AC Source vs DC Source: Charging Efficiency in Battery Storage Systems for Residential Houses

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***Abstract*— Demand of Battery Storage System (BSS) in power engineering applications has been increasing extensively in past few decades specially because of the emerging new concepts such as DC-micro grid, Hybrid grids, renewable energy systems, electric vehicle etc. Particularly, in the developing countries, more attention has been paid towards the battery storage systems to maintain sustainable power systems while eliminating low power quality issues. The purpose of this research is to compare the efficiencies of AC and DC sources for the BSS charging and discharging in same experimental setup to achieve in a reasonable ground. Moreover, it covers the impact of charging efficiency of DC power source compared to the AC power source through measurement and estimation at residential level in City of Karachi, Pakistan. Alongside with study, the impact on carbon footprint has also been analyzed.**

Keywords—Battery Charging, Energy storage, Battery storage, AC and DC comparison, Energy Efficiency, DC home

I. Introduction

The demand of Battery Storage System (BSS) in electrical distribution systems has increased drastically in past few decades. The demand is expected to increase with the development of long life supercapacitors based the BSS options[1]. Major applications of the BSS in the current power system includes uninterruptable power supply (UPS), renewable energy system, battery powered tools like mobile phones, laptops, drills, screwdriver etc. [2].

BSS is used at residential level as a backup supply in case of scheduled/unscheduled electricity load shedding or power outage. In 2013, the total energy consumption in the domestic area of the Karachi city was 3989 GWhr per annum [3]. According to one of the research project in Karachi [4], 13.1% of the total energy was consumed in the BSS charging of the UPSs through the AC source. Therefore, nearly 518.57 GWhr per annum was consumed in the BSS charging.

The BSS has a significant role in the better integration of renewable sources in grid [5] along with dynamic energy management of micro grid [6]. Therefore, the BSS is used to enhance the reliability and security associated with power generation [7]. The BSS could be used to upturn the profits of wind farms and makes it cost-effective [8]. Advance applications include frequency control, energy reserves, and electric vehicles [9] [10].

The demand of BSS is expected to rise due to the charging of electric vehicle BSS through AC power grid [11] [12]. On the other hand, the electric vehicle battery charging from the AC power grid may cause uneven fluctuations in electricity demand of gird [13]. These irregular fluctuations could be sidestepped by the BSS.

The BSS is charged through the AC power in the current electric power system. Various research projects have been completed on the BSS charging through the AC source [14-16]. In [4], the BSS was charged through the AC source, then the same BSS was discharged through an inverter to find the overall efficiency of the installed Energy System (ES). The efficiency of the installed ES achieved in was almost 85%.

The BSS could be charged through the DC source by using DC to DC converter. Various designs have been investigated to improve the efficiency of BSS charging through the DC source [17] [18] [19]. In [20] , the BSS was directly charged through Photovoltaic (PV) panel to compare the efficiency of PV ES with different number of battery cells. It was estimated that the efficiency of grid-tie PV panel ES along with the BSS and inverters could be 86.5% – 90.5% reliant on the type of inverter [20]. The overall efficiency of PV ES (DC-DC charger, battery, and inverter) for various types of batteries were also estimated from 50-85%. Therefore, appropriate battery size could be selected to achieve the maximum efficiency [21].

Based on the literature, the efficiency of BSS charging systems has already been evaluated for AC and DC sources in separately with different inverter types and battery sizes. These results cannot be compared as they are not based on the same basis. Therefore, purpose of this research is to compare the efficiencies of AC and DC sources for the BSS charging and discharging in same experimental setup to achieve in a reasonable ground.

Research methodology and experimental details will be discussed in next section. Results and discussion will be presented in section III followed by the conclusion.

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II. Methodology & Experiment

A residential house in the Karachi city was chosen as a pilot project. An energy system (ES) was installed as per the configuration shown in Fig 1. Specifications of the installed ES are summarized in Table I. A power logger was used to record the AC voltage and current whereas a clamp multi-meter was

TABLE I. Specifications of Components in the Experimental Setup

Item	Specification	
Solar Panel	400 Watts	
Multi-function module rating	Inverter (DC-AC)	1 KVA
	PV Charge Controller (DC-DC)	12V/50A
	Battery Charger/Rectifier (AC-DC)	10A-50A
Batteries	140 Ampere Hour, Lead Acid type	
Wires size	1.5 mm^2 for AC power flow at 230V (AC) 2.5 mm^2 from PV panel to Solar Charger	
AC Circuit breaker	10A (for AC input current into battery charger) 10A (for AC output current from Inverter to load)	
DC Circuit breaker	20A	

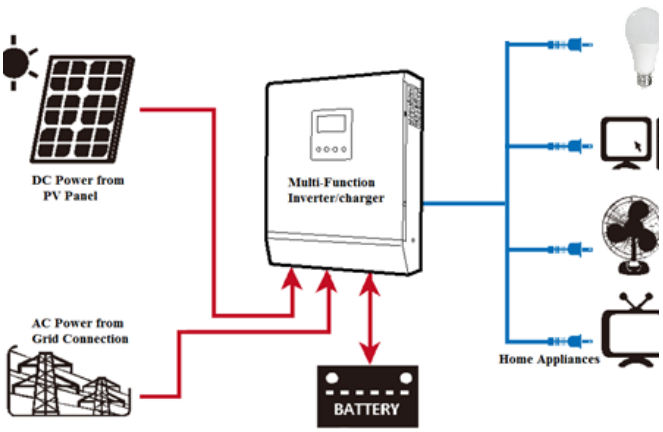

Fig. 2. Layout of the exprimental setup

used to measure the DC voltage and current. The load power factor was approximately equal to 1, therefore power factor is not considered for the purpose of calculations. External AC to DC converter was used before the DC fan whereas the LED lamps and the LCD TV already had the built-in AC to DC converters to utilize the AC power from AC based distribution system of home.

The residential house was operated in two different configurations i.e. AC source mode and DC source mode. Similar procedure was adopted in case of DC source. In the AC source mode, the BSS in a residential house was supplied through the AC power source as shown in Fig 2. The experimental setup of both configurations were similar from the BSS to electrical the loads as shown in Figs 2 and 3. The details of recorded data and the calculations will be discussed in the next sub-sections. Similarly, in the DC source mode, the same BSS was charged through the DC power source as shown in Fig. 3. Then the BSS was discharged similarly in both configurations to find the available output energy. Finally, the energy efficiencies of both modes were calculated as per the charging and discharging energy based on the recorded data.

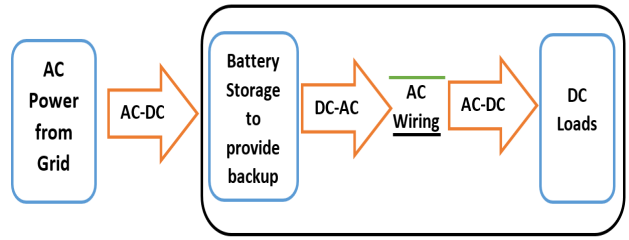

Fig. 1. The energy system configuration for the AC source

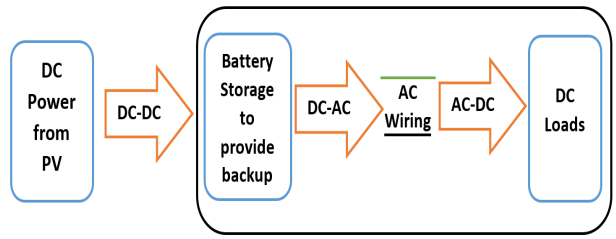

Fig. 3. The energy system configuration for the DC Source

A. The AC Source Mode

The utility supply, 230V, 50Hz AC of the electrical distribution system was used as the AC source. At the start, the initial battery terminal voltage was recorded. Any particular battery voltage may cover a large State of Charge (SoC). In this experiment, initial battery terminal voltage was noted at the instant when it was changed from 12.4V to 12.5V. Then, the BSS was charged through the AC source until the battery terminal voltage was raised to 12.7V. As shown in Fig 4, the input power taken from the AC source was calculated before the AC to DC conversion stage through the measurements of input terminal voltage and the current of the utility supply. The input power ($P_{in,\,AC}$) from the AC source during each interval was calculated by using (1).

$$P_{in,\,AC} = V_{in,\,AC} * I_{in,\,AC} \tag{1}$$

where,
$P_{in,\,AC}$ - Power input through the AC source
$V_{in,\,AC}$ - Input terminal voltage of the AC source
$I_{in,\,AC}$ - Input current through the AC source

These above data were recorded after every 10 seconds and the corresponding input energy data were calculated for each interval of time. For this purpose, it is essential to know the total data samples to find the total input energy from the AC source. Total collected data samples (k) were calculated by using (2).

$$k = T * S \tag{2}$$

where,
k - Total number of samples
T - Total duration of interval in minutes
S - Number of samples per minute

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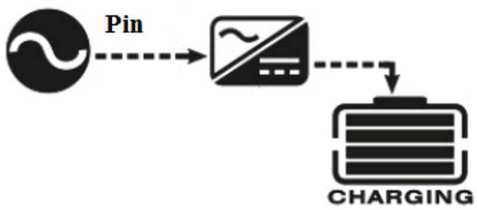

Fig. 4. The BSS charging in the AC source mode

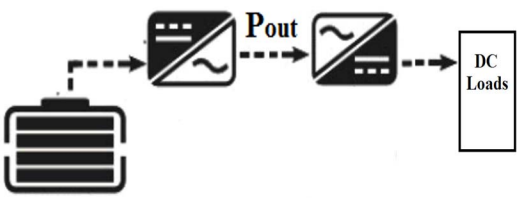

Fig. 5. The BSS discharging in the AC source mode

The input power calculated in (1) can be used to find the total input energy from the AC source. The total input energy ($E_{(c, ac)}$) during the charging time was calculated by using (3).

$$E(c, ac) = \sum_{n=1}^{k} (P_{in,AC} * t) \quad (3)$$

where,
E(c, ac) - The input energy through the AC source during BSS charging
t - Time period of each sample

Then, the BSS was discharged (12.7V battery terminal voltage) through the inverter to find the total available output energy. The BSS was discharged until it reaches the initially noted battery terminal voltage before the charging process. The final battery voltage was noted at the instant when battery terminal voltage was changed from 12.6V to 12.5V. The output power during discharging was measured after the DC to AC conversion as shown in Fig 5 and the output power ($P_{out, AC}$) was calculated by using (4).

$$P_{out, AC} = V_{out, AC} * I_{out, AC} \quad (4)$$

Where,
$P_{out, AC}$ - Power output through the inverter
$V_{out, AC}$ - Output voltage of the inverter (AC)
$I_{out, AC}$ - Output current through the inverter (AC)

Similarly, the energy output ($E_{(d,ac)}$) during the BSS discharge was calculated by using (5).

$$E(d, ac) = \sum_{n=1}^{k} (P_{out,AC} * t) \quad (5)$$

Where,
E(d, ac) - Output energy through the BSS during discharge
t - Time period of each sample

Based on the calculations in (1) and (4), the input and output power curves with respect to clock time in hours were plotted as shown in Fig 6. Here, the positive sign shows the AC power input during charging of the BSS whereas the negative sign shows the power output during the BSS discharge. The recorded experimental data along with the energy efficiency of the system have been summarized in Table II. It is evident from the summary that 13.33% power was lost in this case.

TABLE II. RECORDED DATA AND EFFICIENCY IN THE AC SOURCE MODE

Battery Process	Duration Minutes	Point	Battery Voltage (V)	Clock Time	Energy (Wh)	Efficiency
Charging	9.17	Start	12.5	15:29:59	56.973	86.67%
		End	12.7	15:39:09		
Discharging	22.83	Start	12.7	15:39:09	49.378	
		End	12.5	16:01:59		

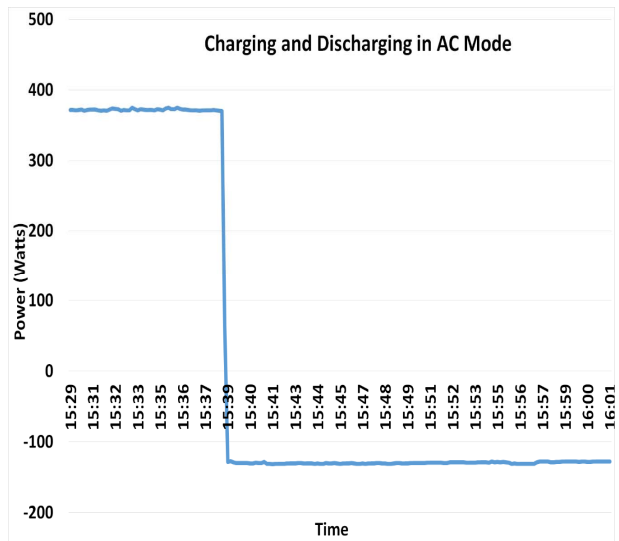

Fig. 6. The BSS Charging and discharging power curve in the AC source mode

B. The DC Source Mode

The Photovoltaic (PV) panels were used as the DC power source in this mode. Observation of the initial and final battery terminal voltage of both systems should be noted in a similar pattern to ensure the similar SoC. Therefore, initial battery terminal voltage was again noted at the instant when it was changed from 12.4V to 12.5V. Similarly, the final battery voltage was noted at the instant when battery terminal voltage was changed from 12.6V to 12.5V.

The total input power was recorded just after the PV panel before the conversion from the DC to DC as mentioned in Figs 7. Therefore, the input power was considered during the complete charging cycle. The input power was calculated for each data sample. The input power ($P_{in,\ DC}$) taken from the DC source was calculated by using (6).

$$P_{in,\ DC} = V_{in,\ DC} * I_{in,\ DC} \tag{6}$$

where,
$P_{in,\ DC}$ - Power input through the DC source
$V_{in,\ DC}$ - Input terminal of the DC source
$I_{in,\ DC}$ - Input current through the DC source

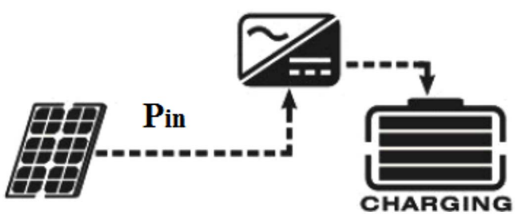

Fig. 7. The BSS charging in the DC source mode

The total input energy ($E_{(c,dc)}$) through the DC source during the BSS charging time was calculated by using (7).

$$\boldsymbol{E(c,dc) = \sum_{n=1}^{k}(P_{in,DC} * t)} \tag{7}$$

where,
E(c,dc) - Input energy through the DC source during the BSS charging
t - Time period of each sample

The total discharge power was measured after the DC to AC conversion as shown in Fig 5. The total output power during battery discharge was calculated by using (4) as used in the previous section. Similarly, the total energy output during the discharge was calculated by using (5).

TABLE III. RECORDED DATA AND EFFICIENCY IN THE DC SOURCE MODE

Battery Process	Duration Minutes	Point	Battery Voltage (V)	Clock Time	Energy (Wh)	Efficiency
Charging	9.83	Start	12.5	11:00:09	57.07	92.85%
		End	12.7	10:29:29		
Discharging	29.34	Start	12.7	11:14:49	52.991	
		End	12.5	11:43:09		

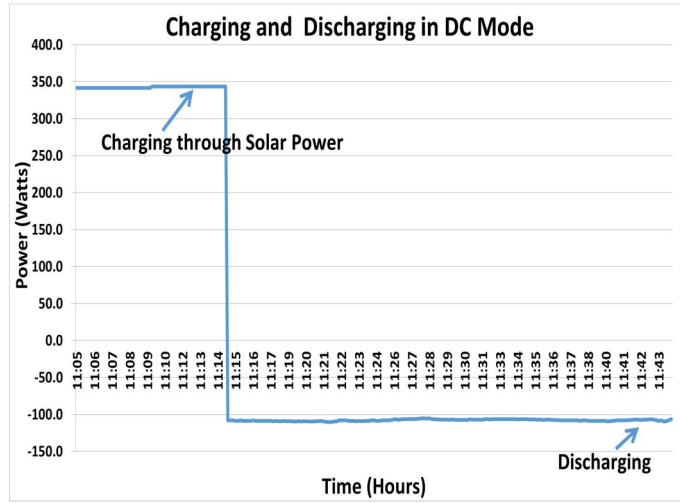

Fig. 8. The BSS charging and discharging power curves in the DC source mode

The BSS charging and discharging power curves in the DC source mode were plotted as shown in Fig 8. The summary of charging and discharging energy along with the efficiencies are shown in Table III. It is evident from the summary that only 7.15% power was lost in case of DC source mode.

III. RESULTS AND DISCUSSION

The charging and discharging energy along with energy efficiencies of the AC source and the DC source modes are summarized in Table IV. The efficiency of the energy system can be increased by 6.39% in a residential house by replacing the AC source with the DC source.

Power losses become more severe in case of the cascade converters due to battery charged appliances and DC loads. The overall efficiency of the AC source in the cascade charging system is reduced further. This result can be slightly changed depending on the nature of the electrical load. The concept of the complete DC home is generated to avoid these cascade converter losses.

On the other hand, the feasibility of the BSS charging from the DC sources e.g. solar energy and wind energy has already been well established. A research revealed that the PV panels are feasible to replace the grid charging [22].

TABLE IV. ENERGY EFFICIENCY COMPARISON

Comparing factors	AC Power Input Mode	DC Power Input Mode
Energy Input	56.973 Wh	57.07 Wh
Energy utilized	49.378Wh	52.991 Wh
Efficiency	86.67%	92.85%

A. Energy Conservation Impact on Karachi City

The significance of this research can be explored with the estimation of energy conservation as the actual consumption of a distribution system such as power consumption of a busy city. A case study has been taken to estimate the impact of this research on the Karachi city. As mentioned in earlier about BSS Charging in Karachi city, nearly 518.57 GWh per annum was consumed in 2013. If similar BSS would be charged from the DC source, then 6.39% of the total charging energy i.e. *33.14 GWh* could be conserved as calculated by using (8).

$$E_{AEC} = E_R * C_{EF} * k \tag{8}$$

where,

E_{AEC} - Annual energy conserved with the DC source

E_R - Annual energy consumption in a residential sector

C_{EF} - Charging Energy Factor i.e. percentage of energy consumed in charging the BSS

k - Energy conservation factor in case of the DC source (in this case k = 0.0639)

B. Environmental Impacts

In the same year (2013), almost 27% energy was generated by furnace oil in the Karachi city [3]. Approximately 0.821 kg of carbon is emitted due to the generation of one kWh of energy through the furnace oil [23]. As per the results of this research, carbon emissions due the generation of 33.14 GWh of energy could be conserved in the DC source mode. About *27.2 Million Metric tons* of the carbon emissions could be avoided as calculated by using (9).

$$CET = f * E_{AEC} \tag{9}$$

where,

CET - Total carbon emissions in Million Metric tons

f - Carbon emissions factor in kg/kWh as per fuel type

E_{AEC} - Annual energy conserved in GWh

Overall, the country level energy conservation would considerably reduce the carbon emissions. Therefore, the transformation of the BSS charging from the AC grid source to the DC sources would be more significant in near future to achieve the environmental targets as well.

IV. Conclusion

The efficiencies of the BSS charging were computed in the AC source and the DC source modes through the experimentally recorded data. The data recorded in both of these systems have been analyzed to conclude a quantitative comparison of energy efficiency for both approaches. The outcome of this research found that the efficiency of a residential house could be increased by circa 6% in case of the DC power input through the PV panel.

Moreover, the energy efficiency result was applied on the Karachi city to estimate the annual energy conservation of a metropolitan city. It was estimated about 33 GWhr energy could be conserved in residential houses in Karachi, Pakistan. As per the results of this research, about *27.2 Million Metric tons* of the carbon emissions could be avoided due to the electricity generation of 33.14 GWhr though furnace oil.

This research identifies the potential of the DC sources in future grids with respect to the total energy conservation and the environmental concerns. Therefore, this research not only encourages the residential electricity users to move toward the renewable energy DC sources for the BSS charging but also persuades the government, shake holders and environmental organizations to consider this option in future investment plans.

References

[1] M. Uno and K. Tanaka, "Accelerated ageing testing and cycle life prediction of supercapacitors for alternative battery applications," in *IEEE 33rd International Telecommunications Energy Conference (INTELEC) 2011*, 2011, pp. 1-6.

[2] A. Joseph and M. Shahidehpour, "Battery storage systems in electric power systems," in *IEEE Power Engineering Society General Meeting*, 2006, p. 8 pp.

[3] NEPRA, "State of industry report 2013," ed: National Electric Power Regulatory Authority Pakistan, p. 188.

[4] S. Khan, S. Waqar, M. Danyal, and M. Yousuf, "Impact of UPS on K-Electric grid " Bachelors of Engineering Electrical Engineering, NED University of Engineering and Technology 2014.

[5] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez, and W. M. Grady, "Battery energy storage for enabling integration of distributed solar power generation," *IEEE Transactions on Smart Grid,* vol. 3, pp. 850-857, 2012.

[6] H. Zhou, T. Bhattacharya, D. Tran, T. S. T. Siew, and A. M. Khambadkone, "Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications," *IEEE Transactions on Power Electronics,* vol. 26, pp. 923-930, 2011.

[7] D. Sutanto and W. R. Lachs, "Battery energy storage systems for sustainable energy development in Asia," *Electric Power Systems Research,* vol. 44, pp. 61-67, 1// 1998.

[8] K. C. Divya and J. Østergaard, "Battery energy storage technology for power systems—An overview," *Electric Power Systems Research,* vol. 79, pp. 511-520, 4// 2009.

[9] C. Wadia, P. Albertus, and V. Srinivasan, "Resource constraints on the battery energy storage potential for grid and transportation applications," *Journal of Power Sources,* vol. 196, pp. 1593-1598, 2/1/ 2011.

[10] H. J. Kunisch, K. G. Kramer, and H. Dominik, "Battery energy storage another option for load-frequency-control and instantaneous reserve," *IEEE Transactions on Energy Conversion,* vol. EC-1, pp. 41-46, 1986.

[11] F. Musavi, M. Edington, W. Eberle, and W. G. Dunford, "Evaluation and efficiency comparison of front end AC-DC plug-in hybrid charger topologies," *IEEE Transactions on Smart Grid,* vol. 3, pp. 413-421, 2012.

[12] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Transactions on Power Electronics,* vol. 28, pp. 2151-2169, 2013.

[13] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Transactions on Smart Grid,* vol. 2, pp. 456-467, 2011.

[14] M. M. Morcos, N. G. Dillman, and C. R. Mersman, "Battery chargers for electric vehicles," *IEEE Power Engineering Review,* vol. 20, pp. 8-11, 18, 2000.

[15] R. W. Johnson Jr and J. C. Paulakonis, "Uninterruptible power supply having improved battery charger," ed: Google Patents, 1993.

[16] M. Chen and G. A. Rincon-Mora, "Accurate, compact, and power-efficient Li-Ion battery charger circuit," *IEEE Transactions on Circuits and Systems II: Express Briefs,* vol. 53, pp. 1180-1184, 2006.

[17] L. Schuch, C. Rech, H. L. Hey, H. A. Grundlinggrundling, H. Pinheiro, and J. R. Pinheiro, "Analysis and design of a new high-efficiency bidirectional integrated ZVT PWM converter for DC-bus and battery-bank interface," *IEEE Transactions on Industry Applications,* vol. 42, pp. 1321-1332, 2006.

[18] D. D. C. Lu and V. G. Agelidis, "Photovoltaic-battery-powered DC bus system for common portable electronic devices," *IEEE Transactions on Power Electronics,* vol. 24, pp. 849-855, 2009.

[19] N. Kularatna, "Supercapacitor Assisted Low Dropout Regulators (SCALDO) for high efficiency DC-DC converters for DC microgrid applications," in *IEEE First International Conference on DC Microgrids (ICDCM), 2015*, 2015, pp. 333-338.

[20] T. L. Gibson and N. A. Kelly, "Solar photovoltaic charging of lithium-ion batteries," *Journal of Power Sources,* vol. 195, pp. 3928-3932, 6/15/ 2010.

[21] C. J. Rydh and B. A. Sandén, "Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies," *Energy Conversion and Management,* vol. 46, pp. 1980-2000, 7// 2005.

[22] X. Li, L. A. C. Lopes, and S. S. Williamson, "On the suitability of plug-in hybrid electric vehicle (PHEV) charging infrastructures based on wind and solar energy," in *IEEE Power & Energy Society General Meeting*, 2009, pp. 1-8.

[23] (30/04/2016). *Carbon dioxide emissions for one kilowatt-hour*. Available: http://blueskymodel.org/kilowatt-hour