Sudan was as low as 40 kWh/capita, compared with UK's 5130 kWh/capita in 2014 [87]. In 2018, the total electricity generation capacity of the region was about 12GW [84, 85]. This is projected to grow to over 55GW by 2040, where a continued dominance is expected from Hydropower (~37%), closely followed by fossil fuel technologies (coal, oil, and natural gas) (~36%) and lastly 'other' renewables (~26%), including biomass and solar PV [26].

East Africa is facing a huge energy deficit and must act fast to close the large gap in energy access, cater to growing populations, and support its rapid economic development. This calls for extensive investments in the electricity sector. As the region embarks on comprehensive energy planning, it has the opportunity to lay the foundation for an energy sector that supports development without negative unintended impacts.

15.2.2 Energy Landscape and East African Power Pool (EAPP)

East Africa is rich in energy resources, ranging from fossil fuels such as oil and natural gas to renewables like geothermal, hydropower, wind, and solar. Currently, hydropower dominates electricity generation capacity (>50%) and oil follows closely (45%). The balance (5%) is made up of a mix of different renewables at a smaller scale including solar PV, wind, and biomass cogeneration [26]. All countries in the region have committed to continuing their investment in renewable technologies [81] and all except South Sudan and Eritrea have ratified the Paris Agreement.

The East African Power Pool (EAPP) is a power-sharing arrangement formed in 2005 with the primary aim of optimizing the use of the region's energy resources in order to avail least cost power to members. Further to this, the body aims to invest in expansive transmission infrastructure in order to transfer low cost power from generation sources to load centers [15]. This will facilitate electricity trades across countries to increase electrification rates in the region. All of the East African countries, except Djibouti, Eritrea, South Sudan, and Somalia, are members of the EAPP.

15.2.3 *Energy Planning Across East Africa*

15.2.3.1 Least Cost Energy Planning

Owing to the low-income levels and scarcity of economic resources in the region, the most common approach to energy planning across East Africa is the least cost analysis. This approach has to-date been applied in Kenya [63], Tanzania [77], Uganda [79], and at the regional level in the EAPP [15].

Least cost energy plans in the region have historically favored hydropower generation. This is because the large hydropower potential in the region, mainly along the River Nile, has allowed the construction of large-scale projects (up to 600 MW in Uganda and 6 GW in Ethiopia), benefitting from the economies of scale. Coupled with the technological maturity of hydropower, the technology has continued to offer the lowest cost power in the region for decades and is foreseen to maintain its dominance in the region's power sector over the next decade [16].

More than half of the new generation capacity is expected to come from large-scale hydropower mainly in Ethiopia and Uganda (see Fig. 15.1). In total, the region expects an addition of 25 GW of hydropower between 2015 and 2030, accounting for about 53% of total added capacity within that period [14]. Geothermal, coal, and gas follow hydropower among the other main energy technologies that have been projected to increase by 2030.

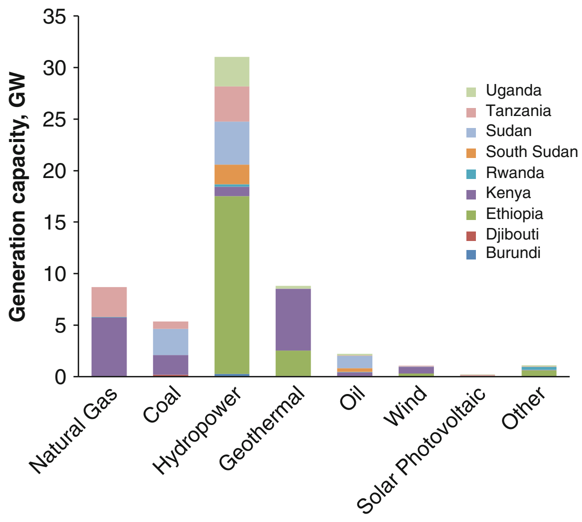

Fig. 15.1 Projected cumulative energy generation capacity of EAPP countries in 2030. (Source: Own translation of EAPP data [16])

A much smaller portion will come from fossil fuels like coal and gas as they become more affordable in Sudan, Kenya, and Tanzania while significant geothermal capacity is expected from Kenya as it scales up existing operations [15].

15.2.3.2 Renewable Energy Plans

As well to least cost energy planning, some countries in the region have recently adopted renewables-centered planning. As part of their efforts to mitigate climate change, countries have developed energy plans for expanding their ‘clean’ energy generation base. For instance, Uganda and Tanzania have created implementation plans for Scaling Up Renewable Energy Program (SREP) [67, 76] that are separate from the existing national least-cost plans.

Comparing the least-cost and renewable-focused energy plans, it is observed that the technologies favored by renewables-focused energy plans vary considerably from those prioritized under the least cost analysis. As an example, in Uganda, renewables-focused approach prioritizes geothermal energy while the least cost analysis prioritizes hydropower. Similarly, in Tanzania, the least cost plan favors natural gas and coal [77] whereas the renewables-focused plan gives precedence to biomass and geothermal.

All these technologies could have their individual benefits, but their suitability varies when evaluated against different criteria. This highlights the major shortcoming of energy plans with a single criterion or limited criteria and emphasizes the need for multi-criteria assessments for informed decision making. This chapter implements an SoS study of energy technologies across East Africa using a multi-criteria decision making (MCDM) framework that has been fostered for analyzing trade-offs under uncertainty [45, 51, 60]. The key objective of the applied decision-making model [69] is to calculate the Relative Aggregate Footprint (RAF) [20] of different energy alternatives based on four performance indicators that represent the climate, land, water, and economic systems. This metric (RAF) communicates the desirability of energy alternatives in the region, with the aim of developing policy recommendations for the future electricity sector of East Africa.

15.3 Method

Energy alternatives that are studied in this analysis include both fossil fuels and renewable technologies. In addition, certain alternatives (such as solar PV) are further broken into distributed and centralized technologies to reflect their respective potentials for rural and urban electrification in East Africa. The assessment criteria selected for this study, namely economic cost, water footprint, land footprint, and carbon footprint, are drawn considering CLEW nexus following the Hadian and Madani [20]. The data used in the analysis are summarized in Table 15.1. These data have been collected from different studies with consistent evaluation methodologies.

Table 15.1 Performance data for the energy alternatives

	Carbon footprint (gCO_2eq/kWh)[a]			Water footprint (m^3/MWh)[c]			Land footprint (km^2/TWh)[e]			Levelized cost of energy (LCOE) (USD/MWh)[f]		
Technologies	Min	Median	Max	Min	Mean	Max	Min	Median[i]	Max	Min	Mean	Max
Biomass	130.0[j]	230.0	420.0	109.0[d]	633.0[d]	1157[d]	557.90	809.7	1254.0	85.0	86.0	87.0
Geothermal	6.0	38.0	79.0	0.0	1.4	2.7	2.10	5.1	10.9	30.0[g]	47.5	65.0[g]
Large Hydropower[k]	1.0	24.0	2200.0	1.1	1530.4	3059.8	16.00	16.9	18.0	61.0	62.0	63.0
Centralized Solar PV	18.0	48.0	180.0	0.0	0.6	1.1	12.30	15.0	16.9	83.0	84.0	85.0
Distributed Solar PV	26.0	41.0	60.0	0.0	0.6	1.1	0.00	0.0[l]	0.0	95.0	96.0	97.0
Solar CSP	8.8	27.0	63.0	0.4	4.1	7.9	12.90	19.3	27.9	102.0	109.0	116.0[m]
Wind – Onshore	7.0	11.0	56.0	0.0	0.0	0.0	126.00	126.9	128.0	81.0	99.0	117.0[n]
Oil	657.0[b]	761.5[b]	866.0[b]	0.8	2.5	4.3	2.00	2.9	4.0	215.0	216.0	217.0
Natural Gas[o]	410.0	490.0	650.0	0.3	2.4	4.5	2.00	2.9	4.0	102.0	114.0	126.0
Coal	740.0	820.0	910.0	0.3	3.9	7.6	0.60	4.0	8.2	105.0	106.0	107.0
Nuclear	3.7	12.0	110.0	0.1	2.6	5.2	0.02	0.1	0.2	110.0	111.0[h]	112.0

Sources: [a]Schlömer et al. [71], [b]World Energy Council [94], [c]Mekonnen et al. [49], [d]Mathioudakis et al. [46], [e]Trainor et al. [78], [f]IRENA [31], [g]IRENA [29], [h]IRENA [30]

[i]All are median values apart from coal, oil and wind where instead, mean values are used

[j] Biomass CO_2 values considered are taken from dedicated plants, instead of co-firing plants

[k]Values for large-scale hydropower

[l]In this study, the land footprint of distributed solar PV, i.e., rooftop solar, is considered to be zero, as it is generally constructed upon an existing building infrastructure, and thus does not involve use of additional or new land

[m]Ranges from LCOE for CSP with storage to CSP with no storage

[n]Ranges from LCOE 30% to 20% capacity factor

[o]Values for CO_2 emission and cost for natural gas are specific to Combined Cycle Gas Turbines (CCGT), costs range from imported gas to domestic

As seen in Table 15.1, most of the performance data were provided in ranges, and some of these may have outliers, which would falsely skew the results if not carefully addressed. Following Ristic et al. [69] and Mahlooji et al. [44], where median is missing or is too close to the mean, a truncated normal distribution is used and where the median of data is significantly different to the mean, a truncated lognormal distribution is applied. To deal with the uncertainty introduced by the ranges across performance values (Table 15.1), a Monte-Carlo selection is employed (as done by Madani et al. [40–42], involving 500,000 random selection of performance values ranking of the energies according to the randomly selected values. There is no single MCDM method that is perfectly suited for applications in the energy sector [56] and each method introduces biases in its approach to evaluating optimality [59]. To minimize such biases, five well-known MCDM methods are applied (namely Simple Additive Weighting (SAW), Maximin, Dominance, Lexicographic, and TOPSIS). Readers are directed to Mokhtari [50] and Madani et al. [40, 41] for the detailed description of these methods. The ranking values are then utilized to calculate the Relative Aggregate Footprint (RAF) of each energy alternative according to the following equation [20]:

$$\mathrm{RAF}_i = 100\left[1 - \left(\frac{A.N - B_i}{N(A-1)}\right)\right] \tag{15.1}$$

where A is the number of energy options, N is the number of MCDM methods used, and B_i is the sum of rankings for alternative 'i' across all MCDM methods used.

RAFs are assigned on a scale of 0–100 and reflect the desirability levels of different alternatives. A low RAF suggests that an alternative is more desirable while a high RAF suggests a less desirable alternative.

In order to develop results relevant to the East Africa region, the local availability of resources in the four selected systems is considered. Following Ristic et al. [69] and Mahlooji et al. [44], the performance evaluation criteria are weighted according to proxies that represent the national resource availability conditions, including carbon emissions per capita [90], annual freshwater withdrawals as a percentage of the internal resource [91], land per capita [88, 89], and the GDP per capita at purchasing power parity [92].

Weights denote the importance of criteria based on the relative availability or scarcity of resources. These weights are calculated by comparison of country-level resources against global benchmark values according to the process explained by Ristic et al. [69]. Generally, countries with high/low availability of a particular resource are assumed to assign a low/high weight to that resource. For example, being a large country, Somalia benefits from high land availability per capita. Thus, a low score is assigned to land footprint when calculating RAF values for Somalia. However, Somalia suffers from severe water scarcity and rightfully a higher weight (priority) is assigned to the water footprint when evaluating the desirability of energy alternatives in Somalia.

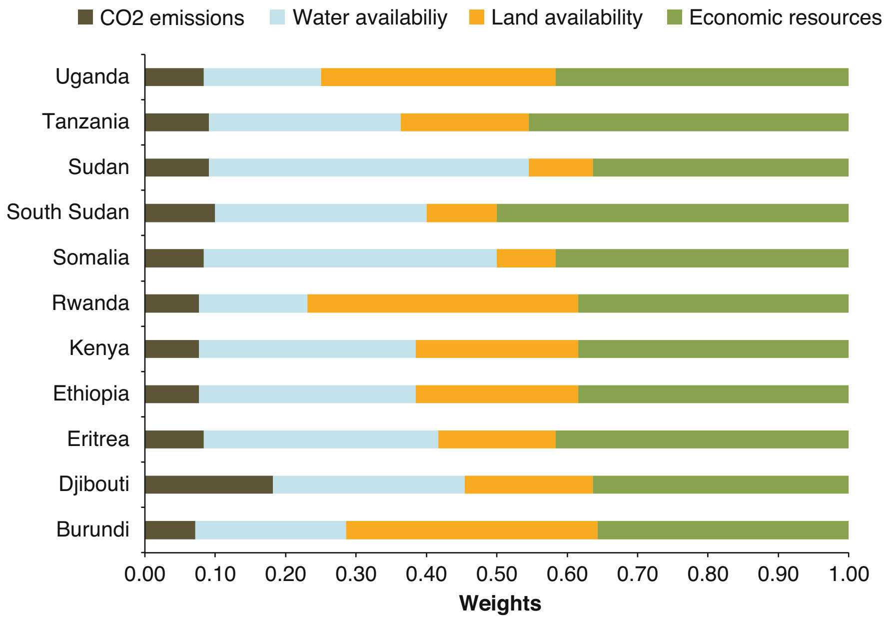

Fig. 15.2 Country-level criteria weights

The calculated weights are summarized in Fig. 15.2. The majority of countries in the region assign the highest weight to cost. This reflects the comparatively low level of economic resources in the region compared to the rest of the world. The exception to this is Sudan, which assigns the highest weight to water, due to its significantly high rate of water withdrawals and low water availability and hence on-going water scarcity. For Rwanda and Burundi, the land is also given equal priority to cost due to the small size of these countries which create additional land pressure with respect to their relatively large population. The calculated weights are used by the MCDM framework to determine the rank of energy technologies during the Monte-Carlo sampling process. For more details about the weighted RAF calculations, readers are referred to Ristic et al. [69].

15.4 Results

15.4.1 Relative Desirability of Energy Sources

Consideration of country-specific weights resulted in an interesting variation in the desirability of alternatives across the region, highlighting the importance of considering local resource availabilities. The relative desirability of energy alternatives for

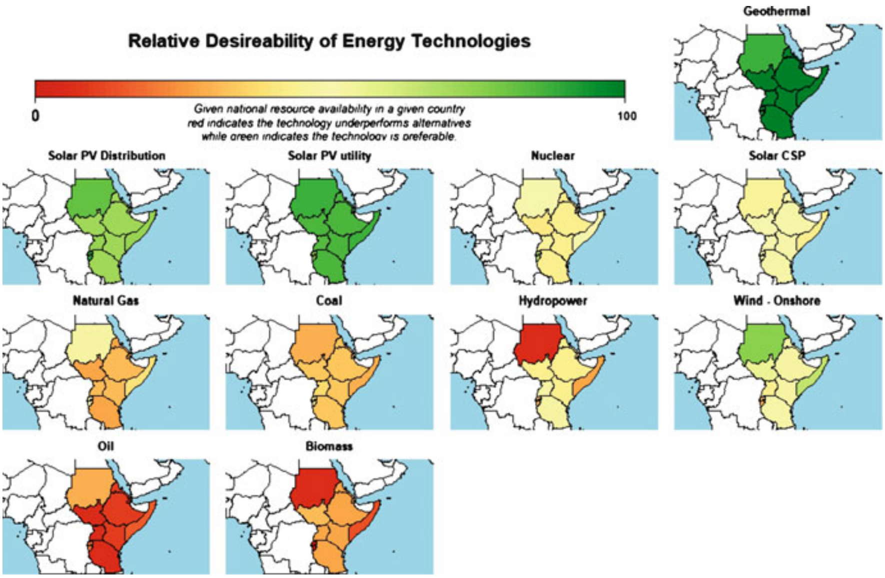

Fig. 15.3 The relative desirability of different energy options across East African

the countries in the region is shown in Fig. 15.3. Relative desirability is defined as the opposite of RAF [20].

Low-carbon energy options such as geothermal and solar PV (both distributed and centralized scale) have high desirability in general. Hydropower, which is very popular in the region, is not highly desirable, while fossil fuels and biomass range from relatively desirable to highly undesirable when their water, land and carbon footprints are taken into account together with the local resource restrictions.

The following sections provide brief insights into the performance of each technology with respect to the available local resources in East Africa.

15.4.2 Geothermal

With a RAF of 0 to 12, geothermal returned the highest desirability for all countries in East Africa. Except for Burundi, Rwanda, and Sudan, the technology had an RAF of 0 (belonging to the strictly desirable energy that outperforms all other options under all MCDM methods) in all other countries.

The region has an estimated potential of over 20 GW of geothermal capacity potential within the Great East African Rift Valley [99]. Currently, only less than 4% of this 20 GW of geothermal energy potential is being exploited in Kenya and Ethiopia [12] while most countries along the Rift Valley are already developing or carrying out feasibility studies for the further expansion of geothermal energy [82].

Table 15.2 Geothermal capacity goals for selected nations in East Africa

Country	Potential (MW)	Target (MW)	Year	Reference
Djibouti	350–650	50	Unspecified	IRENA [32]
Ethiopia	10,000	5000	2037	Lemma [38], pp. 16,18
Kenya	10,000	5000–5500	2031	Republic of Kenya [63], Kenya Ministry of Energy and Petroleum [35]
Rwanda	700	310	2017[a]	African Development Bank [2], Bimenyimana et al. [9]
Tanzania	650	200	2026	African Development Bank [5], Tanzania Ministry of Energy and Minerals [77]
Uganda	450	150	2030	Republic of Uganda [68]

[a]The total 310 MW of geothermal in Rwanda was not achieved by 2017 due to financial, technical, and other limitations

Kenya is leading the way for geothermal energy in the region, satisfying over 40% (650 MW) of its electricity demand with this type of energy. Ethiopia is at a far second, having installed 7.3 MW, while other countries like Djibouti, Eritrea, Tanzania, and Uganda are undertaking preliminary exploratory studies into this technology [70, 82]. Country targets for investment in geothermal are summarized in Table 15.2.

While geothermal energy is highly desirable in the region, it is presented with some challenges that are worth highlighting. First, drilling for the geothermal resource has been claimed to be associated with increased seismic activity while plant exhaust has been found to contain small amounts of hazardous hydrogen sulfide [73, 95]. In addition, geothermal projects have long timelines and are very capital intensive, thus requiring interventions that can attract private investment. This has been addressed to an extent through the implementation of the Africa Union's 115 million Geothermal Risk Mitigation Facility (GRMF) for countries of East Africa, which financed early studies on geothermal potentials in the region [19].

East Africa can pursue the full exploitation of its abundant geothermal resources to meet its electricity needs. The size of the resource in countries like Kenya and Ethiopia also positions them to become exporters of this type of energy to other countries in the region. Special attention should, however, be given to existing and potential 'hot spot' risks (e.g., risk of earthquakes) with regular monitoring.

15.4.3 Solar

East Africa enjoys high solar irradiation levels throughout the year. This study considered variants of solar technology for generation from both centralized (utility-owned) and distributed technologies. At utility scale, both Concentrated Solar Power (CSP) and solar Photovoltaic (PV) were considered, while at the distributed scale, only solar PV was considered.

15.4.3.1 Solar PV

Solar PV is highly desirable in East Africa, its RAF scores varied between 10 and 28 for distributed PV (installed and used by households), and between 12 and 24 for utility-owned (centralized solar) PV (power transmitted from power plants). The slightly higher levelized cost of energy (LCOE) of distributed solar PV meant utility-scale PV was generally more desirable across the region. However, for countries with severe land restrictions such as Burundi and Rwanda, the distributed PV illustrated higher desirability due to its zero-land footprint.

East Africa has an estimated solar PV potential of 219,481 TWh/year ([24], p. 34). Investment in Solar PV is gaining traction in the region with capacities of 2 MW in Kenya, 9 MW in Rwanda, 4 MW in Somalia, and 10 MW in Uganda [36].

Due to the high feasibility of solar energy in the region, most countries have targets to raise their solar PV capacity in the coming years. Some countries are focusing on large-scale investments to boost their centralized energy base. Uganda is leading in large-scale installations – commissioning its 3rd PV plant in 2019 and has a 4th 10 MW-plant under construction in the Eastern district of Mayuge. Uganda is expected to connect a total of 50 MW installed capacity of solar PV to its national grid, with plans to grow this further to 150 MW in the coming years [47]. Tanzania has a least cost national plan with a target of reaching 150 MW of solar PV capacity by 2020 [77] and Ethiopia looks to add 300 MW of solar PV to its portfolio by 2020 [27]. Sudan's solar PV targets are the most ambitious in the region. This country plans for adding 600 MW of centralized solar PV by 2031 [66]. Kenya is aiming to reach the solar PV capacity of 100 MWe by 2020 [35].

Other countries, however, consider solar PV as a route to rural electrification. For example, South Sudan is considering the technology for small-scale off-grid and mini-grid interventions along with solar water heating to serve rural communities [3, 65]. Similarly, Rwanda's plans for solar PV are primarily directed toward electrification of social amenities such as schools and hospitals in rural areas [2].

Solar PV has been shown to offer great benefits for sustainable energy supply in most countries in the region. Coupled with the excellent solar resource in the region and ever-falling prices of components, this technology is well placed to support electrification programs in East Africa. However, a major challenge with solar power is its intermittency – meaning that this energy can only generate power during the day, and even still fluctuate as the sun's irradiance changes during the course of the day. Additional steps need to be taken at the national level to make this technology viable. This can be achieved through strengthening the national grid to withstand these fluctuations through backup power support, or the load profile should be skewed to match the availability of solar power supply. Energy storage is still costly but is another way through which solar PV can become more attractive. As technology develops, prices may begin to fall, making it more viable in low-income regions such as East Africa.

15.4.3.2 Concentrated Solar Power

Concentrated Solar Power (CSP) illustrated an average performance with an RAF between 48 and 52 for all countries. A relatively high-water footprint and one of the highest LCOE of all technologies affected its performance. Most countries across East Africa have potential for CSP which is estimated to be 175,777 TWh/year in total ([24], p. 34). However, the technology is still relatively under-developed even at a global scale and has to date not been implemented across East Africa. The only country in East Africa that includes CSP in its energy plans in Sudan which has a capacity target of 50 MW by 2031 [66].

CSP carries one major advantage over solar PV as it leverages thermal storage to overcome the intermittency challenge without significantly increasing the LCOE. However, the technology is still relatively expensive and only starts to benefit from economies of scale beyond 200 MW capacities while PV is economically efficient at much smaller scales [28].

15.4.4 Onshore Wind

Onshore wind is a growing technology in East Africa, and the region has considerable wind resources in Somalia, Ethiopia, Djibouti, Kenya, and Sudan. The total technical potential of this energy at more than 20% capacity factor is estimated to be 165,873 TWh/year ([24], p. 34). Onshore wind's small water use makes the alternative highly desirable across nations such as Sudan and Djibouti with constrained water availability. However, its large land use makes the alternative less desirable in countries like Burundi and Rwanda with limited land availability.

Currently, the installed capacity of onshore wind is about 90 MW in Kenya, Ethiopia, and Tanzania combined, and all three countries have plans to expand their installations in the coming years. Kenya is implementing two projects that will add 410 MW ([35], p. 59); Ethiopia plans to increase its wind energy capacity by 150 MW [14], while Tanzania foresees adding 450 MW to its wind energy capacity by 2040 [77].

Sudan, Somalia, and Djibouti do not currently have any wind energy capacity, but all have plans to develop this energy. In particular, Djibouti has an excellent wind energy generation potential with a higher capacity factor (50%) than was considered for calculating the LCOE in this study (20–30%). In other words, having more accurate and local performance data for Djibouti might increase the desirability of this technology.

The medium desirability of wind energy is mainly tied to its considerable land footprint (according to the data used in this study). Large rotor diameters and spacing requirements mean that the wind farms take up large pieces of land, despite the fact that their actual footprint (the base of the tower) is very small. As such, wind developers should look into options of co-location [78, 96], where the wind farm shares the land with other productive activities, such as agriculture in order to allow for more efficient land-use and enhance the desirability of this technology.

The wind is a beneficial energy source for countries that have abundant land but suffer from water scarcity. But wind is also intermittent, and electricity generation at any given time is proportional to the wind speed available. The unpredictability of generation rate in the case of wind introduces challenges for grid balancing and matching energy demand and supply [33], with potential for causing power outages and blackouts. In light of this, some countries in the region are intentionally limiting the amount of intermittent capacity in their system in order to maintain reliability ([77], p. 56).

Offshore wind is another variation of electricity generating wind technologies and has achieved huge reductions in cost, especially in Europe. However, this option is still facing some technological challenges in the installation and operation phases. This energy technology option has not mentioned in the regional energy plans and so has been left out of this study.

15.4.5 Nuclear

Nuclear RAF is between 34 and 56 across the region, with the best performance in Burundi and Rwanda, and the worst performance in South Sudan. According to the data used in this study, nuclear has the lowest land footprint of all centralized technologies, making it more attractive for countries with limited land availability such as Burundi and Rwanda. However, its relatively high economic cost reduces its desirability in low-income countries such as South Sudan.

Nuclear is being considered as an electricity generation option in Kenya, Uganda, and Tanzania. The World Nuclear Association lists these countries among ‘emerging nuclear countries’, which are considering or have plans for implementing this technology [97]. Kenya plans to develop 1 GW of nuclear energy capacity by 2024 and add 3 GW to this capacity by 2031 [35]. Uganda has also done some planning and preparatory work in the nuclear sector, training the required expertise, and identifying locations for uranium mining [34]. It has signed agreements with both Russia and China to further support the development of this energy option to help meet the country’s projected growing electricity demand [10]. Tanzania has identified uranium fields and continues to run nuclear energy studies but has not yet included this energy alternative in any of its mid-term plans due to the lack of a clear framework under which this sensitive technology can be implemented, operated, and monitored. The country also cites lack of skilled expertise as a bottleneck to venturing into nuclear energy but remains open to its development in the long-term after many of its existing resources have become depleted [77].

Generally, nuclear energy generally has a number of sensitivities around safety and waste disposal and these are the subjects of debates even at the global level. The nuclear disaster in Fukushima, Japan in 2011 elicited mixed responses, with countries such as Japan and Germany are reducing and phasing it out, while France, Korea, and the UK continue to invest in the alternative [72]. Every country has its priorities and values, which determine which side of the debate they are on – and countries in East Africa need to take a similar stand based on their unique circumstances with careful attention to the risks allied with nuclear alternative. In addition, the large investment requirements of this type of energy in addition to the general size of nuclear plants make this energy less attractive in East African countries with limited financial power and small energy demand. Several countries across the region have peak demands that fall under the size of the smallest commercially available nuclear reactors and so are not well placed to take it up this energy in the near future. The on-going developments in smaller size reactors may avail more appropriate capacities to countries with smaller demands such as those in the East African region ([35], p. 75).

15.4.6 Hydropower

This is the most developed and dominant source of electricity in the region. In 2012, hydropower provided more than half of 8.1 GW of installed energy generation capacity in East Africa [26]. Much of the region's hydropower potential is concentrated in the Nile basin [82]. Hydropower's RAF shows a below-average performance in most of the East African countries. Djibouti, Tanzania, and Uganda had the lowest RAF (highest desirability) for hydropower with a score of 52, while the highest RAF of 94 was observed in Sudan, where water availability restrictions make this water-intensive technology unattractive.

Despite its low high RAF, countries in the region continue to push for more hydropower. Table 15.3 shows the planned capacity additions in different East African countries. Uganda maintains its heavy investment in hydropower. This energy is expected to contribute over 90% of new generation capacity in Uganda from 2016 to 2025 [79]. Hydropower investments in Rwanda and Burundi are projected to increase the combined electricity generation capacity of the two countries by 400 MW in total. Hydropower is the least desirable alternative in Sudan according to its RAF. Nevertheless, this country is home to one of the largest existing hydropower installations (Merowe Dam) of East Africa. In addition, the country has plans to add nearly 1 GW of hydropower capacity by 2020 [26]. Ethiopia has the largest installed hydropower infrastructure across the region, and the highest potential in East Africa (45 GW) and is currently developing the 6 GW of additional capacity through the Grand Renaissance Dam [27]. This would enable Ethiopia to meet local demand and export electricity to neighboring countries like Somalia and Djibouti that have a very small electricity generation base [4, 27, 53], as well as strategic partners like Kenya that will benefit from low cost power to drive development [48].

An important consideration with the continued hydropower dominance in the region is water availability fluctuations. Previously countries have suffered severe power shortages due to long droughts. This has motivated diversification of

Table 15.3 Potential for hydropower energy and projects planned across East Africa

	Potential (MW)	Installed (MW)	Future share of the national energy supply mix (%)	Planned sites and capacity
Burundi[a]	1700	30.8 16.3 imported	86	Ruzizi III (147 MW) Ruzizi IV (287 MW)
Djibouti[b]	–	Imported from Ethiopia	–	–
Ethiopia[c]	45,000	3810	89	Grand Renaissance (6000 MW) Gibe III (1870 MW)
Kenya[d]	3000 (large) 3000 (small)	821	38	24 MW
Rwanda[e,f,g]	313–400	109.7	59	Ruzizi III (48 MW), Ruzizi IV (98 MW)
Somalia[h]	100–120	0	0	Dawa River project with Ethiopia and Kenya
South Sudan[i]	15,000	0	0	Fula (40 MW), Sue (15 MW) Bedden (540 MW), Lakki (410 MW) Shukoli (230 MW), Grand Fula (890 MW)
Sudan [j]	–	1593	49	Up Atbara-Sitat (320 MW) Kijbar (360 MW), Dagash (312 MW)
Tanzania[k]	4000 (large) 480 (small)	577	36	Large (3000 MW, several sites) Small (50.4 MW, several sites)
Uganda[l]	2000 (large) 200 (small)	696	81	Karuma (600 MW) Isimba (180 MW)

[a]Burundi Minister of Energy and Mines [11]
[b]IRENA [32]
[c]International Hydropower Association [27]
[d]Kenya Ministry of Energy and Petroleum [35], pp. 69,70
[e]USAID [83]
[f]African Development Bank, [2]
[g](Republic of Rwanda [64]
[h]African Development Bank [4]
[i]Republic of South Sudan, UNDP [65], p. 28
[j]Republic of Sudan Ministry of Water Resources and Electricity [66]
[k]African Development Bank [5]
[l]Republic of Uganda [67]

portfolios across countries such as Tanzania [5, 76]. With climate change, weather extremes could be even more pronounced, creating additional concerns about sustainable hydroelectricity generation and supply in the region.

Large-scale hydropower can create negative bearings on climate, water, and land/ ecosystem in the region. This technology has a higher-than anticipated carbon emissions [58, 86], significantly high land use, and a large water footprint, making it less desirable. Studies done by Herath et al. [23] suggest the water footprint of hydropower is dictated by the local climate and rainfall patterns. Therefore, through optimal siting and design of future dams, the region may be able to raise the desirability of this technology while taking advantage of its hydropower generation potential and the resulting low-cost power. East Africa has plans to the capacity of small hydropower (plants that are less than 10 MW) considerably. These plants have certain advantages due to their smaller land, water, and carbon footprints [20], but their economic efficiency might be less than large-scale hydropower in some cases.

15.4.7 Coal

Coal has its lowest RAF (58) in Burundi and Rwanda and its highest RAF (70) in Somalia and South Sudan. Coal has a fairly small land footprint, making it desirable in land-stressed Rwanda and Burundi, while its relatively large water footprint compared to other technologies such as nuclear, oil, and natural gas hindered its performance in water-stressed countries of Somalia and Sudan.

Coal reserves are absent in most countries of East Africa, except for Kenya, Tanzania, and Ethiopia which have significant coal reserves of 400, 870, and 300 million tonnes, respectively [14, 35, 77]. Currently, Kenya relies on imported coal to meet local energy demand, particularly in the manufacturing industry. The country is projected to increase its share of coal-fired capacity by 13% by 2030 [35, 52, 63]. In Tanzania, the existing resource of the country is sufficient to support approximately 10 GW coal fired power plants for a period of 30 years [77].

Despite these ambitious plans, studies show that most of the coal used in East Africa over the next years will continue to be imported [54]. For example, Sudan, which has no known coal reserves, has plans for adding 600 MW of coal capacity [66].

In terms of desirability, relying on resource imports complicates the feasibility of coal as an energy source in East Africa due to the increase of cost to a relatively cheap and reduces its desirability across the region.

15.4.8 Oil

Oil plays an important role in the energy landscape of East Africa, and in the region's future plans. This energy's RAF ranges from 70 to 94. The best performance of this energy is observed in Sudan due to this country's relatively low weight assignment to cost.

Kenya currently meets over a quarter of its demand (580 MW) with electricity from imported oil ([35], p. 69). The country has more than 750 million recoverable barrels of oil [55], and is pushing its oil industry into production in order to support electricity generation, among others. The least-cost energy plans project an additional 1.4 GW of oil-based electricity generation capacity by 2031 ([63], pp. 129–130).

Ethiopia has not started commercial oil production, although several exploratory studies have returned promising results for both conventional and unconventional oil in this country [13]. Ethiopia's installed capacity of 87 MW [17] is projected to grow by 70 MW through a phased rise of slow-speed diesel which began in 2018 [37].

Sudan was traditionally the largest oil producer in East Africa until the secession of South Sudan, which resulted in Sudan losing over 75% of its oil wells. These oil wells that were inherited by South Sudan are now old and generation is anticipated to drop drastically by 2035 [55, 65].

Uganda is now expected to grow into an oil major country, rising to the third biggest oil producer across Sub-Saharan Africa in the years to come [55]. With reserves estimated at between 1.7 and 3.5 billion barrels, Uganda is making strides toward research and plans to build a pipeline to the coast of Tanzania [1]. Uganda installed 120 MW of costly oil-based electricity generation capacity when it had a severe energy shortage but currently aims to replace it with more affordable energy options [67].

The other nations in the region do not have significant oil reserves but oil contributes significantly to their energy mixes. Nearly 100% of energy generation in South Sudan [65], Somalia [53], and Djibouti ([32], p. 2) are oil-based, whether centralized or from privately owned diesel generators. Rwanda and Burundi also rely on oil to support their seasonal hydropower supply [62]. However, most of these countries have plans to reduce their dependence on oil mainly due to its cost and according to their climate change mitigation targets.

As the potential of cheaper regional oil becomes more apparent due to the discovery of significant reserves in Uganda, the countries in the region might explore the role that this energy source could play in supporting their development plans. This would require efforts to reduce the carbon intensity of the fuel – and could be achieved through novel generation technologies with higher efficiency, which could include supercritical and advanced cycle power plants [8].

15.4.9 Natural Gas

The RAF of natural gas is between 50 and 72. The lowest RAF for natural gas was observed in Rwanda, due to the combination of its low land footprint and relative affordability. Natural gas is not a dominant energy source in East Africa today, mainly due to the low exploitation of existing gas reserves. But several countries in the region have plans to utilize their local resources to boost their gas-based power generation capacity in the coming years.

Tanzania has the largest installed natural gas-based electricity generation capacity of any other country in the region. The country is responsible for about 860 million cubic meters of natural gas generation [12] and the alternative contributes 500 MW (over 30%) to the overall electricity mix [5]. According to its electricity master plan, up to 8 GW of potential can be expected from natural gas over the next 20 years in Tanzania [77].

Ethiopia also has a significant natural gas resource of up to 130 billion cubic meters; however, this capacity has not been used for commercial production yet [13]. The country has plans to phase expansion of 560 MW of gas-based power starting in 2025 [37]. Uganda had plans to set up a new 50 MW gas plant by 2019; however, its plans are hinged on the commercialization of natural gas in its Albertine region [79] as feasibility studies are still taking place.

Before the secession of South Sudan, Sudan had the biggest natural gas reserves in the region (up to 3 trillion cubic meters). Sudan now holds 490 MW of gas-powered electricity capacity and intends to grow that by nearly 3 GW in the near future [66].

Other countries do not have any known natural gas resource and have not included this option in their future energy plans. Djibouti previously considered importing natural gas via a pipeline from Yemen to contribute, but with the prospect of cheaper hydropower from Ethiopia, this option is no longer economically viable [54].

Much lower carbon emission is observed for natural gas than oil and coal and the alternative is cheaper in relevance to some renewables. Therefore, as nations like those in East Africa grapple with finding the balance between affordable and climate-friendly resources, natural gas might be a favorable alternative during a transitional period to a low-carbon future.

15.4.10 Biomass

Biomass is generally an undesirable technology across the region. This is mainly due to the combined effect of its large footprints across all four criteria. The RAF of this energy is between 68 and 98 across the region. This energy has its highest undesirability in Rwanda and Burundi due to its extremely high land footprint.

A few countries in the region are harnessing the benefits of biomass through co-generation in the manufacturing sector. In Kenya, all tea factories are projected to have a co-generation potential of 300 MW when combined together [62] while in Uganda, sugar co-generation plants contribute nearly 40 MW of capacity [67]. Kenya's energy plans do not anticipate any further expansion of biomass capacity, and in Uganda additional investment to grow this capacity has been stalled by high capital requirements and unfavorable financing conditions for private investors.

Uganda has also recently canceled an initial plan to tap into its local peat resource for energy, arguing that peat emits harmful GHG into the atmosphere and its exploitation involves encroachment on protected wetlands [67]. Rwanda, on the other hand, is moving ahead with harnessing its peat resource that can provide 300–700 MW of electricity generation capacity [2, 64]. The Rwandan decision makers view any GHG emissions from peat as biogenic and as such not contradictory to the country's climate change mitigation commitments [2]. Ethiopia has set the most ambitious target for biomass in the region, planning to add 420 MW of biomass power as one of its key energy priorities for 2016–2020. This will primarily be derived from waste and wood [17].

Mathioudakis et al. [46] compared the resource efficiencies of 1st generation (1G) feedstocks (crops like maize and sugarcane) and 2nd generation (2G) feedstocks (residue like corn cobs and plant stalks). They found that the overall environmental impact of 2G feedstocks was reduced significantly due to the allocation of some of these impacts on the plant itself during its lifecycle. Furthermore, the water footprint of biomass technologies was very dependent on the choice of technology, e.g., pyrolysis, combustion, or gasification. Due to such variabilities, the countries need to conduct project-specific evaluation of the RAF of this type of energy for decision-making. Further exploitation of biomass can lead to unsustainable outcomes when impacts on other resources beyond cost are considered. The significant water and land use can lead to major problems such as competition with food and other nutrients and agriculture. These can be minimized if the choice of technology is made with respect to this energy's impacts on different resources.

15.5 East African Power Pool, EAPP (Regional Weights)

Most countries in East Africa have entered into a power-sharing agreement under the EAPP. This study, therefore, considers the potential role of this body in driving sustainable energy sectors in the region. To estimate the value and impact of cooperation among the countries, a scenario of joint resource sharing and operation was examined. Under this scenario a single united large country with access to the total resources of all 11-member countries was created. The RAF evaluation process was repeated for this united country to see how the desirability of different energy resources will change under full regional cooperation which gives the countries an opportunity to address their resource availability limitations through trades.

Table 15.4 shows the calculated criteria weights for the aggregated state. In line with the criteria weights of the individual countries, the highest weight was given to cost, followed by water, land, and CO_2 emissions under the full regional cooperation scenario.

Figure 15.4 indicates the calculated RAFs for different energies under the full regional cooperation scenario (only centralized (utility-scale) energy options were considered in this case). Geothermal was found to be the absolute best alternative at

Table 15.4 Criteria weights under the full regional cooperation scenario

Criteria	Carbon	Water	Land	Cost
Weight	0.106	0.286	0.212	0.396

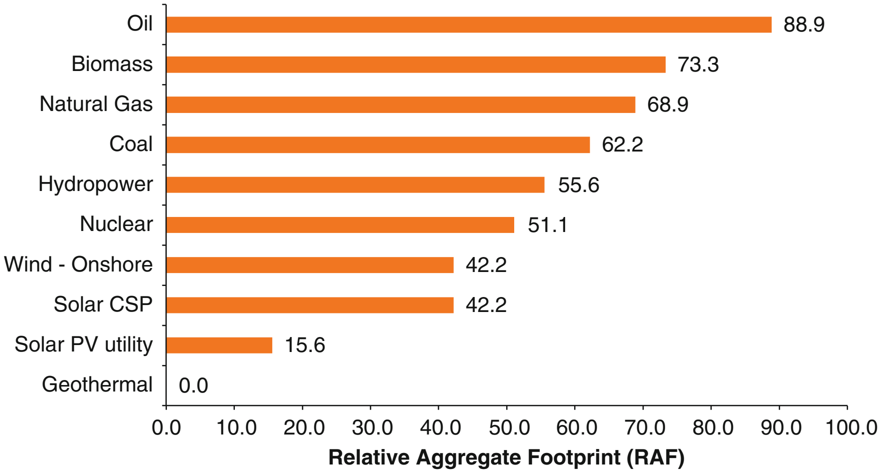

Fig. 15.4 RAF for alternative energy sources under the full regional cooperation scenario

the regional level with an RAF of 0 while oil was the least desirable with an RAF of 88.9. Other notable technology RAF changes from country-level included solar PV (15.6), hydropower (55.6), and biomass (73.3). Biomass with an RAF of 73.3 was more desirable than oil (88.9) because of its lower costs and the limited economic capacity of the region. Solar CSP had an RAF of 42.2, outperforming nuclear power. Although CSP has a larger land use in comparison to nuclear, with more access to land at the regional scale (a lower associated weight to land under the united countries scenario) increased the desirability for CSP. The desirability of nuclear declined because of its high cost while hydropower's relatively low cost made it more desirable than more costly fuels like coal and natural gas.

15.6 The EAPP Master Plan

The EAPP Master Plan [15], devised in 2014, provides a roadmap for future investment across the region's energy sector. The primary focus of this plan is to achieve least-cost energy generation and transmission in the region. East Africa's generation capacity is projected to increase from 10.5 GW in 2015 to 58.4 GW by 2030 [16]. The distribution of projected capacity expansions by 2030 is shown in Fig. 15.5 by energy types.

The expected added capacity will be dominated by hydropower (53%), followed by geothermal (17%), natural gas (16%), and coal (11%), with renewables other than hydropower and geothermal having a very small contribution. The low contribution of other renewables technologies such as solar and wind could be attributed to the relatively high cost that makes them undesirable within a least-cost planning framework.

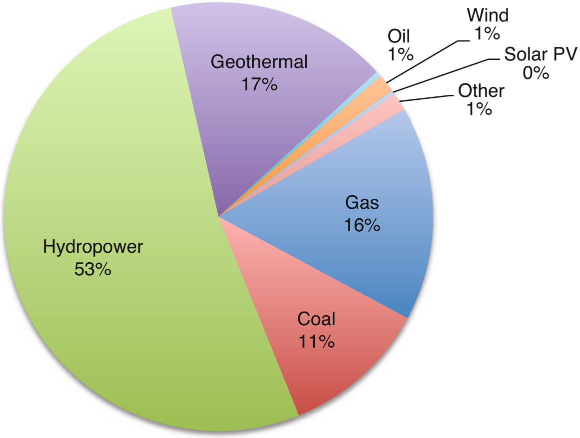

Fig. 15.5 Shares of different types of energies in the projected 48 GW of energy generation capacity increase during the 2015–2030 period. (Source: Own elaboration of EAPP data ([15], p. 48; [16], pp. 44–211)

The continued dominance of hydropower even into the coming decade of accelerated investment in the energy sector raises some concerns. This energy option illustrated an average performance (RAF = 51.1) due to its high land, water, and cost footprints. In addition, the development of this type of energy might lead to social impacts and displacements of people. Furthermore, hydropower is vulnerable to droughts and climate variability, making it unreliable under climate change.

The low cost of some fossil fuels especially natural gas and coal has led to a projected increase in their contribution to East Africa's energy mix. This will undoubtedly increase the carbon emissions from the region, and also cause ripple effects on land and water systems. If these fuels (particularly coal) are imported, new complexities are introduced around the allocation of impacts – since the source countries will bear the burden of land and water system destruction as they source the fuels, while countries using the fuels will have to tackle their increase emissions.

Biomass, which was found to be the least desirable energy option, is projected to contribute a mere 1.08 GW, with installations in Tanzania, Ethiopia, Rwanda, Kenya, and Uganda. Feedstocks will range from agricultural and municipal waste, peat and wood. This calls for new studies on the impacts of these feedstocks, specifically those such as peat, which have not been considered within this study. Solar PV, which has a high generation potential in the region and consistently performed well for most countries and was the second most desirable technology at the regional level, is not projected to have a major role in the future of East Africa. The existing plan foresees an addition of 150 MW by 2030, of which 120 MW will be situated in Tanzania [16]. Nevertheless, the decreasing cost of solar PV is expected to invalidate the pessimistic projections about the future growth of this energy in East Africa.

15.7 Conclusion

East Africa is at a critical point in the development of its energy sector. With a low energy access rate, rising populations, and rapidly increasing economic growth, energy demand for East Africa is projected to grow, requiring large investments in electricity generation. Energy plans have historically prioritized cost, and this has resulted in investment in some unsustainable energy options with irreversible adverse impacts on land, water, and climate systems in the region.

This study applied an SoS approach to calculate the Relative Aggregate Footprint (RAF) of different energy options in East Africa. The outcomes portrayed that there is no ‘one fits all’ solution that can be used across all countries of East Africa. There is a need to consider local resource availability of each country and fabricate policies based on the individual characteristics of each nation. To create a sustainable electricity mix, there is a need for a diversified portfolio which includes different energy options.

Some largely advocated for technologies such as hydropower were shown to be moderately-to-extremely undesirable when their various impacts, as well as local resource availability conditions, are taken into consideration. For example, Sudan, in which large-scale hydropower has low desirability, has the largest existing hydropower investment in the region. This shows that generalized notions of ‘clean’ or ‘green’ energy solutions are not global and must be determined for each country and tailored according to their needs and conditions.

Distributed alternatives such as distributed small-scale PV systems can be desirable in East Africa. By 2030, over 67% of East Africa’s population is expected to remain in rural areas [28], and as such, there is a need for solutions, such as distributed energy systems, including solar PV, to address the needs of and empower rural communities. Distributed solutions can be implemented where implementing a well-planned energy sector in the region might include an optimal balance of both distributed and centralized generation to harness all these benefits while ensuring lowest system impacts and maximum coverage.

Hydropower is currently the largest contributor to electricity capacity in the region and projections by the EAPP suggest that the technology will account for over 50% of new capacity additions between 2015 and 2030. However, the analysis conducted in this chapter has shown that large-scale hydropower only has moderate desirability in the region and is outperformed by other alternatives such as solar PV, onshore wind, and natural gas in most countries. This calls for reconsidering and improving the existing plans to minimize the irreversible impacts of energy development projects in the region. Geothermal energy was also found to highly resource efficient for East Africa. With a significant resource in the East African Rift Valley, the region might consider prioritizing this energy alternative to take advantage of its inherent benefits.

Power pools offer a number of advantages to member states, as they provide opportunities to generate electricity at large scales and hence reduce costs. As seen in this study, resources are distributed unequally across the region, with some countries having better access to resources than others. Power pools allow for optimal siting of power plants so that electricity is generated in a more efficient way and their negative impacts are minimized.

The results show some disparity between the current prioritization of investments in the region's electricity industry and the calculated desirability of energy alternatives based on their RAF. This suggests that the current energy plans in the region have potential negative consequences on valuable resources such as water, land, and climate. This calls for a change in the evaluation techniques to energy planning in the region that replaces single criterion assessments (e.g., cost-based), to more systems-oriented methods that consider trade-offs.

Finally, like any modeling exercise, this study has some limitations that should be considered while translating its results and policy implications [39]. Most importantly, here, the desirability of energy sources was examined without including socio-political and feasibility criteria. Considering such factors at the local scale can have major impacts on the study outcomes. For a comprehensive review of additional limitations of the methods utilized in this study, readers are referred to Hadian and Madani [20], Ristic et al. [69], and Mahlooji et al. [44].

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