Optimal recycling in a fast-learning industry: application to lithium-ion batteries

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This paper theoretically and numerically discusses the optimal launching of recycling of a good produced by an industry facing substantial technological progresses. Such research is mainly motivated by the case of lithium-ion batteries, which are believed to be one the most critical technology for the energy transition. Indeed, they are already central component of electric vehicles, as well as a storage option for power systems with high shares of intermittent renewable energy. A remarkable feature of lithium-ion batteries has been its technological progress. Indeed, battery costs have fallen from USD 1 100 per kilowatt-hour (kWh) in 2010 to USD 156/kWh in 2020 (IEA, 2020). However, lithium-ion batteries are not exempt from environmental concerns. Among them, the end-of-life of batteries may be particularly hazardous. Added to a potential scarcity of some metals (lithium, but also rare earth materials), recycling of used batteries appears as an appealing solution. For these reasons, the European Commission has introduced recycling as a key-element of its reform of the legislation on EU batteries. Recycling is therefore supposed to be part of the European industrial strategy on battery manufacturing. There are broadly two options in battery recycling : total recycling and reconditioning. Total recycling involves recovering key material (lithium and rare earths) from the used battery packs. Reconditioning involves using directly the retired battery for other purposes, such as storage solutions for the power grid.

Our work relates to several streams literature.

First, literature tackling the economics of waste and recycling is significant. Seminal work on resource economics uses optimal control theory to show the arbitration between social costs associated to waste accumulation and resource scarcity, and private costs related to recycling (Smith, 1972; Huhtala, 1999). Combined approach of different externalities with recycling is also the focus of Lafforgue and Lorang (2020) who model an industry with a recycling with a cap on emissions. As our model tackles an industry with important ongoing

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technological evolutions, we also relate to the work of Lafforgue and Rouge (2019) and their analysis of recycling including necessary R&D investments before its deployment. The specific case of recycling coupled with electro-mobility has been a topic of research when dealing with its prominent resource, lithium (Rosendahl and Rubiano, 2019; Lv et al., 2018).

Then it relates to the literature on learning, especially when applied to pollution abatement technologies. The review from Thompson (2010) shows different solutions to implement and analyze passive learning patterns in industrial sectors. The role of learning by doing in the specific case of environmental technologies is tackled by Bramoullé and Olson (2005), as they characterized optimal abatement technologies and their associated cost trajectories. However they analyze two independent sectors, while we focus on connected ones, from the existence of the recycling loop. Later work from Creti et al. (2018) also analyzes this topic and apply it to the more specific case of electro-mobility. They compute the optimal schedule for the production of goods with a carbon price, and the total cost of this program.

Our paper tackles the development a battery recycling sector within a dynamic partial equilibrium model. There are two technologies that feed a stock of general-purpose batteries, whose demand is fixed according an exogenous evolution. We first discuss the optimal strategy for the recycling of batteries using optimal control theory. The battery sector is modeled with recycling, learning by doing spillovers and damage from waste accumulation. We compare marginal costs and full marginal benefits for using regular or recycled input for batteries, and show that it is optimal to start recycling after a certain delay. The steady state is described, with a sensitivity analysis on exogenous parameters. It highlights trade-offs that determine the optimal level of waste accumulation, as it can be both a resource and a source of negative externalities. Optimal timings to start recycling are then numerically analyzed. We show that we recycle earlier when batteries have a shorter lifetime, and later when learning is important on regular production or, paradoxically, when recycling is materially more efficient.