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Design Optimization of Saltwater Magnesium-Air Battery Using Activated Carbon Derived from Waste Coffee Grounds via Genetic Algorithm

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Abstract*—The advent of large-scale renewable energy generation is driving a growing need for new electrochemical energy storage systems. Metal-air batteries, having a promising technology that could address this need, faces challenges due to the costly and locally unavailable production of air-cathode. Thus, the proponents came up with the idea of designing portable metal-air battery with configured air-cathode layering technology using activated carbon derived from waste coffee grounds and saltwater as electrolyte. The design process involves genetic algorithm to optimize both performance and dimensions. In this study it has been proven that activated carbon derived from waste coffee grounds possess characteristics that is significant for the production of air-cathode and batteries such as microporosity and absorption property. The fabricated air-cathode improved conductivity, affordability, and promotes the passage of ambient air required for electrochemical reaction to occur. Result shows that genetic algorithm successfully optimized the dimension of the device making it portable yet with comparable performance. The device is capable of storing 285 mL of saltwater enough to power a radio for 4 hours, LED lightings for 11 hours and can fully charge mobile phones. The device has a rated output of DC 5-30V/ 2A / 10-60W, capacity of 60 Wh and optimized dimension of 130 mm x 80 mm x 172.25 mm.

***Keywords*— electrochemical energy, air-cathode, coffee grounds, activated carbon, genetic algorithm**

I. Introduction

The demand for electrical energy is correlative to the growth of the population wherein renewable energy unravels the needs of it. In fact, many studies related to the production of energy are conducted and continued on the present-day. One of the fascinating studies regarding renewable energy is the fabrication of metal-air battery. Metal-air batteries are electrochemical energy storage like the function of secondary batteries but cheap and eco-friendly. From the past studies, metal-air batteries are promising in producing a relatively high voltage and high theoretical density that provides excellent performance [1].

Metal-air batteries are roughly composed of the following parts: metal anode, air-cathode, saline electrolyte and reactant gases [2] which plays an important role in producing an outstanding performance of the battery. This study focuses on the fabrication of air- cathode which general function is to collect current from the metal anode. Moreover, the structure of the air - cathode is comprised of the four layers: a waterproof breathable layer, a gas diffusion layer, a catalyst layer, and a current collector layer. A waterproof layer not only prevents the electrolyte leakage but also allows the oxygen (O2) to pass through it and blocks the CO2 [1]. However, the requirement for a gas diffusion layer should be high in porosity and high conductivity material. The most recommended material is the polytetrafluoroethylene (PTFE) [1]. In the catalyst layer, oxygen reduction reaction (ORR) is induced wherein the metal anode dissolved in the electrolyte [2] and an effective catalyst helps in the outstanding performance of the ORR.

In addition, carbon is a significant material in the layering of air-cathode. Activated carbon and active black used to have a large surface area which is a fundamental component of electrodes. [3]. There are steps occurs on the cathodic oxygen reduction and anodic oxygen evolution: diffusion of oxygen, adsorption of the oxygen, electron transfer to the adsorbed oxygen and elimination of products formed by the reaction such as OH-, H2O2, H2O through electrolyte or gas state [3].

Many raw materials were used for the activation of carbon such as soft wood, hard wood, lignin, nutshell, lignite, soft coal, petroleum coal, hard coal, and anthracite [4]. According to the Philippine Coffee Industry Roadmap which was signed on March 10, 2017, the local production of coffee in the Philippines is consumed by 431 specialty coffee shops for the year 2012 [5]. These coffee shops yield tons of waste coffee grounds from brewing and end up in the land fields for the year 2012. There are few studies about the probability of acquiring carbon from coffee grounds through activation. As mentioned earlier, activated carbon has a large surface area which is a basic constituent of electrodes and may lead to having a successful electrical output.

In the field of artificial intelligence, a genetic algorithm (GA) is a search heuristic that mimics the process of natural selection. This heuristic is routinely use to generate useful solutions to optimization and search problems. The optimum amount of energy and power for primary batteries is by attaining the proper size and quantity of the electrodes through the use of Genetic Algorithm.

II. Methodology

The general framework as illustrated in Fig.1 was followed to systematically conduct the experiment processes. The optimization started with the activation of coffee grounds which involved carbonization and sterilization of acquired samples of waste coffee grounds. Followed by air-cathode fabrication and optimization of the electrodes. The battery was designed using the optimized dimension via Genetic algorithm.

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Then, the prototype was developed by integrating additional circuits to the battery to complete its function as power supply for low-power loads. It was tested using different types of loads to determine its shelf life.

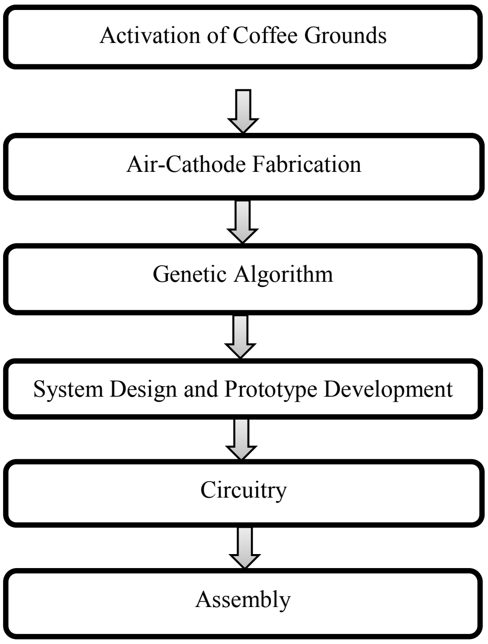


Fig. 1. General framework

A. Materials for Fabrication

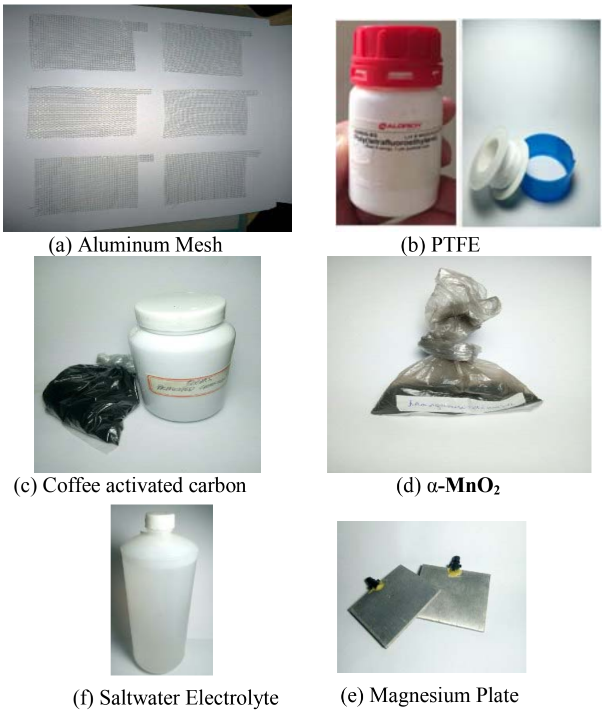
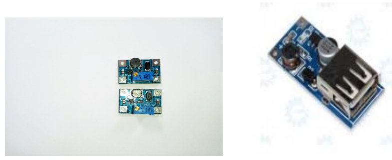


Fig. 2. Materials and Reagents

The materials and reagent needed for the fabrication of air-cathode are shown in Fig. 2 (a) Stainless steel serves as the current collector and ideal metal for saltwater application since it does not corrode. (b) The Polytetrafluoroethylene (PTFE) serves as the wet proofing agent to avoid leakage of water at the same time enabling the passage of air that promote oxidation reduction reaction. (c) Coffee activated carbon is for carbon composite that increases absorption property. (d) The α-MnO2 is used as catalyst. (e) Magnesium plate serves as the anode and (f) Saltwater serves as the electrolyte.

B. The Equipment



(a) (b)

Fig. 3. Booster Circuit

(a) (b)

Fig. 4. Charger, Indicator Circuit, and Arduino UNO

Fig. 3 shows the step-up boost converter used. (a) B6286 Step-up Adjustable Boost Converter, (b) 0.9~5V to 5V StepUp DC-DC voltage converter. Figure 4 shows the regulated charger and indicator with protection circuit and the Arduino Uno for monitoring system.

C. Process for Fabrication

1) Activation of coffee grounds

The coffee grounds were prepared through sterilization and flash pyrolysis before undergoing physical activation. The initial step is sterilization that evaporated the moist from the dried coffee grounds and prevents molds from accumulating [6]. This was heated through flash pyrolysis to remove the remaining moisture and prepare for carbon activation. Fig 5 shows the furnace used for the activation process. At 700°C, the coffee grounds are physically activated (ashing) to extract activated carbon powder, ready for air-cathode fabrication [7][8].

Fig. 5. Vulcan A-130 Furnace

2) Air – cathode fabrication

The core technology of Mg-air is a manufacturing skill of the air-cathode which increases the output to flow the electron as much as possible from the metal anode through the oxidation reaction in the electrolyte solution. Fig. 6 illustrates the layering technology used for fabrication.

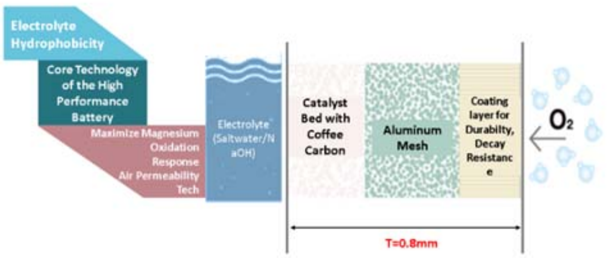


Fig. 6. Air-cathode Layering Technology

The activated carbon was introduced into two different mixture that was applied on each face of the skeletal mesh (stainless steel). Each mixture consists of activated carbon, graphite, manganese dioxide (MnO2) catalyst, and PTFE binder with a ratio of 40:30:20:10, respectively. In mixture A, the solvent used is ethyl alcohol, which differentiates it from mixture B, wherein isopropyl alcohol and DI water are used. The solvent and the powdered chemicals have a of 1:1 ratio. Both mixtures were sonicated for 20 minutes. A 7.25mL of Mixture A is applied first on side A of the mesh before placing it in the heat furnace at 370°C. Mixture A composed of AC 40%, Graphite 30%, MnO2 20%, and 10% PTFE with 150mL ethanol applied to the coated solution side of mesh. Then the 7.25mL of Mixture B was applied on the air-side. Mixture B composed of AC 40%, Graphite 30%, MnO2 20%, and 10% PTFE with 175mL isopropanol and DI water [9].

3) Genetic Algorithm

The genetic algorithm performed random test and genetically chose the fittest parameter to be used in order to have the desired output parameters. The process flow of GA as illustrated in Fig. 7 describes how the genetic parameter optimization algorithm ran multiple test and chose the fittest parameter to be used in the system.

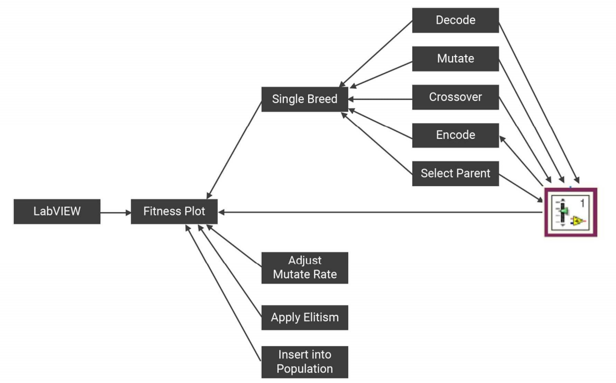


Fig. 7. System Program Process Flow of Genetic Algorithm

The population size used is 50, the generation number is 500 with crossover probability of 0.85. The mutation mode used in the algorithm was one-point distance-adjustable with a mutation rate of 0.005. Steady-state-replace-worst function was used as reproduction plan. Elitism was also considered to guarantee best output.

The optimized parameters using Genetic Algorithm were used for the design construction of the device including the dimension of the electrodes. The Volumetric Capacity (Cv) of the battery was optimized using the equation as seen in (1).

$$C_v = \frac{\frac{\alpha F}{3.6}}{\left(\frac{\omega_{anode}}{\rho_{anode}}\right)+\left(\frac{\varepsilon}{n\beta}\right)\left[\sum_1^n\left(\frac{\omega}{\rho}\right)\right]\left[\gamma+\frac{1-\varepsilon}{\varepsilon}\right]} \quad (1)$$

Alpha (α) - represents the Magnesium's utilization ratio at the anode and is defined as the mass ratio of the Magnesium used during discharge and the total Magnesium onboard at the anode (ranging from 0 to 1.0).

Beta (β) - represents the cathode void volume's utilization ratio o and is defined as the volume ratio of the total products to the total cathode void volume (ranging from 0 to 1.0)

Gamma (γ)- is defined as the ratio of the amount of saltwater onboard in the device and the minimum required saltwater to saturate the cathode void volume (y is greater than or equal to 1:0)

4) System design and prototype development

After the dimensions were optimized, the saltwater container was assembled with the circuitry of the loads and charging system. The chassis of the battery was constructed via 3D printing using an ABS filament since this type of filament is durable and applicable in wet application. The final design of the battery with optimized dimensions is shown in Fig. 8.

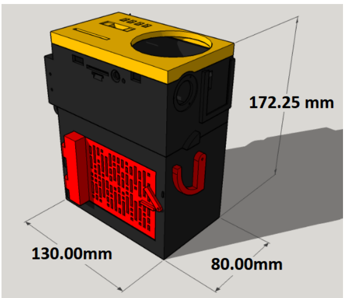


Fig. 8. Optimized Dimension of the Battery

III. Results and Discussion

This section presents the results in the optimizations of the activation of the ground coffee, the air – cathode, and the dimensions of the battery.

A. Ground Coffee Activation Result

The output of chemical activation (CA) and physical activation (PA) process are presented in Table I. The result shows that the optimal process to be used in physical activation of coffee grounds is at 700°C since at this temperature the coffee grounds produced highest carbon yield and with good porosity level.

The graph illustrated in Fig. 9 also shows that the sample TA 700°C has the highest microporous volume which is required for the passage of air in air-cathode.

TABLE I. RESULTS OF TOTAL PORE VOLUME, MICROPORE VOLUME, PORE DIAMETER AND BET SURFACE AREA OF ACTIVATED CARBONS WITH THE CONCENTRATION AGENT AND TEMPERATURE OF ACTIVATION

Sample	H3PO4 (%)	T°	BET (m2/g)	Pore Diameter (A)	Pore Volume (cm3/g)	Micro-pore Volume (m3/g)
CA3_500	30	500	522.52	27.50	0.359	0.087
CA4_500	30	600	53.41	56.76	0.062	0.0005
CA5_500	30	700	84.44	28.77	0.061	0.007
CA3_600	40	500	605.29	33.46	0.506	0.071
CA4_600	40	600	695.59	33.67	0.585	0.101
CA5_600	40	700	420.71	35.84	0.377	0.033
CA3_700	50	500	233.17	38.13	0.222	0.015
CA4_700	50	600	359.66	33.20	0.299	0.031
CA5_700	50	700	352.43	27.10	0.239	0.046
PA_600	-	600	566.51	20.38	0.289	0.214
PA_700	-	700	641.27	20.55	0.329	0.232
PA_800	-	800	522.14	21.91	0.292	0.184

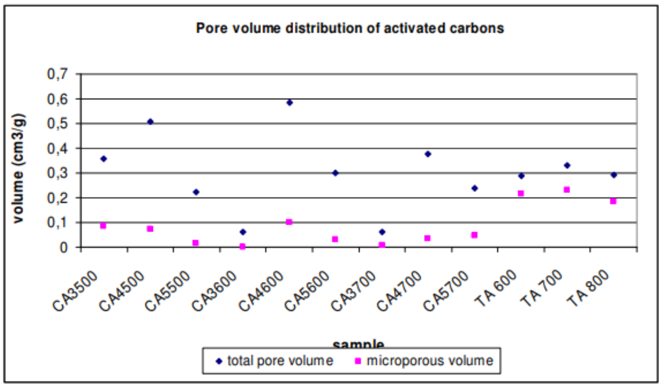


Fig. 9. Total pore volume and micropore volume for both activations

Different types of coffee grounds such as Arabica, Robusta, and mixed of Arabica and Robusta were gathered and activated through an electric furnace for 1 hour. Each sample weighed 100g before it undergone carbon activation. From the result acquired for the laboratory tests, Arabica has the best performance in terms of carbon yield as shown on Table II.

TABLE II. ACTIVATED CARBON YIELD

Type of Coffee Carbon	Carbon yield at Different Temperature				
	300°C	*400°C*	*500°C*	*600°C*	*700°C*
Arabica	16.94	14.77	1.8110	1.8495	1.3000
Robusta	41.8004	28.1822	0	0	0
Mixed	32.8164	17.1857	0	0	0

Note: Carbon Yield for both Robusta and Mixed at 700°C cannot be measured because of insufficient supply.

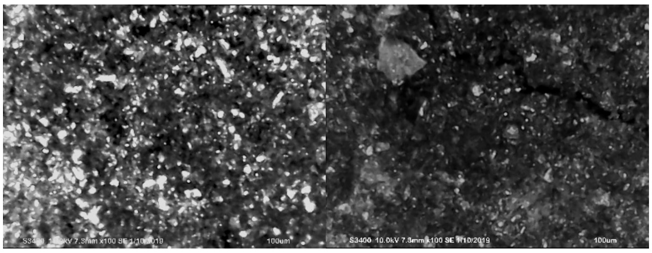
TABLE III. CARBON YIELD RESULT OF ARABICA COFFEE GROUNDS

Coffee Carbon Type	Temperature for Activation (°C)	Carbon Yield (g)	Conductivity (µmhos/cm)	pH level
Arabica	700	1.3	1709	11.63

The Arabica coffee grounds were prepared through sterilization and flash pyrolysis before undergoing physical activation at 700 °C. Table III shows the result of activation process and since Arabica produced the best-activated carbon compared to other samples (Robusta and mixed coffee grounds) because it has the highest carbon yield of 1.3g for every 100g of coffee grounds; it has a conductivity level of 1709 µmhos/cm for the good flow of current; and base pH level of 11.63 that avoids corrosion of metal materials.

B. Air – Cathode Fabrication Result

Scanning Electron Microscopy or SEM imaging have its electrons focus upon the surface of the fabricated air- cathode, thus processing the microscopic imagery [10]. The SEM images of coated side of the cathode at 100 µm in Fig. 10a shows that the coffee carbon/catalyst/binder mixture was well distributed over the cathode structure. Also, the SEM Image of the coated air-side cathode at 100 µm in Fig. 10b depicting porosity and an open nature, shows that the aluminum mesh with coffee carbon/binder/catalyst mixture bound to the mesh has many large and small pores throughout the air cathode which allow the passage of air.



(a) (b)

Fig. 10. SEM Image of Fabricated Air-Cathode

Hydrophobicity test was conducted to determine whether the air-cathode is leak-proof or not. For a simple process, a drop of water onto the cathode will only be needed [11]. The characteristics of the air-cathode must be microporous, conductive, and hydrophobic for it to gather available oxygen in the air while keeping the saltwater electrolyte inside the container since it will serve as the wall of the device. The air-cathode as shown in Fig. 11 is hydrophobic.

Fig. 11. Hydrophobicity test of fabricated Air-cathode

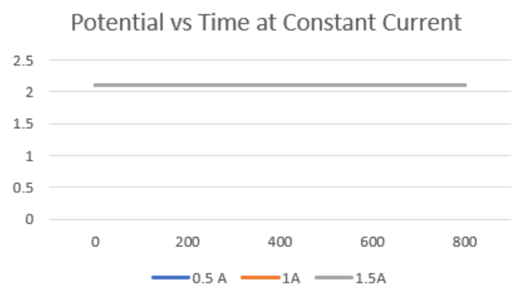
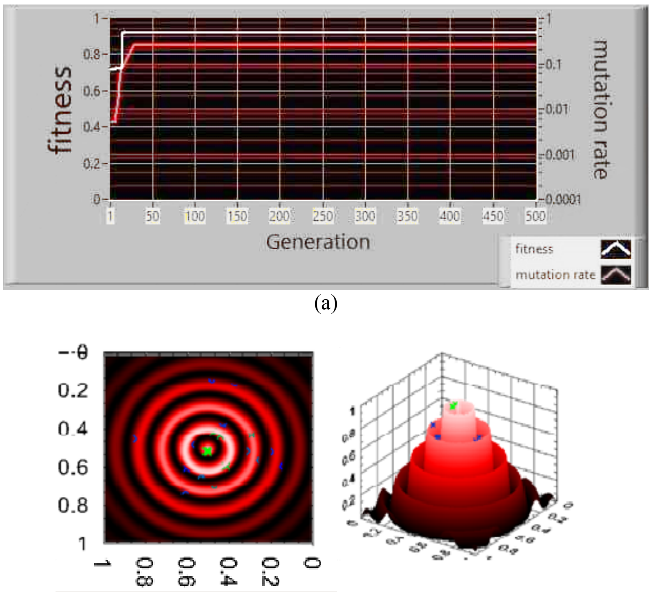


Fig. 12. Chronopotentiometry Test Result

Chronopotentiometry test [12] was also conducted to determine the air-cathode's performance where a constant current is applied to the cathode and the output voltage is compared over time. In this test, the battery produced a steady and flat voltage output of 2.1V at 0.5A, 1A, and 1.5A as illustrated in Fig. 12.

C. Genetic Algorithm Parameter Optimization Result



(a)

(b)

Fig. 13. Fitness plot of Genetic Algorithm

The fitness calculated for solution is shown in Fig. 13. This plot is variant with any parameters to pass to fitness calculation VI. Note that to keep performance these parameters are passed to fitness VI only once, so it should unflatten them and store internally. The satisfying fitness value allowing to finish earlier when reached. The construction of the saltwater battery was based on the acquired results in the GA program.

The dimension for electrode given by the Genetic Algorithm (GA) presented in Table IV were used in the actual size of the electrodes. As indicated in the table, the electrode dimension with thickness of 0.5cm produced the highest capacity.

TABLE IV. GENETIC ALGORITHM OPTIMIZED PARAMETER FOR ELECTRODE

No. of cells	Length	Width	Thickness	Volumetric Capacity	Capacity	Energy Capacity	Current Density
	(cm)	*(cm)*	*(cm)*	*(mAh/cm3)*	*(mAh)*	*(Wh)*	*(mA/ cm2)*
2	5.5	6.5	0.1	286.96	2054.1	10270.7	360
2	5.5	6.5	0.2	286.96	4113.9	20569.7	360
2	5.5	6.5	0.3	286.96	6171.1	30855.5	360
2	5.5	6.5	0.4	286.96	8232.1	41160.8	360
2	5.5	6.5	0.5	286.96	10273	51367	360

Table V shows the allowable time the saltwater and seawater can optimally power certain load. It is recommended to replace the electrolyte after the time stated above since the performance will start to decrease and also to avoid formation of unnecessary corroded magnesium in the surface of air-cathode.

TABLE V. TEST-TO-FAIL DATA USING SALTWATER

Load	Saltwater concentration		Sea water conductivity	Recommended Time before Refill
	water	*salt*		
LED	285	50	4000 μmhos	11-12 hours
Charger	285	50	4000 μmhos	1-2 hours
Radio	285	50	4000 μmhos	4-5 hours
All function	285	50	4000 μmhos	1-2 hours

TABLE VI. ANODE-TO-CATHODE DISTANCE

Distance	Voltage Output	Current Output
1 cm	1.25 V	5 mA
2 cm	1.25 V	5 mA
3 cm	1.25 V	5 mA
4 cm	1.25 V	4.5 mA
5 cm	1.25 V	4 mA

Based on TABLE VI, the distance used for anode-to-cathode separation is 2 cm since it is ideal that the anode is near enough to the cathode but not in contact to have a good current output at the same time there is less unnecessary corrosion of anode due to oxidation reduction reaction.

TABLE VII. OPTIMIZED PROTOTYPE DESIGN

No. of Cells	2
Per Cell container Volume	189, 000 mm^3
Electrode Dimension	6.5 cm x 5.5 cm x 0.5 cm
Prototype Design dimension	130 mm x 80 mm x172.25 mm
Anode-Cathode separation	2 cm
Saltwater Concentration	43.75g of salt for every 285mL of water.

The GA program significantly helped in providing reliable parameters in maximizing the amount of acquired energy while minimizing the dimension of the battery thus avoiding an extensive number of experiments. The final design specifications of the battery is shown in Table VIII.

TABLE VIII. DEVICE SPECIFICATION

Name	Salt Coffee Power Generator
Rated Output	5-30V/ 2A / 10-60W
Capacity	60 Wh
Dimensions	130 mm x 80 mm x172.25 mm
Metal Plate	2x 25 g
LED Mode	2 Modes
USB Interface	1A
Operating Temperature	-30°C to 80°C

IV. CONCLUSIONS

It has been proven that construction of air-cathode using Arabica coffee activated carbon significantly helped the performance of the battery in terms of promoting electrochemical reaction to occur by improving the porosity of the surface needed for the passage of air. The GA program significantly helped in providing reliable parameters such as electrode dimension (6.5 cm x 5.5 cm x 0.5 cm); saltwater concentration which is 43.75g of salt for every 285mL of water and prototype dimension (130 mm x 80 mm x 175.25 mm) that maximize the amount of acquired energy and minimized the dimension of the battery thus avoiding an extensive number of experiments. This device can now be used as a power generator allowing the user to refuel it with saltwater or seawater, thus helping both the community and the environment.

ACKNOWLEDGMENT

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