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

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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.

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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 combustion 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.

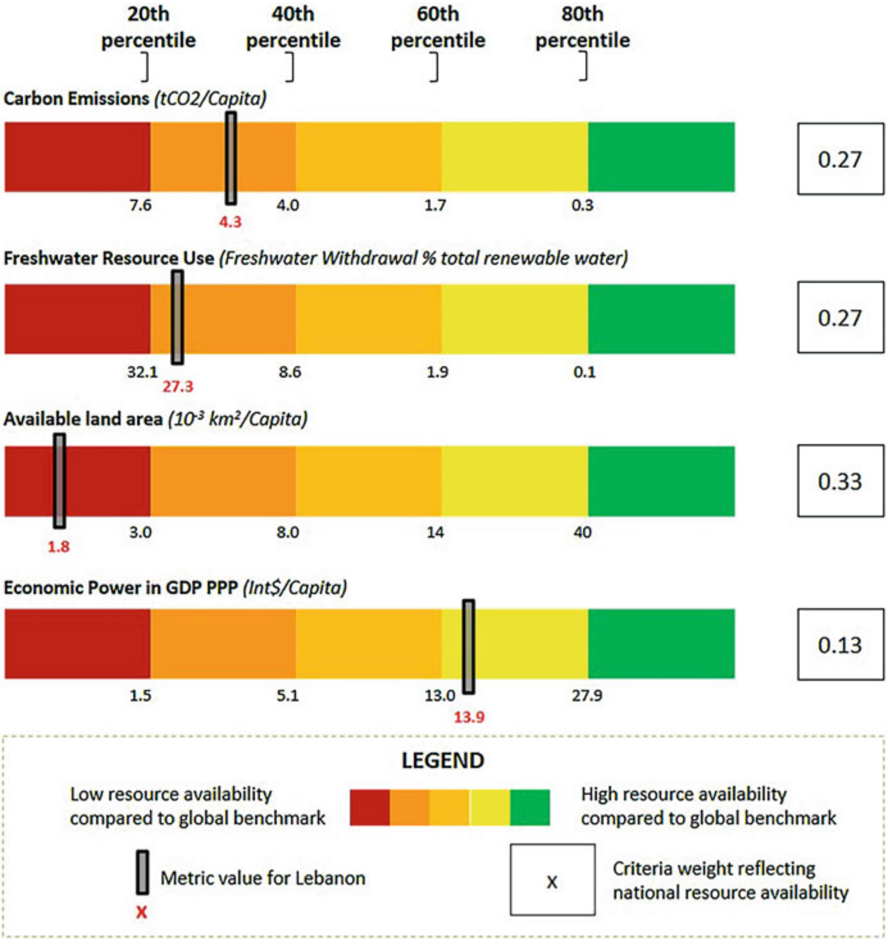


Fig. 1.1 Resource availability across Lebanon relative to the global benchmark and the associated criteria weights for REA

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

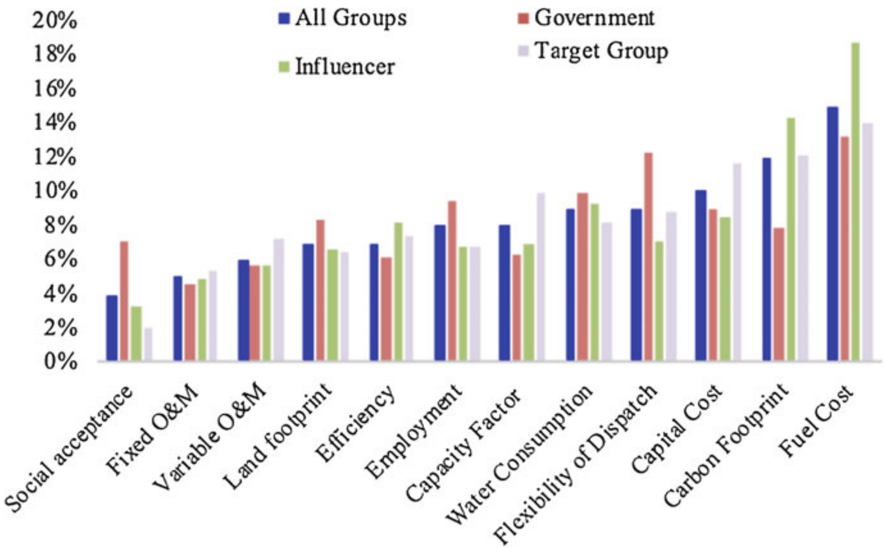


Fig. 1.2 Weights reflecting the stakeholder groups' viewpoints of sustainability priorities

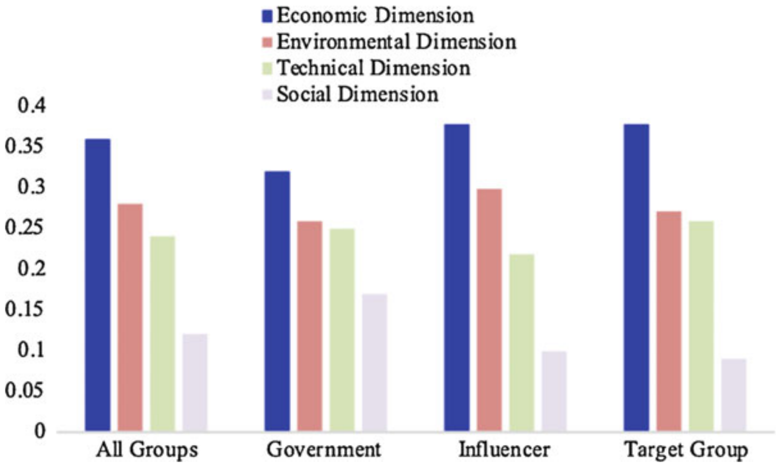
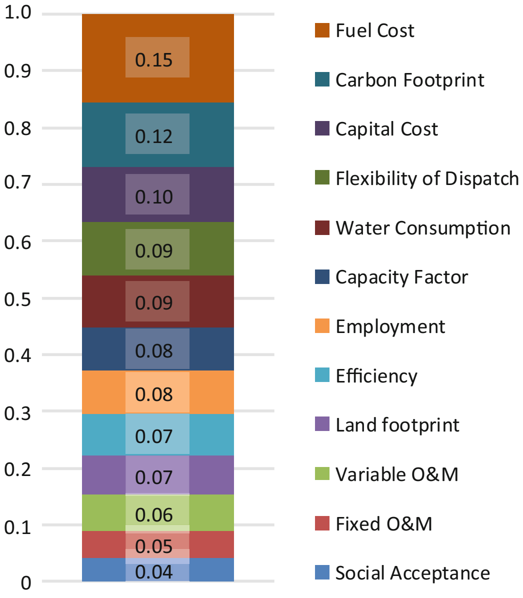


Fig. 1.3 Weights reflecting the stakeholders' viewpoint of the most impacted systems by the Lebanese electricity sector

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

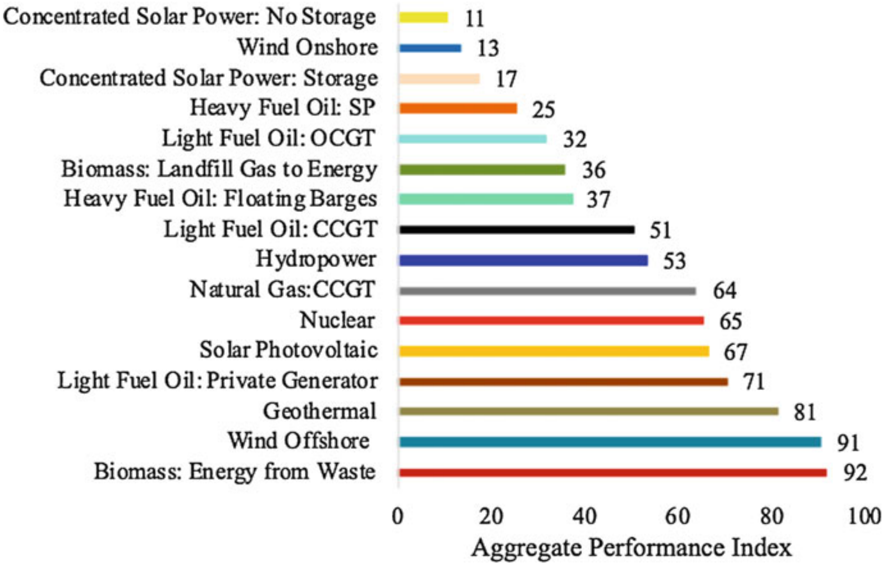


Fig. 1.5 REA scores of electricity supply alternatives for Lebanon

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

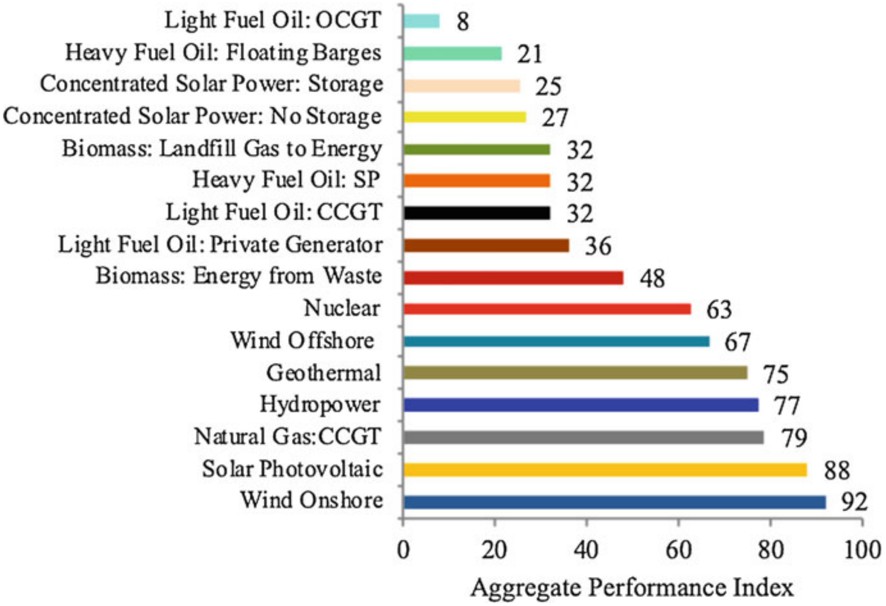


Fig. 1.6 SPA scores of electricity supply alternatives for Lebanon

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**

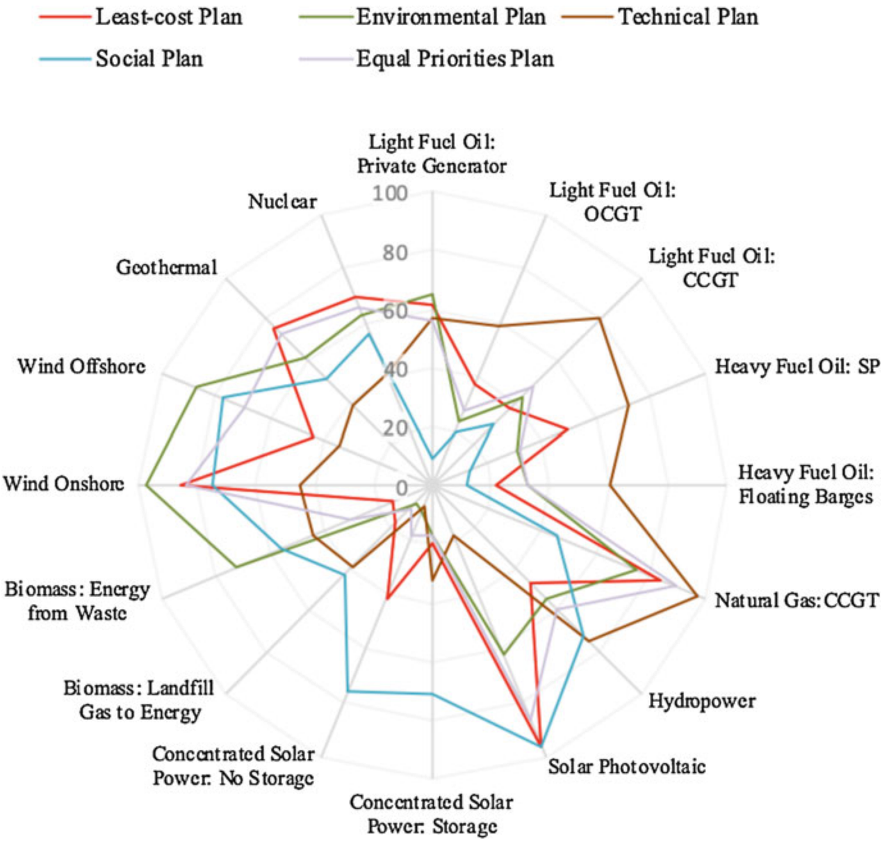


Fig. 1.7 Desirability of different energy generation options under different sensitivity analysis scenarios. The center point indicates an API of 0 (less desirable), the edge returns a score of 100 (more desirable)

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.

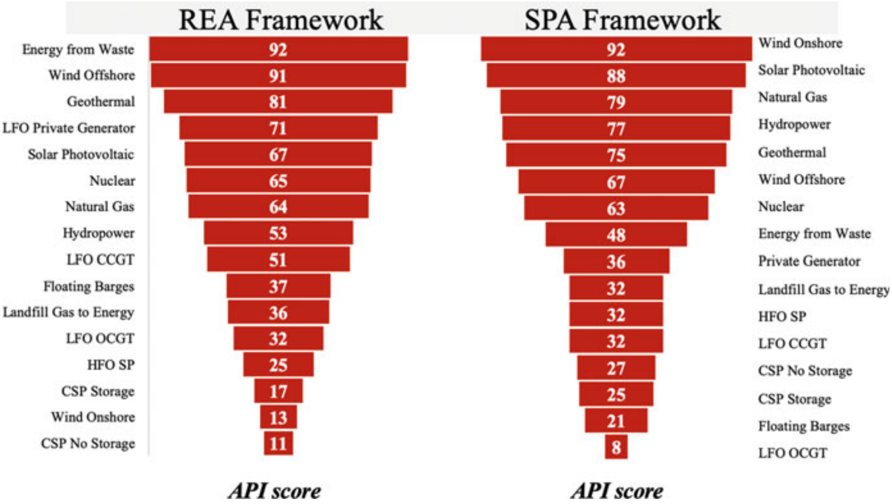


Fig. 1.8 Differences in ranks, trends, and desirability of energy technologies under the SPA and REA frameworks

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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