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Higher-capacity lithium ion battery chemistries for improved residential energy storage with micro-cogeneration ☆

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HIGHLIGHTS

- Characterized two novel high capacity electrode materials for Li-ion batteries.
- A numerical discharge model was run to characterize Li-ion cell behavior.
- Engineering model of Li-ion battery pack developed from cell fundamentals.
- ESP-r model integrated micro-cogeneration and high capacity Li-ion storage.
- Higher capacity batteries shown to improve micro-cogeneration systems.

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ABSTRACT

Combined heat and power on a residential scale, also known as micro-cogeneration, is currently gaining traction as an energy savings practice. The configuration of micro-cogeneration systems is highly variable, as local climate, energy supply, energy market and the feasibility of including renewable type components such as wind turbines or photovoltaic panels are all factors. Large-scale lithium ion batteries for electrical storage in this context can provide cost savings, operational flexibility, and reduced stress on the distribution grid as well as a degree of contingency for installations relying upon unsteady renewables. Concurrently, significant advances in component materials used to make lithium ion cells offer performance improvements in terms of power output, energy capacity, robustness and longevity, thereby enhancing their prospective utility in residential micro-cogeneration installations. The present study evaluates annual residential energy use for a typical Canadian home connected to the electrical grid, equipped with a micro-cogeneration system consisting of a Stirling engine for supplying heat and power, coupled with a nominal 2 kW/6 kW h lithium ion battery. Two novel battery cathode chemistries, one a new Li–NCA material, the other a high voltage Ni-doped lithium manganate, are compared in the residential micro-cogeneration context with a system equipped with the presently conventional $LiMn_2O_4$ spinel-type battery.

1. Introduction

Micro-cogeneration systems are making inroads for electricity generation at the residential level. The devices which provide both heat and power, known as the prime mover of the system, include internal combustion engines, solid oxide fuel cells, proton exchange membrane fuel cells, or Stirling engines (SEs). They typically generate less than 15 kW of electricity and are located within the household. When producing electricity alone, micro-cogeneration devices yield poor efficiencies, however when configured in systems which recover thermal energy generated in the electrical conversion process, the efficiency can rise to over 80%, referenced to the higher heating value of the fuel [1].

Annex 42 of the International Energy Agency's Programme on Energy Conservation in Building and Community Systems (IEA/ECBCSs) was focussed on reducing residential electric demand using micro-cogeneration devices through study with whole-building computer simulation software [2]. Among its conclusions were that engine start-up times, high operating temperatures, large thermal inertia, and internal controls preventing high thermal stresses, all contributed to sub-optimal response of micro-cogeneration systems to transient electrical loading. Accommodating these conditions would assist the transient performance of residential micro-cogeneration systems at times when electricity demand fluctuates rapidly. Forecasting into the future with high penetration rates of micro-cogeneration devices in households, it

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was concluded that the grid could no longer be viewed as an infinite power storage source. Thus, power storage technologies will become essential for residential micro-cogeneration applications.

The succeeding current IEA Annex 54 (www.iea-annex54.org) is expanding the scope of micro-cogeneration systems to also consider components contributing renewable electricity for the building. The temporal character of power generation from transient sources does not coincide with that for power consumption, thus electrical storage capacity is highly necessary for obtaining maximal energy use benefits and the best economy from these micro-cogeneration systems. Storing electricity in a rechargeable battery facilitates a quick transient response to a varying imposed electric load. Thus micro-cogeneration systems with residential energy storage (RES) are well positioned as a good solution for small-scale power generation, and the prospects are promising for scenarios with a large degree of market penetration.

Rechargeable large-scale lithium ion batteries with good capacity and cyclability are among the most promising choices for RES applications. Lithium ion batteries have many characteristics which make them highly suitable for being the electrical storage components of choice. These characteristics include very high energy density, good power output, good cycle life with a broad cycling range, high coulombic efficiencies and comparatively low heat output [3]. For prolonged intensive use, such as a in a micro-cogeneration system, proper control and management of a lithium-ion battery is crucial to ensure high capacity retention, as well as to operate the unit in a safe manner.

Current understanding suggests that lithium ion batteries at ratings around a 2 kW/6 kW h level are of a size suitable for development for residential power supply and storage. It has been shown that they can provide economic benefit under time-of-use pricing structures, as storing energy can reduce peak power demands as well as offset costly infrastructure upgrades to electrical power grid networks [4]. By simulating lithium ion battery physics and chemistry, the aim is to help identify microstructural properties and materials which will respond well to real imposed current loads which have been obtained from recent electrical profile measurements [5]. This approach can also help demonstrate a battery materials parameter set as a target for accompanying material development research to satisfy realistic operating requirements.

At present some large-scale commercial battery energy storage systems (BESSs) have been built and installed [6,7]. For now, at the beginning stages of the adoption of these technologies, economies of scale have not been achieved. Under present conditions, larger BESS systems are more economically viable, as the associated control equipment represents a significant fraction of the unit cost, and it does not increase in proportion with battery size. The battery management electronics for smaller storage systems contributes to their current high cost.

An avenue being pursued to rectify the high cost of BESSs is that of higher capacity battery materials. The quest for higher energy/power density lithium batteries has led to research on higher voltage cathode materials to replace the commonly used $LiMO_2$ (M = Co and Ni) and $LiMn_2O_4$ or even $LiMPO_4$ olivines (M = Fe and Mn). Substituted spinels of the family $LiMn_{2-x}M_xO_4$ (M = Cr, Ni, Cu, Co, and Fe) exhibit a significant capacity above 4.5 V.

Laboratories here at the National Research Council of Canada have had success in developing several of these kinds of materials, two of which are explored in this paper as examples of how improved battery materials can enhance RES units integrated into micro-cogeneration systems. First among these materials is $LiMn_{1.5}Ni_{0.5}O_4$ or LiNMO, which has a relatively high theoretical capacity of 146.7 mA h/g, almost all of which is around 4.7 V, and good cycling capability [8].

The second material, lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ or LiNCA) is a leading candidate for lithium-ion batteries due to its high capacity and durability. The nominal voltage is 3.7 V, and the material capacity is in the 150–180 mA h/g range [9]. NCA is less commonly used in the consumer market. Its great potential as a cathode material has caught the attention of the automotive industry, despite safety and cost being current research issues.

Table 1 presents some cost figures related to materials costs for the three cathode materials considered here [10]. The LiNCA material is significantly more costly on a weight basis compared to the other two materials, owing to the high cost of its cobalt component. The cost per unit of current output however is still higher, but still more or less in line with the other two materials, since the cathode represents only one part of the total cell cost.

Residential energy use studies typically employ whole building simulation tools such as ESP-r to explore operational scenarios and system configurations in order to provide informed comment and recommendations for the suitability of their implementation [11]. ESP-r whole building simulations are used to coordinate all energy related components to evaluate usage scenarios for determining best practices in terms of energy consumption and economics. Strengths of ESP-r include its ability to handle complicated heat flux and plant equipment, as well as its ready availability and open-source format suitable for adding simulation capabilities and models for new technologies [12]. A number of cases can be cited from the literature where building simulations for improving energy efficiency have been studied with systems which included batteries for electrical storage. The concept of including storage batteries with supplementary residential power generation sources has been understood for some time now, an early example provides qualitative discussion about the general applicability of batteries with PV power [13].

Micro-cogeneration models using battery storage for load leveling applications have been developed using lead acid batteries [14]. However, in favor of Li-ion technology, life-cycle analysis has demonstrated the poor economic viability of competing lead acid battery technology [15]. An electric storage model in the building simulation program ESP-r using lead acid and vanadium redox flow batteries (VRFBs) has also been developed [16], which studied battery use coupled with photovoltaic renewable generation, within the power-modeling domain of ESP-r. The present subject is of broader interest, as it has been extended to energy studies of battery use on the community scale, but to this point, has not been coupled with the electrochemical fundamentals more representative of real battery behavior [17].

The main theme of this present work is to present some analysis of the performance of a micro-cogeneration system consisting of a Stirling engine as the combined heat and power (CHP) prime mover, along with a large Li-ion battery for energy storage and provision, according to the varying temporal demands of an annual electrical load profile. The inclusion of the battery in the system allows for less overall draw from the grid, as well as the storage of any temporary excess of electricity for use at a later time. A further theme is to show that by demonstrating improved battery performance through simulating discharge properties of novel higher-capacity cathode materials, the prospects for the viability of such CHP systems with batteries are much enhanced.

Table 1
Comparison of material costs for the three cathode formulations [10].

Material	Capacity (mA h/g)	$/kg	$/A
$LiMn_2O_4$	110	16	0.145
LiNCA	180	40	0.222
LiNMO	147	25	0.170