Energy Policy 38 (2010) 751–761

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The Lebanese electricity system in the context of sustainable development

R.H. El-Fadel [a], G.P. Hammond [b,c], H.A. Harajli [b,*], C.I. Jones [b], V.K. Kabakian [d], A.B. Winnett [c,e]

[a] *Zero Energy First, UK*
[b] *Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK*
[c] *Institute for Sustainable Energy and the Environment (I.SEE), University of Bath, UK*
[d] *Project Manager, Lebanon's Second National Communication to the UNFCCC, Project UNDP, Lebanon*
[e] *Department of Economics, University of Bath, UK*

ARTICLE INFO

Article history:
Received 17 June 2009
Accepted 3 October 2009
Available online 30 October 2009

Keywords:
Lebanon
Electricity supply
Sustainable development

ABSTRACT

The Lebanese electricity system has been evaluated in terms of its sustainability. An integrated approach was adopted to assess the life-cycle technical, environmental, energy and economic attributes of the system. The findings show that the Lebanese electricity system is characterized by a weak performance in all analysed aspects related to the sustainability of energy systems. Specifically, the system lacks adequacy and security leading to a supply–demand deficit and poor diversity. It gives rise to significant environmental emissions (including green-house gases), and produces large economic inefficiencies. The costs and benefits of optimising the performance of the centralised electricity system are presented, indicating substantial net benefits (together with considerable benefits in reduced environmental impacts across the life-cycle assessment categories, including carbon emissions) from improving the transmission and distribution networks, upgrading existing conventional plants to their design standards, and shifting towards the use of natural gas. The expected levelised cost of various energy sources in Lebanon also indicates that renewable energy sources are competitive alternatives at the present time.

1. Introduction

The challenge of any electricity system is to deliver reliable and continuous power to meet the economy's total needs at all times and at a reasonable total cost. However, with the growing concerns about climate change, coupled with local pollution implications on human health and ecosystems, the overall environmental performance of an energy system should receive attention on a par with reliability considerations. 'Sustainable development' may be seen therefore as an overarching goal of development or 'sustainability' (Hammond, 2000). As 'sustainable development' requires that "present generations meet their needs without compromising future generations' ability to meet theirs" (World Commission on Environment and Development (WCED), 1987), it becomes a necessity for current generations to use non-renewable energy resources most efficiently (i.e., produce a unit of output with least input), decouple energy consumption from environmental pollution (including greenhouse gas (GHG) emissions), and invest in renewable energy resources. Investing in the latter will enable the current generation to bequeath non-renewable fuels to future generations (Vob, 2006).

The current Lebanese electricity system (LES) has been assessed in the context of sustainable development, and more specifically against the characteristics of a 'sustainable electricity system'. It attempts to examine the subject from an integrated approach as recommended in Hammond and Winnett (2006), Allen et al. (2008a) and Hammond et al. (2009), specifically relying on environmental life-cycle assessment (LCA), energy analysis and economic appraisal, in addition to a reliability assessment. Section 2 attempts to define what the characteristics of a sustainable electricity system actually are. Section 3 describes the current Lebanon electricity system, while Section 4 evaluates this system through an integrated appraisal toolkit. Discussion and conclusions are presented in Section 5 and 6, respectively.

2. The characteristics of a 'sustainable electricity system'

There is on-going debate as to what constitutes a sustainable electricity system. In its most general terms a sustainable electricity system could be thought of in terms of its energy and economic performance, its environmental impacts and its reliability. The basic requirement of an energy system is to generate power for everyone at an affordable price while ensuring that that power is clean, safe and reliable (Alanne and Saari, 2006).

---

[*] Corresponding author. Tel.: +44 1225 385164; fax: +44 1225 386928.
E-mail address: hh237@bath.ac.uk (H.A. Harajli).

0301-4215/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2009.10.020

Acres (2007) defines a sustainable electricity system by combining the energy hierarchy with a set of economic, social and environmental principles. The energy hierarchy advocates starting with the reduction in the use of energy, followed by energy efficiency measures (improvements), adoption of renewable energy sources, and finally using the most efficient non-renewable conventional energy sources coupled with the best available end-of-pipe technologies (Acres, 2007). Within this hierarchy however, Acres (2007) proposes several principles, namely that the energy system (1) should have zero net emissions of GHGs (i.e. it would not contribute to climate change), (2) should not have any other significant environmental impacts, (3) should enhance security of supply, particularly as power interruptions have considerable social implications, (4) should reduce costs of energy supply and improve access to energy (paying attention to industrial competitiveness and lower income groups' affordability), and (5) should harness renewable energy as much as possible.

Mitchell (2008), on the other hand, indicates some important differences between 'conventional' and 'sustainable' electricity systems, which could clarify the characteristics of each. A conventional system is commonly characterised as a centralised top-down system which focuses on supply-side solutions and delivery, with large conventional plants (most of which need time to ramp up) connected to the 'passive' transmission (and distribution) network to customers who see energy simply as being present at a 'flick of a switch'. Concerns about energy security are met by additional conventional generation, whereas environmental externalities are regarded minimally. The overall market under a conventional system is likely to be a government-owned monopoly, offering little consumer choice, that is unworried about risks or losses due to continuous government support (Mitchell, 2008). In contrast, a sustainable electricity system is characterised by publicly aware citizens that see the connections between energy and the environment, and who use energy efficiently. Within this system, the environment plays a greater role and is an important driver of policy, while energy security concerns are answered through the diversification of generation technologies. It brings together large-scale and distributed renewables sources (including micro-generation), a reduced dependence on imported oil, and the targeting of demand reductions through behaviour change or energy efficiency measures. The sustainable electricity system will contain different technologies and unit sizes, connected to both the transmission and the distribution networks, which become in themselves 'active'. The market structure for such a sustainable electricity system is liberalised and privatized, where choice is given to customers (competition) and risks are faced by the private companies themselves (Mitchell, 2008).

A sustainable electricity system would therefore have to balance several criteria; particularly reliability, economic efficiency, energy efficiency, and environmental impacts, including GHG emissions, in order to move towards 'sustainability'. This paper aims at establishing a baseline or benchmark of several selected sustainability indicators for the LES, against which any future action can be monitored.

3. The Lebanese electricity sector

The Lebanese electricity system (LES) is a publicly owned sector which suffers from substantial inefficiencies, poor management, and under-investment (inadequate maintenance–emergency maintenance instead of preventive with a chronic lack of spare parts). It absorbs approximately 2–6% of national gross domestic product (GDP), as shown in Fig. 1, through annual government subsidies, depending mainly on the price of fuel as Lebanon imports 99% of its primary energy requirements (Houri, 2006a). Additionally it falls far short in terms of satisfying the growing energy demand in the country. Urgent and radical changes in the supply–demand balance are therefore long overdue.

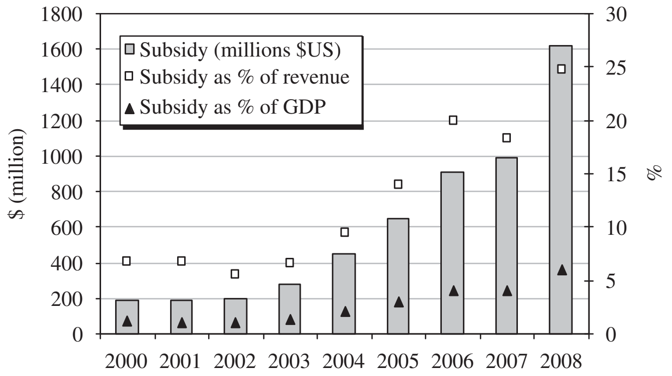

Fig. 1. Total annual subsidies to Electricité du Liban (EDL) and % of total revenues (MOF, 2008; World Bank, 2008).

Electricity supply in Lebanon is managed by Electricité du Liban (EDL), a public institution that has a nominal installed power supply capacity of approximately 2100 MW. 1900 MW of this consists of thermal power capacity and 200 MW of hydro (end of 2006). Available net thermal capacity however has varied from as low as 1600 MW (and sometimes lower) to a maximum of 2000 MW. This is due to several shortcomings such as restoration requirements, plant failures, fuel supply problems, and external hostilities (i.e. damage to fuel storage capacity or electricity generators due to war time hostilities) among other occurrences (World Bank, 2008). Hydro power availability depends on rainfall and has been as low as 80 MW (Abi Said, 2005). A further 200 MW capacity of electricity has been purchased from Syria (International Institute for Energy Conservation (IIEC), 2008). Additionally an electricity supply of 100–150 MW is being currently considered from Egypt. Table 1 shows the most recently published generation supply mix in Lebanon.

In the transmission and distribution (T&D) networks, technical losses are on average 15% in Lebanon, while non-technical losses amount to a further 17.8% of electricity produced (World Bank, 2008). Non-technical losses are high, but have improved from a decade earlier when they were estimated to be approximately 48% (Badelt and Yehia, 2000). These are attributed to either electricity consumed through illegal connections, meter manipulations, or are consumed yet unbilled due to the shortcomings in the billing system. Overall, at least 50% of the electricity went to residential and business customers (i.e., low-voltage demand), while the rest was divided (from higher demand to lower) between industrial, administrative buildings, and concessions, respectively (World Bank, 2008). Other sources place residential demand higher at 65–73% of total electricity consumed (Houri and Ibrahim-Korfali, 2005), or 80% if combined with the commercial sector (Houri, 2006a).

Peak demand for electricity was at least 2600 MW in 2006 (including electricity demand used for generation itself), and is expected to grow between 4% and 6% annually over the period 2008–2015. Based on the nominal design of all power plants as indicated in Table 1 and inclusive of maximum imports from Syria and Egypt this peak demand is just about met subject to the time schedule of the electricity imports. Yet based on the actual reported availability of power plants and including imports from Syria and Egypt, an annual and growing electricity deficit

Table 1
Total capacity in the Lebanese power system (Abi Said, 2005; World Bank, 2008).

MW	Nominal	Available 2004	Available 2008	Current fuel type	Expected retirement dates[d]
Zouk	607	520	365	Fuel oil	2015–2022
Jieh	346	295	187	Fuel oil	2010–2014
Hrayche	75	60	-	Heavy Fuel oil	2022
Sour	70	70	70	Diesel oil[b]	2021–2022
Baalbeck	70	70	70	Diesel oil[b]	2021–2022
Deir Ammar	435	425	425	Diesel oil[c]	2022–2030
Zahrani	435	425	425	Diesel oil[b]	2022–2030
Total conventional	2023	1885	1562	–	–
Hydro	282	80	–	Hydro	–
Syria	200	200	200	Import	–
Egypt[a]	100–150	100–150	100–150	–	–
TOTAL	2605–2655	2265–2315	–	–	–

[a] Under testing period.

[b] Capable of running on natural gas.

[c] May be running on natural gas by the fourth quarter of 2009.

[d] Depends on units within the same plant, information source, whether or not oil is switched for natural gas in plants that may accommodate natural gas, and the levels of maintenance applied.

of 285–335 MW is expected (approximately 635 MW without the electricity imports). This electricity deficit excludes the necessary safety margin required as discussed in Section 4.1. In 2006, electricity consumed in Lebanon was approximately 13,200 GWh, about 61% of which was supplied by EDL, 33.5% was self-generated (most commonly, individual or community-based back-up generators that are used when EDL's supply is unable to meet demand (World Bank, 2008)) broken down as two-thirds by the industrial sector and one-third by the residential and commercial sectors, and around 5.5% was suppressed (World Bank, 2008).

In 2000, labour productivity in the Lebanese electricity sector was 2.3 GWh/employee, significantly lower than the international benchmark of 8.23 GWh/employee (Badelt and Yehia, 2000). With the ongoing freeze of hiring in the public sector since the 1990s (World Bank, 2008), the average age of employees in EDL today stands at 57 years with further negative implications on labour productivity and skills or knowledge transfer—particularly if many old workers retire around the same time (Now Lebanon, 2008).

4. Integrated appraisal of the Lebanese electricity system (LES)

An integrated appraisal of the LES was carried out by using reliability (Section 4.1), environmental (Section 4.2), energy (Section 4.3), and economic criteria (Section 4.4). Each section develops its own scenario or comparative scenarios. Reliability assessment focuses on the current centralised electricity system without taking into account self-generation. The environmental appraisal of the LES is implemented through a life-cycle assessment (LCA) and focuses on the current LES with and without self-generation, and with and without improvements in the centralised electricity system. An energy appraisal gives a brief comparative overview of energy sources in terms of 'energy gain ratios'. Finally, an economic appraisal calculates the costs and benefits of measures that optimize the current performance of the LES, and concurrently calculates the cost of CO_2 abatement of those measures. An indicative cost of moving towards alternative energy sources is also presented.

4.1. *Reliability*

Even though Lebanon has 100% electrification (UNDP, 2007), the overall system lacks reliability. This can easily be seen through the demand–supply discrepancy and the regular power cuts. It is therefore useful to categorise reliability of the system through conventionally used indicators in order to identify required targets and policies. A simple deterministic approach to calculate how much capacity margin is needed in Lebanon is adopted here even though in reality probabilistic techniques are advocated for modern day electricity systems (see Billinton and Allan, 1996). The reliability of a power system is traditionally divided into two elements: system adequacy and system security. 'Adequacy' relates to power plant capacity needed to generate sufficient energy to meet demand (generation adequacy), and the associated transmission and distribution facilities needed to transport that electricity to consumers (transmission adequacy). System security relates to the ability of the system to respond to disturbances arising within it or the system's ability to respond to any perturbation (Billinton and Allan, 1996).

Focusing first on adequacy, the risk of having supply deficits can be measured by the 'Loss of Load Probability' (LOLP), which is the probability of load not being met. Reducing this probability to near zero is prohibitively expensive (and theoretically impossible), and would require excessive capacity and back-up network routes. Focusing on generation, the accepted capacity margin or amount by which capacity should exceed net peak demand differs between nations or regions, however it is usually set so that interruptions of supply do not exceed 9 or 10 winters out of 100, or 9–10%, respectively (Hogan, 2005; Nedic et al., 2005). As shown in Fig. 2, this entails a capacity margin of about 24%. In general however, deterministic methods indicate that capacity margin should not be less than 15–25% (Khatib, 2003). The United Kingdom power sector, for example, operates with a capacity margin in the range of 16.5–22%, although this could rise to 25% if 'mothballed' plants are bought back online (Hammond and Waldron, 2008). For Lebanon which has current peak demand at around 2600 MW (including electricity requirements for generation via EDL), this entails a capacity margin approximately between 400 and 650 MW (subject to this current demand). Total new generation capacity needed is therefore approximately 700–1000 MW. This would rise with increasing annual demand and the retirement of generation plants expected as indicated in Section 3 and Table 1. Furthermore, as the largest electricity producing unit in Lebanon is the Zouk power plant, a further requirement to ensure generation adequacy is the ability of the LES to sustain the sudden loss of power from Zouk or approximately 600 MW of power.

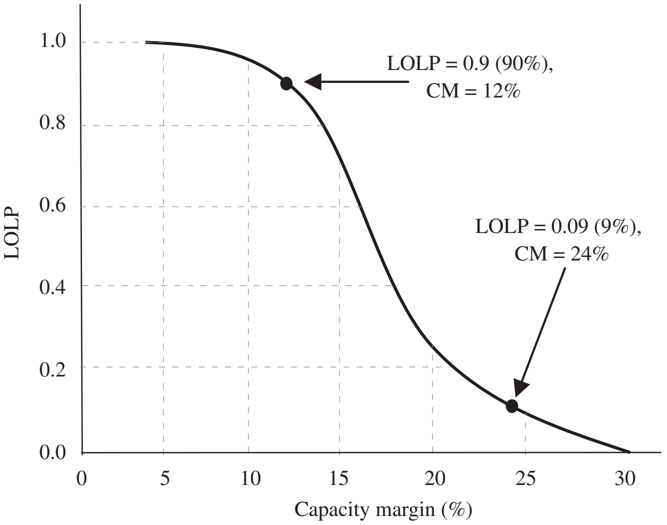

Fig. 2. Capacity margin and loss of load probability (Nedic et al., 2005).

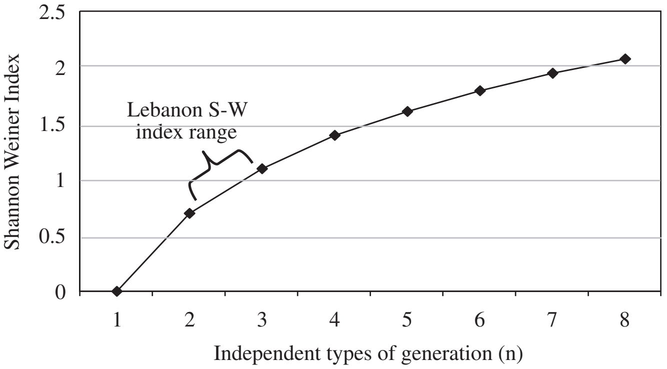

Fig. 3. Shannon–Wiener index (Grubb et al., 2006).

Little published information was found as to the state of the T&D network of Lebanon except that losses stand at 15% of total generation, while generally losses from electricity networks should be around 7–8% (World Bank, 2008). The World Bank (2008) report recommends several investment options to improve transmission adequacy and optimise the supply of electricity (see Section 4.4). Therefore the reliability of the T&D network could not be assessed against criteria and indices used, for example, by Allan and Billinton (1992b) and Allan and Billinton (1993).

The ability of an electricity system to respond to disturbances or perturbations is increased the more 'diverse' a system is. This improves the security of supply. Diversity is "a combination of 'variety' or the number of categories into which the quantity in question is portioned (e.g., gas, coal, wind, and so forth), 'balance' or a pattern in the spread of that quantity across the relevant categories and 'disparity' or the nature and degree to which the categories themselves are different from each other" (Grubb et al., 2006). One of the main indices for measuring diversity is the Shannon–Weiner (S–W) index which includes 'variety' and 'balance' yet not 'disparity'. The S–W index measures diversity by dividing generation according to fuel type according to (Grubb et al., 2006):

$$\sum_{i=1}^{I} -p_i \ln(p_i)$$

where p_i is the proportion of generation represented by the ith type of generation. The S–W index is illustrated in Fig. 3, showing how the diversity index for n equal independent contributions changes as n grows.

A S–W value of below 1 indicates a system that is highly concentrated and dependent upon one or at most two sources which threaten security of supply, whereas a S–W value above 2 indicates a system with numerous sources which could be considered relatively secure (Grubb et al., 2006). Given the current generation mix in Lebanon as expressed in Table 1, the S–W index (as shown also in Fig. 3) for Lebanon based on real availability is approximately 0.83–1.13, depending on whether imports are included, and an index value approximately 1–1.24 based on nominal capacity, depending likewise on the inclusion of electricity imports.

The indicators used above to measure adequacy and system security are subject to significant limitations due mostly to their simplicity. However, the evaluation of other related indicators, such as the loss of load expectation (LOLE) (Allan and Billinton, 1992a) and the Herfindahl–Hirschman index (Grubb et al., 2006) to measure adequacy and security, support the results of the analysis that Lebanon's electricity system lacks generation and transmission adequacy and overall system security. Its generation mix is insufficiently diverse.

4.2. *Environmental performance of the LES*

An environmental life-cycle assessment (LCA) was completed to illustrate the current environmental performance of the Lebanese electricity system, and to provide a baseline that can be used in the near future to assess alternative generating sources and demand-side measures. In a full LCA study the energy and materials used and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle from 'cradle-to-grave' (Hammond and Winnett, 2006). Appropriate methodology of LCA is provided in the International Standards Organisation (ISO) LCA standards (ISO 14040, 1997; ISO 14044, 2006). LCA provides a conceptual framework for a comparative evaluation of various energy supply options with regards to their resources, health, and environmental impacts as important, albeit partial, sustainability impacts (Hammond, 2000; Vob, 2006).

SimaPro V7.1 (proprietary LCA software) was used to complete the LCA along with the ecoinvent V2.1 database. The Lebanese electricity fuel generation mix and the quantity of primary fuels (for electrical generation) were used as the input data. Lebanon's electricity (as outlined in Table 1) is primarily generated from oil-fired power plants (plus a small contribution of hydro power). Given the streamlined nature of the LCA adopted for the present work, the average European impacts from burning oil in a power plant was initially assumed as a proxy for oil burnt in a Lebanese power plant. It was determined that there is a wide impact range for burning oil in European countries and therefore a range was estimated. The upper and lower bounds of the data within European countries were selected as the data range (excluding Slovakia, due to its excessively high impacts over a number of impact categories). This was the starting point of the analysis. The actual Lebanese generation efficiency of the power plants was used in the analysis which was determined from the recorded consumption of oil in Lebanese power plants. In order to tailor the base data (ecoinvent) for Lebanon, the (recorded) direct emissions from the Lebanese power plants were used to calibrate the data for the release of carbon monoxide, methane, volatile organic compounds (VOCs), nitrous oxides, and carbon dioxides using the Intergovernmental Panel on Climate Change (IPCC) measurements (United Nations Development Program (UNDP) and Ministry of Environment (MOE), 2009). The upstream emissions of these substances are accounted for in the SimaPro database and is one reason why the final results may be higher than national estimates.

The functional unit was selected to be '1 kWh of electricity generated in Lebanon and delivered to the Lebanese consumer', and a number of different cases were applied in accordance to the characteristics of the Lebanese electricity system outlined in Section 3. The LCA was completed with and without the impacts of the self-generation. This was estimated in terms of the environmental burdens per kWh (as per the functional unit), and therefore if the self-generation is excluded the LCA was based entirely on the (centralised) Lebanese electricity network. Conversely, when the self-generation was included, the LCA was made up of approximately one-third self-generation and the remainder from the electricity network. It was assumed that the average thermal efficiency of a generator used for self-generation in Lebanon was 20%. In order to slightly offset the lower generation efficiency, it was assumed that there would be a small saving in transmission and (possibly) distribution losses for such generators. The electricity from self-generation has a much shorter distance to travel, and will not pass through the high voltage transmission lines. It was initially assumed that the T&D losses for self-generation were half of that from centralised generation.

The LCA included the impact of constructing transmission and distribution (T&D) networks, and the losses within the cables. The T&D losses in Lebanon were estimated to be 15% of the electricity leaving the power station. The illegal leaching of electricity was not considered within the LCA. From a purely environmental perspective, if the electricity is consumed then it needs to be accounted for in the assessment. The impacts of the low, medium and high voltage T&D networks were included in this assessment (i.e. cable losses and embodied impacts of construction).

The LCA impact assessment method 'CML 2001' was applied for the present purposes. This is a well applied and respected method, and is what is known as a 'midpoint method'. The results are displayed in physical units (i.e., kg, MJ), rather than an 'endpoint' method which may employ units such as Disability Adjusted Life Years (DALYs). The predefined impact categories of the CML 2001, such as abiotic depletion and human toxicity, as shown in Figs. 4–6, are explained in the LCA literature (see for example Sonneman et al., 2004).

Graedel and Klee (2002) state that to set sustainability as a target or goal for our industrial society we must be able to quantify that target or goal. This is a valid concept but it is not a trivial task. Graedel and Klee (2002) point out that such targets need to be revised at regular intervals. However, the setting of the target in the first instance is a particularly difficult task. In LCA such sustainability limits do not yet exist for the majority of indicators. And for indicators that do have general sustainability levels, such as controlling the atmospheric concentrations of carbon dioxide at somewhere between 400 and 550 ppm (although the range suggests that general consensus has yet to be reached) and that anthropogenic CO_2 emissions should be reduced to 80% of the 1990 level (by 2050), there is the additional problem of allocating a fair share to the product system in question (here being a unit of electricity). For these reasons sustainability limits could not be realistically set for the LES. However, the present work offers a baseline from which the future improvement can be judged. Until such a time that these sustainability thresholds may be applied the authors recommend a "less is better" approach, as traditionally adopted in LCA (see Potting et al., 1999).

4.2.1. LCA results

The results of the streamlined LCA are displayed in Figs. 4 and 5 below. Fig. 4 displays the characterised results over 10 different impact categories. Four different cases are presented in a comparative assessment. The four cases are:

1. The full Lebanese electricity mix—this includes the centralised generation of EDL plus self-generation.
2. The full Lebanese electricity mix (case 1) plus Deir Ammar and Zahrani operating on natural gas. Transmission and distribution losses from centralised generation are also assumed to reduce to 10% (from 15% in case 1). This case still includes self-generation.
3. Centralised generation only, this represents the impacts of EDL (i.e. no self-generation, 15% T&D losses).

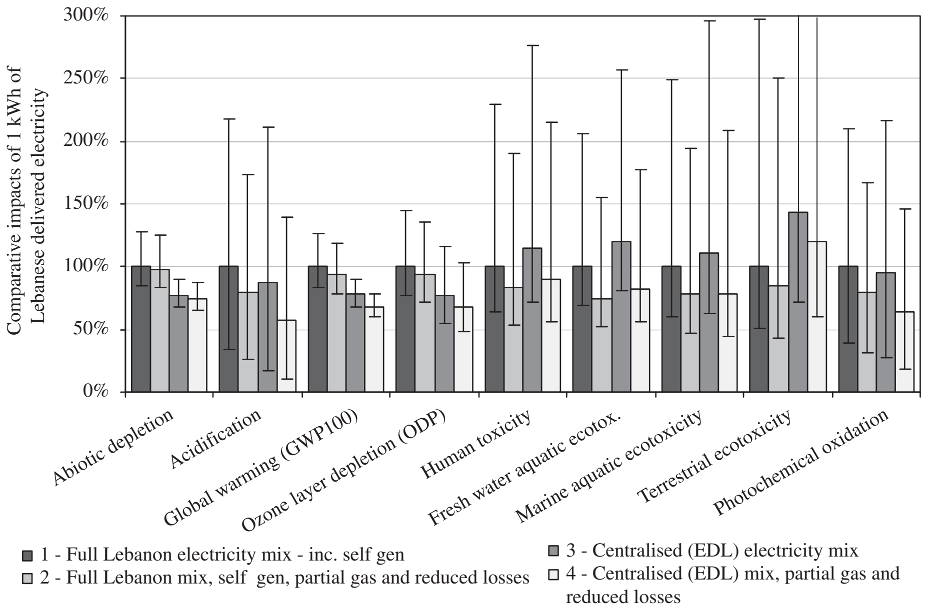

Fig. 4. Characterised impacts of Lebanese electricity per 1 kWh of delivered electricity for a range of cases.

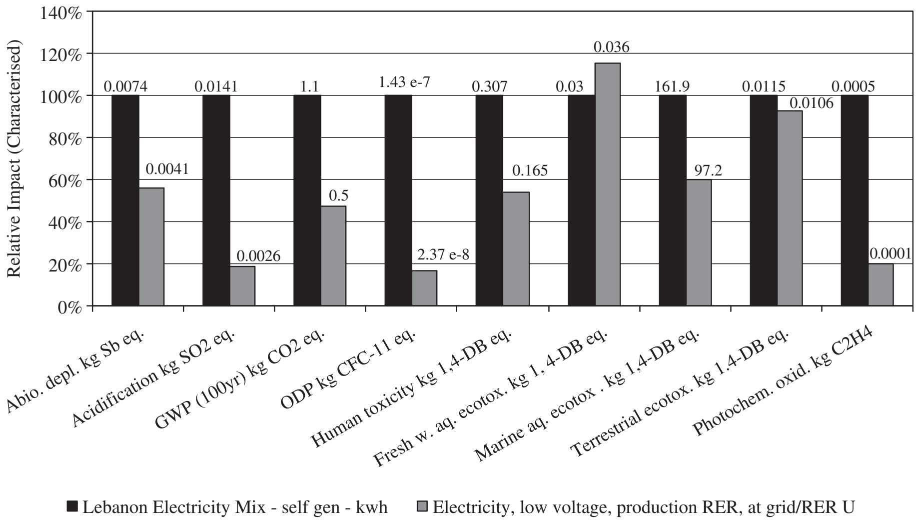

Fig. 5. Characterised LCA results of Lebanese versus European electricity per 1 kWh of delivered electricity.

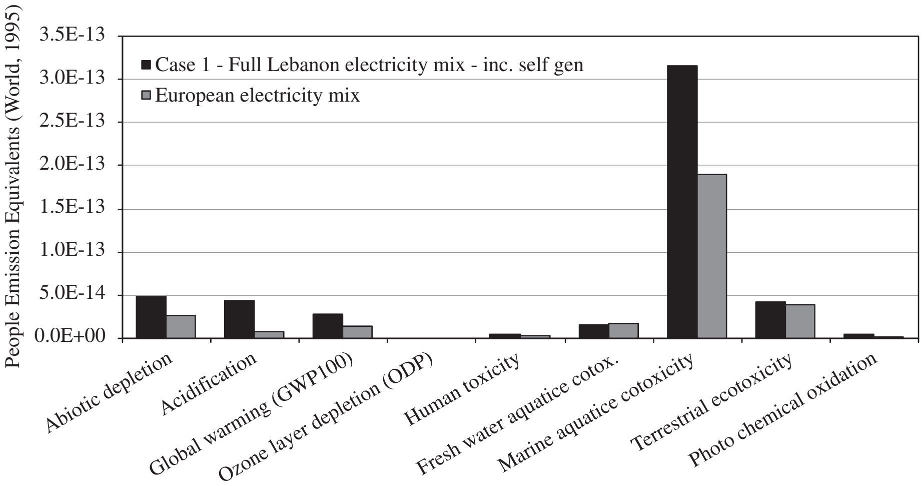

Fig. 6. Normalised LCA results of Lebanese versus European electricity per 1 kWh of delivered electricity.

4. Centralised generation of EDL (case 3) plus Deir Ammar and Zahrani operating on natural gas. Transmission and distribution losses are also assumed to reduce to 10%. This case excludes self-generation.

Case 1 is the normative reference, i.e., all the data in Fig. 4 is indexed to the impact of case 1 per kWh (i.e., case 1 is 100%); it presents the most realistic representation of the average impact of a unit of electricity as consumed by Lebanese consumers. The results show that if Deir Ammar and Zahrani were to operate on natural gas (case 2) and T&D losses were improved to 10%, it would result in a decrease across all impact categories. This includes a small decrease in the impacts of abiotic depletion (of non-living chemical and physical components of the environment, including fossil fuels), global warming potential, ozone layer depletion and terrestrial ecotoxicity. Furthermore, there was a more notable reduction in all the remaining categories (acidification, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and photochemical oxidation). It was interesting to note that were it not for improved T&D losses, abiotic depletion would have a marginal increase of 3%. Despite this a contribution analysis shows that the conversion to gas is responsible for approximately 59% of the improvement in global warming potential and ozone layer depletion, 70% of terrestrial ecotoxicity and almost 80% of human toxicity. In all other categories gas contributed between 85% and 89% of the improvement. The potential system improvements of case 2 would therefore offer a meaningful environmental benefit in terms of reduced environmental impacts from the entire Lebanese consumption of electricity. The global warming potential from case 1 was estimated to be 1.178 kg CO_{2e}/kWh versus 1.101 kg CO_{2e}/kWh for case 2. Both of these cases include the impacts from EDL (centralised generation) plus the self-generation within Lebanon.

Case 3 excludes the impacts of self-generation; it represents the impacts of EDL (and with no partial gas conversion or improved T&D). This only represents the impacts of the current centralised generation. Without the self-generation (i.e. comparison of case 3 with case 1) there is a notable decrease in the impact categories of abiotic depletion, acidification, global warming potential, ozone layer depletion and photochemical oxidation. However, the inclusion of self-generation is estimated to result in an increase in the impacts of the following four categories: (a) human toxicity, (b) fresh water aquatic ecotoxicity, (c) marine aquatic ecotoxicity, and (d) terrestrial ecotoxicity. The latter three categories partially can be explained by the fact that large centralised plants have highly concentrated forms of generation, which require large amounts of cooling water with more concentrated emissions rather than when geographically dispersed. However, a large contributor to these categories was the use of heavy fuel oil in the centralised generation mix in contrast to the diesel from self-generation. In particular, the release of vanadium emissions to the air was a significant contributor to all four impact categories. Other serious impacts result from chromium emissions to soil (in impact category d), nickel emissions to air (category a and to a lesser extent category d), arsenic emissions to air (category a) and vanadium ions to water (category b). Heavy fuel oils are known to have high concentrations of vanadium (see Lee and Wu, 2002; Huffman et al., 2000). The LCA has revealed this to be an undesirable effect of using a high proportion of oil-fired centralised generation.

Case 4 is case 3 with the gas conversion of Deir Ammar and Zahrani and reduced transmission and distribution losses (10% instead of 15%). It therefore does not include self-generation. As expected this case represents an improvement over case 3 across all impact categories. This is demonstrated by an LCA carbon coefficient of electricity under case 4 of 0.803 $\mathrm{kgCO_{2e}/kWh}$ in contrast to case 3 at 0.917 $\mathrm{kgCO_{2e}/kWh}$. Both of these conversion factors are below that from cases 1 and 2 (i.e., the entire Lebanese network including self-generation).

Characterised data is useful to determine which components of the life-cycle are the most dominant in each impact category, although it does have its caveats. It does not give any indication of the scale of *impacts* that can be expected from the estimated quantity of *emissions*. An example of this may be applied to the cases with and without self-generation. Centralised generation plants typically release high concentrations of fine particle emissions, which are a problem for human toxicity, from a high stack and often away from urbanised areas (although the largest Lebanese power plant, Zouk, is located in an urbanised area). In contrast the decentralised self-generation, which was determined to reduce human toxicity emissions, releases its emissions at ground level and within urbanised areas. Clearly further analysis would be necessary in order to determine the comparative impacts of such localised impact categories in detail.

The Lebanese electricity sector may be benchmarked in the future from a 2006 baseline. Thus, progress towards sustainability may be measured over time, once sustainable levels for each indicator have been determined. The results of case 1 (the most representative Lebanese current situation) can be contrasted with typical European emissions from electricity generation in the ecoinvent database (EU-27 countries excluding Baltic countries, but including Norway, Switzerland, and countries of the former state of Yugoslavia, see Dones et al., 2007). This is shown as characterised results in Fig. 5. The chart is annotated with the absolute emission values that constitute the baseline indicators.

Furthermore, the data was normalised to the average worldwide impacts of one citizen for the year 1995, i.e., the average emissions per person globally during 1995. Normalisation determines the relative contribution of the calculated damages to the total damage caused by a reference system (here being the world in 1995). It must, however, be noted that normalised results do not reveal which impacts are more significant (to the environment). For this to be achieved the impact categories need to be weighted, which is typically achieved by expert panel judgement. However, weighted indicators are highly subjective and have greater uncertainties. The present study was therefore terminated at the normalisation stage; in common with May and Brennan (2006) in a similar sustainability assessment of Australian electricity generation. But it must be appreciated that comparison of results between the normalised categories (shown in Fig. 6) is not appropriate.

The results displayed in Figs. 5 and 6 reveal that Lebanon exhibits higher environmental impacts in eight of the nine categories. It is clear that significant progress needs to be made before Lebanon can lower its impacts in terms of abiotic depletion, acidification, global warming potential, and marine aquatic ecotoxicity to the European level. Nevertheless, Lebanon has a slightly lower impact in fresh water aquatic ecotoxicity than the average European electricity. But the difference was comparatively small. It must be appreciated that the average EU emissions from burning oil in a Lebanese oil-fired power station was the starting point of the present LCA study, and that the EU data range was wide. Consequently the small differences in results for fresh water aquatic toxicity and terrestrial ecotoxicity should not be over emphasised. However, this implies that a large proportion of the European results can be attributed to excessively high vanadium-ions to water from oil-fired stations in Greece and coal-fired stations in Poland within the European power plant mix. All other indicators had a comparatively large difference, signifying the comparatively poor environmental performance of Lebanese electricity.

The poor marine aquatic toxicity results of the Lebanese electricity are confirmed in a report regarding the integrated management of the coastal zone in Northern Lebanon. It is indicated that “thermal shocks after cooling the power generators occur on a regular basis, which results in the presence of dead fish on the shores at least of Deir Ammar on a regular basis” (Doumani, 2007).

4.3. Energy analysis

An energy-generating source should produce more energy over its entire lifetime than is required to build, maintain and fuel this energy source. Thus, its ‘energy gain ratio’ (EGR), the ‘full fuel cycle’ energy output divided by the corresponding energy input, should be greater than 1–1.5 (Gagnon, 2008). An EGR too close to 1 represents a poor lifetime efficiency of fuel conversion—this is particularly the case for those technologies consuming depleting fossil fuel resources. For example, a high energy gain ratio allows finite resources to provide the same quantity of electricity with a lower lifetime primary energy consumption, thus extending the life of valuable finite resources. EGRs differ both within the same and between different technology types, depending on location or delivery distances, transportation mode of fuels and their actual accessibility and quality, as well as other parameters such as the use of end-of-pipe scrubbing technology. Fig. 7 illustrates the EGR

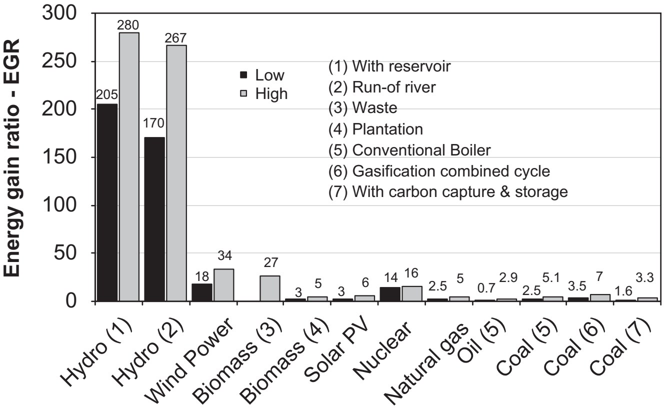

Fig. 7. Typically expected energy gain ratios of electricity generation options based on life-cycle assessments (Gagnon, 2005).

for several technologies, including oil and hydro, suitable for use in Lebanon.

Fig. 7 shows that there is a substantial advantage for renewable energy sources, particularly hydro and wind, in energy terms. However, the EGR values can only be taken as indicative and comparative as each individual generating source will have its own specificity. Moreover, the EGR considered above do not consider the inherent operational energy in the actual fuel consumed, and therefore they are sometimes referred to as 'external gain ratios' (Gagnon, 2005). Allen et al. (2008b) for example provides EGRs inclusive of the inherent energy of fuel (where applicable in non-renewable fuel sources) in the UK context, which result in substantially lower EGRs of coal, gas, oil, and nuclear power equal to 0.29, 0.43, 0.22, and 0.28, respectively (Allen et al., 2008b). In energy terms, the use of hydro in Lebanon would be further advocated, as would a move away from oil in favour of natural gas and towards renewables. This is in agreement with the outcome of the LCA. Renewable energy sources deliver net environmental benefits in addition to energy gain ratios over most impact categories in a LCA when compared to conventional energy sources (see for example Gagnon et al., 2002).

4.4. *Economic appraisal of the LES*

There are various indicators that can be used to measure the economic dimension of sustainability. Afgan et al. (2000) uses an effectiveness indicator defined via a 'thermodynamic efficiency' of the system, a 'capital investment' indicator, and a 'community economic' indicator. In contrast, May and Brennon (2006) use 'capital costs', 'value added', and 'annualized costs'. The IChemE (2002) produced similar indicators, including 'value added', 'return on average capital employed', and 'R&D expenditure' amongst others. The 'value added' economic indicator could be easily deduced for the LES from the annual government subsidies (ranging from US$0.19–1.62 billion annually – see Fig. 1). Given this fact, a simple criterion for the economic dimension of sustainability would be said to be to create wealth or value (Darton, 2003). Applied comparatively to the current LES (and case studies adopted in the present study), a NPV criterion may be employed. Furthermore, potential economic benefits of alternative technology choices to close the demand–supply deficit (and cater for retirement of plant as projected in Table 1) are valued through the levelised cost indicator, as partially done in Evans et al. (2009) and in the New Energy Externalities Developments for Sustainability (NEEDS) project (NEEDS, 2008).

A comparative cost–benefit appraisal is applied on similar (yet not exact) cases as expressed through the LCA, taking into account the social cost of carbon (SCC) only due to the fact that carbon emission damages are not site-specific and due to the extensive literature present on the SCC. The four economic abatement cases are all compared to the current centralised electricity system (EDL), yet avoiding the inclusion of self-generation due to the fact that the measures (i.e., economic cases a–d below) would potentially only reduce the amount of suppressed electricity and not the use of self-generation. The four economic cases, which are to be compared to the baseline centralised electricity system, are:

(a) Centralised baseline system with reduction of T&D losses to 10%.
(b) Centralised baseline system with reduction of T&D losses to 10%, and improvement of plant efficiencies to design standards.

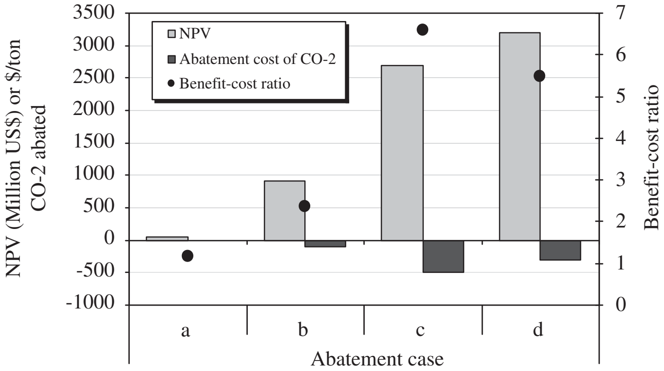

Fig. 8. Net present value (NPV), benefit–cost ratio and abatement cost of CO_2 for 4 abatement cases.

(c) Centralised baseline system with a switch to natural gas for Deir Ammar and Zahrani plants.
(d) Centralised baseline system with reduction of T&D losses to 10%, improvement of plant efficiencies to design standards, and switch to natural gas for Deir Ammar and Zahrani.

Assuming a conservative 10-year lifetime of measures required in cases a–d above, and adopting a mean (and arguably conservative) social cost of carbon of $65 per ton of carbon (2009 value) (AEA Technology, 2005), Fig. 8 shows the net present value (NPV) of the four economic cases assuming that: (1) the marginal investment and maintenance costs of reducing T&D costs and improvements of plant efficiencies to meet design specifications are as estimated by the World Bank (2008); (2) assuming that the natural gas pipeline investment is completed to the Deir Ammar plant, while an additional investment of $200 million[1] is needed for a pipeline to reach Zahrani, (3) adopting mean prices for oil and natural gas ($80/barrel and $7/million British Thermal Unit[2], MBTU, respectively to simplify the analysis), (4) assuming the current average electricity supply tariff of $c9.4/kWh, and (5) adopting a 5% discount rate.

Fig. 8 shows that the potential revenues to be collected from the sale of otherwise lost electricity through improved T&D networks, along with the savings expected from switching to natural gas (from the more expensive diesel oil) are substantially greater than the capital investment and annual maintenance costs required for these measures. This guarantees positive NPVs, or benefit–cost (B–C) ratios greater than one, and delivers abatement of CO_2 at savings of $92–$500 per ton (therefore negative cost) depending on the case assumed. Therefore a substantial Pareto improvement is possible if the centralised system is optimized, given the Kaldor–Hicks criterion (see Boardman et al., 2006).

Improving the performance of the T&D networks, the efficiency of current plants, and the switching to natural gas would go a long way in satisfying the otherwise suppressed electricity demand (as discussed in Section 3). However, these measures (cases a–d) cannot cater for the extra capacity needed and self-generation will remain a necessity, particularly in the face of growing demand for electricity. Given that oil power plants are currently the main suppliers of electricity in Lebanon, Fig. 9 shows that alternative electricity (and energy) sources could provide an additional economic justification over and above environmental (Section 4.2) and energy (Section 4.3) ones.

---

[1] This cost value is an approximation, based on an approximate road distance from Deir Ammar to Zahrani plant (equal to a maximum of ~200 km), at a cost of $1 million per km (Yalibnan, 2008). The cost (and distance required) of the natural gas pipeline could be substantially lower however.

[2] 1 BTU = 1055 J.

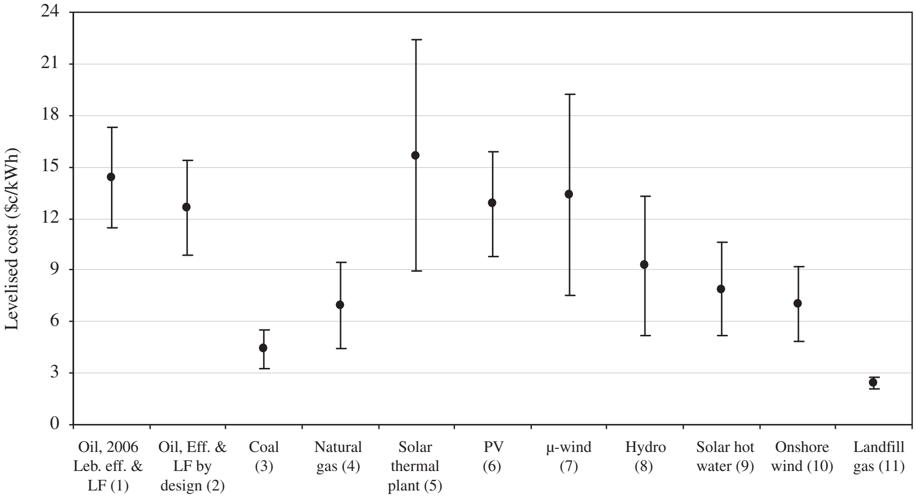

Fig. 9. Expected levelised cost of electricity generating (or displacing) options in Lebanon. (1) Current average total for all oil plants in Lebanon; capital cost from International Energy Agency (IEA) (2005), ± 15%, Load factor (*LF*) and efficiency (*eff.*) of current plants in 2006, fixed operation and maintenance (O&M) from World Bank (2008), running cost range between $60 and $100 per barrel of oil. (2) Design efficiency from World Bank (2008), design load factor from IEA (2005). (3) Average efficiency and load factor from Department of Trade and Industry (DTI) (2006), lifetime and cost parameters from IEA (2005). (4) Capital, O&M estimates and load factor from IEA (2005). Natural gas cost price assumption ranging from $4 to $10 per MBTU. (5) Capital and O&M costs from Retscreen software data (http://www.retscreen.net), large variation due to the different types of solar thermal plants and including or excluding storage capability. (6) Solar irradiance measure from El-Fadel et al. (2003) and Retscreen software data, capital and O&M cost from local Lebanese supplier. (7) Capacity factor based on wind speed at 10 m hub height from El-Fadel et al. (2003), capital and O&M cost from local Lebanese supplier. (8) Capacity factor based on Houri (2006b), and capital and O&M costs based on El-Fadel et al. 2003 and IEA (2005). (9) Solar irradiance from El-Fadel et al. 2003 and Retscreen, costs from local Lebanese supplier. Levelised costs based on displaced electricity equivalence. (10) Capacity factor based on average wind speed measurements (5 km resolution) from 3TIER (http://www.3tiergroup.com/), cost estimates from IEA (2005) and Retscreen software data. An additional $c1.5/ kWh is added to wind levelised cost estimates to compensate for intermittency (i.e., intermittency costs). This value has been approximated from UK Energy Research Centre (UKERC) (2006). (11) Based on IEA (2005).

Fig. 9 shows that oil power plants are among the more expensive options for supplying electricity. Landfill power generation, coal, natural gas, and onshore wind farms are potentially the least costly options in Lebanon (strictly excluding social costs). Microgeneration, or electricity or heat from low-carbon sources with capacities no more than 50 KWe or 45 kWth (Allen et al., 2008a), can also play an important role in satisfying Lebanon's demand for energy. Microgenerators, such as solar hot water (SHW), photovoltaic (PV), and microwind (μ-wind) systems can assist in reducing electricity demand, improving reliability, and enhancing the environmental performance of the electricity system. For example, solar hot water systems (SWH) can contribute to a saving of up to 80% of (hydrocarbon) energy used to heat water and 8% of total electricity used nationally since most hot water boilers are electricity fed (Houri, 2006a). Moreover, most of the renewable energy systems shown in Fig. 9 are experiencing annual capital cost reductions bought about through so-called 'progress ratios' which will further benefit their economic performances. 'Progress ratios' or 'experience curves' indicate the percentage cost reduction experienced for every doubling of global capacity, due to learning-by-doing and economies of scale (Allen et al., 2008a).

The various generating technologies shown in Fig. 9 can be compared and contrasted via other economic indicators as well. This includes those employed as part of the NEEDS project, particularly the report on economic indicators (NEEDS, 2008). However, Fig. 9 ultimately represents the fact that there are more cost-effective technologies to generate electricity, resulting in economic efficiency gains and wealth creation, which is a 'key element of sustainability' for industry (Darton, 2003).

5. Discussion

Given the current demand–supply gap in the LES and the requirements for an adequate capacity margin, the need to eliminate diesel self-generation, the expected retirement of current power plants (see Table 1), and with forecasted annual electricity demand ranging between 3.5% and 6.4% between 2010 and 2015 (see World Bank, 2008), Lebanon will need to both optimize the current electricity system and build up to 8 new 600 MW power plants by 2030 to ensure a LOLP of 9%. This amounts to 1 power plant every 2.5 years, if Lebanon were to adopt centralised supply-side solutions only. This could prove to be an unfeasible task for the Lebanese government given the subsidized costs and inefficient performance of the existing electricity system. Furthermore, achieving a Shannon Weiner index of at least 2 would require the diversification of the supply portfolio considerably more than the current generation mix which was characterized with a S–W index of 0.83–1.24 in Fig. 3.

The LCA revealed the LES to have poor environmental performance, particularly in comparison to typical European electricity. The analysis of four case studies further demonstrated that Lebanon could improve its environmental performance in all impact categories by operating the power stations at Deir Ammar and Zahrani on natural gas and improving transmission and distribution losses across the entire network. The gas conversion would be particularly beneficial and is presently feasible. At the time of writing, the gas conversion had been partially implemented with natural gas beginning to fuel the Deir Ammar plant (Now Lebanon, 2009). These LCA measures aimed at optimizing the LES also improve the economic performance of the system. A CBA reported in this study has shown that considerable net benefits could arise from implementing measures to optimize the current system as implied by the four economic cases (cases a–d). Such measures would help improve the 'value added' indicator. Furthermore, seemingly competitive costs of alternative energy sources exist other than oil, as shown through the levelised costs in Fig. 9.

Relying only on centralised supply-side solutions for the LES would only extend the 'conventional' approach to the electricity sector adopted by the Government of Lebanon since the beginning of the 1990s. This conventional approach to the supply of electricity runs the risk of continued reduction in quality of service and overall coverage, and would lead to further financial deficits due to poor cost recovery (Panayotou, 2002). The deficits have increased the perceived risks for potential lenders or investors in the sector, and have pushed private sector investors to require additional guarantees or contingent liabilities worth approximately $c1.6/kWh according to the World Bank (2008). However, the availability of private sector financing and its requirement for additional guarantees are not major barriers, as many local investors have voiced their willingness and ability to invest in electricity generation (Now Lebanon, 2008), including large-scale renewable energy projects. It is more of a problem of regulatory reform or oversight. Electricity Law 462 of 2002 paved the way for private sector participation by allowing up to 40% of the shares in generation plant and distribution networks to be privatised (GoL, 2002). Transmission management can also be corporatized (GoL, 2002). Yet Law 462, which calls for the establishment of a National Electricity Regulatory Authority (NERA) that would have the sole right to license independent power producers (among other regulatory and oversight responsibilities), has still to be established some 7–8 years on. The result is that no independent power producer has currently invested in energy sources to sell to the Lebanese grid. Law 462 does have many shortcomings, such as not catering for the export of electricity from microgenerators at a household level, however it was a first step towards better regulation of the overall LES, which could have also opened up alternative financing mechanisms for private sector electricity generation, such as the Clean Development Mechanism of the Kyoto Protocol, which Lebanon has signed and ratified, and local level solutions through, for example, Energy Service Companies (ESCOs) or co-operatives that engage and offer partnerships with the local communities (Gregory et al., 1997). This weakness in governance is likely to persist until the electricity sector is taken outside the influence and complexities of Lebanese internal politics[3]. The challenges are compounded when taking into account the growing financial burdens of the central government, including a huge national debt equalling more than 170% of GDP (in 2006).

Radical and simultaneous measures targeting both the supply-side and the demand-side are therefore needed to improve the overall performance of the LES in terms of reliability, environment, and economic affordability. A coherent, transparent, and long-term policy commitment by the government of Lebanon is required to tackle the energy sector's problems holistically. The energy hierarchy and sustainability objectives, as discussed in Section 2, need to set the guidelines, objectives and foundations for energy policy in Lebanon, including the decisions on the current and future generation mix or portfolio desired. The current situation of the LES, as indicated here through reliability, environmental, and economic indicators, could be used as a baseline (2006) against which to monitor year-on-year improvement towards a more 'sustainable energy system'.

6. Concluding remarks

The Lebanese electricity system has been evaluated in terms of its sustainability through the application of several integrated appraisal techniques. Reliability has been assessed via the LOLP and the S–W index. Environmental performance has been assessed through a LCA and the CML 2001 LCA impact assessment method. Energy performance was measured via the 'energy gain ratio', while economic performance has been presented via the NPV and the levelised cost indicators. The findings show that the Lebanese electricity system is characterized by a weak performance in all analysed aspects related to the sustainability of energy systems. Specifically, the system lacks adequacy and security through its supply–demand deficit and a low diversity index. Similarly, the LCA provided a general indication of the poor environmental performance of the current system, particularly when compared with the European situation (Figs. 5 and 6). The LCA also shows the relative environmental merits in shifting towards situations that exclude heavy fuel oil-based generation, but also towards natural gas based generation and improved T&D networks. Furthermore, the current electricity system is characterized by large economic inefficiencies. The costs and benefits of optimising the performance of the centralised system points to substantial net benefits from improving the T&D networks, maintaining conventional existing plants to achieve their design standards, and shifting towards the use of natural gas. Moreover, the expected levelised cost of various energy sources in Lebanon (Fig. 9) indicate that renewable energy sources are highly competitive alternatives to consider and support to meet this reliability objective.

Any measure to improve one aspect of the sustainability of the Lebanese power sector (for example, reliability), at the significant expense of another (for example, environmental performance), would not be considered a 'sustainable solution'. However, the integrated appraisal of the Lebanese electricity sector presented has shown that significant improvements of the energy system could be achieved simultaneously in all three aspects of reliability, economic affordability, and environmental performance. Solutions have been shown to be cost-effective, environmentally justified, and ultimately more beneficial to the reliability of the entire system. Moreover, when the impacts of the energy sector are seen against the potential consequences and/or costs of climate change (at least) in Lebanon, particularly concerns over impacts from reduced freshwater availability (see United Nations Development Program (UNDP) and Ministry of Environment (MOE), 1999; UNDP, 2009), policy makers would be better able to integrate (and relate) environmental concerns with economic ones, and move the country along a pathway towards 'sustainability'.

Acknowledgements

Support has been provided for the research contribution of four of the authors (GPH, HAH, CIJ, and ABW) by the UK Engineering and Physical Science Research Council (EPSRC) via the Supergen 3 'Highly Distributed Power Systems' Consortium; renewed in 2009 as the 'Highly Distributed Energy Future (HiDEF) Supergen Consortium. These consortia have been co-ordinated by Professors Graeme Burt and David Infield of the Institute for Energy and Environment at the University of Strathclyde. The second author (GPH) is presently co-leading a large consortium of university partners (jointly with Professor Peter Pearson, an energy economist from Imperial College, London), funded via a strategic partnership between E.ON UK (the electricity generator) and the EPSRC to study the role of electricity within the context of 'Transition Pathways to a Low Carbon Economy' for the UK. The fourth author (CIJ) has been partly funded from this grant. The authors' names appear alphabetically.

References

Abi Said, C., 2005. Electric Energy and Energy Policy in Lebanon. Global Network on Energy for Sustainable Development (GNESD), Beirut.

Acres, D., 2007. Defining sustainable energy. Proceedings of the Institution of Civil Engineers: Energy 160 (EN3), pp. 99–104.

---

[3] For an in-depth discussion on the Lebanese political system and politics in a historical and current context, see Ziadeh (2006).

AEA Technology, 2005. The Social Cost of Carbon Review; Methodological Approaches for Using SCC Estimates in Policy Assessment. AEA Technology, London.

Afgan, N.H., Carvalho, M.G., Hovanov, N.V., 2000. Energy system assessment with sustainability indicators. Energy Policy 28, 603–612.

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renewable and Sustainable Energy Reviews 10, 539–558.

Allan, R., Billinton, R., 1992a. Power system reliability and its assessment. Part 1: background and generating capacity. Power Engineering Journal, 191–196.

Allan, R., Billinton, R., 1992b. Power system reliability and its assessment. Part 2: composite generation and transmission systems. Power Engineering Journal, 291–297.

Allan, R., Billinton, R., 1993. Power system reliability and its assessment. Part 3: distribution systems and economic considerations. Power Engineering Journal 21, 185–192.

Allen, S.R., Hammond, G.P., Harajli, H.A., Jones, C.I., McManus, M.C., Winnett, A.B., 2008. Integrated appraisal of micro-generators: methods and applications. Proceedings of the Institution of Civil Engineers, Energy, 161(EN2), pp. 73–86.

Allen, S.R., Hammond, G.P., McManus, M.C, 2008. Energy analysis and environmental life-cycle assessment of a microwind turbine. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 222(7), 669–684.

Badelt, G., Yehia, M., 2000. The way to restructure the Lebanese electric power sector: a challenge for transitional management. Energy Policy 28, 39–47.

Billinton, R., Allan, R.N., 1996. Reliability Evaluations of Power Systems, second ed. Plenum Press, New York.

Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2006. Cost–Benefit Analysis; Concepts and Practice. Pearson Education Inc., New Jersey.

Darton, R.C., 2003. Scenarios and metrics as guides to a sustainable future: the case of energy supply. Trans. IChemE, Part B: Process Safety and Environmental Protection 81 (5), 295–302.

Department of Trade and Industry (DTI), 2006. The Energy Challenge Energy Review. DTI, London.

Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Röder, A., Emmenegger, M.F., Frischknecht, R., Jungbluth, N., Tuchschmid, M., 2007. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries, Data V2.0, ecoinvent report No. 5, Swiss Centre for Life Cycle Inventories, Switzerland.

Doumani, F.M., 2007. Integrated Management of East Mediterranean Coastlines: Northern Lebanon, Short and Medium Term Priority Action Program III. University of Balamand, Lebanon.

El-Fadel, M., Chedid, R., Zeinati, M., Hmaidan, W., 2003. Mitigating energy-related GHG emissions through renewable energy. Renewable Energy 28, 1257–1276.

Evans, A., Strezov, V., Evans, T.M., 2009. Assessment of sustainability indicators for renewable energy technologies. Renewable and Sustainable Energy Reviews 13, 1082–1088.

Gagnon, L., Bélanger, C., Uchiyama, Y., 2002. Life-cycle assessment of electricity generation options: the status of research in year 2001. Energy Policy 30, 1267–1278.

Gagnon, L., 2005. Electricity generation options: energy payback ratio-factsheet. Quebec, Hydro Quebec, Quebec.

Gagnon, L., 2008. Civilisation and energy payback. Energy Policy 36, 3317–3322.

GoL, 2002. Law No. 462: Regulation of the Electricity Sector, Government of Lebanon (GoL), Lebanon.

Graedel, T.E., Klee, R.J., 2002. Getting Serious about Sustainability. Environmental Science and Technology 36 (4), 523–529.

Gregory, J., Silveira, S., Derrick, A., Cowley, P., Allison, C., Paish, O., 1997. Financing Renewable Energy Projects; A Guide for Development Workers. IT Publications, Nottingham.

Grubb, M., Butler, L., Twomey, P., 2006. Diversity and security in UK electricity generation: the influence of low-carbon objectives. Energy Policy 34, 4050–4062.

Hammond, G.P., 2000. Energy, environment and sustainable development: a UK perspective. Trans IChemE Part B: Process Safety and Environmental Protection 78 (4), 304–323.

Hammond, G.P., Harajli, H.A., Jones, C.I., Winnett, A.B., 2009. Integrated appraisal of building integrated photovoltaic (BIPV) systems. In: Proceedings of the First International Conference on Sustainable Power Generation and Supply (Supergen), Nanjing, China, 6–7 April, 9 pp.

Hammond, G.P., Waldron, R., 2008. Risk assessment of UK electricity supply in a rapidly evolving energy sector. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 222 (7), 623–642.

Hammond, G.P., Winnett, A.B., 2006. Interdisciplinary perspectives on environmental appraisal and valuation techniques. Proceedings of the Institution of Civil Engineers: Waste and Resource Management 159 (WR3), 117–130.

Hogan, W.W., 2005. Connecting Reliability Standards and Electricity Markets, Harvard Electricity Policy GroupMassachusetts.

Houri, A., 2006a. Solar water heating: current status and future prospects. Renewable Energy 31, 663–675.

Houri, A., 2006b. Prospects and challenges of using hydropower for electricity generation in Lebanon. Renewable Energy 31, 1686–1697.

Houri, A., Ibrahim-Korfali, S., 2005. Residential energy consumption patterns: the case of Lebanon. International Journal of Energy Research 29, 755–766.

Huffman, G.P., Huggins, F.E., Shah, N., Huggins, R., Linak, W.P., Miller, C.A., Pugmire, R.J., Meuzelaar, H.L.C., Seehra, M.S., Manivannan, A., 2000. Characterization of fine particulate matter produced by combustion of residual fuel oil. Journal of Air and Waste Management Association 50, 1106–1114.

Institution of Chemical Engineers (IChemE), 2002. The Sustainability Metrics; Sustainability Development Progress Metrics Recommended for Use in the Process Industry. IChemE, Rugby.

International Energy Agency (IEA), Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA), 2005. Projected Costs of Generating Electricity, 2005 Update, OECD/IEA, Massachusetts.

International Institute for Energy Conservation (IIEC), 2008. Approach to greenhouse gas (GHG) emission reduction analysis. Project 0013385, IIEC, Bangkok.

ISO 14040, 1997. Environmental Management—Life Cycle Assessment—Principles and Framework.

ISO 14044, 2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines.

Khatib, H., 2003. Economic Evaluation of Projects in the Electricity Supply Industry. Institute of Electrical Engineers, Herts.

Lee, S.-R., Wu, C.-Y., 2002. Study of vanadium emission control in combustion systems by thermodynamic equilibrium analyses. Advances in Environmental Research 7, 1–10.

May, J.R., Brennan, D.J., 2006. Sustainability assessment of Australian electricity generation. Trans. IChemE, Part B. Process Safety and Environmental Protection 84 (B2), 131–142.

Mitchell, C., 2008. The Political Economy of Sustainable Energy. Palgrave Macmillan, Basingstoke.

Ministry of Finance (MOF), 2008. Fiscal Performance Reports. Ministry of Finance, Beirut.

Nedic, D., Shakoor, A., Strbac, G., Black, M., Watson, J., Mitchell, C., 2005. Security Assessment of Future UK Electricity Scenarios. Technical Report 30, Tyndall Centre for Climate Change Research, Norwich.

NEEDS, 2008. Final Report on Economic Indicators for Sustainability Assessment of Future Electricity Supply Options, NEEDS Integrated Project, Deliverable D5.2-RS2b, Villigen.

Now Lebanon, 2008. Talking to Ziad Hayek; the truth behind Lebanon's electricity crisis. Published 4-2-2008, accessed on 21-4-2009.

Now Lebanon, 2009. Power production costs to drop, rationing will stay. Published 23-09-2009, accessed on 01-10-2009.

Panayotou, T., 2002. Innovative financial mechanisms for sustainable sector financing, in: Finance for Sustainable Development, Testing New Policy Approaches. In: Proceedings of the Fifth Expert Group Meeting on Finance for Sustainable Development, 1–4 December, United Nations, New York, pp. 311–330.

Potting, J., Hauschild, M., Wenzel, H., 1999. "Less is better" and "only above threshold": two incompatible paradigms for human toxicity in life cycle assessment?. International Journal of LCA 4 (1), 16–24.

Sonneman, G., Castells, F., Schuhmacher, M., 2004. Integrated Life-Cycle and Risk Assessment for Industrial Processes. CRC Press, Florida.

UK Energy Research Centre (UKERC), 2006. The Costs and Impacts of Intermittency: An Assessment of the Evidence on the Costs and Impacts of Intermittent Generation on the British Electricity Network. Imperial College, London.

United Nations Development Program (UNDP), Ministry of Environment (MOE), 1999. Technical Annex to Lebanon's First National Communication: Assessment of Lebanon's Vulnerability to Climate Change, UNDP, Beirut.

United Nations Development Program (UNDP), 2007. Human Development Report 2007/2008, UNDP, New York.

United Nations Development Program (UNDP), Ministry of Environment (MOE), 2009. Lebanon's Second National Communication to the United Nations Framework Convention on Climate Change: National Greenhouse Gas Inventories, Draft Report, UNDP, Beirut.

United Nations Development Program (UNDP), 2009. Arab Human Development Report (2009), UNDP Regional Bureau for Arab States, New York.

Vob, A., 2006. Energy in a sustainable development perspective. In: Ehlers, E., Krafft, T. (Eds.), Earth System Science in the Anthropocene. Springer, New York, pp. 153–166.

World Commission on Environment and Development (WCED), 1987. Our Common Future. Oxford University Press, Oxford.

World Bank, 2008. Republic of Lebanon Electricity Sector Public Expenditure Review, 41421-LB, World Bank, Washington.

Yalibnan, 2008. Lebanon minister in Syria to discuss the Arab Gas Pipeline. Yalibnan, published 23-02-2008, accessed 10-06-2009.

Ziadeh, H., 2006. Sectarianism and Intercommunal Nation-Building in Lebanon. Hurst and Company, London.