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The environmental life cycle assessment of different electricity options in Kuwait

Mohammad Abotalib*, Jaya Jacob**, Hamid Alhamadi*** and Dhary Alkandari*

*Assistant Professor, Department of Earth and Environmental Science, Kuwait University, Khaldiya Campus, Kuwait
**Chemist, Department of Earth and Environmental Science, Kuwait University, Khaldiya Campus, Kuwait
***Assistant Professor, Department of Computer Science, Kuwait University, Khaldiya Campus, Kuwait
*Corresponding Author: Mohammad.abotalib@ku.edu.kw

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ABSTRACT

In Kuwait, electricity is generated from two primary sources, heavy fuel combustion and natural gas combustion. As Kuwait relies mainly on petroleum-based products for electricity generation, identifying and understanding the environmental and energy trade-off of such operations should be carefully investigated. The life cycle assessment (LCA) tool is applied to identify the potential environmental impacts and energy performance of electricity generation under three scenarios, by considering the material flow in various stages involved such as raw-material extraction, transportation, and operations. The three scenarios investigated represent current and futuristic electricity grid mixes. The analysis of four indicators consists of two environmental and two energy indicators per one kWh of the electricity generated.

The environmental indicators examined are global warming potential (GWP) and water consumption (WC), whereas the energy indicators target cumulative energy demand (CED) and net energy ratio (NER). Results indicate that one kWh of electricity generated would have a GWP (0.63-0.77) kg CO_2-eq, mainly from the fuel combustion process, WC (0.0013-0.0015) m^3 of water, about 68% from cooling processes, CED (9.9-10.7) MJ, and NER (0.34-0.39). The variation in results depends on the scenario investigated. It can be observed from the analysis that introducing solar photovoltaic and wind to the electricity grid mix improves the environmental and energy performance of Scenarios 3, where 15% of the electricity generated from renewables (10% solar PV and 5% wind) corresponds to a further decrease in LCA results.

Keywords: Energy; Functional Unit; Global Warming Potential; Life Cycle Assessment.

INTRODUCTION

Globally, the demand for electricity is expected to increase, mainly due to population and economic growth. According to British Petroleum (BP), the world economy is expected to double in the next two decades, and this growth will electrify the energy consumption, mainly used for power generation (British Petroleum, 2017). In Kuwait, the electricity production has doubled from the year 2000 baseline reaching 54 million kWh in 2014 (CIA, 2015). Kuwait is a small country with a total population of 4.5 million; however, the energy consumption per capita is considered as one of the highest in the world (International Energy Agency (International Energy Agency (IEA), 2017; PACI, 2018)). This high consumption can be explained by three main factors. The first factor is the subsidized price of electricity for both public and private sectors. Second, the rapid annual population growth, which is about 3.3% increase (Alotaibi, 2011). Third, the long summer season, which can last for more than seven months, and therefore, increasing the need for continuous operations of air condition (Al-Mutairi, Smallbone, Al-Salem, & Roskilly, 2017). According to Reicher 2010, Kuwait and other GCC countries are accountable for producing the highest amount of carbon dioxide per capita worldwide (Reiche, 2010). In Kuwait, an overwhelming one-third to one-half of the oil produced is consumed by the cogeneration of electricity and water desalination (Darwish, Al-Awadhi, & Darwish, 2008; Fattouh & Mahadeva, 2014; KEPA, 2015). In Kuwait, electricity is produced by seven power plants as illustrated in Table 1. Older power plants use fuel oil as a primary fuel; however, more recent facilities have been designed to operate on gas oil and natural gas (Al Jandal & Al Sayegh, 2015). Some of these power plants are designed to serve the purpose of electricity generation, as well as seawater desalination for potable use (Al Jandal & Al Sayegh, 2015).

Energy-intensive desalination plants (DPs) result in huge ecological and health impacts that need more comprehensive assessment (Al-Abdulghani, El-Sammak, & Sarawi, 2013; Aleisa, Al-Ahmad, & Taha, 2011). However, some power plants generate electricity, as well as water, and combine two or more thermodynamic cycles, resulting in improved overall efficiency, reducing fuel costs. The most common desalination techniques used in Kuwait are multistage flashing (MSF) desalination technique and reverse osmosis (RO). The desalination of seawater till a few years back was accomplished in seven distillation and power plants (Al-Mutairi et al., 2017). The distillation units in these power stations use the MSF evaporation method, and the capacity of the units was between 0.023 to 0.027 Mm^3/d (Oyoh, 2017). Each of the distillation units consists of several stages ranging from 24 to 26 stages. The total capacity of the distillation units in the power and water distillation stations was 1.175 Mm^3/d (Oyoh, 2017).

Table 1. List of power plants in the State of Kuwait.

	Power Plants Name	Capacity in MWe	Desalinated Water(MIG)	Technology	Primary fuel	Secondary fuel
1	Shuwaikh	252	10047	Open cycle gas turbine	Natural gas	-
2	Shuaiba North	876	10297	Power and desalination combined cycle gas turbine	Natural gas	Gas oil
3	Shuaiba South	720	8907	Power and desalination combined cycle gas turbine	Natural gas	Gas oil
4	Doha East	1158	12115	Cogeneration power and desalination steam turbine	Heavy fuel oil, crude oil, gas oil	Natural gas
5	Doha West	2360	33677	Cogeneration power and desalination steam turbine	Heavy fuel oil, crude oil, gas oil	Natural gas
6	Al-Zour	5306	48195.82	Open and combined cycle gas turbine	Natural gas and gas oil	-
7	Sabiya	4867	32736	Power and desalination combined cycle gas turbine	Heavy fuel oil, crude oil, gas oil	Natural gas

Adopted from (Al-Mutairi et al., 2017).

As illustrated in Table 1, fossil fuel such as crude oil, natural gas, and gas oil is the backbone fuel of the current power plants in Kuwait. Therefore, future expansion projects should consider additional capacity from nonconventional sources to grow in line with goals of sustainable development. The new vision of 'Kuwait 2035' incorporates a matrix of seven pillars that include effective public administration, sustainable diverse economy, enhanced infrastructure, sustainable living environment, high quality health care, creative human capital, and enhanced global position (NewKuwait, 2018). Accordingly, Kuwait's 2035 strategy incorporated the use of renewable energy by 15% of country's total power capacity (Tortell & Al-Essa, 2011; UNDP, 2014). To invest in Renewable Energy Technologies (RET) implies reducing the impact of meeting the national demand and the escalating consumption patterns. Energy created from RETs could gradually substitute oil and natural sources and therefore extend the lifeline of the country's nonrenewable resources. Hence, it is about time for the state of Kuwait to understand the environmental profile of the existing and proposed electricity generation practices to make informed strategic decisions about the future choices of electricity conversion technologies. In many situations, most practices or operations do not have immediate local or global environmental implications. Consequently, the decision-making process should address those problems in depth by considering the various technical and geographical variables. This matter has always been a challenging task for policy makers, as decisions are made based on incomplete information. This problem can underestimate or overestimate the magnitude of the situation (Miettinen & Hämäläinen, 1997). In view of that, environmentalists have developed several environmental accounting tools, which can assist in making informed decisions. Among the tools developed is the life cycle assessment (LCA), which is described as an environmental decision-making tool for assessing the potential environmental impacts of a product or service, by accounting for the material flows in every process or stage such as raw-material extraction, transportation, operations, and waste disposal (Bare, 2011). In 2006, the International Standards Organization (ISO) has developed the ISO-14040 series of standards, systematic guidelines for LCA practitioners, which define a clear set of guidelines for conducting LCA studies (ISO, 2006). The basis of LCA analysis identifies system boundaries of the electricity produced as the product and covers processes including fuel supply, fuel transportation, and fuel combustion (i.e., fuel conversion to electricity). Similarly, the National Energy Technology Laboratory (NETL) suggested an approach, which covers important stages starting from material acquisition to electricity end users (NETL, 2010).

In recent years, the LCA tool has been supported by researchers from various fields, including those interested in evaluating the environmental impacts of electricity generation (Lee, Lee, & Hur, 2004). Several LCA studies have already been carried out, which have evaluated the environmental impacts associated with electricity generation in different countries including the United States, the United Kingdom, Germany and China (Cui-Cui, Mei, Pei-Pei, & An-Na, 2013; Di, Nie, Yuan, & Zuo, 2007; EURELECTRIC, 2011; Lee et al., 2004; Reiche, 2010; Stamford & Azapagic, 2014; UChicago Argonne, 2014). In these studies, results have shown wide range of variability because these studies have used inconsistent parameters, as well as different electricity grid mix. This is because each country has a different electricity grid mix profile due to various economic, geographic, and political factors. For example, in Scandinavia, the electricity mix portfolio is more diverse consisting of fair shares of hydro-, geothermal, wind, solar, and nuclear power (IEA, 2017). However, this not the case for oil wealthy nations, like Kuwait, where petroleum-based products are considered the primarily fuel used for electricity generation (IEA, 2017). Another study published by Turconi et al. (2013) reviewed 167 LCA case studies of various electricity generation technologies including fossil fuel-based and renewable energy technologies. The results suggest that it is not sufficient to focus on a single environmental impact indicator to make informed environmental decisions. However, these studies agreed on the fact that fossil fuel-based technologies have their highest GHG emissions during the plant operation phase. On the other hand, the manufacturing and infrastructure phases represent the highest GHG emissions for renewable technologies. Still, the methodology is applied, and the system boundaries play a fundamental role in the LCA results. Accordingly, the environmental friendliness of a specific electricity generation technology depends on various parameters such as source of energy, fuel type, and energy conversion techniques. So far, the LCA of Kuwait's electricity generation has not been evaluated.

To make such informed evaluation, it is necessary to identify the existing electricity grid mix profile with a comprehensive understanding of technologies adopted and the type and the source of fuel used. We will apply the LCA approach to calculate the environmental profile and energy performance of electricity generation in the state of Kuwait (per unit of electricity generated), which accounts for these considerations. The analysis will cover three scenarios. Scenario 1 represents the current electricity grid mix. Scenario 2 represents current electricity grid mix and extends the system boundary by assigning a displacement value for desalinated water, which is a coproduct of power plants. Scenario 3 is the same as Scenario 1; however, it considers a future scenario for electricity grid mix representing Kuwait's electricity grid mix in 2030, which includes 15% renewables.

POTENTIAL SOLAR AND WIND IN KUWAIT

Kuwait has substantial wind capacity, and the highest potential wind energy found in this region is during summer (Al-Nassar, Alhajraf, Al-Enizi, & Al-Awadhi, 2005). Kuwait has an average wind speed of 5m/s in regions like Al-Wafra and Al-Taweel, which is relatively good (Hajiah & Sebzali, 2013). Also, Kuwait already has an existing 2.4MW Salmi Mini-windfarm, completed in 2013, which mainly serves telecommunication towers in remote areas and the fire brigade station in Salmi (Al-Nassar et al., 2005). The ever-increasing population in Kuwait has caused a major drawback to set up onshore wind farms due to urbanization resulting in the scarcity of free land, and hence, it opens doors to the possibility to set up offshore wind farms. On the other hand, Kuwait is abundant in solar energy with long summer season punctuated by dust storms where daily sunshine hours/year ranges from 7 to 12 and annual solar radiation from 2100 to 2200kW/m2 (Al-Nassar et al., 2005).

LCA METHOD AND SYSTEM BOUNDARIES

The LCA approach implemented in this study follows the ISO 14040 series of standards. As a first step, it is important to define the goals and the scope of the study, as well as define the functional unit and the system boundary. For our study, the goal is to assess the environmental and energy performance of electricity generation in Kuwait, where the functional unit selected is one kWh of electricity generated and delivered to consumers. The LCA system boundary accounts for upstream emissions, such as emission associated with fuels supply and the manufacturing of different electricity conversion technologies, as well as operational consequences such as direct emission from fuel combustion. The system boundaries of the three scenarios investigated are illustrated in Figure 1. The system boundary of each scenario includes upstream processes including fuel supply, fuel transportation, and operational processes such as fuel combustion (i.e., fuel conversion to electricity). For oil and natural gas, the upstream processes account for the entire supply chain of crude oil and natural gas covering processes such as exploration, production, processing, the long-distance transport, and the regional distribution to power plants, whereas, for solar photovoltaic and wind, the upstream processes cover the material and energy used to manufacture the needed installations for generating electricity. The power loss from electricity distribution is considered outside the scope of this study. The life cycle inventory (LCI), the second step, was obtained from government publications and industrial data published by Thinkstep AG (MEW, 2017). The Gabi (v.8) LCA modeling software was used to convert the LCI into environmental impact assessment (LCIA) (Thinkstep, 2018). Technologies covered include conventional power conversion technologies such oil-field and natural gas combined cycle plants and nonconventional power conversion technologies such as solar photovoltaics and wind.

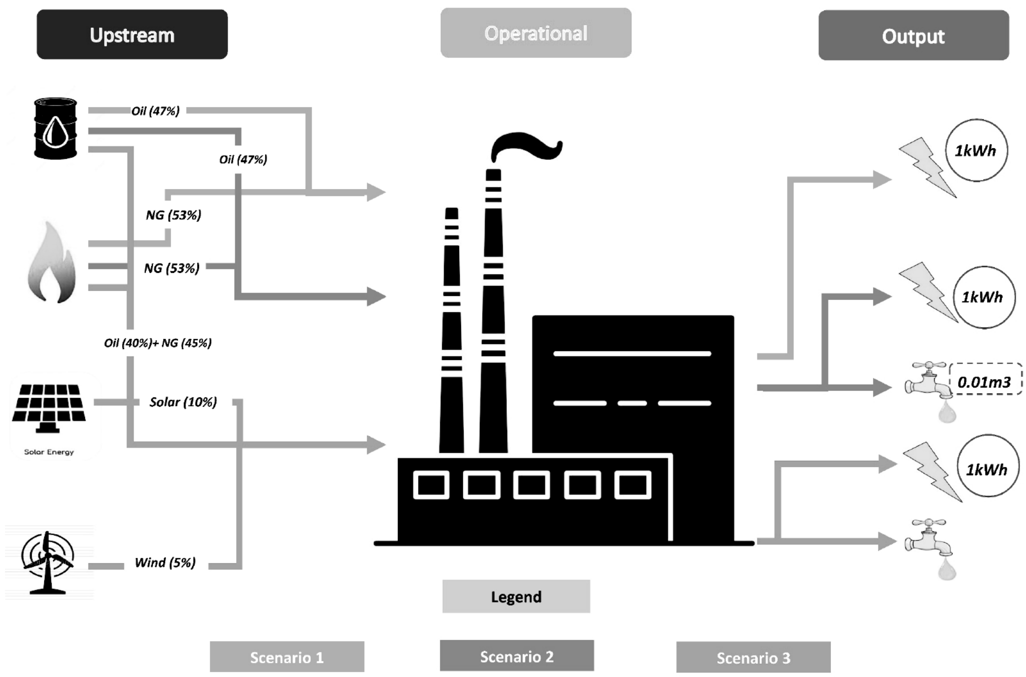

Figure 1. System boundaries for the three scenarios investigated for electricity generation in Kuwait.

MODEL DESCRIPTION

In our model, the functional unit defined is one kWh of electricity generated from power plants in Kuwait and delivered to consumers, as illustrated in Figure 1. Three scenarios are investigated, where Scenario 1 only considers electricity as the singular product of the system. On the other hand, Scenario 2 considers electricity as the main product of the of system and desalinated water as a coproduct of the system. Scenario 3 considers a future scenario for electricity grid mix representing Kuwait's electricity grid mix in 2030, which consists of an electricity grid mix of 40% oil-fired, 45% natural gas, 10% solar PV, and 5% wind.

Table 2. The environmental and energy indicators covered in this study.

Indicator	Formula	Description
Global warming potential (GWP)	GWP= $C_{r,t}$	$C_{r,t}$ the cumulative radiative forcing, both direct and indirect effects over a specific time horizon (commonly 100 years)
Water consumption (WC)	WC= C_w	C_w the cumulative water consumed
Cumulative energy demand (CED)	CED= Ec/Eg	Ec is the energy consumed during the life cycle (infrastructure, fuel supply, transport, processes) and the conversion losses through the electricity generation plant. Eg is the energy generated per kWh Low CED means high energy efficiency
Net energy ratio	NER= Eg/Ec	Eg is the energy generated per kWh Ec is the energy consumed during the life cycle (infrastructure, fuel supply, transport, processes) and the conversion losses through the electricity generation plant. High ENR means high energy efficiency
Source: (IPCC, 2007; Raadal, Modahl, & Bakken, 2012)		

Environmental and energy indicators investigated include GWP, WC, CED, and NER. The calculation, in the case of GWP for example, is illustrated in

$$Net\ GWP\ (x,y,z,w) = GWP_{x,y,x,w} + (-dc) = [kg\ CO_2\ eq.\ per\ kWh] \tag{1}$$

where

$$GWP\ (x,y,z,w) = \sum_{i=1}^{n} P_i = P_1 + P_2 + \cdots + P_n \quad [kg\ CO_2\ per\ kWh] \tag{1.1}$$

x = Electricity from fuel oil

y = Electricity from natural gas

z = Electricity from solar PV

w = Electricity from wind

P_1 = GWP fuel supply and transport (upstream); P_2 = GWP electricity generation (operational); dc = displacement credit [kg CO_2 per m^3 of water desalinated].

$$dc = [units\ of\ coproduct] * \left(\frac{GHG\ displaced\ product}{unit}\right) \tag{1.2}$$

Table 3. Coproduct displacement value from generating 0.01 m^3 of water per kWh of electricity generated.

Coproduct (dc)	Value*
GWP [kg CO2 eq.]	0.035
Water Consumption [m3]	6.97E-05
CED [MJ]	0.491
NER [kWh_g / kWh_cons]+	0.015

*Values are calculated based on the energy required to produce 0.01 m^3 of water desalinated.

+ kWhg is the electricity generated and available to the grid, and kWh_cons is the kWh consumed to generate one kWh of electricity.

To calculate the results of environmental and energy indicators for each scenario, we used the ReCiPe method, integrated in GaBi software, developed by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen, and CE Delft for life cycle impact assessment (LCIA) (Huijbregts et al., 2017)

DATA SOURCES FOR LIFE CYCLE ASSESSMENT

In the scenarios investigated, the required data for the LCI was obtained from government publications and industrial data published by Thinkstep AG in Gabi (v.8) database using regional specific operational parameters for Kuwait. The technologies technical performance parameters, which determine the resources needed to generate electricity, are shown in Table 4.

Table 4. Key technical and operational parameters of electricity conversion technologies.

Parameter	Oil-fired	NG-fired	Solar	Wind
Technology	Steam turbine	Combined cycle	Photovoltaics Mix of mono crystalline and multi crystalline	Mix of onshore and offshore
Efficiency	36%	40%	Mono-Silicon 14 % Multi-Silicon 13.2 %,	40.8%
Production and supply covered	95%	95%	95%	95%
Remarks	The calculation of LCI results refers to net calorific value.	The calculation of LCI results refers to net calorific value.	End-of-Life of the PV-modules is not included in the LCA-model.	Processes covered in the LCA includes production, transportation, installation, operation, dismantling and removal of the wind turbines incl. electrical gear.

Source: (Thinkstep, 2018)

RESULTS

The LCA results, henceforth, are illustrated in mass volume per one kWh of electricity produced and delivered to consumers in all investigated scenarios. The results for the environmental and energy indicators per kWh of electricity generated from different technologies are shown in Figure 2.

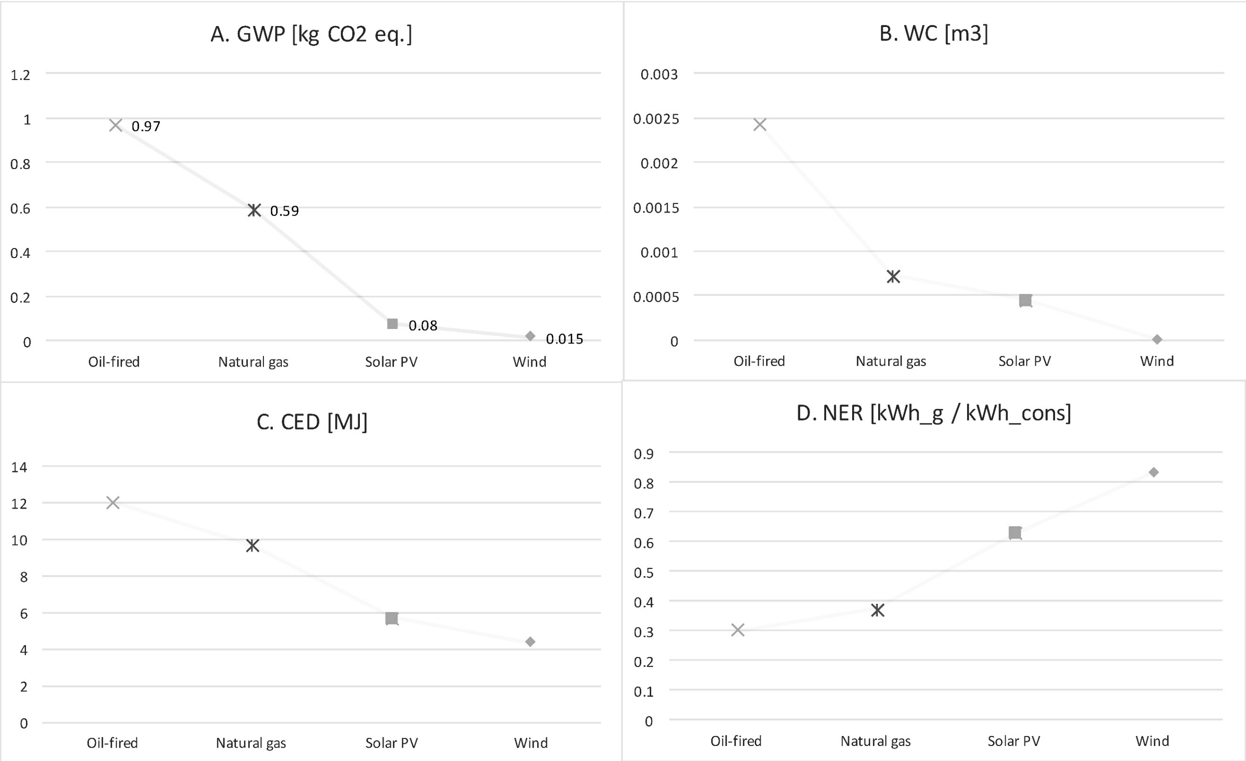

Figure 2. LCA results from different technologies considered in the analysis per kWh of electricity generated.

To further understand the relationship between efficiency, CED, and GWP, Figure 3 shows different technologies and compares their CED with efficiency, where the size of the symbol represents the GWP; that is, the larger the symbol, the greater the GWP.

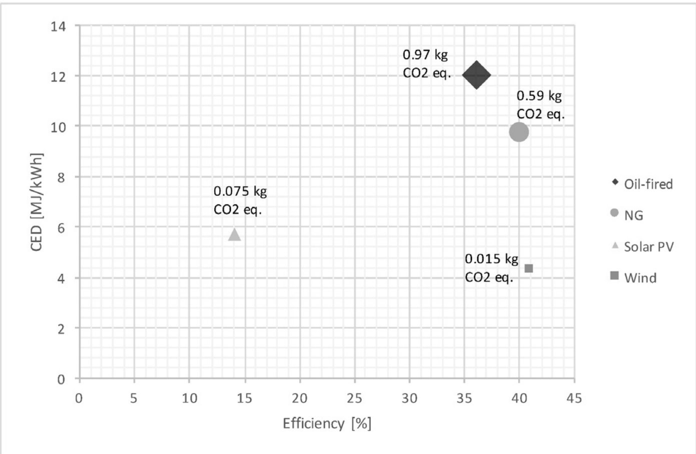

Figure 3. Relationship between technology efficiency CED and GWP for oil-fired, natural gas, solar PV, and wind.

It can be seen from Figure 3 that wind and solar PV consume about half of the nonrenewable resources compared to oil-fired and natural gas technologies. Also, it can be observed that they have lower efficiency, and yet, they are still better than oil-fired and natural gas technologies with regard to their GWP per kWh of electricity generated. Even though wind and solar PV technologies do not generate any greenhouse gas emissions during their operations, trivial upstream emissions are generated during the production phase and the end of life phase.

Three scenarios were examined, representing different electricity generation cases illustrated in Figure 4.

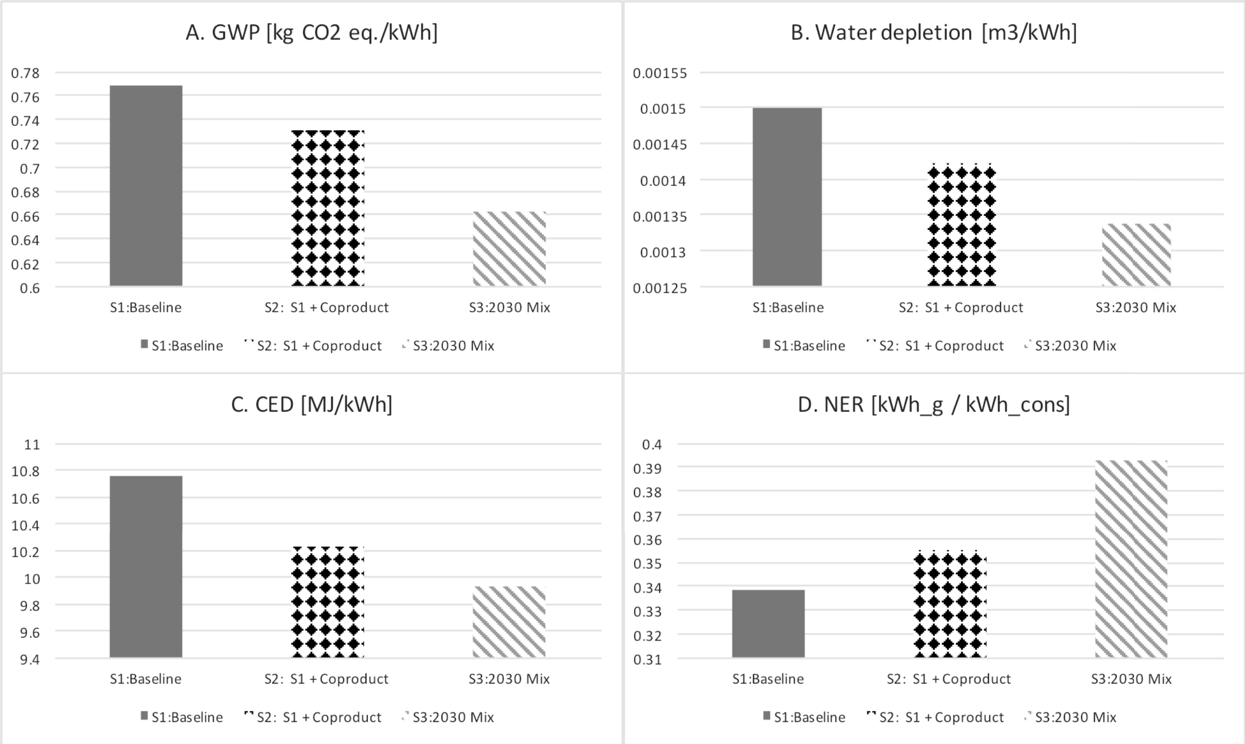

Figure 4. LCA characterization results of environmental impacts categories per kWh of electricity generated.

The scenarios were compared to the current electricity grid mix (Scenario 1), which has a GWP of 0.77kg CO_2 eq./kWh, WC of 0.0015 m^3/kWh, CED 10.7 MJ/kWh, and NER of 0.34 As shown in Figure 4, the LCA results varied among the investigated scenarios, where Scenarios 2 and 3 perform better than Scenario 1. The results in Scenario 2 suggest that using system expansion approach had slightly improved the environmental and energy performance by 5% compared to Scenario 1 as it distributes the environmental impacts over two products (electricity and water). In other words, Scenario 2 performs slightly better than Scenario 1 as it considered displacement credit for the water desalinated from the system (see the method section for details on system expansion). Furthermore, In Scenario 3, the results show more positive outcomes as GWP, WC, and CED were decreased by 14%, 11%, and 8%, respectively. Furthermore, the NER increased by 16%. Therefore, it can be seen that Scenario 3 is the most preferred option compared to Scenarios 1 and 2. In view of that, introducing solar photovoltaic and wind to the electricity grid mix would improve the performance of Scenario 3 and correspond to a further decrease in LCA results of the investigated environmental impact categories. To further understand the contribution of the environmental impacts from various system processes, sensitivity analysis was carried out for GWP as shown in Figure 5.

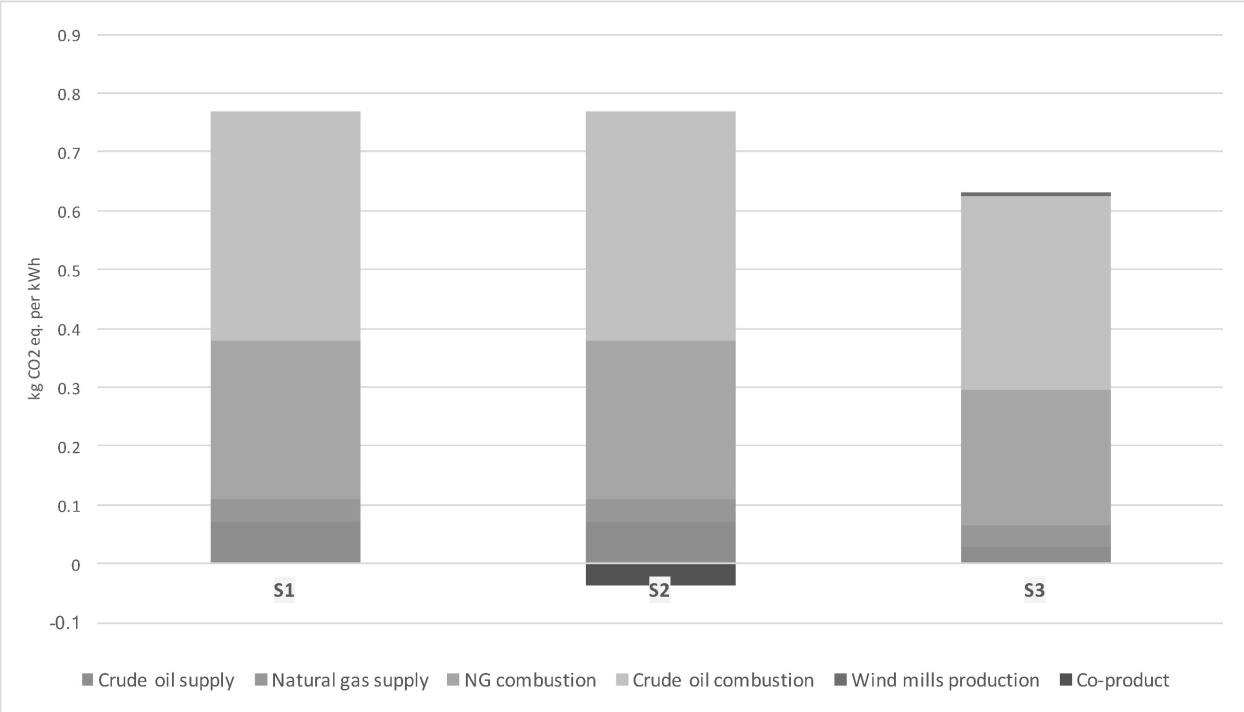

Figure 5. The contribution of GWP from different stages of LCA results for the three scenarios.

For example, the results of Scenarios 1, 2, and 3 were further investigated to identify the share of GWP from processes that have been included in the study system boundary. In Scenario 1, where only nonrenewable fuel was used for the electricity generation, it was found that 90% of the CO_2 emissions were generated from the fuel combustion process. The remaining 10% occurred from the fuel supply and transportation system processes. Hence, adopting carbon capture and sequestration (CCS) technologies could make up to 90% reduction in the in CO_2 emission from the fuel combustion process for fuel-based power plants. However, such application may have different effects on other environmental impacts categories depending on the selected CCS technology. Alternatively, replacing fuel oil can be replaced with natural gas as it has about 400 g of CO_2 eq. per kWh, which is about 50% less GHG emissions compared to fuel oil. However, switching to natural gas does not make a 50% net GWP reduction because the fuel supply process of natural gas has about two-thirds of the CO_2 emissions compared to crude oil.

DISCUSSION AND CONCLUSION

Renewables are a trivial contributor to Kuwait grid mix, whereas the share of fossil fuel technologies accounts for the largest share. Current power generation technologies are carbon and intensive energy, and the seawater desalination could pose some environmental and health concerns because the process generates some byproducts such as brine and hot water. In 2015, the carbon emissions from the power generation industry were approximately 34 million tons of CO2-eq., and this quantity is expected to double by 2030 (see system model for details). A similar increase is expected to take place for WC, CED, and NER. Therefore, a fast transition to renewables is vital to reduce these environmental indicators. Decarbonizing the global economy requires thoughtful long-term policies, which incorporates less carbon intensive energy sources. Results indicate that wind and solar PV are the most appropriate technologies, which will foster the transition towards a better environmentally friendly electricity grid mix in Kuwait.

In contrast, oil-fired and natural gas technologies consume greater amount of nonrenewable primary resources compared to renewable technologies such as solar PV and wind. Accordingly, the new GCC scheme reform commits to investing up to $100 billion in renewable energy projects (REP) over the coming two decades (UNDP 2014). Investing in REP implies reducing the impact of carbon and the escalating consumption patterns while meeting the national demand. Energy created from renewables could gradually substitute crude oil and natural gas and therefore extend the lifeline of the country's fossil fuel resources for some decades. Hence, it is rational to switch and introduce RET to the current electricity grid mix, not only for environmental considerations, but also for sustainable growth. However, it is crucial to actively investigate and carefully analyze diverse renewable energy mixes according to availability, sustainability, durability, and efficiency (Cheng & Hammond, 2017).

Despite the environmental benefits of renewable energy technologies, it is important to consider major concerns such as storage capabilities, hazardous waste generation, and geographic limitations (Hoffacker, Allen, & Hernandez, 2017). In other words, making rational environmental and economic decisions requires a comprehensive understating of region-specific environmental conditions, not only considering immediate possible consequences, but also considering the potential long-term impacts. In Kuwait, where residential land is limited, it is essential to be mindful of the land footprint of renewables to achieve the dual objective of providing clean electricity and preserving valuable land for oil extraction, farming, or residential purposes (Sen, Onat, Kucukvar, & Tatari, 2019). For example, building solar and wind farms in Kuwait mainland clearly creates a new form of competition for land. A study estimated that land use footprint for the installation of Concentrating Solar Power systems (CSP) farms in the US was 15m^2/MWh and 1m^2/MWh for wind. The same study estimated that fossil fuel-based technologies such as natural gas have about 0.2m^2/MWh (Fritsche et al., 2017).

Future studies should not only consider the environmental pillar of the LCA of electricity generation technologies, but also account for the socioeconomic aspect. Recent efforts have focused on integrating the three pillars of sustainability into a single framework, which complements the environmental LCA with life cycle cost assessment (LCC), and social life cycle assessment (S-LCA) (Onat, Aboushaqrah, Kucukvar, Tarlochan, & Hamouda, 2020). With LCC and S-LCA, decision makers can better understand the economic cost and societal benefits of the various electricity generation technologies discussed in this study considering the different phases of life span of each power technology option such as the initial capital cost, cost of operation and maintenance (O&M), and the end of life (Onat, Kucukvar, Aboushaqrah, & Jabbar, 2019; Onat et al., 2020). Also, to further make more informed future energy policies, the integration of renewable energy policies and smart grid principles can be an extremely effective approach. The application of the smart grids would be extremely useful in providing information that can help in making more comprehensive analysis of the share of different power supply technologies. For example, using internet of things (IoT) advancements for renewable and nonrenewable energy generation in smart grids is invaluable as it considers gathering real-time data for decision-making and controlling and monitoring deployed equipment. More specifically, for renewable energy, upstream electricity generation can greatly benefit from real-time measurements of phenomena to optimize energy generation based on measured phenomena (e.g., enough sunlight and interfering dust for solar panels, and enough wind speed for wind turbines).

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