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Manufacturing energy analysis of lithium ion battery pack for electric vehicles

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ABSTRACT

Lithium ion batteries (LIB) are widely used to power electric vehicles. Here we report a comprehensive manufacturing energy analysis of the popular LMO-graphite LIB pack used on Nissan Leaf and Chevrolet Volt. A 24 kWh battery pack with 192 prismatic cells is analysed at each manufacturing process from mixing, coating, calendaring, notching till final cutting and assembly, with data collected and modelled from real industrial processes. It is found that 29.9 GJ of energy is embedded in the battery materials, 58.7 GJ energy consumed in the battery cell production, and 0.3 GJ energy for the final battery pack assembly.

1. Introduction

With the advantages of high energy density, light weight, no memory effect and better environmental performance [1,2], lithium ion batteries are nowadays used for powering all types of electric vehicles (EVs) on the commercial market. Compared with conventional internal combustion engine (ICE) powered vehicles, EVs have a number of technological and environmental advantages: EVs produce zero tailpipe emissions in operations and can reduce the dependence of vehicle operations on foreign oil; EVs also operate quietly and smoothly, have stronger acceleration, and require less maintenance [3]. Due to their superior environmental and societal benefits, EVs are considered the future mode of ground transportation and promoted globally for large fleet deployment in future decades. It is estimated that the global fleet of EVs will reach over 13 million by 2020 and 230 million by 2030 [4], and large fleet deployments of EVs will significantly reduce harmful emissions from the operations of conventional ICE-powered vehicles. As predicted, the EV deployment in 2030 will result in a 20%–69% decline in 2030 greenhouse gas (GHG) emissions from U.S. light-vehicles over 2005 levels [5].

Currently there are three types of EVs on the commercial market [3]: Hybrid EV (e.g. Toyota Prius), Plug-in EV (e.g. Chevrolet Volt) and Battery EV (e.g. Nissan Leaf). Typically, an on-board LIB pack in an EV contains hundreds of single-LIB cells packed together to provide a combined power supply. For example, the Nissan Leaf 24 kWh battery pack has 192 cells and weighs 640 lbs [6], and the Chevrolet Volt 16 kWh battery pack has 288 cells and weighs 435 lbs [7]. Each LIB cell on board of an EV is typically in a prismatic or cylindrical shape and composed of multiple stacked layers of single LIBs. Each single LIB consists of an anode, a cathode, a porous separator and electrolyte filled in between. LIBs work in such a way that the cathode (usually made of lithium metal oxides) generates lithium ions flowing in the electrolyte through the separator to the anode (currently made of carbon graphite) during the charging process and then flowing back from the anode to the cathode during the discharging process. A complete charge and discharge process is called a cycle. EV batteries are required to be able to sustain thousands of cycles to fulfil the service life of electric vehicles.

Electric vehicles powered by lithium ion batteries are mainly for reducing greenhouse gas emissions from ground transportation, while EVs also generate certain amount of greenhouse gas emissions indirectly from the energy consumption of the battery pack, including the embedded energy in the lithium ion battery manufacturing and the consumed energy during the lithium ion battery charging/discharging for EV operations. The energy consumption embedded in the lithium ion battery is significant as the LIB manufacturing involves a series of complicated manufacturing processes with dry room facilities needed to support the manufacturing operations [8]. Due to lack of direct industrial data, the reported energy consumption data for LIB manufacturing in the literature were all estimated and significantly different, by an order of magnitude. For instance, the energy consumed in lithium ion battery pack manufacturing is reported between 0.4–1.4 kWh/kg in Refs. [9–11], but between 16.8–22 kWh/kg as reported in Refs. [12–15].

In this paper, we present a detailed manufacturing energy analysis of the lithium ion battery pack using graphite anode and

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lithium manganese oxides (LMO) cathode, which are popularly used on Nissan Leaf and Chevrolet Volt such EVs. The battery pack is configured with 24 kWh energy storage capacity for all battery EVs. The energy consumption data are directly measured from the industrial pilot scale manufacturing facility of Johnson Controls Inc., for lithium ion battery cell production, and modelled on the GM battery assembly process for battery pack production. This study is based on actual industrial production process, and these manufacturing energy analysis data and models can be useful in supporting future research on sustainable manufacturing of lithium ion batteries for electric vehicles [16].

2. Materials and manufacturing processes of LIB pack

Prior to the manufacturing energy analysis of lithium ion battery, here we first present detailed material compositions of the 24 kWh lithium ion battery pack, and then provide a description about the actual battery manufacturing processes at an industrial scale for subsequent manufacturing energy analysis.

2.1. Material composition of the 24 kWh lithium ion battery pack

As the material composition of lithium ion battery pack dictates the battery manufacturing processes but such detailed data are not available, here we employed the BatPac software from Argonne National Lab to configure the battery material compositions for the 24 kWh LMO-graphite battery pack. Based on the commercial battery cell specifications, the 24 kWh battery pack is composed of 192 LIB cells, with each cell at 3.85 V and 32 Ah capacity. In each battery cell, the cathode contains the LMO active material, carbon black, and polyvinylidene fluoride (PVDF) binder at a mass ratio of 89:6:5. The anode is composed of 95 wt% graphite and 5% carboxymethyl cellulose (CMC) binder with a NP (negative-to-positive capacity) ratio of 1.2. The electrolyte, which is lithium fluorophosphate ($LiPF_6$) dissolved in ethylene carbonate (EC) at a volume ratio of 1:1, is injected into the sealed pouch. Besides, 11 g separator, 399 g positive/negative current collectors and 39.5 g pouch cell case are included in each cell. The total weight of each cell is configured at 868 g. Then 12 cells are grouped and packed in a module. A battery pack contains 16 such modules, with polymer spacers set in between, which are connected in series and situated in an aluminium battery tray. After, the modules are connected with battery management system (BMS) and cooling system covered with an ABS lid to form a battery pack. The battery pack packaging materials typically represents 17–19% mass fraction of the entire battery pack [14,17,18]. Masses of the BMS and the cooling system are linearly correlated with the capacity of the battery pack, with ratios of 0.353 kg kWh^{-1} and 0.373 kg kWh^{-1}, respectively. Consequently, the 24 kWh LMO battery pack with 192 cells weighs a total of 221.6 kg, including 166.6 kg of battery cells, 8.9 kg cooling system, 8.5 kg BMS, and 37.6 kg packaging. The mass composition of the battery pack is illustrated in Fig. 1 below.

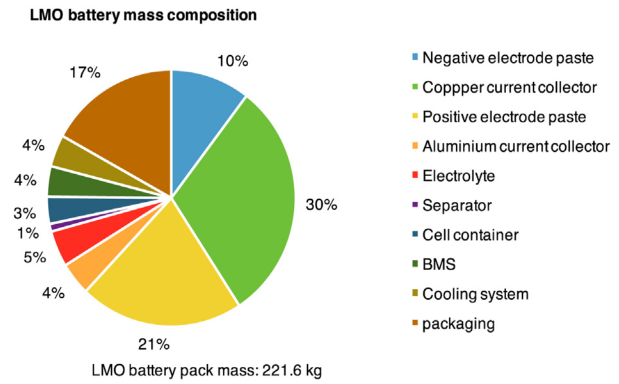

Fig. 1. Mass composition of the LMO battery pack.

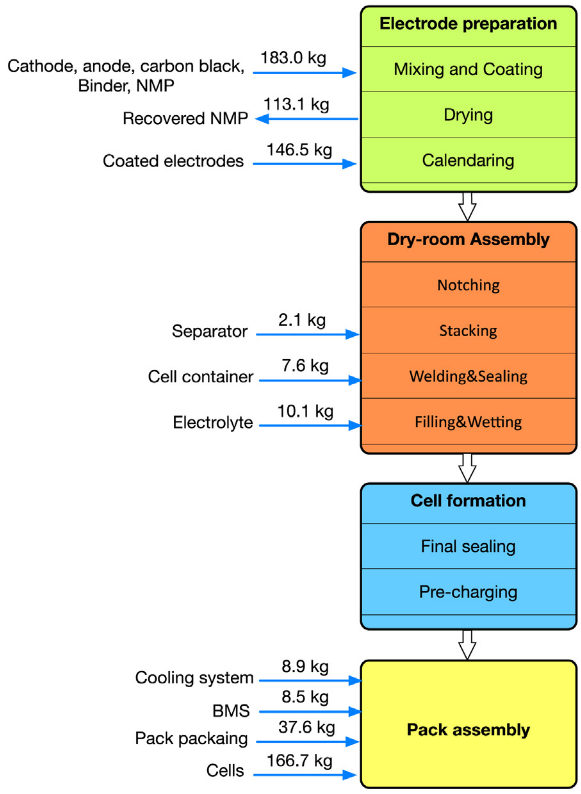

Fig. 2. Manufacturing process and material flows for the 24 kWh LMO-graphite Lithium ion battery pack.

2.2. Lithium ion battery cell manufacturing processes

The manufacturing of a lithium ion battery pack requires a series of manufacturing processes. Fig. 2 below shows the typical manufacturing processes used in current lithium ion battery manufacturing for EVs. For battery pouch cell manufacturing, first, the electrode materials (both LMO and graphite, separately) are uniformly mixed with carbon black additives and binders in NMP (*N*-methyl-2-pyrrolidone) solvent at 4 wt% concentration, and then coated on 12 μm-thick copper foil (graphite anode) and 15 μm-thick alumina foil (LMO cathode), respectively. The coated electrodes are then dried under 150 °C temperature for about 10 h to evaporate and recover the NMP solvent, and then pressed through a calendaring process to obtain the desired density of electrode (10 mg/cm^2) on the copper and alumina current collectors. The dried anode and cathode are then notched into the desired dimensions of 129 × 77 mm for anode and 129 × 73 mm for cathode, respectively, to be paired and stacked into LIB cells. To achieve a high energy density, 24 pairs of the notched anodes and cathodes with 20 μm-thick Celgard separators (porosity 40%) in between, are stacked, welded through ultrasonic welding, filled with $LiPF_6$ electrolyte and sealed into a single LIB cell. Due to the high reactivity of the $LiPF_6$ with moisture, these operations are all accomplished in a dry room facility in which the moisture is controlled below 100 ppm, and the temperature is controlled at 20 °C.

3. Manufacturing energy analysis of lithium ion battery pack

Here a detailed unit process energy analysis of lithium ion battery manufacturing is presented, through direct measurement of the energy data using HOBO UX 120-006M data loggers and Onset CTV-A current meters on Johnson Controls' pilot scale dry room production facility. The dry room is heated by one heat coil with a power demand of 31.8 kW and one condenser with a power demand of 13.4 kW continuously for temperature and moisture control. Other components include fan filter, lighting, exhaust filter, and transformer operating at a power demand of 3.5, 4.0, 0.64, and 10.6 kW, respectively. The dry room facility itself excluding the battery manufacturing machines operates at 64.8 kW of power demand,

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