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Cost-effective supply chain for electric vehicle battery remanufacturing

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HIGHLIGHTS

- A supply chain network integrating Lithium-Ion battery remanufacturing is proposed.
- An optimization model is developed to maximize the profit within the network.
- Case study is presented and 11.14% increase in profit can be achieved.
- The sensitivity analysis is performed to identify the key factors for profitability.

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ABSTRACT

Large-scale adoption of electric vehicles can reap significant energy and environmental benefits while also reducing reliance on fossil fuels. Nonetheless, accompanying the benefits of electric vehicles, several economic and ecological challenges arise from the production of Lithium-ion batteries, which are currently the most popular type of batteries used in electric vehicles. Remanufacturing is a promising end-of-life strategy and can lead to more sustainable Lithium-ion battery supply chains to support large-scale adoption of electric vehicles. Several factors will dictate the feasibility and effectiveness of remanufacturing, including economic viability, production capability, and battery demand and supply. Unfortunately, while there exists significant research efforts on remanufacturing at the laboratory scale, there lacks research that investigates Lithium-ion battery remanufacturing at the enterprise scale. Motivated by this, in this paper, a state-of-the-art closed loop supply chain network model for Lithium-ion battery remanufacturing considering different quality levels of spent battery returns is proposed. An optimization model is developed to maximize the network profit and a sensitivity analysis is performed to determine the impact of several important model parameters on the profitability of the proposed supply chain network. A numerical case study is implemented which shows that 9.81–30.93% increase in profit can be achieved if remanufacturing is integrated in Lithium-ion battery supply chain networks. Moreover, the sensitivity analysis shows that careful implementation of the proposed algorithm coupled with understanding of battery parameters are the keys to implementing cost-effective electric vehicle Lithium-ion battery supply chains. In all, this research will help stimulate the implementation of remanufacturing, promote economically and environmentally sustainable supply chain management in the electric vehicle battery industry, and support the transportation sector in reducing environmental burdens.

1. Introduction

Recently, energy and environmental sustainability concerns have gained increasing attention due to depleting energy sources and climate change. In particular, for the transportation sector, approximately 900 million vehicles are being used worldwide, and 96% of their energy use comes from fossil sources [1]. Fortunately, electric vehicles (EVs) have several energy and environment related advantages, and show to be a steadfast alternative for conventional gasoline vehicles [2]. First, electricity is the main energy source powering EVs, which is primarily generated from domestic sources, including coal, nuclear, natural gas, and renewable sources. Next, EVs are more energy efficient since around 59–62% of the energy they consume can be converted to power at the wheels; whereas conventional gasoline vehicles can only convert around 17–21% of the energy stored in gasoline to power at the wheels [3]. Finally, although electricity generation activities emit pollutants, EVs do not emit tailpipe pollutants. Furthermore, through off-peak charging, the life cycle emissions of EVs can be further reduced [4].

More detailed studies on the efficiency and environmental benefits of EVs are noted as follows. In [5] EV cost, emissions, and water

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Nomenclature

Sets

MM	set of raw material market nodes
CC	set of collection centers, $CC \subseteq F$
RM	set of remanufacturing facilities, $RM \subseteq F$
RC	set of recycling facilities, $RC \subseteq F$
L	set of landfills, $L \subseteq F$
R	set of retailers, $R \subseteq F$
MP	set of manufacturing facilities, $MP \subseteq F$
F	set of node facilities
T	set of time intervals

Indices

i	index of collection centers, $i \in CC$
l	index of landfills, $l \in L$
j	index of remanufacturing facilities, $j \in RM$
p	index of manufacturing facilities, $p \in MP$
r	index of retailers, $r \in R$
k	index of recycling facilities, $k \in RC$
y	index of first/s/third-level LIB quality level, y = 1, 2, 3 respectively
t	index of time intervals, $t \in T$
z	index of value loss location for collection centers, remanufacturing facilities, recycling facilities and manufacturing facilities, z = 1, 2, 3, 4 respectively
f	index of node facilities, $f \in F$

Decision variables

x_f	binary decision variable equal to 1 if facility f is open and 0 otherwise, $\forall f$
QB_{ijt}	quantity of first-level batteries transported from collection center i to remanufacturing facility j in interval t, $i \in CC$, $j \in RM$, $t \in T$
QB_{ikt}	quantity of second-level batteries transported from collection center i to recycling facility k in interval t, $j \in RM$, $k \in RC$, $t \in T$
QB_{ilt}	quantity of third-level batteries transported from collection center i to landfill l in interval t, $i \in CC$, $l \in L$, $t \in T$
QB_{jrt}	quantity of remanufactured batteries transported from remanufacturing facility j to retailer r in interval t, $j \in RM$, $r \in R$, $t \in T$
QC_{kjt}	quantity of the cells transported from recycling facility k to remanufacturing facility j in interval t, $k \in RC$, $j \in RM$, $t \in T$
QC_{kpt}	quantity of the recovered material units transported from recycling facility k to manufacturing facility p in interval t, $k \in RC$, $p \in MP$, $t \in T$
QB_{prt}	quantity of new batteries transported from manufacturing facility p to retailer r in interval t, $p \in MP$, $r \in R$, $t \in T$
QC_{jkt}	quantity of recyclable cells transported from remanufacturing facility j to recycling facility k in interval t, $j \in RM$, $k \in RC$, $t \in T$
QC_{jlt}	quantity of valueless cells transported from remanufacturing facility j to landfill l in interval t, $j \in RM$, $l \in L$, $t \in T$
QC_{klt}	quantity of valueless cells transported from recycling facility k to landfill l in interval t, $k \in RC$, $l \in L$, $t \in T$
QB_{rt}	quantity of batteries sold at retailer r in interval t, $r \in R$, $t \in T$
$M_{p,t}$	quantity of raw material purchased by manufacturing facility p, in battery cell units, in interval t, $p \in MP$, $t \in T$

Parameters

$I_{f,t}$	inventory level of facility f in interval t, $t \in T$, $\forall$ i, j, k, p, $r \in f$
UP	unit selling price for a brand-new LIB
C_f	battery (or battery cell) capacity limit of facility f, $f \in F$, $\forall$ i, j, k, r, $p \in f$
ac_y	acquisition cost for spent first/s/third-level LIB, for y = 1, 2, 3 respectively
$h_{f,t}$	holding cost at node facility f in interval t, $t \in T$, $\forall$ i, j, k, r, $p \in f$
FC_f	fixed opening cost of facility f, $\forall$ i, j, k, l, r, $p \in f$
$DIJ_{i,j}$	distance from collection center i to remanufacturing facility j, $i \in CC$, $j \in RM$
$DIK_{i,k}$	distance from collection center i to recycling facility k, $i \in CC$, $k \in RC$
$DIL_{i,l}$	distance from collection center i to landfill l, $i \in CC$, $l \in L$
$DJR_{j,r}$	distance from remanufacturing facility j to retailer r, $j \in RM$, $r \in R$
$DPR_{p,r}$	distance from manufacturing facility p to retailer r, $p \in MP$, $r \in R$
$DKJ_{k,j}$	distance from recycling facility k to remanufacturing facility j, $k \in RC$, $j \in RM$
$DJL_{j,l}$	distance from remanufacturing facility j to landfill l, $j \in RM$, $l \in L$
$DKL_{k,l}$	distance from recycling facility k to landfill l, $k \in RC$, $l \in L$
$DMMP_p$	distance from raw material market to manufacturing facility p, $p \in MP$
$DKP_{k,p}$	distance from recycling facility k to manufacturing facility p, $k \in RC$, $p \in MP$
tcc	unit transportation cost per battery cell
tcb	unit transportation cost per battery
tcm	unit transportation cost per material unit
α_y	percentage of first/s/third-level batteries among all returns, such that $\sum_y \alpha_y = 1$, $\alpha_y \in [0, 1]$
k_s	unit power capacity loss
pc_f	processing cost of each battery/cell for node facility f, $f \in F$, $\forall$ i, j, k, l, r, $p \in f$
pr_f	processing rate of node facility f, $f \in F$, $\forall$ i, j, k, l, r, $p \in f$
$RT_{i,t}$	number of battery returns sent to collection center i in interval t, $i \in CC$, $t \in T$
bc	number of cells included in a new/like-new LIB
b_j^k	number of remanufacture-able cells extracted from a LIB and processed at a recycling facility
b_k^j	number of recyclable cells extracted from a LIB and processed at a remanufacturing facility
b_l^k	number of valueless cells extracted from a LIB and processed at a recycling facility
b_l^j	number of valueless cells in a LIB and processed at a remanufacturing facility
$N_{f,t}$	number of batteries (or battery cells) processed at node facility f in interval t, $f \in F$, $\forall$ i, j, k, l, r, $p \in f$, $t \in T$
$B_{f,t}$	number of batteries (or battery cells) shipped to the node facility f in interval t, $f \in F$, $\forall$ i, j, k, l, r, $p \in f$, $t \in T$
$remt$	the remaining useful lifespan for a remanufactured battery
dt	designed lifespan extension (warranty years) for remanufactured batteries
et	expected lifespan of a brand-new LIB
ry	age of batteries returned to a collection center during the analysis period
C_{raw}	unit raw material purchasing cost
γ_z	value loss for a battery/cell waiting at facility z
D_t	battery demand during each interval
PT	fixed time duration in an interval