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Techno-Economic Analysis of an Autonomous Hybrid PV-Biomass-Battery Power System

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Abstract- This paper attempts to retrofit the diesel generating systems - used for electrification of the Middle East and North Africa (MENA) off-grid remote areas - with hybrid renewable energy (RE) systems, in which biomass is integrated with solar. For this purpose, five alternative RE systems comprised of different configurations of the following components: photovoltaic (PV) array, biogas fueled generator (BGG) and batteries (BATT) are investigated to identify the most appropriate configuration to be used for rural electrification of the aforesaid areas. These five systems are simulated, optimized and analyzed based on their techno-economic performance with the condition of fully meeting the load demand. The results unveil that – among the optimal configurations – of the investigated systems, the BGG-PV-BATT hybrid RE system is the most appropriate one for off-grid rural electrification. This system is able to entirely meet the load demand with the least cost of electricity (COE), and it has the lowest net present cost (NPC). Results of investigating the possibility of extending the electricity grid to the site disclose that - based on the site's distance from the grid - the grid extension option is more expensive than the off-grid BGG-PV-BATT hybrid system one. Based on this fact and considering all of the obtained results, the BGG-PV-BATT proved to be the most appropriate solution - from environmental and techno-economic points of view - for off-grid rural electrification in the remote off-grid MENA sites and in other sites in the globe having the same conditions.

Keywords: Hybrid PV-biomass-battery system, techno-economic analysis, sensitivity analysis, homer, rural electrification.

1. Introduction

Rural electrification of remote areas is a vital requirement for their socio-economic development. Extending a grid to meet the electricity demand of such areas - that are sparse and located far away from the grid - seems to be an appropriate solution; nevertheless, it is expensive and practically infeasible [1]. Another alternative is utilizing stand-alone diesel generating systems. But - because of their reliance on diesel as fuel - these diesel generating systems cause environmental pollution and suffer from: i) interruption in fuel supply, ii) high costs of the fuel and its transportation, iii) high operation and maintenance costs and iv) their interruptible operation during frequent maintenance periods [2]. All of these factors make utilization of diesel generating systems for rural electrification an unattractive option, especially, in countries that lack indigenous fossil fuel resources [3]. Therefore, using the clean renewable energy (RE) systems could be – depending on the location of the RE resources - an economically viable and an environmentally friendly solution for fulfilling the electricity needs of rural areas, especially if modern techniques are used with these systems to harness better the RE sources.

Luckily, like many countries located in the North Africa and Middle East (MENA) region, Jordan is blessed with abundant RE resources such as solar [4] and wind [5-8]; but it has low potential of geothermal and hydro energies [9, 10]. Unfortunately, RE resources are not well exploited in the MENA region [11]. In 2019, in Jordan - as a representative of the MENA region - RE contributed only 10.7% to the total generated electricity (of which 7.03% from solar energy, 3.52% from wind, 0.11% from hydro and only 0.02% from biogas) [12]. The latest figure of the biomass share in the total electricity generation is an indication that biomass is not in the focus of the Jordanian government - especially the biomass that comes from animal waste - although it is abundant in the rural areas that are characterized by: i) having no access to grid electricity and ii) their population is, mostly, engaged in livestock breeding [13]. In these areas, the bulk of the animal waste is disposed in landfills or spilled to the environment. This act leads to: i) soil contamination and ii) waste decomposition which leads to release of CO_2 and methane in the atmosphere and subsequent contribution to global warming [14]. Therefore, further investigations focusing on the assessment and exploitation of the available biomass resources - besides other RE resources - in addition to their utilization for electricity generation in rural MENA areas are required. In this regard, exploring the possibility of integrating biomass with other RE energies (such as solar, wind, etc.) in a hybrid system (to overcome the drawback of utilizing a single RE source) with/without storage is a very appealing solution for rural electrification. In such systems, biomass is used as a continuous energy source that offers an uninterruptable supply of electricity to overcome the intermittent nature of other RE sources such as wind and solar and - at the same time - to reduce both the cost of solid waste's disposal and the release of CO_2 and methane in the atmosphere.

Hybrid RE systems based on biomass with various combinations of other RE sources have been subjected to investigation by many authors. In [15], the possibility of retrofitting a diesel generating system - that is used to power a remote Nigerian hospital - by a system comprised of diesel generators, solar photovoltaic (PV) array, biogas fueled generator (BGG) and batteries (BATT) was investigated. It has been found that the investigated system can reduce the CO_2 emissions considerably. Perkins found that integrating biomass with PV in a hybrid system is economically viable when using woody biomass feedstocks [16]. The researchers in [17] found that a hybrid system consisting of 24 PV panels having a rated capacity of 131.04 kW, 4 biomass generators with a rated capacity of 200 kW, and 298 Ni-Fe battery (BATT) with a rated capacity of 1430 kW is the optimal configuration to fully electrify a remote Egyptian village. The authors in [18] incorporated a fuel cell with a PV-biomass system to be used for electrification of a rural Iranian area and found it to be a cost-effective solution. Reserachers in [19] found that the investigated by them PV-wind-biomass hybrid system is a reliable and cost-effective option for electrification of a rural Chinese village and that it is – compared to the grid extension - more viable from the economic point of view. The possibility of using a hybrid PV-wind-BGG system for rural electrification in Iran and concluded was investigated and the results unveiled that the most optimal system to be used is comprised of 150 kW BGG, 80.7 kW PV array in addition to storage BATT and a converter [20]. It was also found that utilizing this system instead of conventional fossil fuel-based systems will save more than 800 US$ annually due to expected reduction in CO_2. A micro-grid - comprised of 10 kW PV array, 1 kW wind turbine, 15 kVA BGG in addition to storage BATT – was modeled and validated by practical implementation of the micro-grid. The results showed that the model and the installed system are economically feasible and can provide uninterruptable - with no losses - electric power supply [21]. The possibility of improving both the efficiency and the reliability of a wind farm by hybridization it with biomass gasifier in a 1.5 MW power plant was investigated [22]. The obtained results revealed – by techno-economic analysis - that biomass is very effective in covering the weaknesses of wind resource. A hybrid PV-fuel cell- biomass gasifier-BATT system was modeled and optimized [23]. It was found that the optimal size of its components are 5 kW for each of the PV array, the biomass gasifier and the fuel cell. The system was able to satisfy the load demand all over the year without interruption. A feasibility assessment of a hybrid BGG-PV- Wind-Battery system to fulfill the energy needs of 20 houses in each of two cities located in the UK and Bulgaria was conducted in [24]. The BGG was found to generate most of the system's electricity (about 60% to 65%), hence offering an uninterruptable basal electricity and at the same time reducing the cost of solid waste's disposal.

The above surveyed works indicate that integration of biomass with other RE sources in a hybrid system enhances the reliability of the system, improves the certainty of satisfying the load demand and covers the weaknesses of other intermittent RE resources.

Although, hybrid RE systems - in which biomass is integrated with other RE sources - has been investigated by many researchers, none has been reported for the MENA regions. On top of that, other researchers didn't investigate - in one research work – RE systems comprised of different configurations of BGG, PV array and BATT. For this reason, this paper aims to i) Develop a sustainable hybrid system - that combines biomass with other RE sources - and provide a reliable energy source for daily activities in remote off-grid MENA areas ii) utilize efficiently the - abundant and freely available in such areas - biomass resources that comes from animal waste and iii) reduce harmful CO_2 and methane emissions as well as energy costs.

2. Site Description and Assessment of the Available RE Resources

Alashari village - as a representative of MENA remote villages - is located in Jordan with an agricultural community comprised of 700 households with 5410 inhabitants [25]. Since the village is located at a distance of 60 km from the national electricity grid, it is not connected to the grid and this situation is not expected to change, at least, in the near future [26]. Currently, the village's electricity needs are met by diesel generators that are problematic from the economic and environmental points of view. This obliged the authorities to seek other ways that are - contrary to the diesel generators - environmentally friendly and economically viable for satisfying the village's electricity needs. Luckily, the village is blessed with high solar energy potential [27]. Moreover, since almost all of the village's inhabitants are occupied in livestock breeding, the village is endowed with high biomass potential that results from the animal's waste [28]. But, unfortunately, the village has a low potential of wind energy [29]. Based on the aforementioned facts and the available RE resources, the authorities - for economic and environmental reasons - set a goal to retrofit the village's diesel generating system by an off-grid RE system; namely solar and /or biomass energies.

2.1. Load Data

The village's electricity consumption is due to both residential and agricultural activity loads (such as water pumping for irrigation, etc). Figs. 1 and 2 show – the obtained from National Electric Power Co. [13] - village's hourly load and monthly average load for one year, respectively. They reveal that the peak daily load occurs at 14:30 in August while the minimum daily load is at 5:00 in January. They also point out that the peak load is in the months of May to September (the summer months) with the maximum occurring in August whereas the lowest load occurs in the months of January to April, with a minimum load in February.

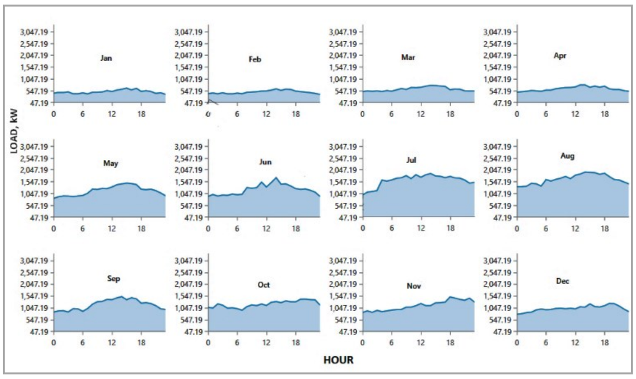

Fig. 1. Village's hourly load for one year

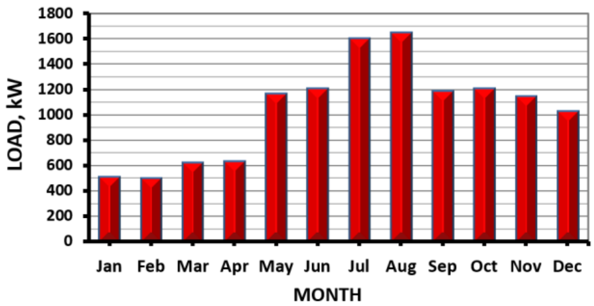

Fig. 2. Village's monthly average load

2.2. Solar Energy

The monthly average of the global solar radiation (GSR) data - calculated using measured at the site GSR for a ten-year period [27] - is depicted in Fig. 3. The GSR values range between a minimum of 4.45 kWh/m^2 in January and a maximum of 6.6 kWh/m^2 in August. These high GSR values complemented by the fact that they almost follow the load trend (highest GSR values are noticed in the summer months of May to September when the load demand is at its peak) creates a favorable situation for utilizing solar energy for electricity generation at the site.

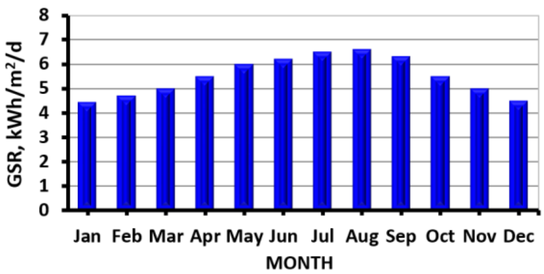

Fig. 3. Monthly average of the recorded GSR at the village

2.3. Biomass

The village's biomass resource comes from the livestock's manure which can be converted to biogas by anaerobic digesters or a gasifier. In this research, anaerobic digester is utilized because it is – compared to a gasifier – cheap and more appropriate for small size applications [24].

The volume of the produced biogas is given by [30]:

$$B_V = \sum_{n=1}^{i} N_i \, . \, DM_i \, . \, O_{mi} \, . \, B_{PFi} \quad (1)$$

Where: Ni is the number of specific animal type, DMi - mass of waste's dry matter (DM) of a specific animal type (it is the matter left after moisture's removal), OMi : fraction of the organic matter available in the waste's DM, B_{PFi} is the production factor of biogas from waste. It constitutes the biogas yield from the waste's organic matter.

Table 1 depicts the number of livestock in the village, its waste's characteristics and production in addition to the potential of biogas production. It shows that the village has a great potential of biomass energy that makes it a suitable candidate for utilizing the biomass energy for generating electricity.

3. The Investigated RE Systems

This research investigates five RE systems, comprised of different configurations of the following components: PV array, BGG, BATT and converter (CONV). As depicted in fig. 4, these systems are: i) BGG, ii) BGG -BATT, iii) PV-BAT , iv) BGG -PV and v) BGG -PV-BATT.

The investigated systems that contain a PV array use it for converting the incident sun light into electricity. The array is formed from PV modules, which in their turn are comprised of series/parallel connected solar cells to produce the desirable output power that can be described by [31]:

$$P_o = C_{NOM} f_D \left(\frac{SR_T}{SR_{T,STC}}\right) \left[1 + \beta_p \left(T_{PV} - T_{PV,STC}\right)\right] \quad (2)$$

Where: C_{NOM} – nominal capacity of the PV array estimated under standard test conditions expressed in[kW], F_D – PV array's derating factor [%], SR_T - solar radiation hitting the array's surface, expressed in [kW/m^2], $SR_{T,\ STC}$ – solar radiation striking the array's surface under standard test conditions. It equals 1 kW/m^2, β_P - a coefficient that shows to which degree the output power of the array is affected by the temperature of its surface. It is called the PV array's temperature coefficient of power, expressed in [%/°C.], T_{PV} – solar cell's temperature [°C] and $T_{PV,\ STC}$ – solar cell's temperature under standard test conditions. It is equal to 25°C.

Table 1. The available biomass resource at the site

Animal Type	Animal Number N_i [32]	Daily dry matter production (kg/head/day) DM_i [33]	Organic matter fraction of the dry matter O_{mi} [34]	Biogas production factor (m^3/kg of OM) B_{PFi}	Annual biogas Production (thousand m^3/year) B_{Vi}
Cattle	42	2.86	0.934	0.20 [35]	8.19
Sheep	3500	0.329	0.912	0.31 [36]	118.83
Goat	173	0.552	0.598	0.31 [36]	6.46
Donkey	242	2.303	0.951	0.16 [35]	30.95
Horse	88	3.3	0.876	0.16 [35]	14.86
Poultry	7238	0.043	0.465	0.18 [35, 36]	9.51

Mechanical and electrical properties of the PV modules - employed in the investigated RE systems - are exhibited in Table 2 [37].

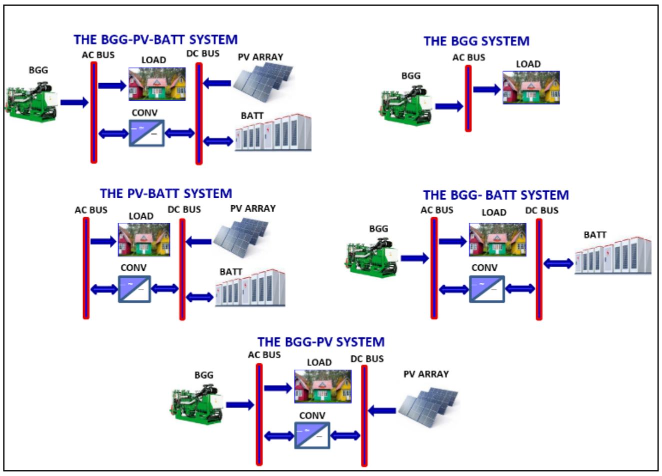

Fig. 4. The investigated RE systems.

The BGG is a biogas fueled generator used - in some of the investigated systems - as a continuous power source for electricity generation. The BGG fuel is obtained from the anaerobic digester that converts the biomass resource - available at the site in the form of animal waste - to biogas. Table 3 exhibits specifications of the utilized BGG [38].

Table 2. Specifications of the utilized PV module

Item	Specification
Manufacturer	SUNTECH Co.
Type of solar cells	Mono-crystalline silicon 166 mm
No of cells	120 (6 × 20)
Operating Temperature	-40 °C to +85 °C
Nominal power	0.37 kW
Efficiency	20.3%
Optimum operating current (Imp)	8.69 A
Optimum operating voltage (Vmp)	32 V
Short circuit current (Isc)	9.17 A
Open circuit voltage (Voc)	38.7 V
Module's weight	20.3 kg
Module's dimensions	1756 × 1039 × 35 mm

Table 3. Specifications of the BGG

Item	Specification
Manufacturer	Weifang Junwei Machinery Co.
Rated Current	15A
Rated Voltage	220/240 V
Frequency	50Hz/60Hz
Power	10 kW
Speed	1500 rpm
Efficiency	27.5%

Some of the investigated RE systems include a BATT for storing the excess electricity (electricity above the mean hourly demand) generated by the PV array and/or the BGG until the BATT is fully charged. This stored energy is retrieved whenever the system fails to fulfill the load demand. If the BATT is fully charged and the power generated by the system overweighs the load demand, the excess electricity goes to some dump load. Table 4 shows the specifications of the utilized BATT [39].

Table 4. Specifications of the BATT

Item	Specification
Manufacturer	redT Energy Co.
Technology	Vanadium flow
Nominal voltage	48 V
Nominal capacity	417 Ah
Roundtrip efficiency	75%

In the investigated systems - with the purpose of preserving the energy flow between the DC bus and the AC bus – a power converter manufactured by Fronius Co. is utilized. It has a life time of 20 years and 98% efficiency [40].

4. Economics

The total net present cost (CTNPC) and the cost of the generated electricity COE are the main economic indicators for selecting optimized configuration of each of the investigated five RE systems. A certain system's CTNPC constitutes the difference between the present value of all the lifetime costs incurred by the system and the present value of all its lifetime earnings. It is calculated using the following equation [41]:

$$C_{TNPC} = \frac{C_{ANN,T}}{CRF} \tag{3}$$

Where $C_{ANN,T}$ constitutes the total annualized cost; i.e., sum of all annualized costs of each system component that includes capital, replacement and operation and maintenance costs whereas *CRF* is the constant annuity divided by the present value of receiving such annuity for the system's lifetime.

COE constitutes the mean cost of 1 kWh of the generated electricity. It is calculated by:

$$COE = \frac{C_{ANN,T}}{E_{SR}} \tag{4}$$

Where: E_{SR} is total served load by the system.

Table 5 depicts the cost data of the investigated systems' individual components that was obtained from their manufactures [37-40].

5. Results and Discussion

Hybrid Optimization of Multiple Energy Resources (HOMER) software of the National Renewable Energy Laboratory (NREL)/ USA is utilized to both find the most appropriate RE system (that is economically viable, sustainable and can fulfill the load demand) and accurately size its components. For this purpose HOMER executes both the simulation and the optimization for each of the five investigated systems, namely i) BGG, ii) BGG -BATT, iii) PV-BAT , iv) BGG -PV and v) BGG -PV-BATT. Input data for HOMER comprises the village's load data, solar data, system's components and their costs and specifications with the assumption that each of the investigated systems has a 6.0% interest rate and 25.0 years of lifetime. In the simulation stage, HOMER performs thousands of hourly simulations for the operation of the investigated systems in order to find the feasible solutions (systems with the proper size of their components that fulfill the load demand) for each of the five investigated systems [42]. In addition, HOMER eliminates all of the unfeasible solutions (systems with capacity shortage that can't satisfy the load demand). The optimization stage comes after all simulations with the objective of minimizing the NPC and COE of each feasible solution. HOMER optimizer utilizes the grid search algorithm to search for the systems with the lowest costs and rank order them based on their COE and NPC [43-45]. HOMER output - for all feasible solutions for each of the investigated systems with the proper size of their components – includes the operation results of the system's components in each time step in addition to COE and NPC, which should be taken in account when evaluating and comparing the investigated systems.

Table 5. Cost data of the investigated systems' individual components

Component	Cost, $		
	Capital	Replacement	Maintenance
BGG (including the anaerobic digester)	800/kW	800/kW	0.1/op.hr.
PV module	2600/kW	2600/kW	8/yr
BATT	2900/unit	2900/unit	8/yr
CONV	280/kW	280/kW	0.1/kW

Table 6 shows - as a result of HOMER simulations and optimization - the optimal configuration for each of the five investigated RE systems in addition to the size of its components. These optimal configurations are characterized by having the lowest NPC and COE values among the feasible solutions for each of the five investigated systems. It is noticed that the size of the BGG in BGG-PV-BATT system is half that of BGG in the rest of systems that include BGG; i.e., in BGG-PV, BGG-BATT and in the BGG only systems. This is mainly due to the presence of both the PV array and the BATT in one configuration. Here, the PV array - as a power generation source - aids the BGG in fulfilling the load demand and the BATT contribute their charge (stored when there is an excess generated electricity; i.e., when the generated electricity overweighs the load demand) during the periods when there is an electricity generation shortage; i.e. when the generated electricity by both the BGG and the PV array does not satisfy the load demand. It is also noticed that the number of BATT in the PV-BATT system is fivefold that of the BGG-PV-BATT system. This is mainly because PV array is the sole generation source in PV-BATT configuration and its operation is severely affected by the intermittent nature of solar energy - especially during the night. Therefore, there is a need for more BATT in the PV-BATT configuration to increase the storage capabilities of the excess electricity generated during the day to be used during the night.

Table 6. The optimal configuration for each of the five investigated systems

System	Component			
	PV, kW	BGG, kW	BATT	CONV, kW
BGG-PV-BATT	27.7	10	5	8.83
PV-BATT	69.4	-	25	21.8
BGG	-	20	-	-
BGG –PV	0.865	20	-	0.177
BGG – BATT	-	20	1	0.708

Performance and economics of the aforementioned optimal configurations of the investigated systems were intensively investigated. Details of these investigations are presented in the following subsections.

5.1. Electricity Production by the Optimal Configurations of the Investigated Systems

Fig. 5 exhibits the annual electricity production - expressed in MWh/year - by components of the optimal configurations of the investigated systems. It is obvious that BGG produces all of the electricity in the BGG only system because BGG - in such system - is the sole power generation source. This is also true for both the PV-BATT and the BGG-BATT optimal configurations, since only the PV array (in the PV-BATT optimal configuration) and the BGG (in the BGG-BATT optimal configuration) generate electricity and the BATT are used solely for storing the excess electricity if any. It is noticed that in the optimal configuration of the BGG-PV system, most of the generated electricity is produced by the BGG, due to the intermittent nature of solar energy that affects the operation of the PV array. However, the presence of BATT in the BGG-PV-BATT optimal configuration changes the situation. Here, the PV array generates about 60% of the electricity while 40% is accounted for BGG. This is because the presence of BATT - in this configuration - severely affects the number of operation hours of the BGG compared to BGG-PV optimal configuration. In the BGG-PV-BATT optimal configuration, BGG is turned off when the PV array and the stored electricity in the BATT can satisfy the load, leading to reduction in BGG operation hours and, consequently, its generated electricity. But when needed, the BGG is brought back to operation, especially when the PV array can't satisfy the load demand or when the BATT is depleted.

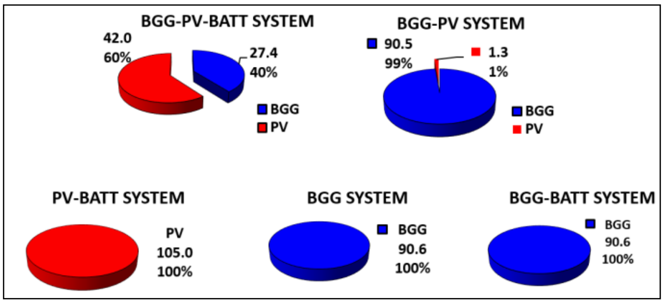

Fig. 5. Annual electricity - expressed in MWh/yr - produced by components of the optimal configurations of the investigated systems

Fig. 6 exhibits the excess electricity that is produced when the generated electricity overweighs the load demand and when the BATT is fully charged. This excess electricity goes unused or dumped. The figure shows that the lowest value of excess electricity is generated by the BGG-PV-BATT indicating the proper sizing of its components. It is also due to the presence of the BATT which stores any electricity that overweighs the load demand until it is fully charged.

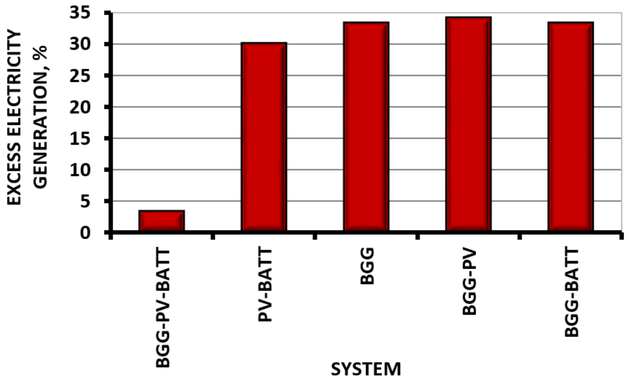

Fig. 6. Excess electricity generated by the optimal configurations of the investigated systems.

5.2. *Economic Analysis*

C_{TNPC} for the optimal configurations of the investigated RE systems in addition to the NPC of each of their components are exhibited in fig. 7. The results reveal that the highest values of NPC are accounted to those optimal configurations that include BGG, namely BGG only, BGG-PV and BGG-BATT, due to the high capital and operation costs of BGG. On the contrary, BGG-PV-BATT optimal configuration has the lowest NPC, although it includes BBG. This is due to the presence of both the BATT and the PV array that: i) leads to reducing the BGG size to the half of that in other configurations as discussed earlier and ii) reduces the BGG operation hours and, consequently, its operation costs. This also elucidates why the NPC of the BGG in the BGG-PV-BATT system is much lower than that for the rest of the systems that include BGG.

Since the NPC affects to a great extent the COE, it is noticed - as revealed by Fig. 8 - that the COE generated by the optimal configurations follows the same pattern of the NPC.

It is obvious that BGG-BATT, BGG-PV and the BGG only systems have the highest COE values of 0.38 US$, 0.379US$ and 0.377 US$, respectively, making them unsuitable for implementation at the site. On the other hand, the lowest COE value of 0.199 US$ is accounted for the BGG-PV-BATT system. This low COE value complemented by the lowest value of NPC obtained by this configuration makes it the most appropriate configuration - among the investigated ones - for implementation at the site.

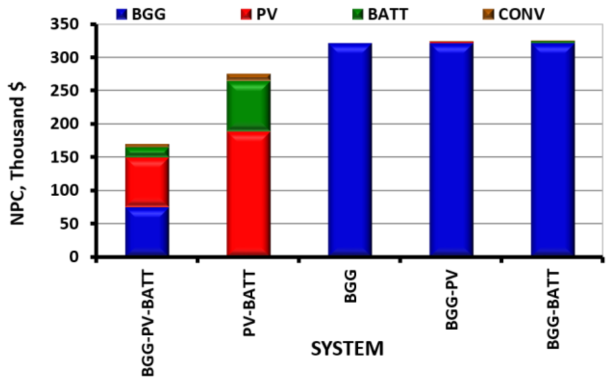

Fig. 7. NPC of the optimal configurations of the investigated systems

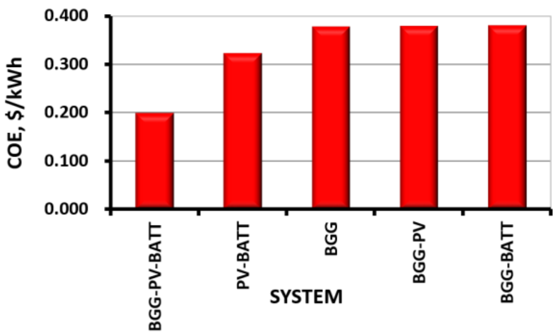

Fig. 8. COE generated by the optimal configurations of the investigated systems

5.3. *Analysis of the BGG-PV-BATT Hybrid System*

The BGG-PV-BATT hybrid RE system - with the size of its components, depicted in table 6 – proved to be the most appropriate for implementation at the site among the optimal configurations of the five investigated system. It has the ability to fulfill the load demand with lowest values of NPC, COE and excess electricity. For these reasons it was subjected to further investigation to explore the factors that might affect its performance and the COE. Details of these investigations are found in the following subsections.

5.3.1. *Payback period*

A payback period is utilized to define the time - in years - that is needed for an investment to be recovered. To calculate such period for a certain system, a base case system is required. In this investigation the BGG only system is utilized as a base case system for calculating the payback period of the BGG-PV-BATT configuration. Calculation results of the payback are exhibited in table 6. The nominal cash flow is utilized for simple payback calculation while the discounted cash flow is used for calculating the discounted payback. The discounted and the nominal cash flows differ in the considered time value of money in the performed analysis. In order to find their present values, the future cash flows are estimated and discounted. As exhibited in table 7, the payback period of the BGG-PV-BATT system is 5.07 years.

Table 7. Payback period analysis for the BGG-PV-BATT hybrid system

Parameter	Value
Present worth	151050 $
Annual worth	10717 $
Simple payback	5.07 yr
Discounted payback	6.12 yr

5.3.2. *Sensitivity analysis*

Generally the sensitivity analysis is performed to see the effect of different variables on the performance and COE of a hybrid energy system by entering multiple values of such variables. In this investigation, we explored the effect of two variables, namely the GSR and the mass of the daily waste production - that is used in the BGG after its conversion to biogas – on the COE. To accomplish this task, the GSR and the daily waste production were varied by ±30% from their base case values of 5.52 kWh/m^2/day and 11.95 tons/day, respectively. The results, depicted in Fig. 9, reveal that the waste production has minor effect on the COE since the waste is available for free at the site. On the other hand, it is noted that the GSR is inversely proportional with COE. It was found that the COE varies between 0.207 US$ to 0.188 US$ when varying the GSR from -30% to +30% of its base case value. This is mainly due to the fact that increasing GSR leads to more electricity generation by the PV array which, in its turn, reduces the operation hours of the BGG and the associated with it maintenance and operation costs and eventually leads to reduction in COE.

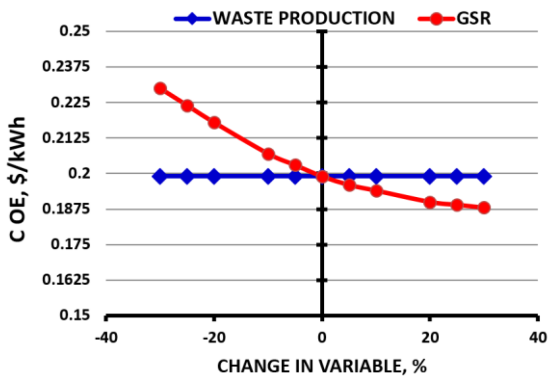

Fig. 9. Sensitivity analysis for the BGG-PV-BATT hybrid system.

5.3.3. Grid extension

The cost of extending the electricity grid to the site is explored and compared - based on the site distance from the grid - with the cost of utilizing the BGG-PV-BATT optimal configuration as an off grid solution. The results - shown in fig. 10 - reveal that the breakeven distance (the distance at which the NPC of the grid extension and the BGG-PV-BATT are equal) is about 32 km. In our case, since the village – as mentioned earlier - is located at a distance of 60 km from the national electricity grid, the grid extension option is more expensive – in terms of NPC - than the BGG-PV-BATT hybrid system, emphasizing the fact that the stand alone BGG-PV-BATT system is more appropriate solution for electricity generation at the site than the grid extension option.

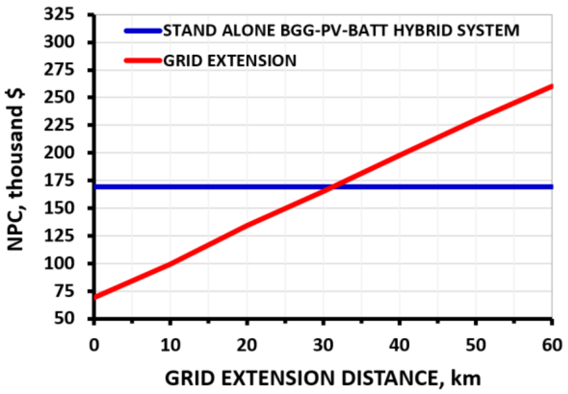

Fig. 10. Breakeven grid extension diagram for the BGG-PV-BATT hybrid system.

6. Conclusion

The paper presented a techno-economic analysis of RE systems - in which biomass is integrated with solar energy - to better exploit the abundant RE resources in the remote areas of the MENA region to attain their sustainable development. The obtained results highlight and confirm the huge potential of solar and biomass resources in the remote MENA areas, which makes them suitable candidates for implementing such RE systems.

The results also unveil that - based on its techno-economic performance - the BGG-PV-BATT hybrid RE system is the most appropriate RE system for implementation in the remote MENA areas. Examining the possibility of extending the electricity grid to the site unveil that the grid extension option is more expensive than the proposed off-grid hybrid system one.

We hope that the outcomes of this research will assist the policymakers in the MENA countries and in other countries - that experience the same energy and environmental difficulties - in their quest for alternatives that would retrofit the diesel generating systems in rural off-grid areas. Utilizing the proposed hybrid RE system, not only will ensure uninterruptable basal electricity and reduce the cost and environmental effects of solid waste's disposal in landfills or spilling to the environment, but will also reduce dependency on fuel, mitigate the environmental impacts of CO_2 and methane emissions that negatively affect the population's health and, ultimately, contribute sustainably to the socio-economic evolution of rural areas.

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