HYBRID ENERGY HARVESTING SYSTEM MODELING AND SIMULATION FOR AIRCRAFT'S PASSENGER SERVICE UNIT

Saed Amer, Postdoctoral at Tennessee State University, USA (samer01@my.tnstate.edu)
Landon Onyebueke, Professor at Tennessee State University, USA (lonyebueke@tnstate.edu)

ABSTRACT

The service units in passenger aircrafts provide multiple amenities to ensure the traveler's wellbeing. Service units usually provide customers withHVAC, reading light, flight attendant call, emergency oxygen kit dispenser and entertainment. Achieving such services to hundreds of passengers create several challenges such as fitting, power consumption, complex wiring and intricatetrouble shooting. Power consumption for the passenger service unitsin the passenger aircraft can significantly exhaust the power from the supplying batteries and the network of cables required to provide power to each unit is weight bearing and expensive to build and maintain.This work proposes a modeling and simulation techniquethat utilizes a hybrid energy harvesting system tointegrate multiple energy sources and cultivatesrenewable energy obtained fromclean thermal, solar, and kinetic energy sources. Mathematical foundations were used to base the modeling of each energy-harvesting module with respect to theobserved natural phenomena (light, heat, vibration, etc.). For example, thermal modeling is performed by analyzing the temperature difference between a heating source and a sink temperature. In the same hand, a mathematical model is employed to simulate photovoltaic generators using solar radiation and heat generated on photovoltaic module surface. The vibration energy harvester is modeled as an electric generatorby means of the inertia of a seismic phenomenon. The integration process is simulated using .Net environment to optimize and manage the harvesting sources and provide the system with energy storage to exploit the excess energy when needed. Finally, for stability and robustness, the system is reinforced with conventional power supply from the aircraft main line to backs up the system when the harvested energy is insufficient.

NOMENCLATURE

I_{PH}	Light-generated current or photocurrent
I_S	Cell saturation of dark current
q	($= 1.6 \times 10^{-19}$C) is an electron charge
k	($= 1.38 \times 10^{-23}$J/K) is a Boltzmann's constant
T_C	Cell's working temperature,
A	Ideal factor
R_{SH}	Shunt resistance
R_S	Series resistance
I_{SC}	Short-circuit current at a 25°C and 1kW/m^2
K_I	Short-circuit current temperature coefficient
T_{ref}	Cell's reference temperature
λ	Solar insolation in kW/m^2
I_{RS}	Cell's reverse saturation current at a reference temperature and a solar radiation
E_G	Bang-gap energy of the semiconductor used in the cell
N_S	Number of solar cells in series
N_P	Number of solar cells in parallel
ρ	Eelectrical resistivity,
l	Length of a pellet and
m	Electrical resistance ratio
α	Seebeck coefficient of a pellet
ΔT	Temperature difference between the cold side temperature of the TEG and the hot side temperature
α_c	The coupling factor between the electrical and the mechanical domains
M	The equivalent mass
C_p	The capacitance
Z	The damping ratio.
ω_a	The resonance frequency of the harvester
ω_r	The anti-resonance frequency.

ω the excitation frequency
a_b the amplitude of the excitation acceleration

INTRODUCTION

Passenger Service Unit (PSU) is an electronic unit provided for each airline passenger seat to ensure a level of comfort to the airline passengers. PSUs are mounted beneath the luggage compartments arranged in the upper area of the cabin fitted with flaps or shells that can be adjusted. Consequently, the service units are conventionally displaced laterally between passengers in window seats and center seats [1]. It is important for the passengers to have a sense of comfort and well-being when situated in the aircraft seats and need to retain a spacious appearance to avoid a closed-in feeling. The arrangements of the service units, therefore, need to have freedom to adjust and move when the arrangement of the passenger seats change; however, the resilience of PSU provisions can be problematic due to the centralized power supply system. The proposed solution can solve such dilemma by creating distributed power supply system that accommodates the PSUs with different layouts.

The electrical components in aircrafts operate on many different voltages both AC and DC. Most systems use 115 volts (V) AC at 400 hertz (Hz) or 28 volts DCgenerally provided by self-exciting generators containing electromagnetics, where the power is generated by accommodator which regulates the output voltage of 28VDC. AC power, normally at a phase voltage of 115V, is generated by an alternator, generally in a three-phase system. The Airplanes have both transformer rectifiers to turn the 400Hz voltage into DC for the 28V buss, and they also have a static inverter to create the AC400Hz in case the airplane is down to battery power whichoffers a short-term power storage capability. Meanwhile, there are other methods used for providing back-up power including Ram Air Turbine (RAT), Back-Up Converters and the Permanent Magnet Generators [2].

This study proposes a new power supply system that infuses three major energy harvesting techniques to reduce the dependence on the conventional power supplies. The new technique permits the distributed power supplies which facilitatesflexible PSU positioning. The first major energy harvester utilizes the photovoltaic (PV)effect which is considered the most essential and prerequisitesustainable resource because of the ubiquityof solar radiant energy. Regardless of theintermittency of sunlight, solar energy is widely available and completely free of cost. PV systems are static, quite, and free of moving parts and have little operation and maintenance costs. Solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor [3]. The electromagnetic radiation of solar energy can directly convertelectricity through photovoltaic effect. Being exposed to sunlight, photons with energy greater than the band-gap energy of the semiconductor are absorbed and create some electron-hole pairs proportional to the incident irradiation. Under the influence of the internal electric fields of the p-n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar insolation. PV system naturally exhibits a nonlinear I-V and P-V characteristics which vary with the radiant intensity and cell temperature [4, 5].

The second environment-friendly energy source is the thermoelectric power generation which has attracted considerable interest due to its compactness, zero emission, few moving parts, low noise, high reliability, zero fuel consumption and cleanness of energy production. A thermoelectric generator (TEG) converts thermal energy directly into electricity based on the Seebeck effect [6].Recently, it is expected as a waste heat recovery power generator using various heat sources such as combustion of solid waste, geothermal energy, power plants, vehicle exhaust gas, human body and other industrial heat-generating processes [7]. TEG is a solid state energy device which converts thermal energy from a temperature difference directly into electrical energy. Seebeck effect harvests thermoelectric power depending on a temperature difference when a closed loop is formed of two different metals joined in two junctions [8]. In general, it includes an array of pellets which are composed of *p* and *n* type semiconductor material as displayed in Figure 1. The thermoelectric couples are electrically connected in series and thermally in parallel.

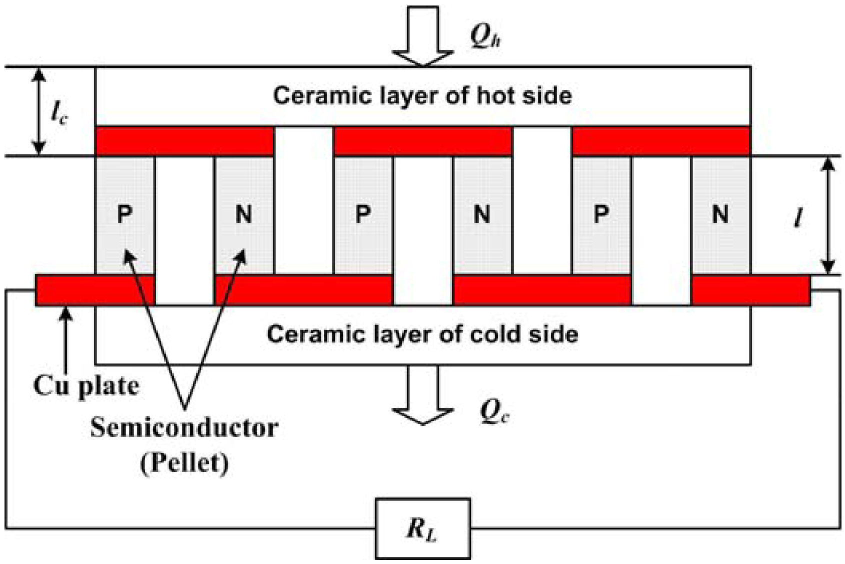

Figure 1. One-stage Thermoelectric Generator [9].

The third technique exploits the energy harvested from vibration which can be transformed through three types of electrical generation consisting of electromagnetic transduction, electrostatic transduction, and piezoelectric transduction [10]. Vibration harvesters are known to have two common assemblies fitted to serve different situations. Some are fit for lower frequency and large displacement applications and are usually made with a cantilever beam system.Theother type ofthe vibration harvesters assemblies usually consist of spring-mass system and are fit for high frequency applications.Piezoelectric harvester typically contains three elements to ensure full system performance. As showing in Figure 2, these elements include reservoir capacitors, full-wave rectifiers and primary loading device.

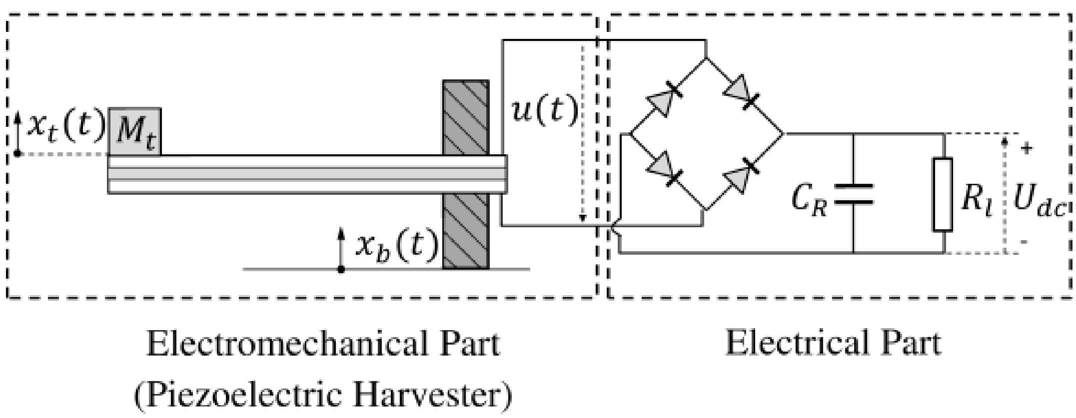

Figure 2: Layout for piezoelectric harvester

One of the innovative and remarkable techniques available in this age is the battery-free wireless switch. Such switch is equipped with a common electro-dynamic energy transducer or piezoelectric generator actuated with a push ofa button. Electrical energy is created when the energy arch is pushed down and a Radio Frequency (RF) telegram is transmitted. Releasing the energy arch generates different telegram data and every telegram contains the information that the arch was pressed or released. [11].

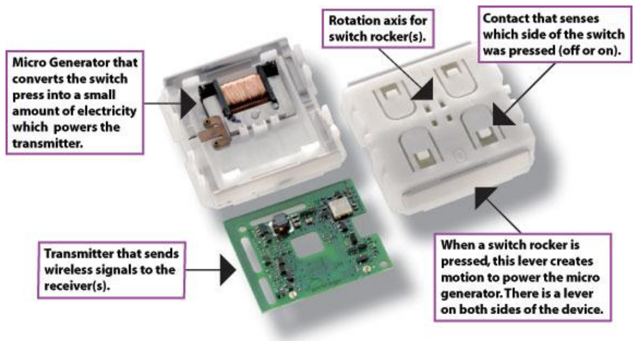

Figure 3: Battery Free Plug-in switch by EnOcean

THE MATHEMATICAL MODELS

A general mathematical description of I-V output characteristics for a PV cell considers equivalent circuit which consists of a photo current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow. The voltage-current characteristic equation of a solar cell is given as [12]:

$$I = I_{PH} - I_s\left[e^{q(V+IR_s)/kT_cA} - 1\right] - \left(V + IR_s\right)/R_{SH} \tag{1}$$

Mainly depending on the cell's working temperatureand solar insolation, the photocurrent (I_{PH}) can be calculated using the following relationship.

$$I_{PH} = \left[I_{SC} + K_I\left(T_c - T_{ref}\right)\right]\lambda \tag{2}$$

The cell's saturation current (I_S) is, also dependent on the Cell's temperature and can be found from this relation:

$$I_S = I_{RS}\left(T_C / T_{ref}\right)^3 e^{\left[qE_G\left(1/T_{ref} - 1/T_C\right)/kA\right]} \tag{3}$$

PV cells are generally connected in series configuration to form a PV module in order to obtain adequate working voltage. PV modules are then arranged in series-parallel structure to achieve desired power output. It can be shown that $N_S = N_P = 1$ for a PV cell. The most simplified model of generalized PV module is described by[13]:

$$I = N_P I_{PH} - N_P I_s\left[e^{qV/N_skT_cA} - 1\right] \tag{4}$$

Five thermoelectric phenomena consisting ofSeebeck, Peltier, Fourier, Joule and Thomson effects simultaneously take place in a thermoelectric generator [14]. The open-circuit voltage is given by:

$$V_{OCV} = 2\alpha\Delta T \tag{5}$$

The electrical current can be obtained from Ohms law as follows:

$$I = \frac{2\alpha\Delta T}{\rho l(1+m)} \tag{6}$$

The power output has a maximum value when the external load resistance is equal to the internal resistance. The voltage output can be expressed with N as the number of couples.

$$V = 2N\left(\frac{m}{1+m}\right)\alpha\Delta T \tag{7}$$

Both mechanical and electrical characteristics are considered in modeling the piezoelectric harvester and are governed by two boundary conditions–open circuit and resistive load [15]. When used in autonomous systems,piezoelectric harvesters for should always be designed with consideration of the electrical part of the system. This is due to the fact that piezoelectric harvester experiences two alternating load conditions caused by the rectification process.The amplitude of the generated voltage in open circuit condition can be expressed as

$$\hat{u} = \frac{\alpha_c R_l \omega \hat{a}_b}{\sqrt{\left[\omega_r^2 - \left(1 + 2\zeta\omega_r R_l C_p\right)\omega^2\right]^2 + \omega^2\left[2\zeta\omega_r + R_l C_p\left(\omega_a^2 - \omega^2\right)\right]^2}} \tag{8}$$

THE MODELING AND SIMULATION TECHNIQUE

This work employs C# programming capabilities to simulation the pursued harvesting techniques mathematically. The proposed program suggests different flight scenarios representing the various states that the airplane experiences during a trip. For example, as depicted in Figure 4,the first considered scenario mimics the aircraft when standing immobilizedin the airport. In this state, it is expected that the energy extracted from the thermal or the vibration harvesters is low while the energy harvested from solar generators is unaffected. The system, additionally, considers the airplane's orientation, time of the day, and varying weather patterns.

Figure 4: Suggested flight scenarios simulated in the software

In order to make the tool perform at a comfortable level for user's operation, the program is split into subsystems that simulate the processes of each energy harvester separately then are integrated into the main user friendly graphic interface. The graphic interface directs the user to open the new windows with the subsystems to control and manipulate the harvester's parameters. Meanwhile, the system performs the simulation by running the different scenarios then updates the environmental factors that affect the harvesting process within the sub-systems. By tuning the harvester's parameters, the system suggests the optimum sizing and capabilities of the harvesters required to ensure the energy cultivation that meets the passenger service unit demand. The first subsystem allows the control and modeling of the photovoltaic energy harvester considering the size and arrangement of the PV cells (series or parallel connections) and reviles the outcomes with different solar irradiation and variable cell's operating temperatures. This module also allows the user to fine tune the intrinsic parameters of the PV harvester to facilitate the device selection. As depicted in Figure 5, these parameters include the diode ideality constant, thermal voltage, nominal open circuit voltage, short circuit current, series resistance and band gap energy.

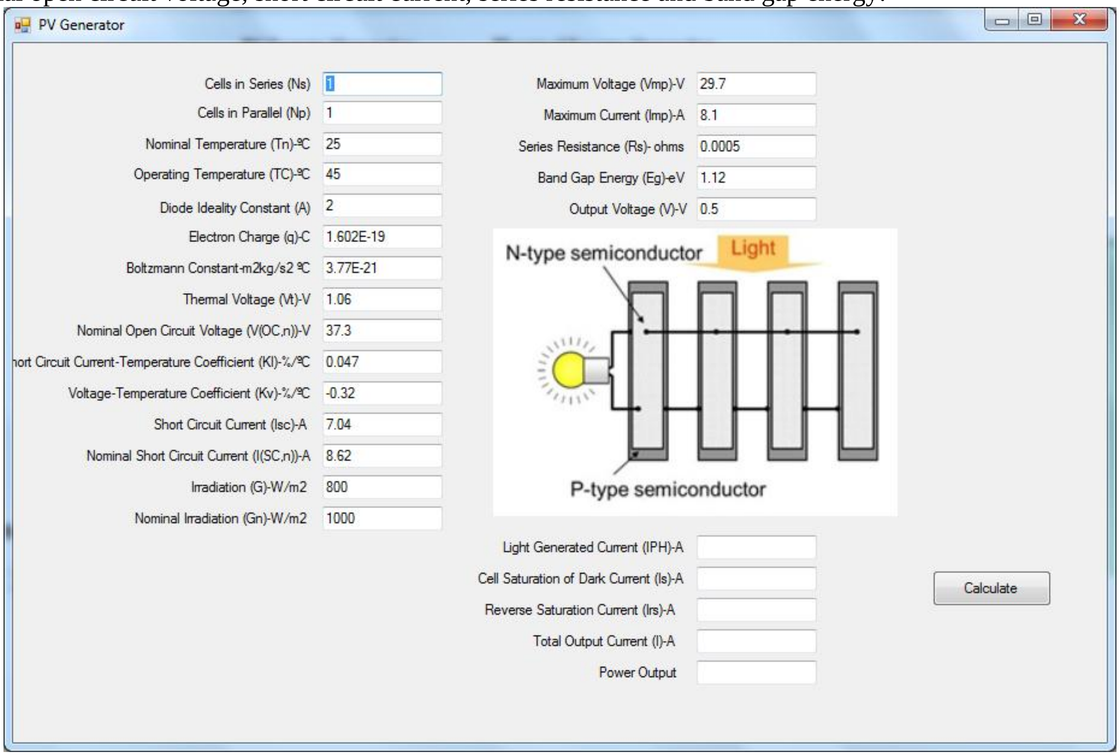

Figure 5: PVGenerator Refinement GUI

Correspondingly, another sub system is designed to model the thermal-electric harvester and allows the user to manipulate the intrinsic parameters of the device. Showing in Figure 6 the GUI includes the electrical internal resistance, the electrical resistivity, the thermal conductivity, length of pellet, area of pellet, number of couples, the electrical contact resistivity ratio, the thermal contact resistance ratio, the load resistance and the electrical resistance ratio. Figure 7shows that the selection of the optimum vibration harvesting device is also facilitated in the system by testing the outcomes of different device parameters to ensure the maximum utilization of the vibration energy.

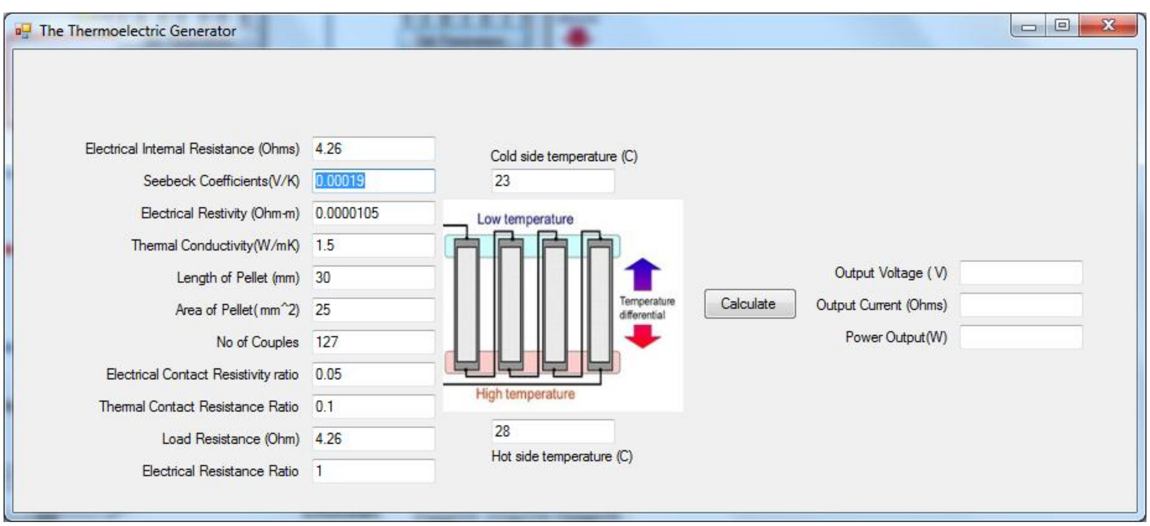

Figure 6: TEG Generator Tuning GUI

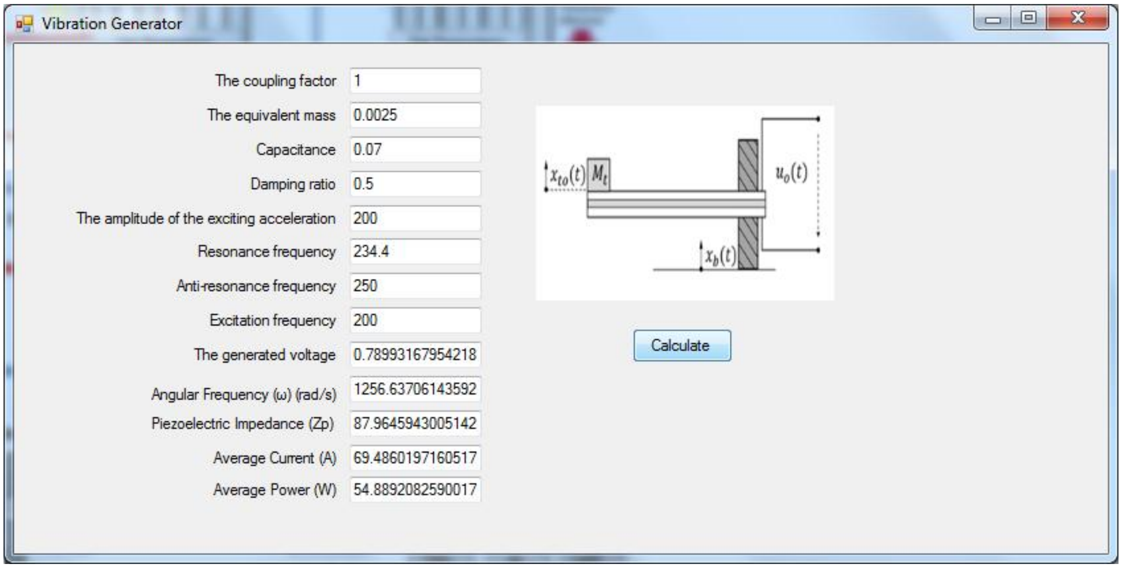

Figure 7: Piezoelectric Generator Tuning GUI

The main user interface of the proposed software animate the various flight scenarios, as demonstrated in Figure 8, and shows the outputs of each harvester readily as the airplane undergoes different states. The system permits the integration process of threeenergyharvesting techniques and performs modeling of the energy conversion techniques that allows the input of various electrical voltages and currents and guarantees consistent outputs to be connected to the passenger service unit. The system also considers energy storage mechanism that exploits the surplus energy and backs up the system when the harvesters fail to meet the PSU demands.

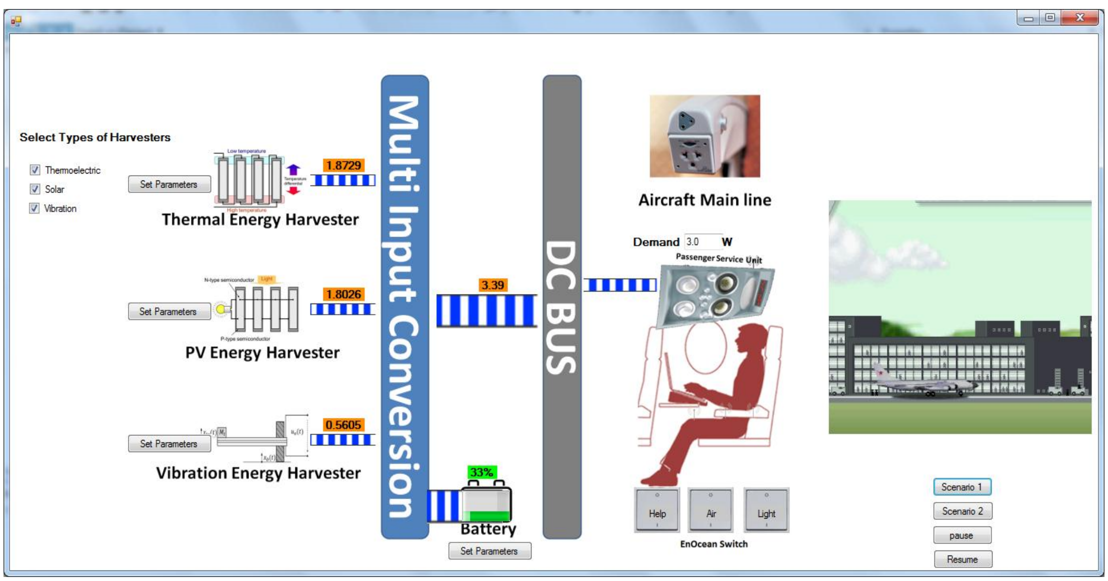

Figure 8: The Main System's GUI

CONCLUSION

This study aims to model and simulate a proposed system that utilized energy harvesting technique to provide adequate power supply to the passenger service unites in passenger airplanes. The advantages of such system include promoting green energy utilization and reducing cost and environmental predicaments. The proposed system allows permits more freedom to rearranging the PSU by employing a more resilient distributed power supply rather than the customary centralized ones. Using a distributed power supply for multiple PSUs also reduce the dependence on the complicated wire network used to supply hundreds of PSUs with multiple functionalities. Physical prototyping of such system is tedious and pricey; therefore, this study proposes a fast, economical and adaptable to the testing circumstances.

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