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Circular Economy Modeling for Waste and Energy Management in A Developing Country: The Case of Greater Beirut Area

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Abstract: Lebanon's energy system depends largely on imported fuels. Lebanon presented its commitment to increase by 30% its share of Renewable Energies (RE) by 2030. GBA lacks an integrated Municipal Solid Waste Management (MSWM) system. The waste composition in the Greater Beirut Area (GBA) is made of 52.2% organic waste which can be exploited for the production of green Hydrogen (H_2) by gasification alongside. Energy Production from green H_2 will be assisted by the integration of PV solar systems installation especially for the residential sector which is steadily increasing. The main objective of this study is the implementation of a Circular Economy (CE) model which links the waste management best practices to the production of green energy for long-term sustainability targets in GBA. In the base of the CE modeling goal, 4 configurations of electrical power supply for GBA were simulated using HOMER-Pro software. With a Nominal Discount Rate of 10%, the off-grid solar PV system presents the lowest Levelized Cost of Electricity (LCOE) of 0.47 $/kWh, followed by the PV + Fuel Cell (FC) system with an LCOE of 13.43 $/kWh, while the FC's LCOE is the higher one. For PV and FC systems the renewable energy penetration is high. This energy production configuration should be accompanied by avoiding 12-18% of waste generation, it will have a significant impact in reducing the waste management cost by about 11,147,051$. The proposed CE model is of great benefit for long-term sustainability development in GBA. The opportunity of employing fuel cells in the future is high due to the trend of its cost decreasing.

Keywords: Circular Economy, Fuel Cell, Greater Beirut Area, Green Hydrogen, Hommer-Pro, Solar Power

Introduction

Imported fuels play a crucial role in Lebanon’s energy system. Current electrical energy production status in Lebanon is based on private diesel generators and on Electricité Du Liban’s (EDL) power facilities, even if in the last years a high increase of PV solar systems installation was observed. Thanks to its possession of abundant Renewable Energy (RE) potential, Lebanon developed an action plan to endorse RE deployment in 2010 before almost every Arab country. In 2015, Lebanon presented its commitment to increase by 30% its share of REs by 2030 (Kai, 2022).

To improve waste management efficiencies, the internal sectoral targets include energy recovery equal to the emissions avoidable from landfilling (Kai, 2022), which includes a waste recycling rate target of 30%. Lebanon should pursue deep decarbonization strategies, Hydrogen (H_2) is one solution amongst others. The waste composition in the Greater Beirut Area (GBA) is made by 52.2% of organic waste which can be exploited for the production of H_2 by gasification.

PV solar systems have gained a huge market in Lebanon in the last few years, especially in the residential sector, due to electricity blackouts. These solar systems can be incorporated into processes for the generation of green energy, but the waste generation of these solar systems might be an environmental concern in the long term.

The large ecosystems' degradation in the last few years and the shortage of natural resources have caused serious restrictions on economic realities. Worldwide a new development paradigm, based on the concept of a green economy, is widely adopted. The main task of Circular Economy (CE) is to ensure maximum efficiency of processes or services life cycle by improving resource efficiency and therefore increasing economic growth in a long-term sustainable manner. Public, private, and international entities are actively involved in discussing the issues of the attractiveness of the transition to a closed-cycle economy in Lebanon to find harmony between the economy, society, and the environment.

In 2021, Lebanon emitted 24,96 Mt CO_2eq.; (Ersoy *et al*., 2022) reported the contribution to greenhouse gas emissions of different sectors in Lebanon: Electricity generation (60%), transport (32%) industry, and residential (4% each) (Ersoy *et al*., 2022). Almost 40% of the overall electricity Greenhouse Gas (GHG) emissions can be attributed to private diesel generators, whose installation is in residential areas with high density, implying high danger to public health (Ahmad, 2020). For each MWp added to the distributed renewables generation in Lebanon, approximately 1000 t CO_2eq is removed. EDL's thermal power plants are another relevant source of pollution, mainly due to the position of the facilities, which are often installed within areas with a high-density of population. EDL power plants emit 0.65 kg of CO_2 for each kWh produced, thus 2 kW PV system can contribute to a daily saving of approximately 5 kg of CO_2, equal to 47,000 kg of carbon dioxide considering the system lifetime (C.E.D.R.O., 2013a-b).

The gradual phasing out of diesel generators would allow the Lebanese public to save around 800 million $/year, considering the EDL's tariff level of approximately 0.09 $/kWh and the private generator one at around 0.30 $/kWh. In any case, a doubled EDL tariff would imply a savings of around 400 million USD. Ahmad (2020).

A typical 2 kWp PV solar system, if properly designed and if energy efficiency measures are carried out for residences, then the diesel generator rent will be removed equal to at least 100 $/month and EDL bills can be cut in half, therefore, a saving of around 120-150 USD/month is achievable.

It is evident that turning to RE for electrical energy production in GBA is economically and environmentally viable.

The main objective of this study is the implementation of a CE model where it links waste management best practices to the production of green energy for long-term sustainability targets in GBA.

Materials and Methods

Energy Need in Lebanon/GBA

In 2018 the EDL's power plants contributed to electricity provision with about 1,884 MW, while in 2019 the installed production capacity reached 2,600 MW, but the effective generation ranged between 1,88 and 2,00 MW; in the same year, Lebanon's consumer peak reached around 3,669 MW. this highlights the need of an additional 1,500 MW production to cope the real demand. (Ahmad, 2020). Real electricity demand has followed the drop in real GDP and its decrease was around 25% (Boukather, 2023).

Transport dominates energy consumption among all activities with a share of 52%, while the residential one is 19% and that of industry is 14%. (International Energy Agency, 2020). The energy mix in 2018 was made mainly by oil, with a 95% share; coal share was around 2% while the contribution of REs was around 2.95%. International Energy Agency (2020). In 2018, cooling energy represented approximately 32% of total Lebanese electricity consumption. Buildings' energy consumption in Lebanon is estimated to increase by 75% by 2030, notwithstanding the challenges in the economics area. (Republic of Lebanon, 2020).

Renewable Energy Context in Lebanon/GBA

Despite having great RE potential, the total power installed exploiting renewables is limited to 286 MW from hydropower, 9 MW from bioenergy, wind capacity of 3 MW, and around 250 MW of solar power by the end of 2022. In the last years, the installed capacity of solar energy across the country has increased significantly, largely from rooftop solar. Over 650 MW were installed in 2022 alone, bringing Lebanon's total solar capacity to 870 MW. Installed capacity should reach 1,000MW in June 2023 (Moussa, 2022). To increase renewable energy by 30% by 2030, further action is needed, to reach 1000 MW of wind energy, 601 MW of Hydropower, 2500 MW of Centralized Solar PV, 500 MW of Decentralized Solar PV, and 13 MW for Biogas (I.R.E.N.A., 2021).

The UNPD report estimates the biodegradable waste production in Lebanon equal to around 863,000 tons per year; which corresponds to 743 GWh of steam energy potential and 278 GWh of methane. C.E.D.R.O. (2012).

Waste Streams in Lebanon/GBA

To estimate the waste prices in Lebanon, extra data, which nowadays is not collected, is needed about the national market and the economics of waste recovery. The Lebanese municipalities estimated waste collection costs from 120 to 169 USD, which represents 39% of the municipal budget and is five times the average cost of 35 USD per ton. A.C.T.E.D. (2020).

The waste fraction sold to the industry as secondary raw material has improved from 74% observed in 2014-2015 to 95% in 2017-209. U.N.D.P. (2020).

A target of 30% of recycling has been set by Lebanon's NDC (Nationally Determined Contribution). Waste recycling in GBA is still scant, only 6-8% of the waste is being recycled. Note that 10-12% of GBA's solid waste cannot be composted or recycled.

The economic potential of e-waste, in cost-recovery, represents 64 million USD per year, evaluating the average cost of 1350 USD per ton. However, only advanced integrated facilities can treat e-waste to recycle it and such industries are not currently available in Lebanon. As a result, landfills and the natural environment are now the final destination, with Municipal waste, of electronic and electric devices at the end of their life (A.C.T.E.D., 2020).

The plastics industry is energy-intensive in all its sectors, from production to recycling, which is the biggest obstacle to improving these activities. Therefore, the energy costs decrease is essential for the development of the recycling sector. In order for recycled plastic to be absorbed effectively into local industries, measures should be taken to improve the efficiency of waste collection and sorting logistics by increasing the prices of virgin plastics through taxes and customs (A.C.T.E.D., 2020).

Recycled paper and cardboard in Lebanon can be absorbed by the local industries and participate in the CE, but to achieve this goal small and large producers should decrease prices and reach an economy of scale (A.C.T.E.D., 2020).

Moreover, glass can ensure circular material flows without any leakages. It is fully recyclable and therefore is an ideal material for the circular economy. Moreover, recycling glass by crushing and remelting is less energy-intensive than producing it from raw material. A.C.T.E.D. (2020).

Roadside dumping and burying of CDW as backfill material is a common practice in the country.

Currently, there is no infrastructure capable of collecting, treating, and properly disposing of hazardous industrial waste, which is usually not sorted and follows the MSW or is discharged into the environment (E.L.A.R.D., 2022; Ministry of Environment - Republic of Lebanon, 2018).

Organic Waste

A large fraction of organic waste in Lebanon is sent to landfills, where very little bioenergy is recovered from it. In fact, the estimated emissions from landfills in Lebanon are more than 1840 Gg CO_2eq. This value highlights the fundamental role of recovering energy from bio-waste with appropriate management systems.

Composting

The compost products in Lebanon suffer from low quality because of the lack of standard Nitrogen Phosphorous Potassium ratios, which causes a chemical imbalance in the soil. Furthermore, the household-level process of sorting organic waste is inadequate and this implies a high presence of plastics and other non-biological waste in the locally-made compost. Last but not least, imported compost, coming from the European Union (EU) has almost saturated the small agricultural market of Lebanon. Another major challenge of the composting business in GBA is the lack of the needed area (Azzi, 2017).

Biogas Production

Anaerobic bio-digesters have huge market potential in Lebanon: They can yield solid revenue for businesses thanks to their cost-effectiveness. Currently, the bio-digesters owned by Lebanese businesses generate two main products. The first is liquid fertilizer, which is given away for free, the second is methane gas, which is exploited in winter to heat the water needed by the digester and is burnt off in summer. Huber (2019).

Other types of waste such as metals, textiles, wood, used tires, used batteries, and used oil are recovered directly by scavengers and private companies. There is as well, a marketing for recovering used cooking oil for biodiesel production. The major fraction of the medical waste is managed by hospitals and the rest is sent with the municipal waste stream (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH 2014).

Every year about 12.43 kg BOD/cap of organic sludge is removed from wastewater after default treatment in Lebanon and this material is suitable for energy conversion (C.E.D.R.O., 2013a-b).

Area of Study

GBA consists of Beirut, which is the capital, and 5 other districts: Matn, Baabda, Alley, Chouf, and Keserwan with an area of 200 km^2 and a population density of about 11,000 inhabitants per km^2. GBA has a population of approximately 2,668,000 million people of which 268,000 are refugees (Lebanese Arabic Institute s.d.).

The waste generation in GBA is around 2077 tons of waste per day Lebanese Ministry of Environment (2023). The composition of municipal solid waste in GBA is made of 52.5% organic waste, 16% Paper and Cardboard, 11.5% Plastics, 5.5% Metals, 3.5% Glass, and 11% Others such as Textile, Wood, Miscellaneous (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH 2014).

Data Collection

The data on waste generation quantity, types, and disposal methods were collected from the Lebanese Ministry of Environment. These data were analyzed and compared to the data found in the literature.

Energy Production Potential in GBA

In addition to other potential alternatives for waste management and energy production, it was indispensable to take into consideration 2 potential technologies for the production of energy in GBA. The Waste to Hydrogen (WtH_2) technology, since a great fraction of the MSW in GBA is made from organic waste. Another energy generation technology is solar power, given that in the last 2 years, there has been a high increase in decentralized solar power systems installation in GBA.

Any potential energy generation alternative has to respect the best MSWM practices in terms of recycling opportunities and social acceptance.

Waste to Hydrogen

Hydrogen has many applications: It can easily be stored and transported and therefore is a great energy carrier, useful for industrial activities that spread over large areas and need energy transportation. The global H_2 market in 2018 was valued at over $135.5 billion, with an estimated annual growth rate of 8 percent until 2023 (Sisternes *et al*., 2020). For H_2 to become a sustainable alternative to fossil fuels, it is essential that it is produced using renewable energy. Excess electricity coming from solar and wind plants can be exploited for green H2 production, which therefore becomes a complementary activity to that energy production. Green H_2 technology could be a powerful support for developing countries in the race to their sustainable energy goals and decarbonization strategies. It could also provide some energy security, lowering the dependency on oil, its price volatility, and its supply disruption.

Cost reduction and efficiency improvement are the main research topics to cope with capital-intensive technologies, such as those exploiting H_2. Large literature studies the global hydrogen market and its recent progress in developed countries, but further research in the fuel cells field and other applications in developing countries must be addressed.

As per the decarbonization perspective, McKinsey conducted research for the Hydrogen Council in 2017: He showed that 7.5 gigatons of annual CO_2 could be abated by 2050 thanks to the transition to the hydrogen economy (Hydrogen for Net-Zero, 2021).

Solar Power

International Renewable Energy Agency's (IRENA) Global Atlas for Renewable Energy indicates that the annual average solar irradiation in Lebanon ranges between 1520 and 2148 kWh/m^2/year. IRENA estimates that the potential for utility-scale solar PV could reach 182 GW, based on building solar irradiation (IRENA, 2020).

Ahmad (2020) estimates the solar PV capacity for Beirut city: In the case of distributed rooftops, it is between 200 and 300 MWp. The rooftop occupancy factor and an average area considered equal to 185 m^2, allow us to estimate the capacity to an average value between 12 and 17 kWp.

It is interesting to simulate the best alternatives for energy production in GBA in terms of CE's modeling, to perform such simulations, HOMER-Pro software was used.

Homer-Pro Software

Homer-Pro is a high-level software application for modeling and analyzing hybrid energy systems. It can simulate both Alternate Current and Direct Current power systems, making it possible to analyze hybrid systems that use both sources of power. HOMER Pro allows the simulation of grid-connected and off-grid-connected systems that generate electricity from various combinations of solar PV modules, wind turbines, biomass-based power generators, fuel cells, batteries, hydrogen storage, and traditional sources such as diesel generators.

In our study, HOMER-Pro software has been used for the evaluation of the optimal solution of the life-cycle cost of the proposed hybrid energy system. HOMER ranked its result based on the least cost combination (Al-Badi *et al*., 2022; Vendoti *et al*., 2021).

Circular Economy Model

CE is a regenerative system in which closed and narrowed energy and material loops minimize raw material exploitation, waste, emissions, and energy waste. CE modeling assisted by RE technologies provides a great asset for the resolution of Lebanon's waste and energy crisis in a sustainable means bringing significant economic, social, and environmental benefits to the Lebanese economy. The CE model proposed in this study links the best waste management practices for green energy generation in GBA. Specifically, this model takes into consideration the social factor in dealing with waste treatment, since GBA's citizens are concerned about the pollution that might be emitted from the waste treatment technologies. This CE model can be further optimized based on the cost reduction of the adopted energy generation technologies.

Results and Discussion

Waste Recycling in GBA

The percentage of waste recycling in GBA is the same as at the national level:

- Current Status of Recycling in Lebanon (6-8%)
- Recycling Target in Lebanon by 2030 (30%)

Paper and glass waste merit to be recycled, since their recycling is beneficial due to the economic and environmental profits. Paper can replace plastic products in many applications and nowadays around 110,160 tons of paper are sorted and sold every year. The sorting process cost is related to the quality and grade of the paper and varies between 29 and 198 $/ton. This means that material recovery is worth between 2.6-21.81 million in the value chain of paper.

Collection and transportation of 1 ton of glass are worth around 169$, while ACTED reports that the import of virgin glass bottles into Lebanon costs for each ton (which is about 2500 bottles), 500$. By simple calculation, it will be evident that recycling 1 ton represents a saving of about 330$.

Construction and Demolition waste may be a big asset for the material circularity, considering that a large amount of this waste is used by private civil contractors as filling material for new construction sites; furthermore, the C&D waste recycling plant system is not technically complicated and it is available in Lebanon.

Before talking about plastic recycling, it is better to avoid its generation by replacing it with recycled paper where possible. Elimination of plastic waste requires design innovation to remove it from new products, improve the recyclability of plastics, and improve the performance of recycling systems. Realistically, plastic will continue to dominate our packaging, because it is moisture-proof and airtight.

Composting is of substantial aspect of treating organic waste, but it is essential to overcome various challenges, such as the needed area for the composting plant, the quality of the compost produced, and the competition with the European compost products.

Even if there are not so many biogas generation plants in GBA, it appears that it is a promising technology from an economic and environmental perspective.

Waste Management Scenarios in GBA

Table (1) a comparison of the different solid waste management methods, where it is estimated the material recovery quantity and energy production. The main idea is to highlight the benefits of each technology in the context of CE.

The incineration process requires 8400 kJ/kg to produce electricity. The calorific value of MSW is low, due to the organic fraction weight in Lebanon's waste, equal to 52%. This means that the highest calorific value reachable from waste is around 6500 KJ/kg and that to reach the needed optimal temperature of 850°C inside the burner other fuel and waste must be added. This approach makes the WtE facilities competitive in the recycling markets in the sector of paper and plastic. The only material that Waste to Energy (WtE) facilities are claiming to recycle is metal as a residual of the incineration process.

AD has advantages such as ease of operation and maintenance, a reduced capital expenditure, but on the other side AD has a high running expense, particularly energy expenditures and it can only treat organic waste.

Modern technologies have led WtE plants to a massive reduction in air pollution; despite this, fly ash and other pollutants can be released and toxic bottom ash is still disposed of in landfills. Anyway, WtE is far less pollutant than the fossil sector. Heavy fuel and diesel oil exploitation lead to 0.778 tons of CO_2 per MWh, natural gas to 0.433 tons/MWh, while the emissions of CO_2 by biomass gasification is about 0.03 tons/MWh (El Helou *et al*., 2022).

The CO_2 emissions of Incineration + Electrolyzer and WtH_2 are mainly due to the waste combustion and its carbon content (1.43 $kgCO_2$/kg of waste) together with those of minor weight coming from other fuels fed to WtH_2 systems if RE technologies are not implemented. Substituting Incineration + Electrolyzer with WtH_2 implies a decrease in CO_2 emission from around 3.9 kg of CO_2 per Nm^3 H_2 to 0.94 kg of CO_2 per Nm^3 H_2. (Hydrogen-Based Energy Conversion, 2014).

The emissions level from gasification depends on the primary energy supply to run the gasification plant. The scope is to incorporate solar-thermal energy into a gasification plant system for emissions minimization.

Table 1: Waste management scenarios in GBA

Method	Waste Quantity (tons/year) Waste Type	MWh/year	Material Recovery tons/year
Recycling	360193 non of*	0	As per 2030 target: 108058 As per current status: 21611
Composting	398109 of	0	As a typical value (30%): 119432 As per current status (15%): 59716
Incineration	758302 of + non of	424649	Metals from residual ash
Incineration non of	360194 non of	201708	Metals from residual ash
Anaerobic Digestion (AD)	398108 of	119432	Digestate (liquid & solid portions)
WtH_2	398108 of	270148	Biochar
Incineration + electrolyzer	758302 of + non of	121328	Metals from residual ash

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The comparison evidences that the combustion-based configuration WtE + Electrolyzer produces about 121,328 MWh, conversely, the gasification scheme (WtH_2) produces about 270,148 MWh, knowing that for WtH_2 only the organic fraction is being treated (398108 tons/year), while for Incineration + Electrolyzer all the MSW quantity is going to be treated (758,302 tons/year). The results show that WtH_2 results are more competitive under the assumption made in terms of energy generation and CO_2 emissions.

H_2 production has many advantages, such as:

- Less emissions that methane (from AD)
- High calorific value
- Versatility of applications
- High energy conversion efficiency
- No CO_2 emission occurs if it is used in fuel cells
- H_2 can help increase energy security by allowing Lebanon to produce this versatile energy carrier, which is perfect for long-term storage and exploits local resources, such as renewable power and water

The high organic fraction in GBA induces promising prosperity for H_2 production by biomass gasification, perhaps using RE technologies such as solar energy to minimize the emissions from the gasification plant. H_2 applicability in GBA will face challenges, such as the lack of infrastructure for H_2 transportation and the lack of financing.

Hydrogen vs Solar Energy for Energy Generation in GBA

In the previous paragraph, it was evident the advantages of the WtH_2 technology in terms of energy and environmental benefits. In addition, PV solar systems are becoming an essential component of the GBA's residential sector. Therefore, it was essential to identify the economic benefits and burdens of these 2 emerging technologies.

Hydrogen Cost

The costs of green hydrogen production are lowering, thanks to the reduction of electrolyzers' costs and the similar behavior of renewable electricity costs. Note that each kg of H_2 produced from Gasification has a cost of 1.77-2.77 $ (Davoodabadi *et al*., 2021).

Price parity between blue and green H_2 will start to be achieved by 2030. The reduction in green H_2 cost is expected to accelerate, perhaps reaching as low as €0.68/kg H_2 by 2050 (I.R.E.N.A., 2021).

Most H_2 produced today is exploited near the point of production, highlighting the lack of the needed storage infrastructure and transport systems operating on a large scale. The costs of these infrastructures are difficult to predict, but they can be estimated at around 1.20 to € 2.20/kg H_2 by 2030 (Global, 2022).

Large commercial buildings can advantageously exploit H_2 from the economic point of view, as well as district energy networks.

The improvement of fuel cells' costs, durability, and efficiency make their storage capacity a valid solution to cope with heating, cooling, and electricity requests, allowing the on-site exploitation of renewable energies.

PV Solar System Cost

The average cost of a solar system in Lebanon is 0.28 $/watt. The average solar panel system size in Lebanon is around 3-5 kilowatts. The PV solar system is aesthetically integrated into buildings with low running cost and low maintenance; as well, PV solar systems are safe and they have an investment payback of about 5-8 years. The solar system is more suitable for decentralized and residential applications and it is especially attractive for regions with abundant sunlight such as GBA.

Homer Simulations

Solar Resources

The solar resources of GBA were collected from the NASA surface meteorology and solar energy database through HOMER Pro software. A scaled annual average of 5.32 $kWh/m^2/day$ has been given by the software. The scaled annual average electrical load is 11,130 kWh/d.

In our study, simulations are performed for the following systems:

- Generators running on petroleum products (current situation in GBA)
- PV solar system (PV)
- Fuel Cell (FC)
- PV + FC

The PV solar system's given values are based on the current Lebanese market, while for the FC system, the values are gathered by literature research (Al-Badi *et al*., 2022).

The parameter values given to the software for running the simulations are listed below:

PV Inputs

- 1 kW capacity
- 1500$ Capital cost
- 800$ Replacement cost
- 10 $/Year O&M cost
- 2% Annual real interest rate
- 25 Years project lifetime
- 80% Derating factor

FC Inputs

- 250 kW capacity
- 500,000$ capital cost
- 375,000 Replacement cost
- 0.1$ O&M cost
- 5% Annual real interest rate
- 25 Years project lifetime

All systems are simulated in off-grid. The project life was estimated at 25 years, assuming an interest rate of 5% yearly. The system components include Capital, Operation, and Maintenance (O&M) costs, as detailed above, while any subsidy is foreseen, neither from the territorial nor municipal government.

Simulations Results

Economic Comparison

In Table (2), significant economic parameters are presented to highlight the detailed economic side of each energy generation system. Many configurations are designed to find the optimal one for reaching the lowest investment and operation costs and so to meet the technical and emission constraints. With a Nominal Discount Rate of 10%, the off-grid solar PV system presents the lowest Levelized Cost of Electricity (LCOE) of 0.47 $/kWh, followed by PV + FC system with an LCOE of 13.43 $/kWh, while the FC's LCOE is the higher one. An increase in the system's capital cost results in an increase in NPC and LCOE. Despite the low initial cost of the diesel generators compared to the high costs of the other RE's systems, the disturbing noise and the environmental pollutants emissions from these generators affect adversely the surrounding area.

The operating cost of the PV system shows the lowest value, same for the O&M cost. The replacement cost of the FC system is too high, while for the PV + FC system, this cost is alike the PV system one.

By analyzing the annualized costs, the PV + FC system shows promising results, even if this system does not possess the lowest LCOE, FC cost will become affordable in the near future.

PV solar power is highly advantageous due to the long sunny days in GBA. The large development reached by small solar PV projects between 2010 and 2023 highlights that they can be a good alternative, also thanks to the large interest of the local investors.

Figure (1) illustrates the cash flow through 25 years of the PV system's life cycle. The initial investment is 11,600$ and around 3800$ as an additional replacement cost each 6-7 years. The operating cost is not significant and it has been stable over the years, which is of great asset noting that the operating cost is highly considerable in numerous energy generation technologies. A salvage value of about 3000$ is available at the end of the system's life cycle.

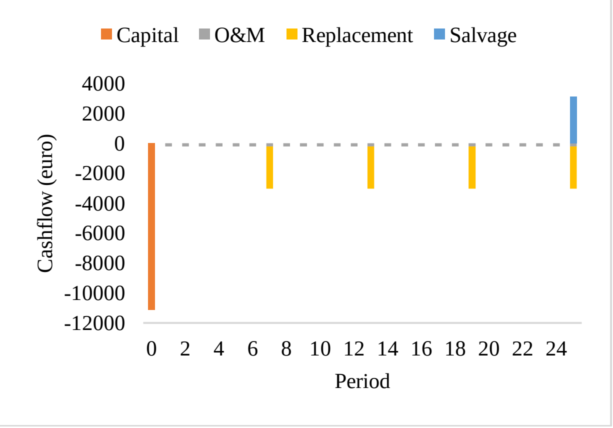

Fig. 1: PV solar system-cash flow

Table 2: Economic comparison between energy generation systems

	Current status in lebanon (Generator running on petroleum products) 2.7 kW	Generic flat plate PV 3.96 kW (PV)	Generic 250 kW Fuel Cell (FC)	PV + FC
Nominal discount rate (%)	10	10	10	10
Total NPC ($)	21823	16959	1048913	483795
LCOE ($)	0.6	0.47	23.57	13.43
Operating Cost ($)	2285	640	50674	2859
CAPEX ($)	1080	11145	500650	509747
O&M Cost ($)	6440	1993	9477	2149
Replacement ($)	4104	4106	572049	4180
Salvage ($)	30	286	35230	32455
Annualized				
CAPEX ($)	118.98	1227	46273	56157
O&M Cost ($)	709	219	876	236
Replacement ($)	452	452	52872	460
Salvage ($)	3.3	31	3256	3575

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Figure (2) shows the cash flow of the FC system's life cycle. The initial investment is 500,000$, and an additional replacement cost of about 39,000$ is estimated every 6 years. The operating cost is not significant, a salvage value of about 210,000$ is available for the system at the end of its life cycle. The initial cost of the FC system is the main burden, especially in GBA due to the lack of funding. FC system's cost needs further time to become competitive.

For the PV + FC system, the capital cost is high due to the FC cost, the operating cost is not significant, and the salvage is about 320,000$, as shown in Fig. (3). The replacement cost is not significant in the PV + FC system contrary to the single PV and FC systems. With the future decrease of the FC cost, this system will turn out to be a vigorous alternative.

Table (3) shows the values of power production for solar PV plants (6749 kWh/year) and for FC (4329 kWh/year); for the PV + FC system, the PV capacity is high, resulting in a penetration value of 92.3%.

The value for unmet electricity is the lowest for the diesel generators, followed by the FC system. The PV +FC's capacity shortage on a yearly basis is acceptable.

The intermittency problem, peculiar to PV, can be coped with and overcome thanks to the coordinated exploitation of PV and FC.

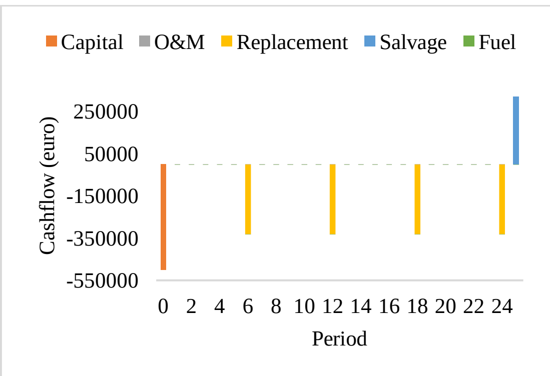

Fig. 2: FC system-cash flow PV + FC

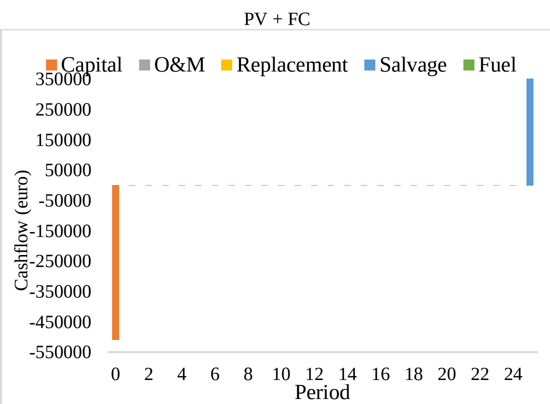

Fig. 3: PV + FC-cash flow

Table 3: Electrical comparison

System	Production KWh/yr	%
PV		
Generic Flat Plate PV	6749	100
FC		
Generic 250 kW Fuel Cell	4329	100
PV + FC		
Generic flat plate PV	5510	92.3
Generic 250 kW Fuel Cell	459	7.69
Total	5969	100
Generator		
Autosize Genset	6336	100
	Unmet electricity load kWh/yr	Capacity shortage kWh/yr
Generic Flat Plate PV (PV)	146	204
Generic 250 kW Fuel Cell (FC)	0.4	1.66
PV + FC	92.5	145
Generator	0	0

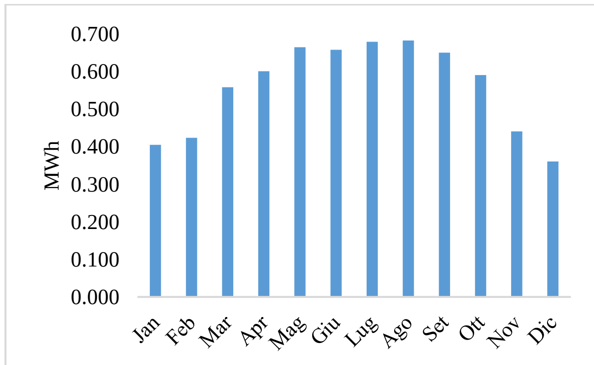

Fig. 4: PV solar system energy production

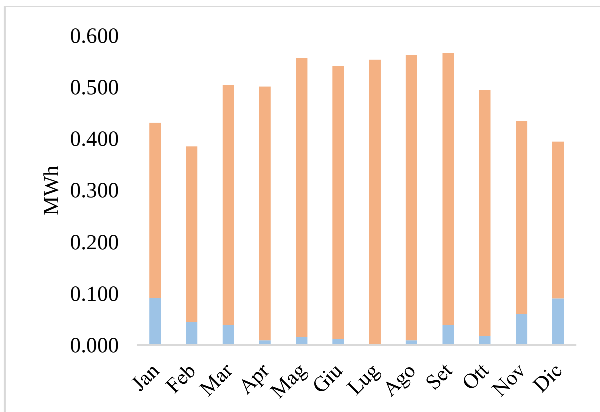

Fig. 5: PV + FC systems-monthly average energy production

Solar panel temperature and solar radiation highly influence the power production of PV: Fig. (4) shows the yearly energy output, highlighting the best months (July and August) and the worst ones (December).

The monthly average electricity production of the solar PV system and fuel cell is shown in the above Fig. (5), which is evident in the notable power production from the solar power in the period from April to August. The FC system production is more significant in the period from September to March, anyway, the main scope of the FC system is to generate electricity continually owing to the high organic fraction in GBA treated by gasification to produce H_2.

The PV + FC system reduces the high capital cost associated with FC and also reduces the fuel, and O&M costs associated with the FC.

Renewable Energy

In both cases the renewable energy penetration is high. At high penetration levels, a combination of the following actions is required to maintain system integrity, such as enabling system generation to follow the load, changing demand levels in response to power supply variability, and policies that promote a flexible power market structure.

The renewable energy penetration for PV is 1722% while for PV + FC is about 1512%.

Environmental Comparison

The emissions from the diesel generator are listed as per Homer-Pro simulation results:

- 7,374 kg/year of carbon dioxide
- 46.5 kg/year carbon monoxide
- 2.03 kg/year unburned hydrocarbons
- 0.282 kg/year particulate matter
- 18.1 kg/year sulfur dioxide
- 43.7 kg/year nitrogen oxides

An estimation of the emissions for different H_2 production and from PV solar systems is shown below (Legarreta *et al*., 2023):

- 18-20 kg CO_2/kg H_2 brown
- 10-12 kg CO_2/kg H_2 grey
- 0.6-3.5 kg CO_2/kg H_2 blue
- 0 kg CO_2/kg H_2 green
- 0 kg CO_2 for PV solar system

A very important aspect that merits be highlighted is the huge amount of waste that will generated from the PV solar panels at the end of their life, knowing that the PV panels enclose hazardous materials. Industry and research sectors are engaged in coping with the emerging PV waste problem: The recovery of useful material from cells needs new technologies to reduce environmental impact and costs.

Circular Economy Model for GBA

The goal is to implement the CE concepts, by optimizing waste recycling, its treatment, and green energy generation.

Current Status in GBA

Recycling (6%) + composting (15%) + landfills (44%) + dumpsite (35%) + small amount of energy production from waste.

Our Proposed Circular Economy Model

Avoiding generation of waste (plastic, nylon, etc.) + recycling (30% as per 2030 target, especially paper, glass, C&D) + WtH_2 (for the organic waste) + solar energy.

Table 4: Circular economy in GBA

	Avoiding generation of waste (%)	Recycling (%)	Composting (%)	Landfills (%)	Dumpsite (%)	Energy from petroleum products (%)	Bio-Energy (%) (MWh)	Solar Energy (MW)	WtH_2 + Solar Energy
Current Status in GBA	0 to little initiatives	6	15	44	35	92	9%	250 MW	-
Proposed CE Model	11.5% plastic waste + some percentage of the other waste (11%)	30% (full recycling of glass, paper/cardboard and C&D)	As per adopting or no WtH2	Only a part that cannot be recycled or composted (8 to 12%)	0	As minimum as possible	FC ≈ 270148 MWh	3000 MW As per 030 target	WtH_2 ≈ 270148 MWh + solar energy 3000 MW as per 2030 target
LCOE ($/kWh)						0.62	23.57	0.47	13.43

The proposed CE model, as reported in Table (4), is based on adopting the best waste management practices, choosing the best alternative in terms of energy production and environmental benefits, and taking into account an acceptable economic perspective.

This CE model is of great benefit for long-term sustainability development in GBA, avoiding 12-18% of waste generation, which will have a significant impact in reducing the waste management cost by about 11,147,051$. Regarding the environmental side, using RE such as PV solar system and green H_2 will prevent a high percentage of GHG emissions, knowing that the diesel generators in GBA have a high GHG emissions impact.

Challenges

- Not all the waste can be recycled or composted, hence 8-12% of the waste should be sent to landfills, for that it is indispensable to avoid the generation of waste as much as possible
- Industries should be shifted to produce eco-friendly product
- The importation of no eco-friendly products to Lebanon should be minimized
- No infrastructure for H_2 supply in GBA, so it is crucial to install a Fuel Cell in the H_2 production site

Conclusion

The goal of this study is the implementation of a CE model that links waste management best practices to the production of green energy for long-term sustainability targets in GBA.

The main contributor to greenhouse gas emissions in Lebanon remains the electricity generation and transportation sector. Applying best waste management practices and switching from fossil fuels to renewable energies is an unavoidable approach for an efficient CE strategy in GBA. The transition to a circular economy should take into consideration the recycling opportunities, waste processing technologies, modernization of existing industries, and the development of biotechnology-based products.

The waste composition in GBA is made by 52.2% of organic waste which can be exploited for the production of H_2 by gasification. H_2 is playing an important role in supporting the decarbonization of various sectors. The main advantages of fuel cells are their reliability, versatility, and silence; on the other hand, the exploitation of this technology is slowed down by the high cost of the electricity produced. However, the increasing mass production should lead to a dramatic decrease in prices.

PV solar systems have gained a huge market in Lebanon, especially in the residential sector, due to electricity blackouts. Based on current market and technology conditions, distributed rooftop solar PV systems are cost-competitive for the majority of buildings in Beirut.

In base on a CE modeling goal, four configurations of electrical power supply for GBA were simulated using HOMER-Pro software in order to find out useful economic, electrical, and environmental parameters.

With a Nominal Discount Rate of 10%, the off-grid solar PV system presents the lowest LCOE of 0.47 $/kWh, followed by the PV + FC system with an LCOE of 13.43 $/kWh, while the FC's LCOE is the higher one. An increase in the system's capital cost results in an increase in NPC and LCOE. Despite the low initial cost of diesel generators, the disturbing noise and the environmental pollutants emissions from these generators affect adversely the surrounding area. The operating, O&M costs of the PV system show the lowest value. The PV + FC system reduces the high capital, and O&M costs associated with the FC. The replacement cost of the FC system is too high, while for the PV + FC system, this cost is alike the PV system. For PV and FC systems the renewable energy penetration is high.

As per the annualized costs, the PV + FC system shows promising results. PV solar power is highly advantageous due to the long sunny days in GBA. Small solar PV projects could be a better alternative, especially for the residential sector.

A suitable option is to integrate solar power to supply the energy needed for running the biomass gasification plant.

The proposed CE model is of great benefit for long-term sustainability development in GBA. Avoiding 12 to 18% of waste generation will have a significant impact in reducing the waste management cost by about 11,147,051$ and a profit will be created thanks to the recycling processes.

Regarding the environmental side, using REs such as PV solar systems and green H_2 will prevent a high percentage of GHG emissions.

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Author's Contributions

Abbas El Toufaili: Involved in conceptualization, data collection and analysis, and in writing the original manuscript.

Dario Pozzetto and Elio Padoano: Involved in conceptualization and in reviewing the manuscript.

Luca Toneatti: Involved in data analysis, in writing the original manuscript and in reviewing it.

Ghassan Fakhoury: Involved in data analysis.

Ethics

Authors should address any ethical issues that may arise after the publication of this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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