

# Preface

The industrial revolution (1750–1850) fueled the largest economic growth in the history of the world. It has provided the means for a gigantic leap forward toward the modern world of mechanized manufacturing, motorized transportation, central power stations, big cities, cheap agriculture, clean water, commercial flights, telecommunications, personal computing, space travel, and a longer and better life for all of us. Two main contributions have been the invention of the combustion engine and the long-distance transfer of electricity. Most of our daily life hinges on the development of these two monumental discoveries. However, some have recently proposed that the current rate of innovation is slowing down in part due to more resources being dedicated to discoveries which impact society on a more superficial level. For example, according to recent metrics, most recent startups focus on e-business (Alibaba, Amazon, Twitter, Facebook, Groupon, or Snapchat). According to these critics, these e-companies do not improve the quality of our life in as a grandiose fashion as the first commercial airliner did at the turn of the last century. Therefore, monumental, game-changing inventions are sought after more than ever in today's incremental world. While many radical new ideas are being pursued (Randell Mill's SunCell® would be high on that list), the world seems to have entered an electrification race. Gradual improvements in technologies such as electrochemical storage and photovoltaics have reached a tipping point which could foster a new era of decentralized power generation and autonomous storage. These alternative methods of energy storage have already started to compete with the 150-year-old model of the central power station.

Today, most electricity is generated at a central power plant and is transferred as alternative current via high-voltage cables to power large, congested nearby cities. Advanced commerce and modern lifestyles are enabled by automotive transportation powered by internal combustion engines which are fueled by a network of gasoline stations. However, advances in solar, wind, and battery technology have reached the necessary critical mass to offer an alternative. Electric cars and solar roofs are now a commercial reality. In the near future, economies of scale promise to bring down their cost which will make autonomous power generation and usage an option for anyone interested. With a current energy density of 265 Wh/kg (and

possible improvements of up to 20%), the lithium-ion battery has the required lifetime to power personal terrestrial vehicles or autonomous or ad hoc power grids. According to Tesla and Volkswagen, the price of 1 kWh of lithium-ion storage will drop to \$100 by 2020 which translates into a \$10,000–\$15,000 cost for the battery pack in any personal car (sedan or SUV). Tesla has the aggressive goal of a one million mile warranty for its drivetrain which amounts to the complete lifetime of the vehicle.

Nonetheless, we dare to look further and desire higher energy densities and longer lifetimes at ever cheaper prices. This quest is the exciting field of post-lithium-ion batteries which may open the door to currently inaccessible markets such as electric commercial flight or commercial terrestrial transportation which require a strenuous, nonstop schedule of operation. These new markets require large improvements in energy density ( $>500$  Wh/kg) and cycle life ( $>10,000$  full cycles) or steep cost reductions. Rechargeable magnesium batteries are promising next-generation batteries due to the safety, low cost, and high volumetric energy density of magnesium. For example, an ultralow-cost contender is the intrinsically safe magnesium-sulfur battery (280 Wh/kg) which may cost less than \$10 for 1 kWh of energy. Sony Corporation is reportedly working on this battery and is planning to bring it to market by 2020. Such a post-lithium-ion battery may create entirely new markets and improve the standard of living for all mankind.

This brief is written for the battery enthusiast, who may either desire to invest in the field, is curious about a new exciting area of research, or is simply a college student who wants to learn more about future battery tech. A minimal familiarity with concepts of lithium-ion is necessary to grasp concepts related to electrolyte or cathode development. The brief starts off with a short history of battery and how we reached the tipping point of lithium-ion and makes the case for a transition beyond lithium-ion. A rechargeable battery with a magnesium metal anode is then proposed, and recent developments in the field of magnesium electrolytes and electrodes are discussed and critiqued. Challenges in these key areas are unearthed, analyzed, and explained. In the end, a conclusion summarizes key recent findings and proposes future direction.

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