Renewable Energy Integration with Energy Storage Systems and Safety

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Abstract

One of the major goals of sustainable energy systems is to provide clean, affordable, accessible energy with benign environmental impact. Development of reliable energy systems without toxic byproducts to preserve the environment while powering the future is urgently needed. This need has led to the design and implementation of power generating systems using photovoltaics (PV) and energy storage devices. Currently, there is an excess increase in the fossil fuels cost due to increase in consumption of electric grid energy and its inability to meet up with the demand. Optimizing the generation, storage and use of electric power by using renewables (PV) and storage devices will enhance efficient, effective and reliable power consumption. This chapter proposes an efficient approach for the integration of renewable energy systems (PV) and energy storage devices as well as their safety and tradeoffs in the environment.

Keywords: renewable energy, energy storage, safety, integration and grid

1. Introduction

A major goal of sustainable energy system using renewable energy is to provide clean, affordable, accessible energy with efficient energy storage with depleting the earth resources. There is a need to develop reliable energy systems that do not depend on fossil fuel to preserve the environment while powering the present and the future. This has led to the development of power generating systems utilizing renewables (photovoltaics and wind) [1]. There has being rapid increase in the power generation from PV over there the years [2]. Due to the rapid increase in PV generation, energy storage is serves as a storage medium for excess generation which can use when needed. Energy storage systems also serve as a means of increasing the power utilization and consumption rate. Implementing battery storage is limited due to relatively high cost. In some grid connected systems, Plug in Hybrid Electric Vehicles (PHEV) is use as storage which can function as double use systems [1, 3–8]. Future smart and micro grids could benefit from the double use functionality of electric vehicles as part of the energy network to provide vehicle-to-grid services (V2G) as described in [1]. Research shows that the average car is parked 15 hours a day and can provide storage and or grid services 60% of the time [1]. The idea of integration renewable energy (photovoltaics) with energy storage devices for a double use is illustrated.

2. Systems, integration and load layout

The system block diagram shown in **Figure 1** consist of renewable energy source (RES), power and energy management system (PEMS), grid, energy storage devices (ESD), residential load. The system is design to integrate RES and ESD using the PEMS.

2.1. Renewable energy source (RES)

The renewable energy source in the design above is solar photovoltaics (PV) use for power generation. Solar cells also called PV convert sunlight directly to electricity. The power generated from solar highly depend on the amount of sun light. Maximum generation is usually achieved during peaks of day light, if sufficient enough, excess generation is stored in energy storage devices such as lithium ion batteries for later use during off peak hours usually in the early morning and late in the evening to mid-night. Considering a renewable source rated at 3 kW, roof mounted system with the area of the solar cells approximately 20 m^2 with an efficiency of 15%. The power from the PV system is determined using a linear model based on the irradiance level. The equation representing the simplified model is given in [4]:

$$PV_{output(t)} = GHI(t) \times S \times PV_{\eta} \tag{1}$$

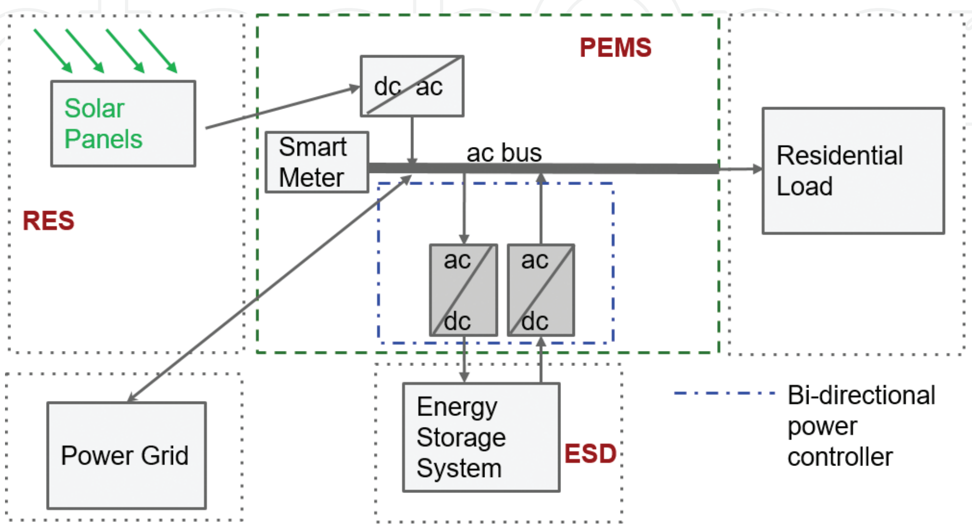

Figure 1. Detailed diagram of the integration module.

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where GHI(t) is the global horizontal irradiation in W/m^2, S is the total area for the PV modules in m^2 and PVη is the efficiency of the PV modules.

The PV generator is connected to the system via a DC to AC inverter with maximum power point tracking and constant efficiency. The change in efficiency of the inverter depending on the input and required output are not considered. The generation of electricity for PV is also temperature sensitive and that is also not considered in this project. This however does not significantly hamper the system and this simplification has been applied successfully in previous works including [4, 9].

The PV system was implemented and simulated using the System Advisor Model (SAM) developed and distributed by the National Renewable Energy Lab (NREL) [9]. A detailed residential PV model was developed. The PV generator size was chosen to cover our peak load requirement of 2.5 kW while being reasonably priced and having a footprint that can easily fit on the rooftop of an average-sized house. The SAM simulation, using the GHI data for the south side of Tallahassee, provided the expected power production from the PV generator for the period of a year. This is shown in **Figure 2** along with the expected AC production.

2.2. The power and energy management system (PEMS)

The PEMS in the system design serve as control for energy flow and conversion from RES, grid and energy storage. It contains the power electronics required to interface the power systems and the load. The PV generator is connected to the AC bus via an inverter and the energy storage device is connected the AC bus via a bi-directional controller as shown if **Figure 1**. Net

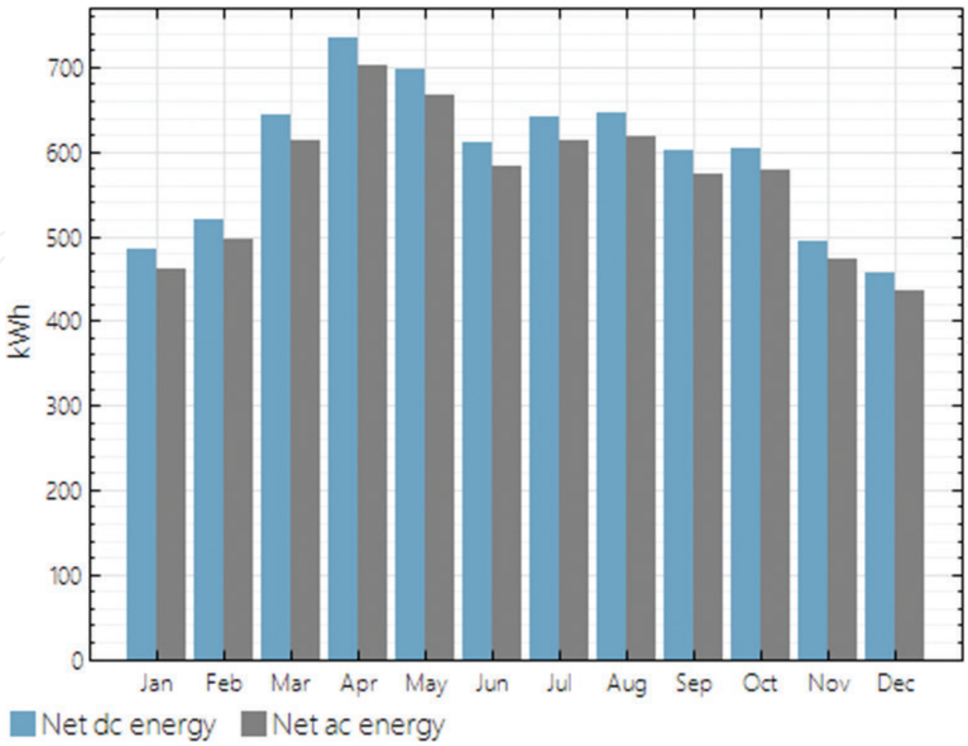

Figure 2. PV production over the period of 1 year based on SAM simulation [9].

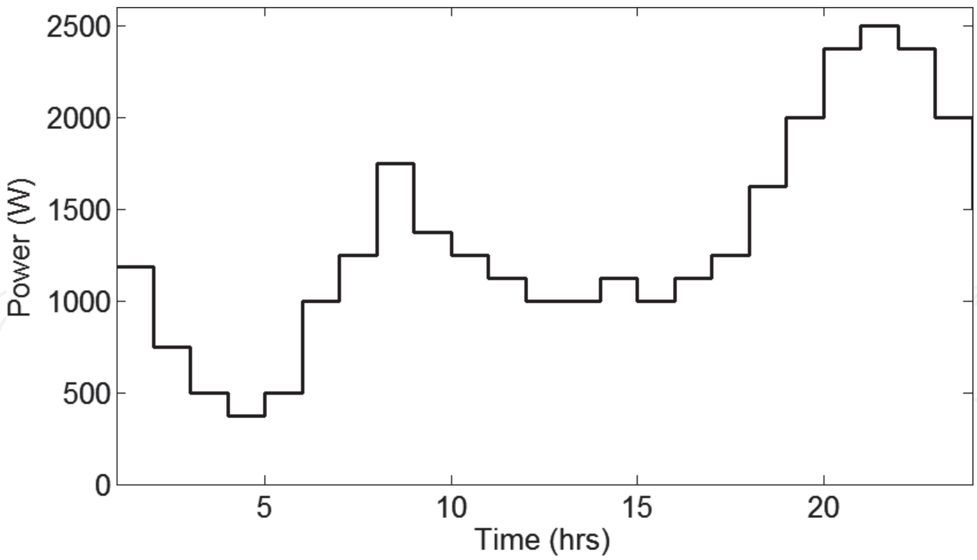

Figure 3. Residential load for system analysis with hourly resolution.

metering is in effect to account for excess flow of power to the grid and the meter is smart to monitor the power usage of different components. Two DC-DC boost converters and a single inverter is use in the power and energy management system. This is due to the differences in the output of the PV and the storage device voltage. This PV array converter also function as maximum power point tracking (MPPT). The power flow in the circuit is been monitored and controlled by the operation mode control logic which is embedded in the PEMS.

2.3. Energy storage devices (ESD)

Energy storage devices plays a vital role in the transition to clean, efficient and reliable power source for energy sustainability. In this chapter, lithium ion battery (LIB) is used as the ESD. LIBs are highly in demand for portable electrical/electronic devices and commercial application. It is currently gaining traction as backup power source for residential. This follows the lunch of Tesla power wall which consist of lithium ion batteries.

2.4. System load

A typical residential house load is illustrated in **Figure 3**.

3. RES integration with ESD

The integration of renewable energy source and energy storage devices is growing immensely to reduce overdependence on grid power generation. In this section, various mode of integration principles and operation will be discussed. These modes of operations account for different conditions that can affects the RES, ESD and Grid during a 24 hours' period which observes the morning, afternoon, evening and night times.

3.1. Operation mode of grid-supported PV

This mode of operation topology is showed in **Figure 4**. The figure describes the cases when the PV is generating but not sufficient to power the residential load. The grid is used to supplement the required power for the residential load. The ESD used due to cases of low state of charge or off-peak grid price. During this period of off peak grid pricing, the ESD also can be charge and not discharge because of the losses due to the round-trip efficiency from the AC bus to the battery and back to the AC bus in **Figure 1**.

3.2. Operation mode of grid and energy storage system-supported PV

The mode of operation describes cases when the PV generation is below the residential load requirement and need to supplement with both power from the energy storage and the grid before meeting the load required. **Figure 5** illustrates this mode of operation.

3.3. Operation mode of energy storage system-supported PV

This mode describes when the PV power is not sufficient to power the load and the ESD is available. In this scenario, the load is power by the PV and the ESD. This mainly happens during on-peak grid pricing times when the ESD is charged during off-peak grid pricing times (**Figure 6**).

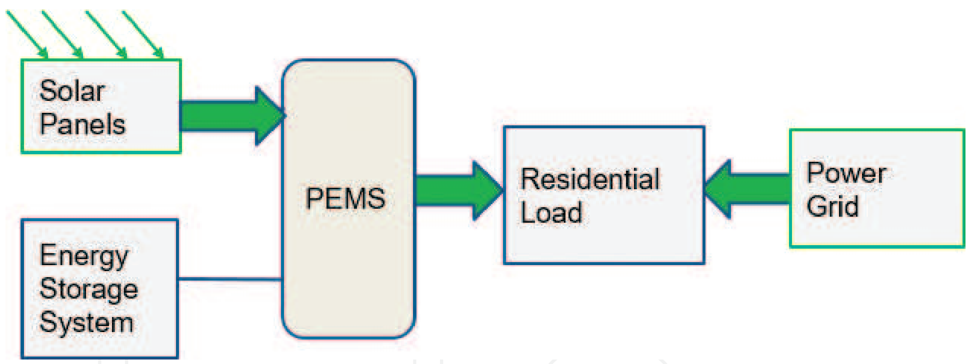

Figure 4. Grid and PV supplying the residential load.

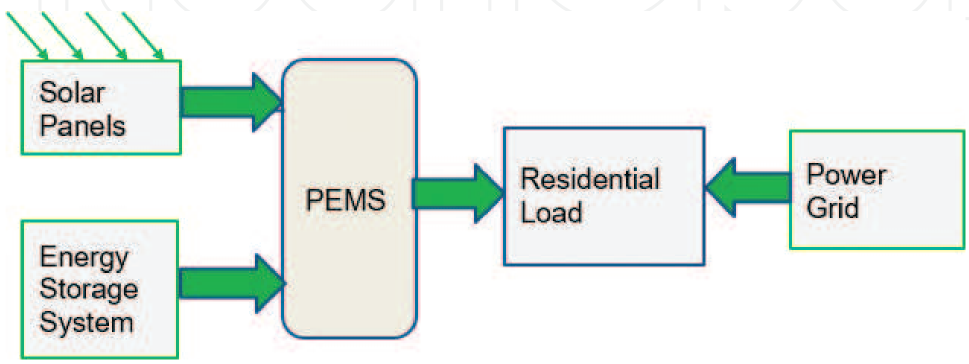

Figure 5. The grid, ESD and PV supplying the residential load.

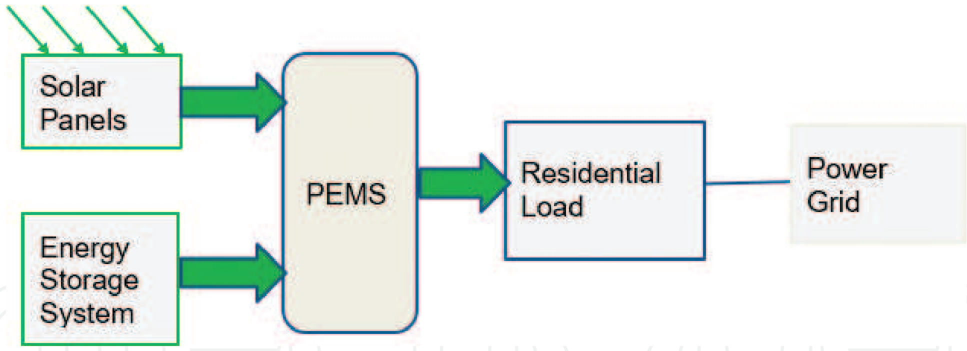

Figure 6. The PV and ESD supplying the residential load.

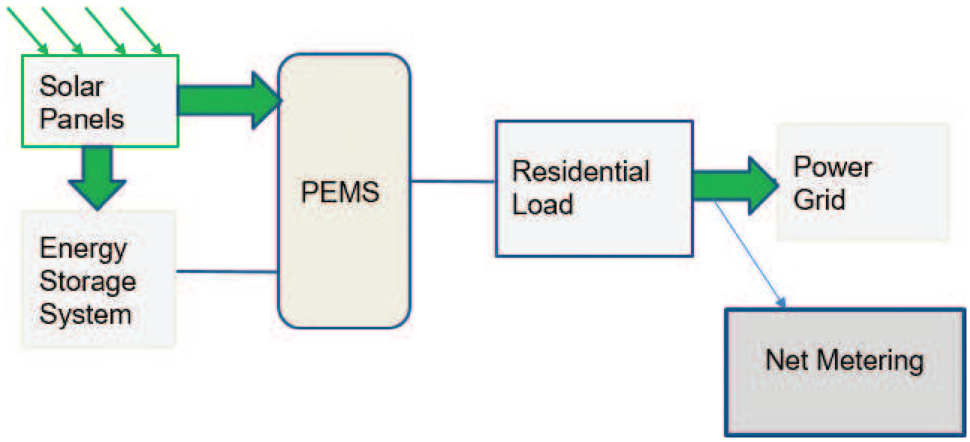

Figure 7. The PV supplying the residential load, grid and charging the ESD.

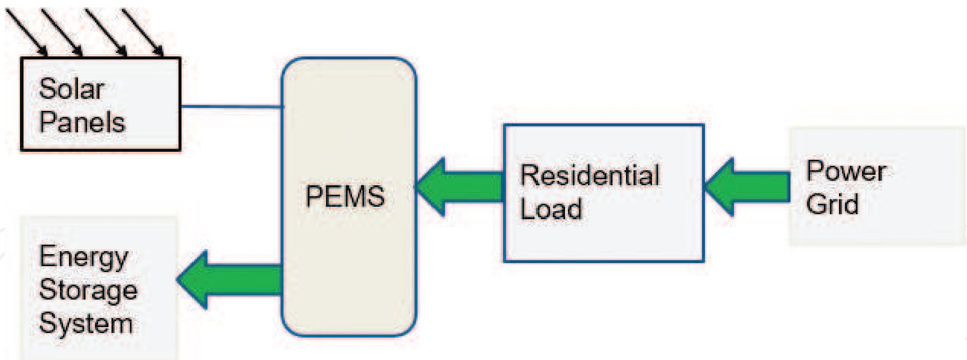

Figure 8. The grid supplying the residential and charging the ESD.

3.4. Operation mode of PV in peak hours

Figure 7 shows mode 4, this mode of operation generally occurs during the peak hours of PV generation. In this scenario, the PV powers the load, charges the ESD and supplies power to the grid for credit. The process of supplying power back to grid is called net metering.

3.5. Operation mode of grid

This mode of operation describes cases when the PV is not generating any power. The power needed by the load is supplied from the grid. The grid also charges the ESD when the state of

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charge is less than the thresh hold (maximum charge). Charging is usually done on off-peak grid hours to save cost (**Figure 8**).

4. Safety issues relating with the integration of RES and ESD

To effectively have a safe and reliable sustainable energy systems. Safety is highly imperative in the integration of the RES and ESD. Energy storage devices (ESD) such as lithium ion battery a high-performance storage device is used but has a drawback in its safety based on their material and chemical composition. Lithium ion batteries are the enabling technology for storage solutions in many applications. A typical Li-ion cell consists; positive electrode, negative electrode, electrolyte, and separator. Like all electrochemical batteries, the chemical energy is converted into electrical energy. According to the second law of thermodynamics, any conversion between two forms of energy occurs with an energy loss. This energy loss increases the temperature of the cell, which, negatively, affects the battery life, and possibly exceeds safety limits. The safety issues related to Li-ion batteries are caused by abuse conditions which are basically divide into electrical, mechanical and environmental, can result in abrupt behavior of the batteries. The electrical abuse conditions include, short circuiting and overcharge with an over-charging current rate and charging time. The mechanical abuse conditions include crush test, nail penetration test and external heating. These off-nominal operating conditions can lead to critical failure of lithium ion batteries. Safety of lithium ion battery has been the technical obstacle for high power demand applications in RES and ESD integration, hybrid electric vehicles (HEV) and electric vehicles (EV). These abuse conditions can initiate thermal runaway in LIB wherein chain exothermic reaction can cause the battery to attain temperature of over >500°C. The major response of the cells to the abuse conditions is usually increased in temperature due to decomposition of the electrolyte, melting of separator which in turn leads to exothermic reaction. Most of these responses eventually leads to thermal runaway before resulting into explosion or fire. The safety of LIB directly related to the type of material chemistry and their thermal stability.

The unforeseen battery failure potential has created public awareness for battery safety, particularly because of very large product recalls involving battery failures. Typical battery failure response can be energetic and non-energetic. Both energetic and non-energetic failures of Li-ion batteries often occur for due to poor cell design (electrochemical or mechanical), cell manufacturing flaws, external abuse of cells (thermal, mechanical, or electrical), poor battery pack design or manufacture, poor protection electronics design or manufacture [10]. Thus, Li-ion battery reliability and safety are generally considered a function of the design and manufacturing process. Standard performance regulation has been designed to test cell and battery pack designs to pass compliance with Underwriter Laboratories (UL), United Nations (UN) organizations standards. Failures that occur in the field are seldom related to cell design; rather, they are predominantly the result of manufacturing defects or subtle abuse scenarios that result in the development of latent cell internal faults. The failure modes can be classified into Energetic and Non-energetic failures.

- Energetic failure: This type of failures often leads to thermal runaway. Thermal runaway refers to excessive heating of a cell due to exothermic chemical reaction, this is a major occurrence with batteries when abused [10]. During this failure, the energy stored in the cell is rapidly removed. The rate of thermal runaway is proportional to the amount of energy stored. The thermal runaway reactions level is also related to the cell content such as electrolyte and electrode material chemistry [11].

- Non-Energetic failure: This type of failure mode which is usually considered benign result to loss of capacity, internal impedance increase. The ideal lithium ion battery failure mode is slow capacity fading and internal impedance increase caused by normal aging of the cells within the battery [11].

4.1. Temperature hazard of a lithium ion battery

Temperature is a major hazard response of lithium ion battery when subject to an abuse condition. Most lithium ion batteries should operate in temperature range of −10 to 50°C. During low temperature, reactions rate is slower according to Arrhenius law, which also reduce the transfer rate of ions and electron and causes reduction in the capacity. Lithium ion batteries at high temperature, are more vulnerable to high risk of failure than at lower temperature. Major failure response resulting in destruction of batteries are due to relatively high temperature. This could be because of electrolyte decomposition, melting of separator which in turns leads to thermal runaway after exothermal reactions before eventually resulting into explosion and/or fire. Thermal runaway is an adverse condition that is caused by a battery charging or other process that produces more internal heat than it can dissipate which refers to a situation where an increase in temperature changes the condition of the battery that further increases the temperature, often lead to explosion and/or fire. The type of abuse condition and the cell chemistry as well as the design affect the cell reaction. The onset temperature of the thermal runaway depends on the chemistry of the battery. This reaction is sustained by battery's oxygen content which varies by different cathode materials. The occurrence of a cell thermal runaway event depend on factors including; the state of charge of a cell (volume of electrical energy stored in the form of chemical potential energy), the ambient temperature, the cell electrochemical design (cell chemistry), and the mechanical design of the cell (cell size, electrolyte volume, etc.) [12]. The most severe thermal runaway reaction will be achieved when the cell is at 100% SOC, or subject to an abuse conditions such as overcharge, short circuiting, crushing etc. The following occurs when a cell undergoes thermal runaway;

- Cell internal temperature increases.
- Cell internal pressure increases
- Cell undergoes venting
- Cell content may be ejected.

The general root cause of energetic battery failure is; electrical abuse, mechanical abuse, poor electrochemical design and thermal abuse. Each of these failure modes have an impact on the environment.

4.2. Thermal characterization of Li-ion battery

The lithium ion battery relatively has large volume with a small surface area which makes the extraction of heat from the battery very important. There is an increase in the battery temperature if the heat generated is not removed which can lead to thermal runaway. Abuse by overcharge adds energy to the battery due to the input of electric power while in short circuit test no energy is added to the cell [13]. This could also affect the amount of energy delivered by the battery. To get optimum performance and effectively maximize the battery, it is imperative to operate the battery within the specify temperature range by the battery's manufacturer [15]. For instance, the preferred operating temperature for most lithium ion battery is −20 to 50°C. The second law of thermodynamics limits the rate of energy conversion during charging and discharging, leading to a non-ideal process with energy loss in the form of heat [14]. Bernadi et al. [14] classic work, estimates the heat generated from batteries using a mathematical model. According to their study, the heat is generated due to four main reasons; the irreversible resistive heating, the reversible entropic heat, the heat change of chemical side reactions, and heat of mixing due to the generation and relaxation of concentration gradients. The irreversible resistive (ohmic loss) occurs during both charge and discharge when the battery current flows through an internal resistance. The irreversible resistive heat occurs following the deviation of the battery potential from its equilibrium potential due to internal resistances. Therefore, the differences between the terminal voltage and the open circuit voltage is converted into heat [15].

The reversible entropic heat is the heat absorbed by the battery itself through a temperature change. Heat generated from the battery can also be determined experimentally by methods such as temperature measurements, thermal imaging, and calorimeter. A Calorimeter is a device that measures the amount of heat released and/or absorbed during a process. Differential Scanning Calorimetry (DSC) provides method of determining thermal stability by an induced heat and the subsequent heat generated by different materials is measured.

5. Conclusion

This chapter discussed safe integration of renewable energy with energy storage devices which is needed to have a reliable and efficient sustainable energy systems. Proper implementation of the different modes of operation which considers the working state of RES, ESD and grid will immensely reduce the over dependence on grid especially during on peak grid pricing. The ever increasing environmental problem will reduce drastically when renewable source of power is used with adequate storage capacity for energy sustainability. Improving the energy storage device capacity is necessary but also poses safety risk as well because the higher the capacity of energy storage device, the higher the safety risk associated with it. Therefore, there is need to effectively balance these tradeoffs in order to have both safe and high performing systems.

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