Smart energy solution for an optimised sustainable hospital in the green city of NEOM

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Abstract

Hybrid optimisation of multiple energy resources has been performed on a micro grid model of a hospital to investigate the capability of a standalone energy system and simultaneous mitigation of hospital waste. The main objectives of this study were to collect renewable energy resource data of a hybrid hospital, use the average amount of hospital waste from the literature and NASA surface meteorology in addition to the solar energy database from HOMER Pro software to construct a hybrid model for a conceptual hospital in the new green city in Saudi Arabia, NEOM. The hybrid model consisted of biogas Cofire and diesel generators, PV solar array and batteries. Simulations were performed to analyse the load requirements of a standalone hospital. The mechanism of energy storage was designed based on Tesla batteries. Then, the hybrid hospital model was tested with NEOM's natural resources, load demand of 250 kWh/day and the average amount of daily hospital waste of 0.6 tons based on the literature data. This condition allows the smart hospital to be tested with real features. The outcome of the COE, NPC and the amount of reduction of carbon dioxide in the hybrid hospital were analysed. Many of the hybrid properties and constraints that define the hospital were adopted from previous literature concentrating on similar domains. The optimal solution of a hybrid micro grid consisted of biogas cofire, PV array, and batteries. Of the total load demand, 32.3% and 67.6% were produced by PV array and biogas cofire generators, respectively, together with eight Tesla PowerWall2.0 batteries. The cost of energy was 0.21 USD/kWh and the net present cost was 243,699.17 USD. In this study, we compared renewable energy with conventional energy and found that the optimal solution would be able to reduce carbon emission and diesel consumption by almost 84% and 81%, respectively. The results were verified through a sensitivity study and compared with other studies.

Nomenclature

AC	Alternative Current	NREL	National Renewable Energy Laboratory
BioCo	Biogas Cofire generator	NASA	National Aeronautics and Space Administration
DG	Diesel generator	NPC	Net Present Cost
DC	Direct Current	PV	PhotoVoltaic
HOMER Pro	Hybrid Optimisation Model for Electrical Renewable	RF	Renewable Fraction
LCOE- COE	Levelised Cost Of Energy	GHG	Greenhouse Gas
STC	Standard Test Conditions	GHI	Global Horizontal Irradiation
USD	United States Dollar		

C_{cap}	Capital cost of grid extension in USD/year/km	C_{wh}	Battery capacity
E_{demand}	Total annual electrical demand (primary plus deferrable) kWh/year	E_L	Average energy load per day in kWh/day
C_{power}	Cost of power from the grid extension in USD/km	AD	Days of autonomy of battery
R_{proj}	Project lifetime in years	DOD	Battery discharge depth
i	Real discount rate in %	η_{inv}	Efficiency of inverter
CRF	Capital recovery factor	η_{Batt}	Efficiency of battery
C_{NPC}	Total net present cost of the standalone power system (USD)	F_0	Intercept coefficient of the generator's fuel curve in (L/hr/kw)
C_{om}	Operation and maintenance of grid extension in USD/year/km	Y_{gen}	Generator rated capacity in KW
$\dot{m}_0$	Flow rate of pure fossil fuel (kg/hr)	F_1	Slope of the generator's fuel curve in (L/hr/kw)
ρ_{fossil}	Density of fossil fuel in (kg/L)	P_{gen}	Generator output power in KW
COE	Cost Of Electricity	WHO	World Health Organization

Introduction

The usage of waste has become a source of sustainable energy mainly because of the reduction in CO_2emissions [1]. Currently, waste-to-energy is considered to be one of the primary sources of energy that will reduce future CO_2 emissions [2, 3]. Using biomass as an energy source has socio-economic advantages, as it would allow the conversion of hospital disposals into energy without wastage. According to the Department of Energy, hospitals consume the second highest amount of energy compared to other infrastructures and due to the high energy demand, most of the hospitals' energy tends to be produced from conventional energy resources [4]. The World Health Organization (WHO) states that the improper disposal of healthcare waste in landfills could pose a risk of drinking water contamination in landfill sites [5]. Consequently, there is a need for more efficient and effective waste disposal methods and alternative energy resources to tackle these issues. Therefore, using hospital waste as a source of energy is an optimal option to produce electricity and simultaneously mitigate the abovementioned issues. The importance is increased for developing countries such as Saudi Arabia, which invests in renewable energy sources by planning some novel green cities, such as NEOM. NEOM is a 475 billion USD megacity in Saudi Arabia that will be constructed on its border with Egypt. It will be centred at 28°13.2' north latitude, 34°53.3' east longitude, and will have an approximate area of 26,000 square meters to serve a large population. Its energy is planned to be supplied from renewable sources such as solar power, biomass, or wind energy. However, one of the main users of the electrical energy is the hospitals, for which these solar plants need to have a sustainable supply of electricity, while a portion of this energy needs to be stored.

Literature review

The Sustainable Development Unit (SDU), which was founded in 2008 by the United Kingdom's National Health Service (NHS), defined sustainable healthcare as "delivering high-quality care and improved public health without exhausting natural resources or causing severe ecological damage" [6]. Numerous approaches are reported in the literature to address this issue. McGain and Naylor (2014) conducted a systematic environmental review of hospital sustainability by investigating relevant articles over the period from 1900 – 2013 [7]. The authors were able to identify common research themes such as hospital design, energy consumption, and waste. They asserted that there was a lack of evidence in hospital sustainability when they assessed natural resources. Several researchers designed sustainable models to solve the environmental issue [8] so as to be applicable and achievable in the current era. Recently, it has been found that 85% of hospital waste is general waste (non-hazardous) whereas 15% is infectious waste (hazardous). Hazardous waste poses a particular radioactive, biological, physical, or chemical hazard to the environment [5]. In the last decade, some healthcare organisations have realised the consequences of health equipment on the environment [9]; as a result, they have updated their programmes to take environmental factors into consideration. According to the Environmental Protection Agency (EPA) in the United States (1974), a survey conducted by the University of Minnesota of 80 general hospitals revealed that the average amount of waste generated from a hospital was approximately 4 kg per bed per day [10]. Similarly, Al Zahrani et al. (2000) investigated the amount of waste generated from Saudi Arabia healthcare. A questionnaire was sent to 43 medical centres, and they found that the mean rate of hospital waste generation was 1.13± 0.96 kg/bed per day and 0.08± 0.08 kg per bed per visitor [11]. Although this study distinguished between the amount of waste produced by patients or visitors, the sample duration used to determine the amount of collected waste was insufficient. Another recent study by Malekahmadi et al. (2014) surveyed 114 hospitals to determine the status of healthcare waste management in Tehran; they found that the average waste per bed was around 3 kg/day [12]. This waste appears to be a considerable amount when multiplied by the number of patients. In several developed countries including the United Kingdom, bioenergy has been tied to government strategies in mitigating CO_2 emissions from transportation and electricity production [13]. Waste to energy schemes have been utilised extensively around the world for both heating and power supply. In the last decade, in Austria and Sweden, the use of biomass has multiplied six- and eight-fold, respectively, mainly because of positive impacts at federal and society levels [14, 15]. Also, it has been shown that biomass can generate 94% lower emissions than fossil fuels [16, 17].

The impact of bio-fuel on the pollutants emitted and the overall thermal structure has been identified experimentally [18]. The experiment consists of biomass material such as wood, straw and others, combined with conventional coal. In this study, the significant impact and variation of biomass flame characteristics come from the physical and chemical components of the biomass used. Another study by Freiberg (2018) conducted a scoping review of the human health effects of using biomass to generate electricity [19]. This study concentrated on residential and occupational environments. They concluded that the accidental leakage of hydrogen sulphide in biomass plants tends to impact negatively on human health. Although biomass has certain limitations, it could be an essential component for reducing hospital waste. Due to these limitations, hybrid models for hospitals have to consider reducing its usage while increasing the use of other renewable energy sources. Olatomiwa (2016) asserts that a hybrid system could help in reducing fossil fuel consumption and CO_2emissions, by testing three types of renewable energy resources at three rural health clinics in Nigeria [20]. A hybrid microgrid model for St. Peter's hospital on Likoma Island, Malawi was optimised with a load demand of 193 kWh/day [21]. Also, some studies were conducted in Italy which analysed the possible use of cogenerators in hospitals for district heating [22, 23]. The authors calculated the load needs for this hospital to manage electric demand, which has also been used as the input values for our study.

Materials and methods

The study begins by defining sustainability parameters for a healthcare centre (see Figure 1). The renewable energy resources were selected based on a combination of the local availability and reduction of hospital waste to form a hybrid micro grid. Possible solutions were sorted based on the selected optimisation variables and HOMER Optimizer™ [24]. This helped to identify the least cost-effective choices for the micro grid system. A sensitivity study was carried out to understand the effects of the main influential parameter on the changes in the optimal system. In this study, the electricity load requirements were captured based on an Italian reference hospital [25]. This building includes all the main departments such as operation theatres, diagnostics, intensive care unit (ICU), laboratories, ambulatories and administrative offices. Ascione et al. (2016) stated that the average annual demand load is approximately 200 kWh per day [25]. Similarly, a study conducted on the development of a co-generation system for the Malaysia Medical Centre

(UKMMC) building [22, 26] stated that the average load consumption was 250 kWh per day, and therefore, the load demand and sensitivity analysis were performed within these ranges. The used methodology for this study is shown in Figure 1.

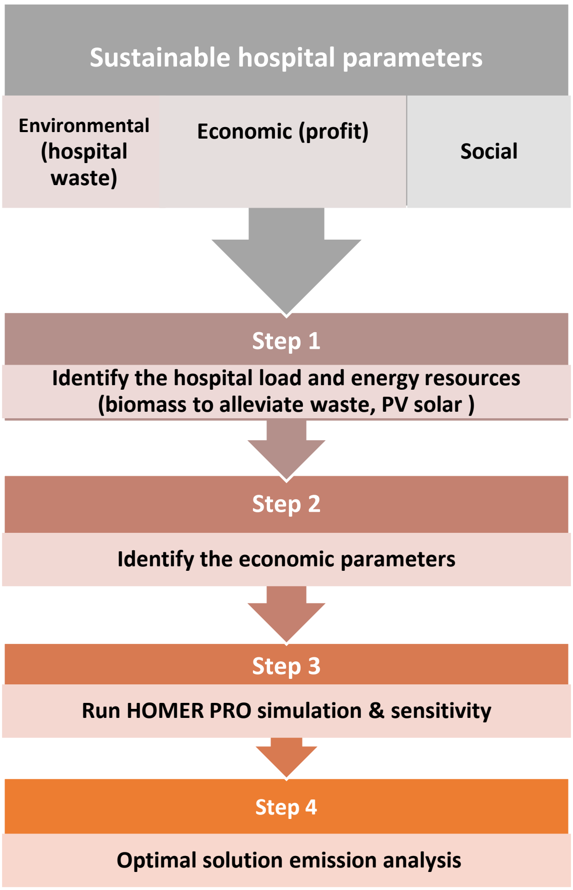


Figure 1 Methodology flow chart

The seasonal and yearly load profiles were obtained from the HOMER Pro database for electricity consumption (see Figures 2 and 3). The highest monthly load consumption would be in July, which is equal to 28 kW for the assigned location. The average baseline and scaled loads are 165.59 and 250 kWh/day, distributed as peak values of 23.31 and 35.2 KW respectively, with a = load factor of 0.3.

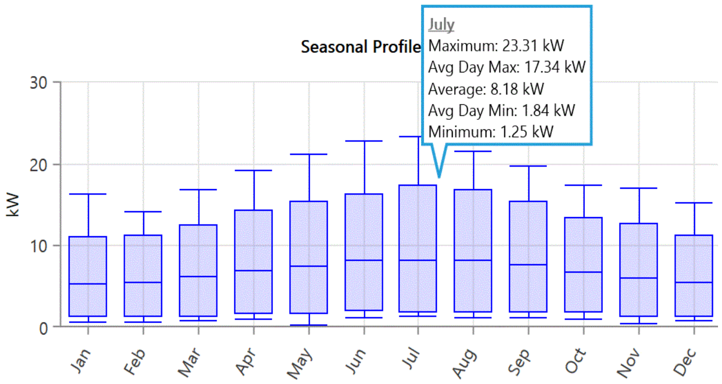


Figure 2 Seasonal profile of the conceptual model in NEOM based

on HOMER software

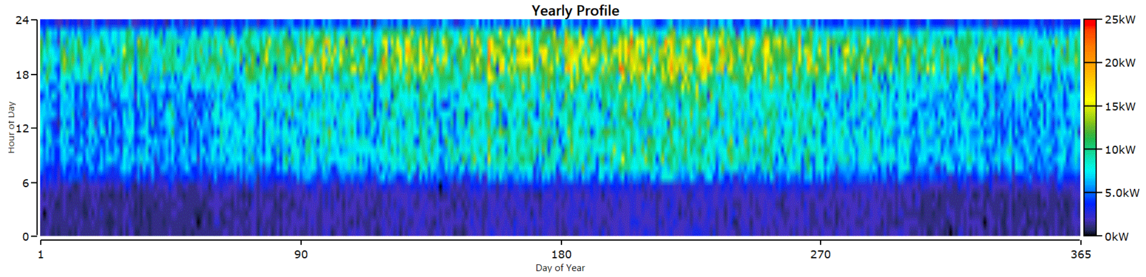


Figure 3 Annual load profile at NEOM (NASA Surface Metrology and Solar Energy)

The solar radiation in NEOM was calculated based on the geographical location of Saudi Arabia using NASA Surface meteorology and Solar Energy database. The average annual Global Horizontal Irradiation (GHI) for NEOM is 5.77 KWh/m²/day (see Figure 4).

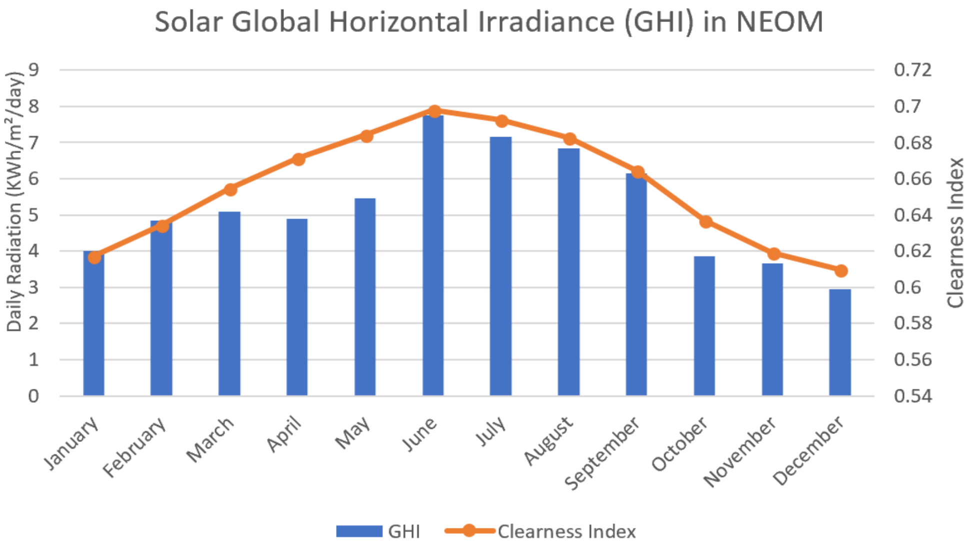


Figure 4 Solar Global Horizontal Irradiance (GHI) in NEOM (From NASA Surface Meteorology and Solar Energy)

Temperature data was also added as the input to the numerical model (see Figure 5). The air temperature and monthly average were collected over a 22 year period (July 1983 – June 2005).

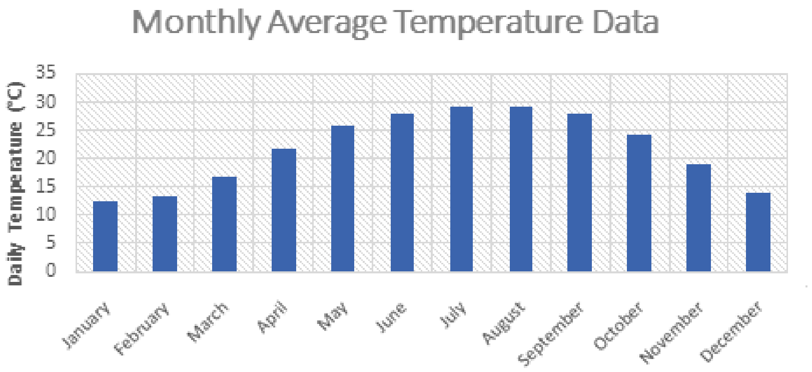


Figure 5 Monthly Average Temperature Data at NEOM (NASA Surface Meteorology and Solar Energy)

Electrical load and different types of renewable energy equipment were applied to the model (see Figure 6). Subsequently, this hybrid model simulated four scenarios for a sustainable hospital: grid, PV solar with batteries, biogas co-fire with batteries and finally all previously available systems, including the grid.

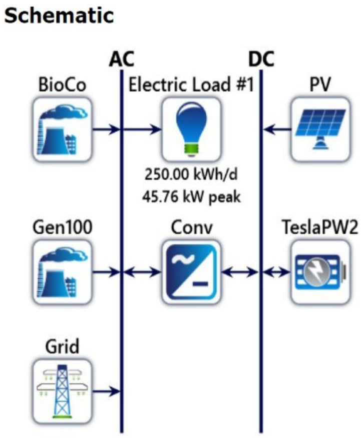


Figure 6 Schematic model of a hybrid hospital

Models were executed for the average hospital load consumption, which is approximately 250 kWh/day. PV panels were assembled in HOMER as a cell that generates DC voltages once exposed to solar irradiance, and the outcome power may be found from the equation (1) [27]:

$$P_{pv-out} = P_{pv-rated} \times f_{pv}\left(\frac{G}{G_{ref}}\right) \times [\,1 + K_T\left(T_c - T_{ref}\right)] \qquad \text{Equation (1)}$$

where $P_{pv-rated}$ is photovoltaic rated power and measured in kW. f_{pv} is the factor of pv derating calculated in percentage, G and Gr_{ef} (kW/m^2) are the global solar irradiance incident on the photovoltaic surface and radiation, respectively. K_T is the coefficient of PV module and T_c is panel temperature obtained by $T_c = T_{amb}$+(0.0256G). T_{ref} is panel temperature, which is a constant (25°C) based on Standard Test Conditions (STC).

Figure 7 shows the PV electric output of the optimal solution for the whole year. This DMAP presented a PV production throughout the year. It is clear that PV production starts from approximately 7 a.m. and lasts until approximately 6 p.m.

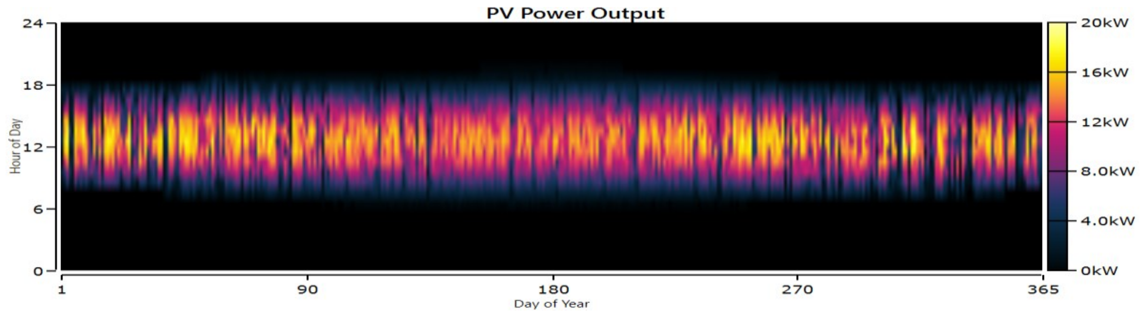


Figure 7 PV power output Data Map (DMap)

The diesel generator and biomass separately are well-known, however, in a hybrid system, the combination of the two can reduce almost 50% of the generated pollution [28]. The initial capital and replacement costs are estimated to be 150,000 Saudi Riyal (SR) (equal to 40,000 USD) for a 100 kW biogas co-fire, while the total operation and maintenance cost of the system is approximately SR 7.5 per hour (equal to 2 USD per hour). The biogas co-fire has a minimum load ratio of 25% and a lifetime of 15,000 hours. A generator consumes a mixture of biogas and fossil fuel. In each iteration, the software calculates the generator output requirement at the same time as the mass flow rates of diesel and biogas. The fuel curve uses equation (2) to obtain co-fire's fuel consumption [27]:

$$\dot{m}_0 = \rho_{fossil} \left(F_0 \cdot Y_{gen} + F_1 \cdot P_{gen}\right) \qquad \text{Equation (2)}$$

where $\dot{m}_0$ (kg/hr) is the flow rate of pure fossil fuel, ρ_{fossil} (kg/L) is the density of fossil fuel, F_0 (L/hr/k) is the intercept coefficient of generator's fuel, Y_{gen} (kW) is the generator rated capacity, F_1 (L/hr/kW) is the slope of the generator's fuel curve, and P_{gen} (kW) is the generator's output power. The output of renewable energy resources may fluctuate at a specific time because of the nature of the collected energy. Therefore, excess energy production should be stored to utilise when it is required. Franco et al. (2017) asserted that the storage system enhances the hospital, with a continuous supply in case of power shortage in addition to harmonising alternative energy sources [29]. The following equation (3) demonstrates the capacity of the storage battery [30] that was used for storing energy for the mentioned hospital.

$$C_{wh} = \frac{E_L \times AD}{\eta_{inv} \times \eta_{Batt} \times DOD} \qquad \text{Equation (3)}$$

Where C_{wh} is the battery capacity, E_L is the average energy load per day in kWh/day, AD is the number of autonomous days of the battery, DOD is the battery discharge depth, whereas η_{inv} and η_{Batt} demonstrate the efficiency of the inverter and battery, respectively. In this hybrid system for our conceptual hospital model, lithium ion batteries of 13.5 kWh, known as Tesla Powerwall 2.0, were used. The Tesla Powerwall 2.0 properties indicate that the battery has a warranty of 10 years or a life-time of 5,000 cycles, with a round trip efficiency of 89%. The capital cost of the Tesla Powerwall 2.0 battery was estimated to be 6497.89 USD.

In this study, the grid extension function has been considered to obtain the break-even grid extension distance. The break-even distance is defined as the distance from the grid when the total net present cost of the standalone system is equal to the total net present cost of the grid extension. This distance helps to identify optimal solutions when it is closer to either the standalone system or the grid. The break-even grid extension distance was calculated using the following equation (4):

$$D_{grid} = \frac{C_{NPC} \cdot CRF(i,R_{proj}) - C_{power} \cdot E_{demand}}{C_{cap} \cdot CRF(i,R_{proj}) + C_{om}} \qquad \text{Equation (4)}$$

where C_{NPC} is the total net present cost of the standalone power system in USD, CRF is the capital recovery factor, i is real discount rate %, R_{proj} is project lifetime in years, C_{power} is the cost of power from the grid extension in USD/km, E_{demand} is the total annual electrical demand (primary plus deferrable) in kWh/year, C_{cap} is the capital cost of grid extension in USD/year/km, and C_{om} is the operation and maintenance cost of grid extension in USD/year/km.

For dispatching energy, the cycles charging strategy was applied by assuming that the generator works at its maximum capacity associated with the surplus power that charges the battery storage. The cost of energy (COE) is defined as the average cost per kWh of electrical energy provided by the system. COE was determined from the equation (5):

$$COE = \frac{Cann,tot - c_{boiler} H_{served}}{E_{served}} \qquad \text{Equation (5)}$$

where $C_{ann,tot}$ is the total annual cost of the model in (USD/year), c_{boiler} is the boiler marginal cost USD/kWh, H_{served} is the total thermal load served in kWh/year, and E_{served} is the sum of electric load served by the hybrid model in kWh/year. This is considered as the major parameter in comparing the results after optimisation.

Results and validation

The optimal configuration models for NEOM were applied based on its location and the requirements of the model data. The components of the hybrid hospital were selected according to the availability of renewable resources. This software analysed an hourly simulation for every feasible system configuration to assess the operational factors, such as electricity production, grid extension, renewable fraction and fuel consumption. Renewable energy resources such as biogas cofire and diesel generator were examined. This investigation fulfils the load demand at the lowest NPC and subsequently, it presents the simulation results in order of optimal configurations and sensitivity analysis. Table 1 shows four optimal configuration results for the hybrid hospital model. From these scenarios, it is clear that the optimal hybrid configuration for NEOM is Scenario 1, which is the combination of PV-Biogas Cofire-TeslaPW2.0, due to its lowest NPC among other scenarios. PV-DG-TeslaPW2.0 (Scenario 3) has a similar configuration, with the exception that biogas cofire is substituted for a diesel generator. Scenario 3 is considered to be the worst configuration due to its high fossil fuel consumption. In scenarios 1 and 3, biomass and diesel are the main sources of the hybrid model respectively, and both systems have a PV array as and generate a substantial amount of electricity. A total of 67.7% of the power supply is generated by biogas cofire or diesel generator and 32.3% from the PV array. In scenario 1, the fraction of renewable energy is almost four times greater than in scenario 3. Scenario 1 is less dependent on fossil fuel than scenario 3. The optimal solutions for a hybrid hospital is shown in Table 1.

Table 1 Optimal solution results of hybrid hospital

Scenario	System configuration	PV (kW)	BioCo (kW)	DG100 (kW)	Battery Units TeslaPW	COE (USD/kWh)	NPC (USD)	Initial capital (USD)	RF (%)	Total fuel (L/year)
1	**PV-bioCo-TeslaPW2**	18.5	100	null	8	0.21	243699	147470	78.4	5,819
2	**BioCo-TeslaPW2**	null	100	null	11	0.22	255322	111463	39.3	15,749
3	**PV-DG-Tesla PW2.0**	18.7	null	100	8	0.23	0.27 M	147941	22.5	20,905
4	**DG-Tesla PW2.0**	null	null	100	11	0.24	0.28 M	111463	0	31,135

The optimal solution, scenario 1, is configured in this hybrid model by 18 kW PV, 100 kW biogas cofire, 8 batteries of TeslaPW2.0. with a COE of 0.21 USD/kWh and an NPC of 243699.17 USD. This optimal scenario, when compared to scenario 3, which is considered a conventional energy resource, mitigates the diesel consumption by almost 15,000 (L/year). Zalengera (2015) optimised a hybrid micro grid model for St. Peter's hospital on Likoma Island in Malawi with a load demand of 193 kWh/d [21]. In this study, it anticipated a COE of 0.524 USD per kWh for a PV-wind-battery system. This is double the cost of the results for NEOM's hospital (at 0.21 USD per kWh). However, for the St. Peter's hospital study, the interest rate was 10 percent, which is significantly higher than the 2 percent applicable for this study. Moreover, the diesel price was 2.3 USD/L, more expensive than the diesel price at NEOM hospital. The results of this simulation are then compared with the study by Rahman (2014), which optimises a hybrid model in Bangladesh with a load demand of 50 kWh/day and predicted COE of 0.697 USD per kWh for a PV-wind-biogas cofire system [28]. Also, a similar pattern of results was obtained in a micro grid study for the community on St. Martin's Island, Bangladesh with a load demand of 155 kWh/day [31]. This study found a COE of 0.40 USD per kWh for a PV-Biomass-Diesel generator-battery. This is double the price of the proposed model, which is estimated at 0.21 USD/kWh. This change is because of the use of two generators instead of using one as a dual generator. In addition to this, the diesel price is five times greater than the proposed system. The present study confirmed the findings regarding hybrid hospitals, verifying that using renewable energy produces similar results. Table 2 shows the output of the generator for all three scenarios. This table shows that the electrical production for scenarios 1 and 3 is almost 70,800 kWh/year, whereas for scenario 2 it is around 109,500 kWh/year. In scenario 2 it is obviously high because of the system's dependence on generators. Scenario 3 utilised diesel at about 21,000 L/year, and in scenario 2, when considering only biogas cofire, the fuel consumption dropped from 21,000 to about 15,000 L/year, whereas in the optimal solution, it was found that when the biogas generator was combined with the PV system, there was a dramatic drop from 21,000 to 5,819 L/year. The following table shows the details of optimisation solutions in three possible scenarios (See Table 2).

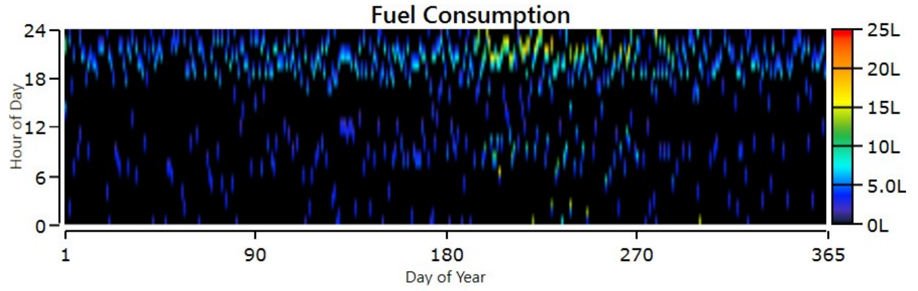
Table 2 Details of the optimisation solutions

Generic 100kW Genset with/without Biogas Cofire	Scenario 1	Scenario 2	Scenario 3
		Electrical Summary	
Electrical Production (kWh/yr)	70,904	109,496	70,687
Mean Electrical Output (kW)	65.4	89.3	65.5
Minimum Electrical Output (kW)	29.8	63.1	32.9
Maximum Electrical Output (kW)	95.2	100	95.2
		Statistics	
Hours of Operation (hours/year)	1,084	1,226	1,079
Number of Starts (starts/year)	545	613	541
Operational Life (year)	13.8	12.2	13.9
Capacity Factor (%)	8.09	12.5	8.07
Fixed Generation Cost (USD/hour)	4.75	4.75	5.00
Marginal Generation Cost (USD/kWh)	0.0063	0.0063	0.032
		Fuel Summary	
Fuel Consumption (L/year)	5,819	15,749	20,905

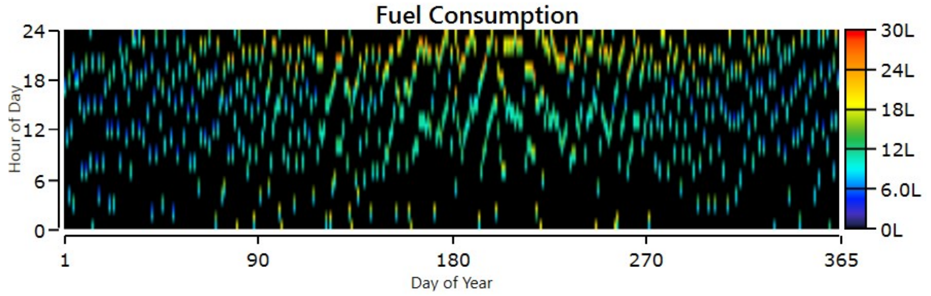
Specific Fuel Consumption (L/kWh)	0.0821	0.144	0.296
Fuel Energy Input (kWh/year)	218,636	318,814	205,704
Mean Electrical Efficiency (%)	32.4	34.3	34.4
Biomass Feedstock Consumption (ton/year)	151	153	null
	Tesla PW 2.0 results & statistical data		
Number of Batteries	8	11	8
Storage Wear Cost (USD/kWh)	0.10	0.10	0.10
Nominal Capacity (kWh)	106	145	106
Bus Voltage (V)	220	220	220
Lifetime Throughput (kWh)	540,000	742,500	539,717
Expected Life (year)	9.99	8.89	10
Average Energy Cost (USD/kWh)	0.0052	0.0062	0.026
Energy In (kWh/year)	57,265	88,413	57,150
Energy Out (kWh/year)	51,019	78,758	50,917
Storage Depletion (kWh/year)	56.6	74.5	56.6
Losses (kWh/year)	6,302	9,730	6,290
Annual Throughput (kWh/year)	54,080	83,483	53,972
	Renewable Energy Summary		
Total Renewable Production Divided by Load (%)	94.3	61.7	37.3
Total Renewable Production Divided by Generation (%)	82.3	51.4	32.5
One Minus Total Non-Renewable Production Divided by Load (%)	22.3	-20	22.5

Figure 8 shows the fuel consumption during the year for different scenarios. Scenario 1 has a low fuel consumption, while scenario 2 presents a higher fuel consumption compared scenario 1. Scenario 3, diesel generator-PV-Battery, consumes more fuel than the biogas cofire-PV-battery configuration used in scenario 1.

Scenario 1



Scenario 2



Scenario 3

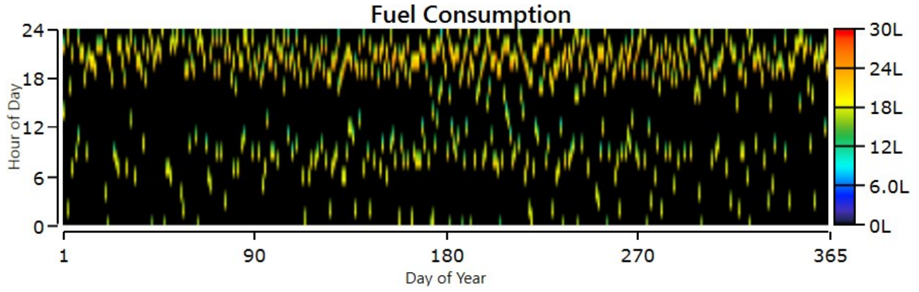


Figure 8 Annual fuel consumption for each optimal scenario

Discussions

The highest load consumption will be in July due to the climate of NEOM, and therefore PV and BioCo make a trade-off to achieve electricity demand. Electricity demand is proportional to the renewable energy factor, which harnesses renewable resources such as PV solar and biomass. Extra electricity is acquired when PV and biogas Co-fire output is greater than demand. Figure 9 presents the monthly average electricity production for each scenario. The average monthly electricity production for each scenario is illustrated in Figure 9.

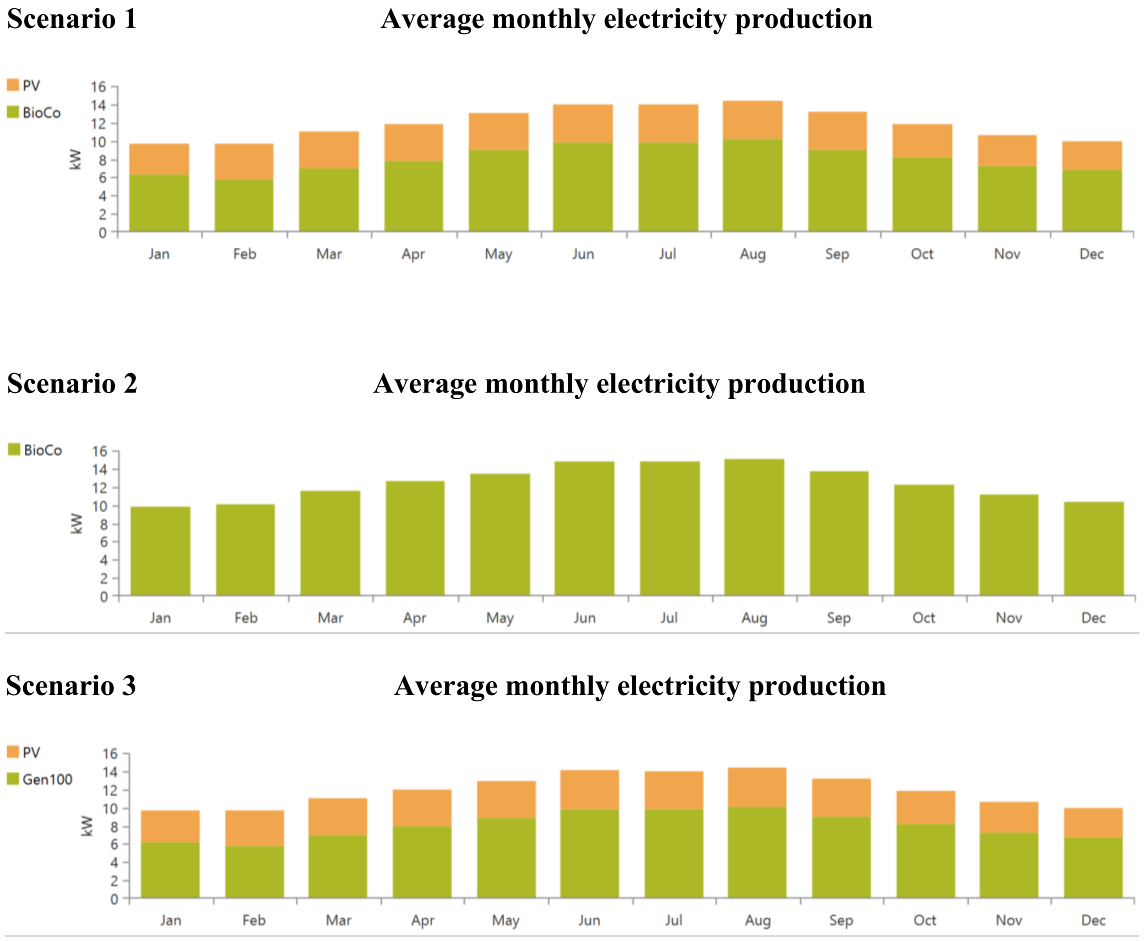


Figure 9 Average monthly electricity production for each scenario

Scenario 1 (PV-BioCo-TeslaPW) and scenario 3 (PV-DG-TeslaPW) have similarities in system configuration, except that the main energy resources are Biogas Co-fire in scenario 1 and diesel generators in scenario 3. Therefore, it is essential to examine the economic influence of these main energy resources by comparing both scenarios. This comparison helps us to recognise the variation in the cost of renewable energy over 25 years. In order to verify the results, sensitivity analyses were performed to test the influence of input parameters on a hybrid hospital. To achieve this, the two most significant input parameters of the HOMER Pro model were selected to study the impact of the inputs on the cost of energy (COE) production. Electricity load and the average amount of biomass were varied by -30% and -50% respectively. The electricity load variation was examined for three scenarios, while the variation of biomass was examined only for an optimal solution, scenario 1, as this approach includes the specific configuration, i.e. biogas cofire. The variations of COE with changes in average available biomass is presented in Figure 10.

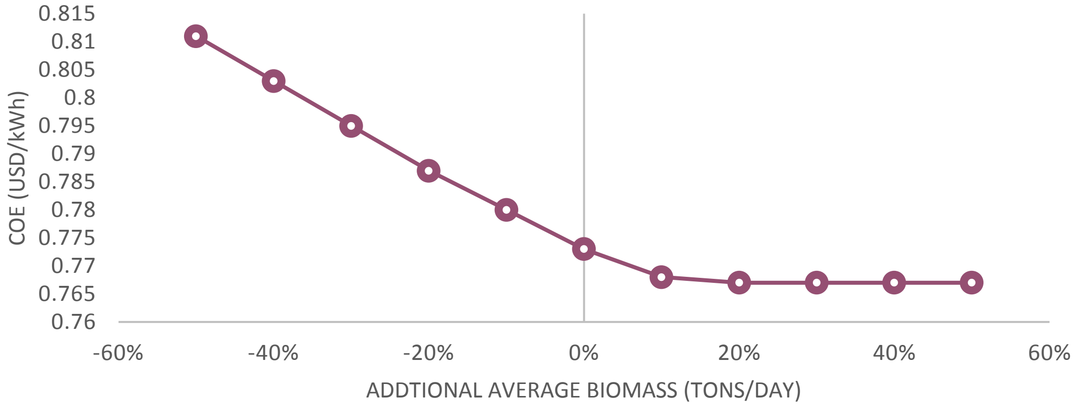


Figure 10 Variation of COE with changes in average available biomass

Figure 10 shows the results of the sensitivity analysis for average available biomass. There is no significant change in COE when the amount of biomass increases from 10 to 50%. This constant value of COE seems to be when the biogas co-fire reached its maximum potential. Figure 11 shows the sensitivity analysis results of the electric load. For all three scenarios, it was observed that the increase in electric load leads to a gradual reduction in the cost of energy production. The outcome of each scenario was almost linear. The results are considered to be valid due to the fluctuation of solar irradiation GHI during the year. All three scenarios showed a relatively linear relation to electric load. Consequently, this suggested a linear relationship between the three scenarios when compared to each other. In Figure 11, the COE at varying electric load is shown.

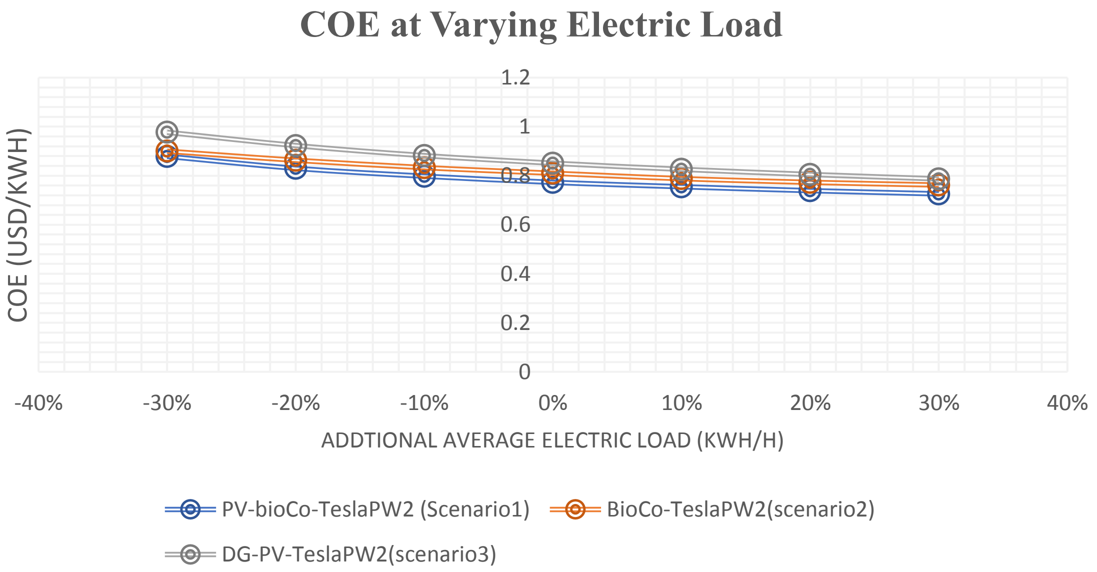


Figure 11 COE at varying electric load

Besides the COE, the annual pollutant emission of the three scenarios was also considered. It is therefore possible to compare the pollutant emission of conventional energy with renewable energy resources. These emissions consist of several greenhouse gases, such as carbon dioxide (CO_2), carbon monoxide (CO) and sulphur dioxide (SO_2). These have a significant impact on the environment and society. The conventional diesel generator alone produces 209, 1,424 and 513 kg/year of carbon dioxide (CO_2), carbon monoxide (CO), and sulphur dioxide (SO_2) respectively, whereas the optimal configuration produces less pollutant gas than conventional energy by 84, 74 and 95% of CO_2, CO, and SO_2, respectively. Table 3 shows the mass of pollutant gases per year for each scenario.

Table 3 Pollutant gases from each scenario (kg/year)

System configuration	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Unburned Hydrocarbons (UH)	Particulate Matter (PM)	Sulphur Dioxide (SO_2)	Nitrogen Oxide (NO_2)
PV-bioCo-TeslaPW2 (Scenario1)	34,234	374	15.1	1.5	26.9	29.9
BioCo-TeslaPW2 (Scenario2)	60,406	554	22.4	2.22	39.9	44.3
DG-PV-TeslaPW2.0 (Scenario3)	54,678	372	15.1	1.49	134	29.8
Other scenarios considered						
DG-Tesla PW2.0	81,437	554	22.4	2.22	200	44.3
Biogas Cofire alone	188,220	1,424	57.6	5.7	103	114
DG alone	209,263	1,424	57.6	5.7	513	114
PV-TeslaPW2	0	0	0	0	0	0

Conclusions

This study examined a hybrid model consisting of PV, biogas cofire, diesel generator, and battery (TeslaPW) under an electric load of 250 kWh/day with three feasible scenarios. Most of the load is obtained from diesel and biogas cofire generators. The diesel generator consumes a lot of fuel in a hybrid micro grid when there is increased load demand. This is where much of the carbon dioxide is observed in the sensitivity analysis, meaning that there is a very small reduction of carbon dioxide in scenario 2, and no reduction in waste. The biogas cofire generator is the main component in scenario 1, which combines biomass and diesel fuel to operate the same power capacity as a diesel generator. The biogas cofire generator consumes 81% less diesel fuel than the diesel generator, thus mitigating the hospital waste. When electricity demand is 250 kWh/day, the hybrid hospital at NEOM consisting of PV-biogas cofire-TeslaPW (battery) shows an optimal solution, reducing the CO_2 emissions by almost 84%. Although the results have been validated, there are certain limitations to this study. The first is the lack of available data for electricity consumption in Saudi Arabia. This information was not accessible for use in comparative studies, therefore, the data from other hospitals were used as input. Also, for a reliable future study, further steps could be taken to integrate new systems into a hybrid hospital, which may alter the consequences. The key component that can be included in the analysis would be the solar track system. Solar trackers could increase solar output by up to 40% compared with an stationary array. The most important solar track system that may be included in the modelling of the solar array is the dual axis tracker, which is an essential solar tracker in the hybrid hospital. Moreover, now that a hybrid micro grid model of the hospital has been developed, new hospital models under various circumstances may be built to compare the alterations between them. In addition, using materials at low energy consumptions (using smart windows) [32], using systems to recover the heat [33] and designing mechanism to monitor the air pollutants in proximity of hospitals [34] are other possible methods to increase the sustainability of these structures. These alterations might include load demand and economic constraints or hospital hybrid configurations that have certain load related problems, which would alter their components' resources. Analysing these comparisons could allow for a growing understanding of hospital-related energy issues. Furthermore, various load demand and technical constraints could be assessed to identify the alteration in the outcome.

Competing interests

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References

1. Wang, T., et al., *A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties.* Renewable and Sustainable Energy Reviews, 2018. **90**: p. 223-247.

2. Bhuiyan, A.A., et al., *A review on thermo-chemical characteristics of coal/biomass co-firing in industrial furnace.* Journal of the Energy Institute, 2018. **91**(1): p. 1-18.
3. Rockström, J., et al., *A roadmap for rapid decarbonization.* Science, 2017. **355**(6331): p. 1269-1271.
4. Williams, M.C., J.P. Strakey, and W.A. Surdoval, *The US department of energy, office of fossil energy stationary fuel cell program.* Journal of Power Sources, 2005. **143**(1-2): p. 191-196.
5. Organization, W.H. and Unicef, *Water, sanitation and hygiene in health care facilities: status in low and middle income countries and way forward.* 2015.
6. Charlesworth, K.E., et al., *Developing an environmentally sustainable NHS: outcomes of implementing an educational intervention on sustainable health care with UK public health registrars.* New South Wales public health bulletin, 2012. **23**(2): p. 27-30.
7. McGain, F. and C. Naylor, *Environmental sustainability in hospitals–a systematic review and research agenda.* Journal of health services research & policy, 2014. **19**(4): p. 245-252.
8. Kim, H., et al., *Comparative Analysis between the Government Micro-Grid Plan and Computer Simulation Results Based on Real Data: The Practical Case for a South Korean Island.* Sustainability, 2017. **9**(2): p. 197.
9. Wu, Z., *Evaluation of a sustainable hospital design based on its social and environmental outcomes.* 2011.
10. Arcuri, C., et al., *Medical waste to energy: experiMental study.* ORAL & implantology, 2013. **6**(4): p. 83.
11. Al-Zahrani, M.A., et al., *Healthcare risk waste in Saudi Arabia. Rate of generation.* Saudi Medical Journal, 2000. **21**(3): p. 245-250.
12. Malekahmadi, F. and M. Yunesian, *Analysis of the healthcare waste management status in Tehran hospitals.* Journal of Environmental Health Science and Engineering, 2014. **12**(1): p. 116.
13. Gudka, B., et al., *A review of the mitigation of deposition and emission problems during biomass combustion through washing pre-treatment.* Journal of the Energy Institute, 2016. **89**(2): p. 159-171.
14. Veringa, H. and P. Alderliesten, *Advanced techniques for generation of energy from biomass and waste.* ECM biomass, 2004.
15. Dong, L., H. Liu, and S. Riffat, *Development of small-scale and micro-scale biomass-fuelled CHP systems–A literature review.* Applied thermal engineering, 2009. **29**(11-12): p. 2119-2126.
16. van den Broek, R., et al., *Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua: A comparison with fuel oil electricity generation on the basis of costs, macro-economic impacts and environmental emissions.* Biomass and Bioenergy, 2000. **19**(5): p. 311-335.
17. Evans, A., V. Strezov, and T.J. Evans, *Sustainability considerations for electricity generation from biomass.* Renewable and sustainable energy reviews, 2010. **14**(5): p. 1419-1427.
18. Lu, G., et al., *Impact of co-firing coal and biomass on flame characteristics and stability.* Fuel, 2008. **87**(7): p. 1133-1140.
19. Freiberg, A., et al., *The Use of Biomass for Electricity Generation: A Scoping Review of Health Effects on Humans in Residential and Occupational Settings.* International journal of environmental research and public health, 2018. **15**(2): p. 354.
20. Olatomiwa, L., *Optimal configuration assessments of hybrid renewable power supply for rural healthcare facilities.* Energy Reports, 2016. **2**: p. 141-146.
21. Zalengera, C., *A study into the techno-economic feasibility of photovoltaic and wind generated electricity for enhancement of sustainable livelihoods on Likoma Island in Malawi*. 2015, © Collen Zalengera.
22. Cannistraro, G., et al., *Technical and economic evaluations about the integration of co-Trigeneration systems in the dairy industry.* Int. J. Heat Technol, 2016. **34**: p. 332-336.
23. Cannistraro, G., et al., *Evaluation on the convenience of a citizen service district heating for residential use. A new scenario introduced by high efficiency energy systems.* International Journal of Heat & Technology, 2015. **33**(4): p. 167.
24. Shiroudi, A., et al., *Case study: Simulation and optimization of photovoltaic-wind-battery hybrid energy system in Taleghan-Iran using homer software.* Journal of Renewable and Sustainable Energy, 2012. **4**(5): p. 053111.
25. Ascione, F., et al., *Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: A new approach to assess cost-optimality.* Applied Energy, 2016. **174**: p. 37-68.
26. Isa, N.M., et al., *A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital.* Energy, 2016. **112**: p. 75-90.
27. Lambert, T., P. Gilman, and P. Lilienthal, *Micropower system modeling with HOMER.* Integration of alternative sources of energy, 2005: p. 379-418.
28. Rahman, M.W., et al. *Prospect of decentralized hybrid power generation in Bangladesh using biomass, solar PV & wind*. in *2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)*. 2014. IEEE.

29. Franco, A., et al., *A review of sustainable energy access and technologies for healthcare facilities in the Global South.* Sustainable Energy Technologies and Assessments, 2017. **22**: p. 92-105.
30. Ismail, M., M. Moghavvemi, and T. Mahlia, *Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate.* Energy Conversion and Management, 2013. **69**: p. 163-173.
31. Lipu, M.S.H., et al., *Design Optimization and Sensitivity Analysis of Hybrid Renewable Energy Systems: A case of Saint Martin Island in Bangladesh.* International Journal of Renewable Energy Research (IJRER), 2017. **7**(2): p. 988-998.
32. Cannistraro, M., M.E. Castelluccio, and D. Germanò, *New sol-gel deposition technique in the Smart-Windows– Computation of possible applications of Smart-Windows in buildings.* Journal of Building Engineering, 2018. **19**: p. 295-301.
33. Cannistraro, M., A. Galvagno, and G. Trovato, *Analysis and measures for energy savings in operating theaters.* Int. J. Heat Technol, 2017. **35**: p. S422-S448.
34. Cannistraro, G., et al., *Analysis of air pollution in the urban center of four cities Sicilian.* Int. J. Heat Technol, 2016. **34**: p. S219-S225.