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# How effective is lithium recycling as a remedy for resource scarcity?

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## Abstract

We investigate to what extent recycling can remedy resource scarcity, and whether market intervention is desired. For doing so, we develop a dynamic model of the global lithium market. An efficient market for resource waste allows consumers to internalize the waste value when they buy the resource. In the analytical part of our paper, we show that the efficient market can alternatively be realized through a proper set of worldwide subsidies to either buyers or sellers of both virgin and recycled lithium. In our numerical simulations, we find that optimal subsidies may become quite substantial in the second half of this century. The size of these subsidies depends, however, on a number of uncertain assumptions such as technological progress in both extraction and recycling, quality-grade of recovered lithium, and demand elasticity.

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## Highlights

- Lithium scarcity will be much more evident without the possibility to recycle lithium
- Unless an efficient market for depreciated lithium develops, a market intervention is needed
- In a free market solution, the incentives to recycle lithium may be low
- Proper subsidies to either buyers or sellers of lithium may realize the optimal solution
- Optimal subsidies size depend on uncertain assumptions regarding the future lithium market development.

## 1. Introduction

Lithium resources are crucial for the electrical revolution, especially when it comes to electrifying the transport sector through lithium-ion batteries (LiBs). Lithium is a non-renewable resource, and its availability allows low-carbon technologies development and electricity storage from intermittent sources like sun and wind, such as smart grid storage. A shortage of identified lithium reserves is likely to happen, and if the world finds no remedies for scarcity, there exist clear limitations to continuing this energy transition.

Lithium recycling can extend the life span of the lithium stocks, yet, some researchers have questioned the potential for such a solution (Kushnir and Sanden, 2012); (Pehlken *et al.*, 2017). Nowadays, lithium recycling is neither functional nor economically feasible (Andersson *et al.*, 2017). Therefore, a market for second hand lithium does not exist. In this paper, we question whether an efficient market for depreciated lithium will emerge in the future, and whether market intervention will be needed.

We investigate to what extent a recycling market can remedy resource scarcity, and whether market intervention is desired. To do so, we develop a dynamic model of the global market for lithium. By market forces, lithium prices are likely to climb as lithium demand continues to rise. Also, the rush of lithium will promote new investments and discoveries. Even remote and costly reserves from the ocean could become economically attractive, and then increase available stocks (Sverdrup, 2016). The incentives to recycle depreciated lithium will also be enhanced as lithium prices rise.

Increasing prices of lithium could dampen the demand growth. However, higher lithium prices will not affect the cost of battery systems to a large extent (Ciez and Whitacre, 2016). Technological developments have pushed batteries' cost down and can lower the price of electric vehicles (EVs), and make them affordable to a broader segment of consumers. The International Energy Agency – IEA (2017) – foresees a vast increase in the global stock of EVs towards 2030. Still, the effect of higher lithium prices on other consumer sectors remains unknown.

As EVs and electronics demand increases, the volume of used batteries and lithium waste will surge too. A LiB can typically achieve 8 years of life (Wood, 2012). Current collection rates of spent LiBs is less than 10% in USA (Wang *et al.*, 2014) and less than 1% in Europe (Swain, 2017). Lack of regulation aggravates LiB waste management (Gaines, 2014), and neither the market nor the governments provide incentives to collect used LiBs.

With current technology, recycling costs are relatively high compared to raw lithium extraction costs. Recycled lithium comes as a by-product of recovering other and more pricy materials like cobalt (Richa *et al.*, 2014). In discarded batteries of electronics, lithium has low magnitude or quality-grade (Ziemann *et al.*, 2012), collection and separation is costly, and recovered lithium has a lower quality-grade level (Commission, 2016) (European Commission, 2016).

The engineer and material science literature continuously debate technical requirements that can reduce recycling costs. Battery design can make recycling easier, reduce material losses and increase mineral recovery (Ciacci *et al.*, 2015). Strict industrial standards can ensure that recovered material meets the same high quality-grade as virgin minerals (Gaines, 2014). Moreover, recycling industry profits build upon economies of scale and the infrastructure capable to absorb the vast diversity of battery design (Wang *et al.*, 2014).

Local market conditions can make recycling feasible (Rohr *et al.*, 2017). Yet, there is no consensus about to what extent local developments can reduce stress on foreign lithium dependency and shape a global competitive market of recycled lithium. This question affects mostly Europe and industrialized countries in the northern hemisphere that are making great advances on grid storage and electric cars production and consumption.

Recycling is a way to conserve natural resources. Economists studying this issue reformulated the traditional Hoteling model of resource exhaustion and indicated the recycling effects in two perspectives. First, recycling enlarges supply with waste recovery (Schulze, 1974), releases affordability concerns (Weinstein and Zeckhauser, 1974), and even contributes to the long-term growth of the economy (Pittel *et al.*, 2010). Second, recycling can mitigate environmental damages (Hoel, 1978). It can lower landfill costs of waste, reduce water and energy use, and preserve ecosystems mostly affected by strip mining. Here, we set aside environmental waste impacts and focus on the opportunity of "mining" valuable discarded resources.

Lithium's durability through the recycling process provides it with additional consumer utility. Lithium can withstand regular recycling without losing useful properties. As a result, durability promotes added longevity to value. Thus, the mineral will hold value as long as people find it a useful substance in consumer products, and this influences price behavior (Levhari and Pindyck, 1981). In batteries and electronic consumer products, lithium will lose apparent value as the product depreciates, but the recycling process restores value to the discarded material, or re-*circulation of matter*.

Collecting and recycling depreciated resources affects mineral consumers and producers. Mineral suppliers can affect both what remains to be extracted and what could be recycled in the next period, creating potential competition between mining firms and recyclers (Ba and Mahenc, 2015). Mining firms may find that their most important competition comes not from other firms' products, but from their own earlier production. In our case, recycling greatly affects consumer surplus and producers' profitability. Our model assesses what happens when recyclable minerals could return indefinitely to the market, and the effects of simultaneous actions by consumers and producers.

However, only a fraction of used material might return as recoverable waste. Schulze (1974) assumes that waste stock decays along time at a constant rate. In contrast, Pittel et al. (2010) assume complete recycling is possible with enough energy and space for waste storage. In line with Schulze (1974), we assume that just a fraction of used material is recyclable, but the fraction is endogenous and depends on profitability. If recycling does not happen the following year or period, then depreciated lithium stocks are assumed to be unavailable for recycling in the future either, due to excessive collection and storage costs.

We assume unit extraction cost increases with accumulated production, but decreases along time due to progress in technology. We further demonstrate the effect of technological change in both extraction and recycling. Because of continuous technological advances, extraction costs continue at moderate levels even when digging into less accessible resources.

Part of the literature on recycling of non-renewable resources disregards recycling costs (Weinstein and Zeckhauser, 1974), (Andre and Cerda, 2006); (Pittel *et al.*, 2010). We acknowledge that recycling costs are positive, assuming that marginal costs are strictly increasing in the recycled quantity, creating a gap between the shadow price of depreciated lithium and the resale value of recycled lithium. In line with Schulze (1974), we point out that scrap resources will become so precious that the society cannot afford the opportunity cost of accumulating waste.

Consumers will always benefit from recycling if this sector is independent from the extractive industry and there is no chance of vertical integration in the supply chain (Martin, 1982). However, even if recycling takes place as a result of market forces, that will not ensure an optimal recycling level, e.g., if there exists market power (Grant, 1999) (Sourisseau *et al.*, 2017) (Martin, 1982).

An efficient market for resource waste allows consumers to internalize the waste value when they buy the resource. Pittel et al. (2010) propose subsidies to resource extractors and recyclers to restore optimality in an inefficient market. We evaluate, in the context of lithium resources, how subsidies may enhance society's welfare while market shifts from an unregulated and inefficient market to a social planner solution. Although our work is close to Pittel et al. (2010), the models differ in several respects. In particular, where they assume zero extraction and recycling costs, we consider non-linear cost functions for both extraction and recycling. We also apply the model to the lithium market and simulate a range of scenarios to get a better insight about this market, in particular the importance of recycling and the potential need for market intervention. We are not aware of previous studies that have applied dynamic models of non-renewable and recyclable resources to a particular mineral resource.

In this paper, we question whether an efficient market for depreciated lithium will emerge in the future, and whether market intervention will be needed. In Section 2 we introduce the model and emphasize the differences between the (free) market outcome and the efficient (social planner) solution. We show that a proper set of subsidies to buyers or sellers of both virgin and recycled lithium can realize an efficient solution. Section 3 describes the numerical model, building on the analytical Section 2, and presents our simulations for the global lithium market. We find that optimal worldwide subsidies may become quite substantial in the second half of this century. The size of these subsidies depends, however, on uncertain assumptions, such as technological progress in both extraction and recycling, quality-grade of recovered lithium, and demand elasticity. To conclude, in Section 4 we provide policy insights and outline some issues worthy of further research.

## 2. Analytical model for the global lithium market

This section presents our theoretical model for the global lithium market. Although we formulate it in the lithium context, it generalizes to other non-renewable and recyclable resources. We first derive the efficient or global social planner solution (Section 2.1), then describe the market solution (Section 2.2), and compare with the efficient one (Section 2.3). In the theoretical model, we consider one representative consumer and one representative producer.

## 2.1. Efficient (social planner) solution

The efficient solution is derived by maximizing the net present value of the sum of consumer and producer surplus in the global lithium market, which we will refer to as (global) welfare. As we are not concerned about distributional aspects between consumers and producers, or between regions, the welfare in each period is simply given by the gross consumer surplus minus extraction and recycling costs.

Let $U(x+qw)$ denote consumer's money-metric utility of using lithium, where $x$ denotes virgin lithium, $w$ denotes recycled lithium, and $q \leq 1$ the quality-grade of recycled lithium relative to virgin lithium. In order to simplify the analysis, we assume the two types of lithium are homogeneous, when adjusting for possibly inferior quality-grade of recycled lithium. Furthermore, let $MU(x+qw)$ denote the marginal utility of consuming lithium, so that $U(x+qw) = \int_0^{x+qw} MU(s)ds$ represents the willingness to pay for combined industry output, raw and recycled. This also represents the gross consumer surplus of consuming lithium.

We assume unit extraction costs $c^E(A)$ increase with accumulated extraction $A$ ($c_A^E > 0$), where accumulated extraction increases according to $\dot{A} = x$. Total extraction costs are given by $C^E = c^E(A)x$.

The stock of lithium in use $L$ develops according to $\dot{L} = x + qw - \gamma L$, where $\gamma$ denotes the annual depreciation rate of lithium stocks in use. The depreciated lithium is available for recycling. Thus, we have $w \leq l \leq \gamma L$, where $l$ represents the input of depreciated lithium that enters the recycling process.

Recycling cost is given by $C^W(w,l)$, where we assume that $C_w^W > 0$, $C_{ww}^W > 0$, $C_l^W \leq 0$, $C_{wl}^W \leq 0$;with strict inequality for $C_l^W$ and $C_{wl}^W$ when $w > 0$. Moreover, we assume that $\lim_{w \to l} C_w^W = \infty$. Thus, the constraint $w \leq l$ will never be binding.

The efficient solution is given by maximizing the following welfare expression related to a social discount rate $r$:

$$\max_{x,w>0} W = \int_0^\infty \left[ \int_0^{x+qw} MU(s)ds - c^E(A)x - C^W(w,l) \right] e^{-rt}dt \tag{1}$$

Given the following constraints:

$$\dot{A} = x \quad \text{and} \quad A(\dot{0}) = 0 \tag{2}$$

$$\dot{L} = x + qw - \gamma L \quad \text{and} \quad \dot{L}(0) = 0 \tag{3}$$

$$l \leq \gamma L \tag{4}$$

The current-value Hamiltonian is:

$$H^C = \int_0^{x+qw} MU\,(s)ds - c^E(A)x - C^W(w,l) + \lambda x + \varphi(x + qw - \gamma L) - \theta(l - \gamma L) \tag{5}$$

Where $\lambda \leq 0$ and $\varphi \geq 0$ denote the shadow prices of the stock variables $A$ and $L$, respectively, whereas $\theta \geq 0$ denotes the shadow price of the constraint $l \leq \gamma L$.

We then get the following first order conditions:

$$\frac{\partial H^C}{\partial x} = MU(x + qw) - c^E(A) + \lambda + \varphi \leq 0 \quad \perp \quad x \geq 0 \tag{6}$$

$$\frac{\partial H^C}{\partial w} = qMU(x + qw) - C_w^W(w, l) + q\varphi \leq 0 \quad \perp \quad w \geq 0 \tag{7}$$

$$\frac{\partial H^C}{\partial l} = -C_l^W(w, l) - \theta \leq 0 \quad \perp \quad l \geq 0 \tag{8}$$

$$-\frac{\partial H^C}{\partial A} = c_A^E(A)x = \dot{\lambda} - r\lambda \tag{9}$$

$$-\frac{\partial H^C}{\partial L} = \gamma\varphi - \gamma\theta = \dot{\varphi} - r\varphi \tag{10}$$

By having $x > 0$, and $w > 0$, from (6) and (7) we get

$$MU(x + qw) = c^E(A) - \lambda - \varphi \tag{11}$$

$$MU(x + qw) = \frac{C_w^W(w, l)}{q} - \varphi \tag{12}$$

Equation (11) states the marginal utility of consuming lithium should equal the unit extraction costs plus the resource rent $(-\lambda)$ , i.e., the shadow price of accumulated extraction $A$; minus the shadow price of the lithium stock in use $(\varphi)$. The latter shadow price takes into account that the extracted lithium has an additional value given by the ability to recycle the resource and use it again.

Equation (12) states that the marginal utility of consuming lithium should equal the marginal recycling costs (adjusting for the quality-grade of the recycled lithium) minus the shadow price of the lithium stock in use $(\varphi)$. Again, the shadow price takes into account that the recycled resource may be recycled once more.

Combining (11) and (12) to eliminate $MU(x + qw)$, we have:

$$c^E(A) - \frac{C_w^W(w, l)}{q} = \lambda \tag{13}$$

The state variables $\lambda$ and $\varphi$ move in this way:

$$\dot{\lambda} = r\lambda + c_A^E(A)x \tag{14}$$

$$\dot{\varphi} = (r + \gamma)\varphi - \gamma\theta \tag{15}$$

If $l > 0$, plugging (8) in (15) we get: $\dot{\varphi} = (r + \gamma)\varphi + \gamma C_l^W(w, l)$.

The transversality conditions on terminal stocks $A$ and $L$, and their shadow prices $\lambda$ and $\varphi$, require that the discounted shadow values tend to zero as time goes to infinity:

$$\lim_{t\to\infty} e^{-rt}\lambda\, A = 0 \tag{16}$$

$$\lim_{t\to\infty} e^{-rt}\varphi\, L = 0 \tag{17}$$

## 2.2. Market solution

We now consider the market outcome. Let $P^L$ denote the market price of lithium, i.e., either virgin lithium or recycled but quality-grade adjusted lithium. Further, let $P^W$ denote the price of depreciated waste of lithium, which the recycling industry may buy in the market, and $P_C^W$ the price consumers may get if they are able to sell their used lithium. In general we assume that $P_C^W \leq P^W$, and will in particular consider the cases $P_C^W = P^W$ and $P_C^W = 0$ (see discussion below).

### Extraction of lithium

We first consider the optimization problem of the primary lithium producer:

$$\max_{x>0} \pi^E = \int_0^\infty [P^L x - c^E(A)x]e^{-rt}dt \tag{18}$$

Subject to equation (2).

The current-value Hamiltonian is: $H^C = P^L x - c^E(A)x + \lambda^E x$. Thus, the necessary conditions for an interior solution are:

$$\frac{\partial H^C}{\partial x} = P^L - c^E(A) + \lambda^E \leq 0 \quad \perp \quad x \geq 0 \tag{19}$$

$$-\frac{\partial H^C}{\partial A} = c_A^E(A)x = \dot{\lambda}^E - r\lambda^E \tag{20}$$

Thus, with interior solution, $x > 0$, we have:

$$P^L = c^E(A) - \lambda^E \tag{21}$$

The transversality condition holds with complementarity slackness as was shown in equation (16).

### Consumption of Lithium

The representative consumer faces the following optimization problem, maximizing their net consumer surplus $CS$:

$$\max_{(x+qw),l>0} CS = \int_0^\infty \left[\int_0^{x+qw} MU(s)ds - P^L(x+qw) + P_C^W l\right] e^{-rt}dt \tag{22}$$

Subject to equations (3) and (4), we have the following current-value Hamiltonian for the consumer:

$$H^C = \int_0^{x+qw} MU(s)ds - P^L(x+qw) + P_C^W l + \varphi^C(x+qw-\gamma L) - \theta^C(l-\gamma L) \tag{23}$$

Which gives:

$$\frac{\partial H^C}{\partial x} = MU(x+qw) - P^L + \varphi^C \leq 0 \quad \perp \quad x \geq 0 \tag{24}$$

$$\frac{\partial H^C}{\partial w} = MU(x+qw)q - P^L q + \varphi^C q \leq 0 \quad \perp \quad w \geq 0 \tag{25}$$

$$\frac{\partial H^C}{\partial l} = P_C^W - \theta^C \leq 0 \quad \perp \quad l \geq 0 \tag{26}$$

$$-\frac{\partial H^C}{\partial L} = \gamma\varphi^C - \gamma\theta^C = \dot{\varphi}^C - r\varphi^C \quad (27)$$

Thus, with interior solutions we have:

$$MU(x + qw) = P^L - \varphi^C \quad (28)$$
$$P_C^W = \theta^C \quad (29)$$
$$\dot{\varphi}^C = (r + \gamma)\varphi^C - \gamma\theta^C = (r + \gamma)\varphi^C - \gamma P_C^W \quad (30)$$

The first FOC states that consumers will demand lithium up until the point where their marginal utility $MU(x + qw)$ equals the difference between the price of lithium and the shadow value of lithium stocks in use. Depreciated lithium may be sold in the future at a price $P_C^W$. If this price equals zero in all future periods, or if the consumers are myopic and do not expect to sell used lithium, the shadow price $\varphi^C = 0$, and we have the usual FOC that price is equal to marginal utility. The second FOC simply says that if $P_C^W > 0$, then the shadow price $\theta^C > 0$, and accordingly we must have $l = \gamma L$. That is, all depreciated lithium is sold to the recycling industry, as the depreciated lithium has no other value. The transversality condition also holds as in equation (17).

### Recycling of lithium

The competitive recycling industry buys depreciated $l$ at the price $P^W$. This input price could be determined by the market, and e.g. equal to $P_C^W$, or it could be regulated by the government and possibly set equal to zero. We assume the recyclers do not have property rights over the stocks of depreciated waste of lithium, and that storing used lithium is too costly to be profitable, so their problem is solved in a static fashion. They recycle (parts of) the lithium at cost $C^W(w, l)$, and sell the recovered lithium $w$ at price $P^L q$. Thereby, their instantaneous profit maximization problem is:

$$\max_{w,l>0} \pi^W = P^L qw - P^W l - C^W(w, l) \quad (31)$$

However, recyclers cannot buy more input than $\gamma L$, so we need to account for this constraint (with shadow price $\kappa^R$).

This gives the following FOCs:

$$P^L q - C_w^W(w, l) \leq 0 \qquad \perp \qquad w \geq 0 \quad (32)$$
$$-P^W - C_l^W(w, l) - \kappa^R \leq 0 \qquad \perp \qquad l \geq 0 \quad (33)$$

Interior solution gives:

$$P^L q = C_w^W(w, l) \quad (34)$$
$$P^W = -C_l^W(w, l) - \kappa^R \quad (35)$$

The first FOC states that the recycling industry will recycle lithium up until the point where marginal recycling costs equal the quality-adjusted price of lithium, i.e., a standard competitive condition. The second FOC states that the industry will buy depreciated lithium as long as the price of lithium waste does not exceed the marginal cost reduction of having access to more lithium waste. Since the latter is always strictly positive if recycling is profitable (i.e., $-C_l^W(w, l) > 0$ for all $w > 0$), and the alternative cost of depreciated lithium is zero, we assume that $l = \gamma L$ whether or not there is an efficient market for used lithium. Then the constraint on input may be binding, in which case $\kappa^R > 0$. Thus, we get $P^W = -C_l^W(w, \gamma L) - \kappa^R$. Either there is an efficient market for used lithium (in which case the price is bid up until $\kappa^R = 0$), or the recycling industry is able to collect the used lithium in some other way (e.g., through government intervention).

### Comparing efficient solution and market outcome

In a decentralized economy or free market, consumers may expect to sell their depreciated lithium at some price $P_C^W$, while recyclers expect to buy depreciated resources at some price $P^W$. If these prices are equal, e.g. determined in the market, and consumers correctly anticipate this when they buy lithium, the market will provide an efficient solution. This can be seen by comparing all conditions above: (21) and (28) are equivalent with (11), (28) and (34) with (12), (20) with (14), (30) with (15), and (29) and (35) with (8) (given that $P_C^W = P^W$ and $\kappa^R = 0$).

On the other hand, if there is no efficient market for lithium waste, e.g., that consumers do not take into account that they can sell depreciated lithium, then the shadow price of the stock of lithium is equal to zero ($\varphi^C = 0$ if $P_C^W = 0$ in all future periods). Consequently, consumers are not willing to pay more than their marginal utility, which tends to depress the price of lithium, reducing the incentives to both extract and recycle lithium. This is a positive externality, as consumers do not take into account that used lithium has a value for the society.

The externality may be corrected by e.g. introducing a subsidy equal to $\varphi^C$ for purchase of virgin lithium, and a subsidy equal to $\varphi^C q$ for purchase of recycled lithium. This reestablishes the equality between the social optimal solution, given by (11) and (12), and the market solution, given by (28) in combination with (21) and (34). With such a social planner intervention, the positive externality is internalized by the consumers, providing an efficient solution.

## 3. Numerical simulation

We now extend the analytical model application and investigate the lithium recycling potential in the global market for lithium. For doing so, we apply a Mixed Linear Complementarity Model - MCP. Here, we have an equilibrium model with a mixture of nonlinear equations and adjacent inequalities or complementarity constraints. Section 3.1 describes the numerical model. Section 3.2 presents the scenarios we consider, and Section 3.3 presents the simulation results. We are particularly interested in comparing the market outcome with the efficient solution, but also the importance of recycling in the future market for lithium.

### 3.1. Numerical model description

The numerical model extends and adjusts the analytical model (Section 2), to reflect the current market situation for lithium. Here we describe the numerical model, relate it to the analytical model, and present how we calibrate the parameters.

The global lithium market is divided into four lithium consuming sectors $i$ (Table 1), and seven lithium extracting regions $j$ (Table 2). Lithium demand in electric transport accounts for less than 5% of total lithium consumption. Grid storage has a marginal share today (less than 1%) but could grow substantially in the future in parallel with increasing market shares of intermittent renewable energy such as solar and wind power.

Consumer electronics demand accounts for 33%, and industrial applications consume around 60% of total lithium consumption. Those applications include lubricating greases, ceramics and glass, air conditioning units, aluminum and pharmaceutics production.

*Table 1. Lithium consuming sectors*

| | Transportation | Grid Storage | Consumer Electronics | Industrial Applications | Total |
|---|---|---|---|---|---|
| **Base year demand 2016 (1,000 tons)** | 9.6 | 2.3 | 66.6 | 123.2 | 201.8 |
| **Assumed annual depreciation rate*** | 10% | 7% | 90% | - | Not Applicable (N/A) |

Total lithium consumption is estimated as an extrapolation of 8 years (2005-2012) with data from (Cochilco, 2013). Sector demand proportions are based on (USGS, 2017)

* For lithium used in industrial applications we assume no recycling

*Table 2. Lithium extracting regions*

| | Argentina | Australia | Bolivia | Chile | China | USA | Rest world | Total |
|---|---|---|---|---|---|---|---|---|
| **Identified reserves* (Million Tons)** | 7.1 | 2 | 8.9 | 8.0 | 7 | 6.9 | 2.3 | 42.23 |
| **Base year Production 2016 (1,000 Tons)**** | 24.0 | 80.8 | 0.02 | 78 | 14 | 2.7 | 2 | 201.8 |
| **Assumed initial unit cost of extraction***(USD/kg)** | 2.7[a] | 2.7[b] | 2.7[c] | 2.3[d] | 3.3[e] | 3[f] | 3.4[g] | N/A |
| **Transport Cost (Thousand USD/Tons)** | 2 | 2.5 | 2 | 2 | 1.25 | 2.5 | 1.25 | N/A |

(*) Sources: (Cochilco, 2013), (USGS, 2017)

(**) Extrapolation for 2015 based on data from (Cochilco, 2013)
(***) Nominal values. Data Source: (a) (Orocobre, 2015)(b)(Galaxy, 2015), (c)(Comibol, 2017), (d) and (e)(Cochilco, 2013), (f) (Yaksic and Tilton, 2009)(g) (Nemaska Lithium, 2017)

We assume the following standard utility function for use of lithium $y_{it}$ (in all consuming sectors $i$):

$$U_{it}(y_{it}) = \Phi_i + \frac{\alpha_i}{1+\alpha_i} y_{i0}\sigma_{it} \left(\frac{y_{it}}{y_{i0}\sigma_{it}}\right)^{\frac{1+\alpha_i}{\alpha_i}} \quad (36)$$

Where $\Phi_i$ is a constant, $\alpha_i$ represents the (long-term) price elasticity of demand, and $y_{i0}$ denotes the initial demand level. The factor $\sigma_{it}$ is an exogenous growth function reflecting the underlying growth in demand. The elasticity $\alpha_i$ is -0.5 in the benchmark scenarios.[1] This gives the following marginal utility function:

$$U_{it}'(y_{it}) = \left(\frac{y_{it}}{y_{i0}\sigma_{it}}\right)^{\frac{1}{\alpha_i}} \quad (37)$$

And thereby the derived demand function:

$$y_{it} - y_{i0}\sigma_{it}\left(\frac{p_t}{p_0}\right)^{\alpha_i} \geq 0 \perp \quad y_{it} \geq 0 \quad (38)$$

The growth function $\sigma_{it}$ is calibrated based on projections from the IEA (2017) for the medium term (to 2030) and Kushnir et al. (2012) for the longer term, using a logistic functional form with several parameters. Obviously, the long-run growth in demand is highly uncertain. More details on the functional form and the calibrated parameters are found in the Appendix A.

Lithium supplies can come from extracting virgin minerals ($x_{jt}$), or from recycling depreciated lithium ($qw_t$). Recycling happens in most sectors (except for example pharmaceutical use, ceramics, and air conditioning). As explained in Section 2, we assume that recycled lithium suplants perfectly primary lithium, when adjusting for lower quality-grade.

We are interested in the long-run effects. Thus we assume the lithium market clears when aggregate demand ($y_{it}$) equals the aggregate extraction level plus recovered lithium. Free entry in both the mining industry and the recycling sector is assumed, except that access to lithium resources are needed in order to supply primary lithium, and firms are price takers.

$$\sum_{j=1}^{7} x_{jt} + qw_t - \sum_{i=1}^{4} y_{it} \geq 0 \perp p_i \geq 0 \quad (39)$$

Extraction costs vary with ore-grades. Thus, it is economically optimal to deplete the cheapest reserves first (Solow and Wan, 1976); (Boyce, 2012). As low-cost resources become exhausted, extraction must turn towards deeper and costlier deposits. While

[1] As far as we know, there exists no empirical studies of demand elasticities of lithium. Thus, the size of this elasticity is very uncertain, especially in the long run when the price sensitivity depends for instance, on the availability of substitutes. Therefore, we perform sensitivity analysis with respect to this elasticity.

extraction costs increase, scarcity rents may or may not decrease with time (Hanson, 1980).

In contrast to Pittel et al. (2010), we use a cost function of virgin lithium extraction that considers the effect of accumulated production and technological change:

$$C_{jt} - c_{j0}e^{\eta_j A_{jt} - \tau_E t}x_{jt} - c_j^T x_{jt} - C_{jt}^A(x_{jt}, x_{j0}) \geq 0 \perp C_{jt} \geq 0 \tag{40}$$

The cost function consists of three parts. The first part, $(c_{j0}e^{\eta_j A_{jt} - \tau_E t}x_{jt})$ adopted from e.g. Grimsrud *et al.* (2014), assumes unit extraction costs (starting at $c_{j0}$) increase with accumulated supply $(A_{jt})$ and decrease with (exogenous) technological progress$(\tau_E)$. The parameter $\eta_j$ represents the rising costs rate as accumulated production increases and is calibrated to the initial stock levels of lithium resources for each producer (see Table 2 above). The second part, $(c_j^T x_{jt})$, is the lithium transporting costs to the world market. The third part, $C_{jt}^A(x_{jt}, x_{j0})$, is a quadratic term to consider that it is costly to ramp up production substantially in the short to medium term, and also that sunk costs make sudden output reductions less profitable. One particular example is Bolivia, which has enormous and profitable lithium resources, but where production is close to zero due to institutional barriers such as constraints on property rights and on foreign investments. The term $C_{jt}^A(x_{jt}, x_{j0})$ equals zero if production equals the base year output, is quadratic in deviation from the base year output, and reduces gradually over time.

We assume the following recycling costs function:

$$CR_t = \left[cr_0 - ln\left(1 - \left(\frac{w_t}{l_t}\right)^\rho\right)\right]e^{-\tau_R t}w_t \perp CR_t \geq 0 \tag{41}$$

The cost function reflects that recycling unit costs vary depending on how large the share of used lithium is recycled $\left(\frac{w_t}{l_t}\right)$. The cost of the cheapest unit is $cr_0$. The parameter $\rho$ determines how fast marginal costs increase as the share of used lithium available for recycling is actually recycled. When $w_t \to l_t$, we see that the (marginal) costs go towards infinity. Here too we include technological progress that reduces the unit costs exogenously over time through the parameter $\tau_R$.

From the equations above and the problem presented in (18)-(35) we derive the first order conditions for the producers of primary lithium, and for the recycling firms (see Appendix B).

As already indicated, some model parameters are uncertain, both on the demand side ($\alpha_i$ and $\sigma_{it}$), in extraction ($\eta_j$ and $\tau_E$), and in recycling ($\rho$ and $\tau_R$). We therefore perform a sensitivity analysis. Thus, the benchmark scenario should not be taken as a forecast of the future lithium market. This model exercise aims to get a better understanding of the lithium market, to highlight the recycling value and to observe how different the efficient solution is from the market outcome.

We assume a common (real) discount rate of 5 percent, both for the producers of lithium and for the social planner. The model is simulated in (GAMS) using MCP. We run the model with a set of time of 150 years (one-year periods), beginning in the calibration year 2015, focusing on the time towards 2100.[2]

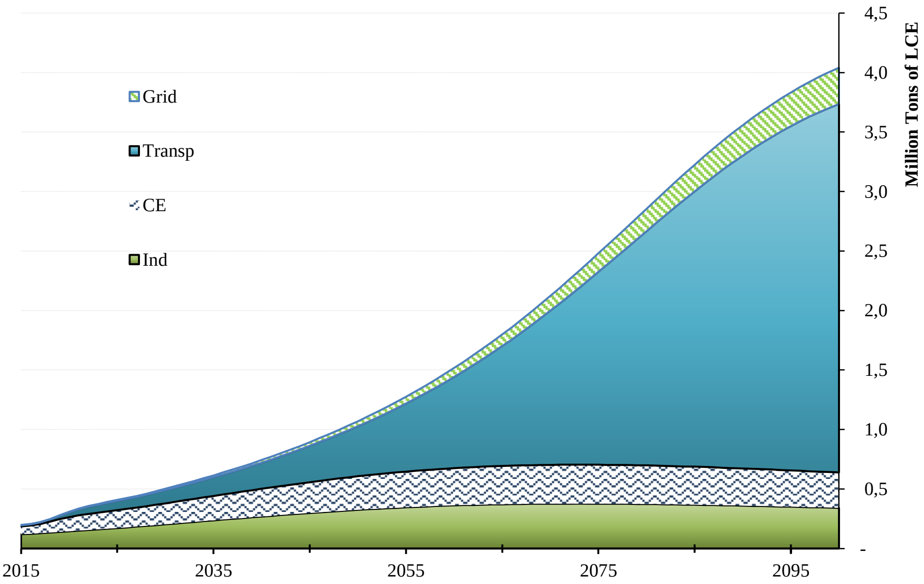
### 3.2. Simulation results

We start by presenting the market outcome, given our benchmark parameters, where we assume no efficient market for used lithium. As demonstrated in Section 3, the market outcome will then give too little incentive to extract and recycle lithium, so next we investigate how the market outcome compares with the efficient market. Finally, we consider how our results change if we change some of the important but uncertain parameters in the model.

#### Market Solution (MS) – benchmark scenario

We project the demand of lithium carbonate equivalent –LCE– towards 2100, observing a momentous growth in all consumer sectors until 2030 (Fig. 1). Afterwards, it stabilizes gradually for industrial applications (Ind) and consumer electronics (CE), which are the dominating sectors today.

*Fig. 1. Demand of Lithium Carbonate Equivalent (LCE) by sectors*




*Note: The amount of lithium content in batteries is important for the dynamics of lithium demand. An energy storage system (Grid) needs on average 100 tons of lithium per kWh. The range of lithium content in the transport sector (Transp) varies from 9kg per kWh for a plug-in hybrid vehicle (PHEV) to 15kg for battery electric vehicles (BEV) and 144kg for an E-bus battery. Batteries for small electronics (CE) i.e., cell phone and laptops contain 12gr and 58gr of LCE respectively. Data based on (Mackenzie, 2017).*

Whereas the transport sector accounts for less than 5% of current global lithium demand, it is expected to expand substantially in the following decades and become the dominating lithium demand sector in the second half of the century. While electric vehicle sales have already started to take off in several countries, LiBs improvements, in both the transport sector (e.g., E-bus) and the energy sector (e.g., Grid Storage), spur new markets with batteries of huge capacities. The grid storage expansion is uncertain

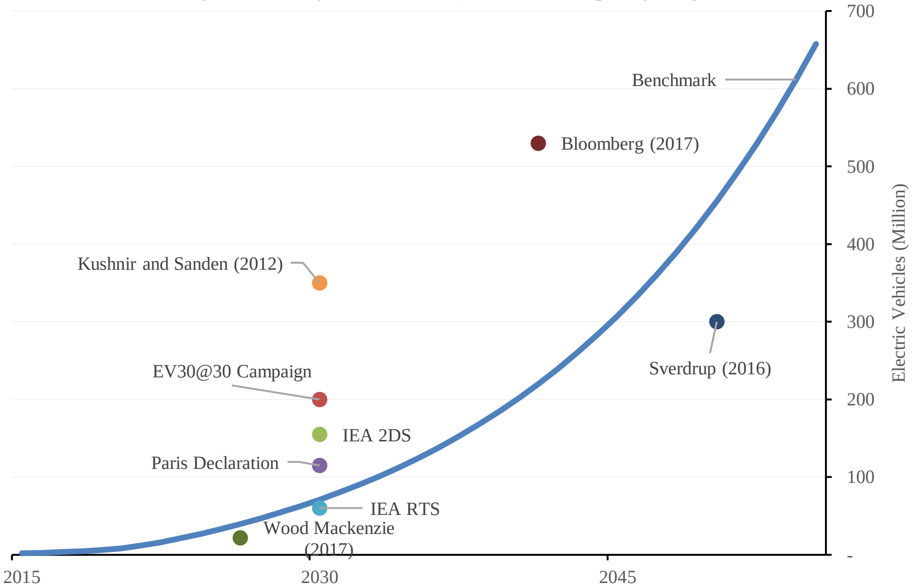
[2] Thus, we run the model 65 years beyond the time horizon we consider. All shadow prices are set equal to zero in the last period of the simulation. Whereas the analytical model has an infinite time horizon, this is not possible for the numerical model. By running the model sufficiently many years beyond our time horizon, the results are practically identical to the results of an infinite time horizon model (this is confirmed by running the model for even longer periods).

– in our benchmark scenario its demand in 2100 compares to industrial applications (Ind) and consumer electronics (CE). Technological developments may reduce battery costs, and resolve the forthcoming lithium demand, especially when it comes to transport and grid storage.

We estimate how many batteries (light commercial vehicles) are likely to be produced with the amount of lithium consumed by the transport sector, and assume that sales evolve at the pace shown in Fig. 1. We compare our projections with the literature and find that it will be challenging to achieve the ambitions of electric vehicle adoption suggested by some academics and policy makers (see Fig. 2).

For example, Kushnir and Sanden (2012) assume similar lithium content per EV battery as we do, and project that even with a low level of vehicle population growth (0.2 cars/capita), EV adoption reaches about 350 million EVs by 2030. Alternatively, the Clean Energy Ministerial forum launched a campaign *"EV30@30"* to accelerate EV, and reach 30% market share for electric vehicles in the total of all passenger cars, light commercial vehicles, buses and trucks by 2030 (IEA, 2017). The assumptions of vehicle population and lithium content per battery for these estimations are unknown. Other studies consider how many EV batteries are realizable with the lithium resources available and linear demand trends (Bloomberg, 2017);(Sverdrup, 2016); (Mackenzie, 2017).

*Fig. 2. Stock of electric cars (realizable vs. policy targets)*

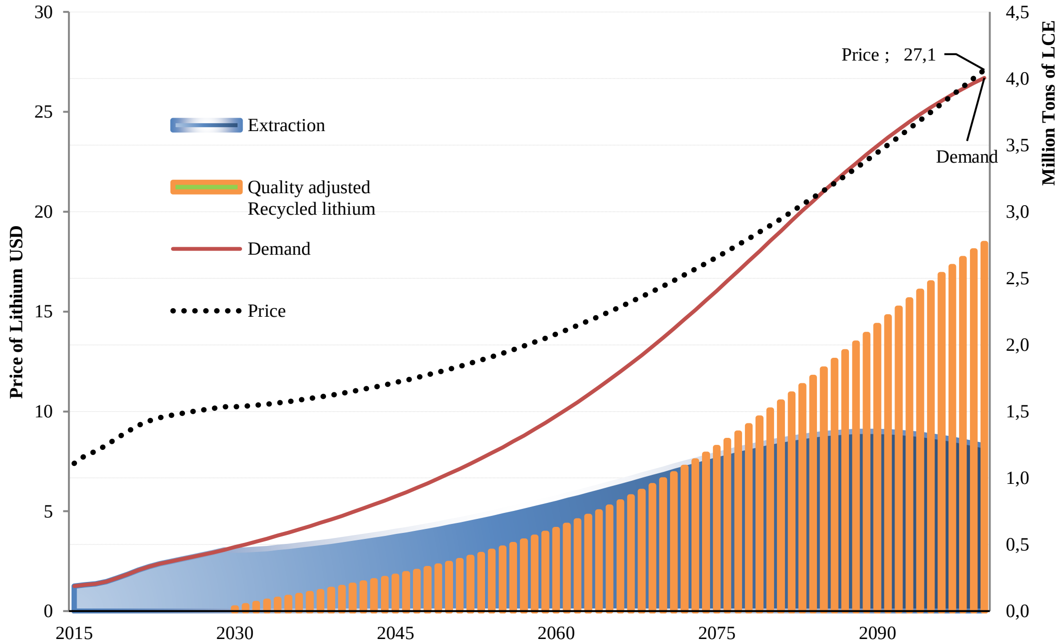



*Note: The IEA 2DS is in line with a 50% likelihood of limiting the expected global warming to 2'C. The IEA RTS incorporates improvements to the current technological state. The Paris Declaration refers to the Electro-Mobility and Climate Change and Call to Action. These projections and and EV30@30 Campaign are based on IEA (2017). We assume that EVs sales will follow historical fashion, about 60% of electric vehicles (EVs) are battery electric vehicles (BEVs) and 40% plug-in hybrid vehicles (PHEVs).*

Fig. 3 shows how virgin and recycled lithium satiate demand in a (free) market solution. Initially, recycling is too expensive, therefore extraction equals demand. From 2030, some recycling becomes profitable, and from around 2070 recycled waste accounts for more than half of the lithium market. This change reflects a combination of higher demand and higher extraction costs, which together cause soaring lithium prices (see Fig. 3), making recycling gradually more profitable. The increase in recycled lithium is partly due to more lithium waste being available for recycling, and partly because the higher lithium price makes it profitable to recycle a larger share of the lithium waste.

In 2040 about half of the lithium waste is recycled – in 2060 the share has grown to above 80% in this scenario.

*Fig. 3. Annual global demand, extraction and recycling of lithium*

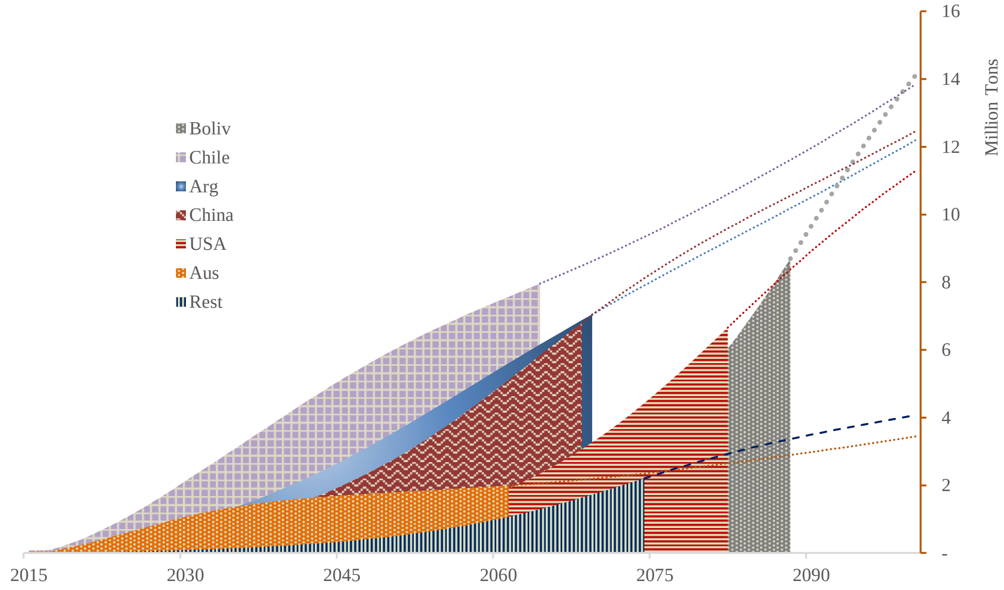



As mentioned in Section 4.1, most lithium reserves are located in a few countries, with slightly more than half of identified reserves found in the three South American countries Argentina, Bolivia and Chile. Furthermore, all identified reserves globally, 42 million tons, are located onshore (brines, pegmatite and clays). However, more resources will be made available for the market, both because of technological progress and higher prices. This is captured in our benchmark scenario, where accumulated extraction until 2100 exceeds currently identified reserves by 70% (Fig. 4).

Fig. 4 shows accumulated extraction for individual countries in the benchmark scenario. It also shows, for each country, when accumulated extraction surpasses the currently identified reserves. We see that Australia and Chile, the two biggest producers today, will run out of reserves around 2065. Chile has large reserves and continues as one of the largest producers throughout the century, whereas Australia has rather limited reserves compared to the others. On the other hand, lithium reserves in Bolivia and USA will last longer, i.e., almost until the end of this century. These two producers have a very low production level today due to relatively high extraction, transport and/or institutional costs, and at the same time large reserves. In the second half of this century, Bolivia is the biggest producer of lithium. Argentina and China also have large reserves and are important suppliers throughout our time horizon.

As already demonstrated in Fig. 3, recycling lithium waste will become crucial for the future lithium market. In fact, recycled lithium will meet around half of accumulated lithium demand from today until 2100. This suggests that without the ability to recycle lithium, prices of lithium would likely have to be much higher in order to balance supply and demand, especially in the future but also today. Thus, given the highly uncertain nature of future recycling costs, it is important to explore how different assumptions about this may affect the lithium market. Moreover, in the scenario presented so far, we have assumed an inefficient market outcome, where consumers are not able to sell lithium waste to the recycling industry. Given the importance of recycling, it is interesting to examine how an efficient solution would look compared to the market outcome. This is what we turn to now.

*Fig. 4. Accumulated production and identified reserves of Lithium*




## Comparing efficient and market solutions

As explained in the theoretical part, when consumers cannot sell lithium waste (i.e.,$P_C^W = 0$), their marginal willingness to pay for lithium is lower than if they can sell it after use. We now consider the efficient solution, which is realized if there is an efficient market for depreciated lithium. In that case, consumers anticipate having a positive shadow price ($\varphi^C$) of used lithium stock. LiB consumers then get paid for their worn-out batteries, proving that the waste stock is a valuable resource. This will boost lithium prices and increase the incentives to extract and recycle more lithium.

Alternatively, if an efficient market for used lithium is difficult to realize, proper subsidies to all sales of lithium can also realize the efficient solution. This is the variant we will consider here.[3] A subsidy puts a wedge between the producer and the consumer prices, with the latter prices being below the former. Subsidized consumer prices correspond to equations (11) and (12). And equations (21) and (34) correspond to the (free) market prices for primary and recycled lithium respectively.

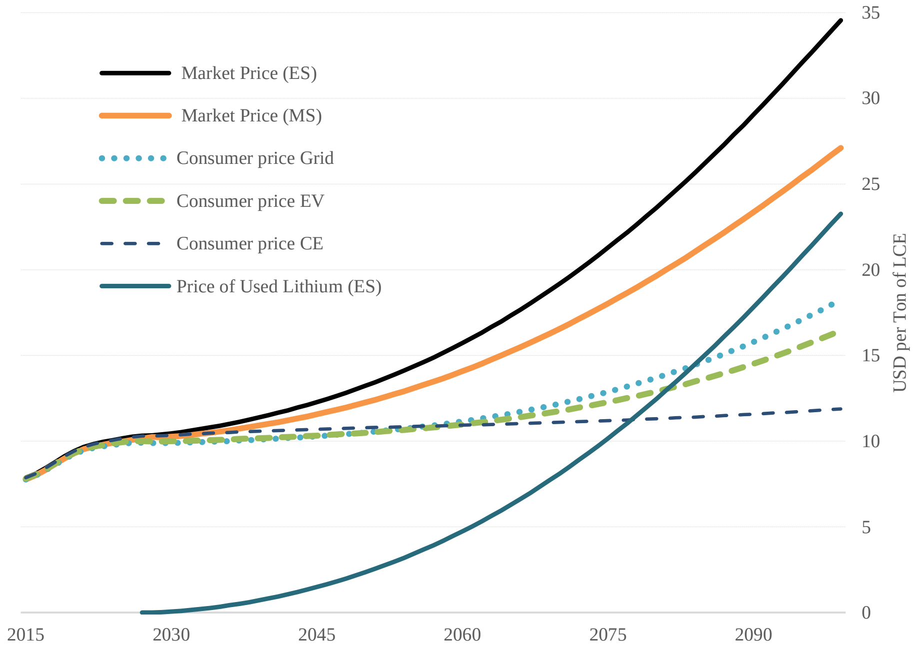
Fig. 5 shows the producer and consumer lithium prices in the efficient solution, together with the market price in the inefficient solution discussed above. We notice that lithium market prices increase in the efficient solution (compared to the market solution), especially in the second half of the century, whereas consumer prices decrease substantially. Thus, sizeable subsidies realize the efficient solution. The subsidy is sector-specific due to different depreciation rates of lithium across sectors. Consequently, consumer prices differ too.[4] Buyers of lithium for consumer electronics

[3] Whereas the quantities obviously are the same in the two alternative efficient solutions, the consumer prices are different.

[4] If price discrimination is difficult, the efficient solution could alternatively be realized through a common subsidy to delivery of used lithium.

will perceive a relatively low lithium price due to a high depreciation rate, implying highest subsidy levels for this sector.[5] In 2100, lithium producer (market) prices are 2-3 times higher than consumer prices, illustrating the need for high subsidy rates unless an efficient market for used lithium arises by itself.

*Fig. 5. Market and consumer prices of lithium in the efficient (ES) and market (MS) solution*

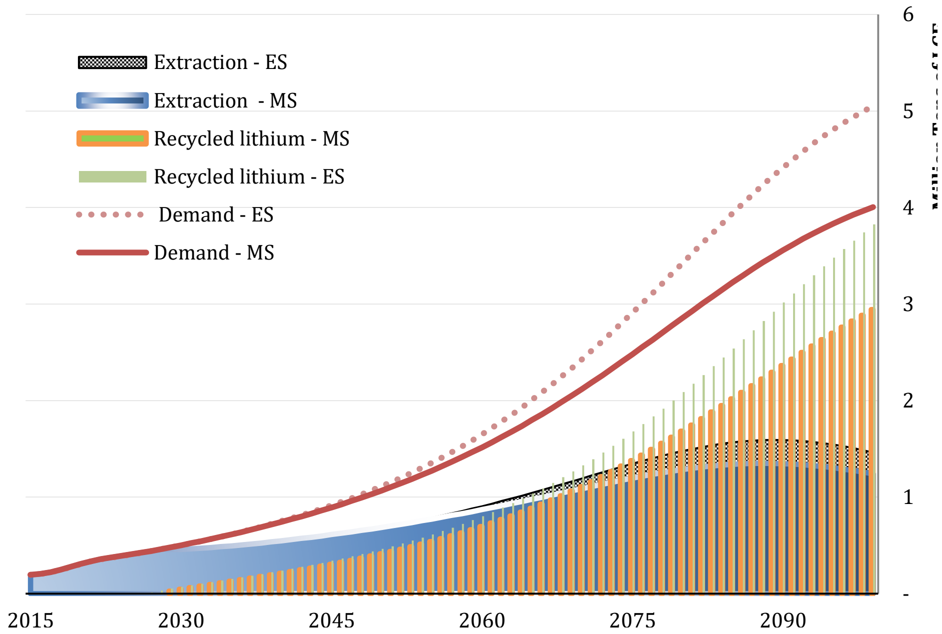



Along time, higher subsidy rates reflect higher lithium prices, also allied to higher shadow prices of used lithium (See Fig. 5). Therefore, the value of used lithium increases and recycling is more rewarding. Initially, however, the subsidies are low – the first ten years of recycling the shadow price of used lithium is less than 50 cents per ton of lithium.

In the efficient scenario, the subsidies generate greater supply and recovered waste, absorbing a bigger demand level (Fig. 6). Additional accumulated demand between 2015 and 2100 will be 25 tons greater than in the (unregulated) market solution, which is more than a half of currently identified lithium reserves. One quarter of the additional demand during this century comes from more extraction, while three quarters come from more recycling, which starts two years earlier in the efficient solution.

[5] This is not the case initially, however, when the lithium price increases rapidly.

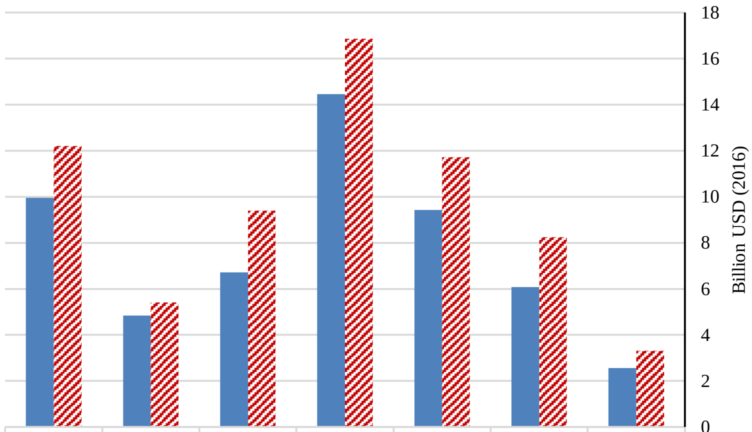
*Fig. 6. Annual global demand, supply and recycling of lithium in the efficient (ES) and market (MS) solution*




Both consumers and producers benefit from having an efficient market. Lithium producers earn greater resource rent compared to an unregulated market, bringing greater profit levels to all producer countries (Fig. 7). For all the five biggest countries (with respect to lithium reserves), the net present value of future profits increase by more than 2 billion USD, amounting to an increase of 15-40%. Total profits for all producers increase by 13 billion USD (net present value). Especially Bolivia and the US, which have lower net present value profits than the three others due to slow start-up of extraction, benefit from the efficient market. The explanation is that the increase in the lithium price is highest in the second half of the century when these two countries have high market shares.

Consumers also benefit due to the subsidy, that is, by 41 billion USD, whereas the recycling industry increases their profits by 36 billion USD, as long as they don't have to pay for the used lithium. Nevertheless, the subsidy expenses have to be counted as a cost, and they amount to 84 billion USD. In total, net present value of global welfare (equation 1) increases by 5.6 billion USD, that is, less than half of the increased profits for lithium producers. The increased welfare is consistent with the conclusions by Pittel et al. (2010), i.e., a "higher circulation of matter" enhances welfare.

*Fig. 7. Net present value of profits for lithium producers in the efficient and market solution*




| | Arg | Aus | Boliv | Chile | China | USA | Rest |
|---|---|---|---|---|---|---|---|
| Unregulated (No subsidies) | 10,0 | 4,8 | 6,7 | 14,5 | 9,4 | 6,1 | 2,6 |
| Efficient Market (With Subs) | 12,2 | 5,4 | 9,4 | 16,9 | 11,7 | 8,2 | 3,3 |

## Sensitivity analysis

As stressed in the numerical model description above, there are several important but uncertain parameters in the model. This is obvious when we attempt to model a market towards 2100. We perform sensitivity analysis with respect to four parameters (see Table 3). The size of lithium price elasticity is very uncertain, especially in the long run when the price sensitivity depends e.g. on the availability of substitutes in batteries. Thus, we consider -0.25 and -0.75 in addition to the benchmark assumption of -0.5. Technological progress, both in extraction and in recycling, is crucial for the future costs of supplying lithium, but they are likely to have different impacts on the market. Here we consider annual growth rates of 2%, compared to 0.5% in the benchmark simulations. Finally, the quality-grade of recovered lithium is essential for the value of recycling, both to the recycling industry itself and more generally to the future lithium market. The benchmark assumption has been 0.9, i.e., a small difference in quality-grade, while here we also consider a quality-grade factor of 0.5, in which case two tons of recycled lithium is equivalent to one ton of virgin lithium.

*Table 3. Parameters and Scenarios for sensitivity analysis*

| **Parameters** | | **Benchmark** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|---|
| $q$ | Initial quality factor | 0.9 | | | 0.5 | | |
| $\alpha_I$ | Elasticity of demand | -0.5 | | | | -0.25 | -0.75 |
| $\theta^E_j$ | Technological change in extraction | 0.005 | | 0.02 | | | |
| $\theta^R_j$ | Technological change in recycling | 0.005 | 0.02 | | | | |

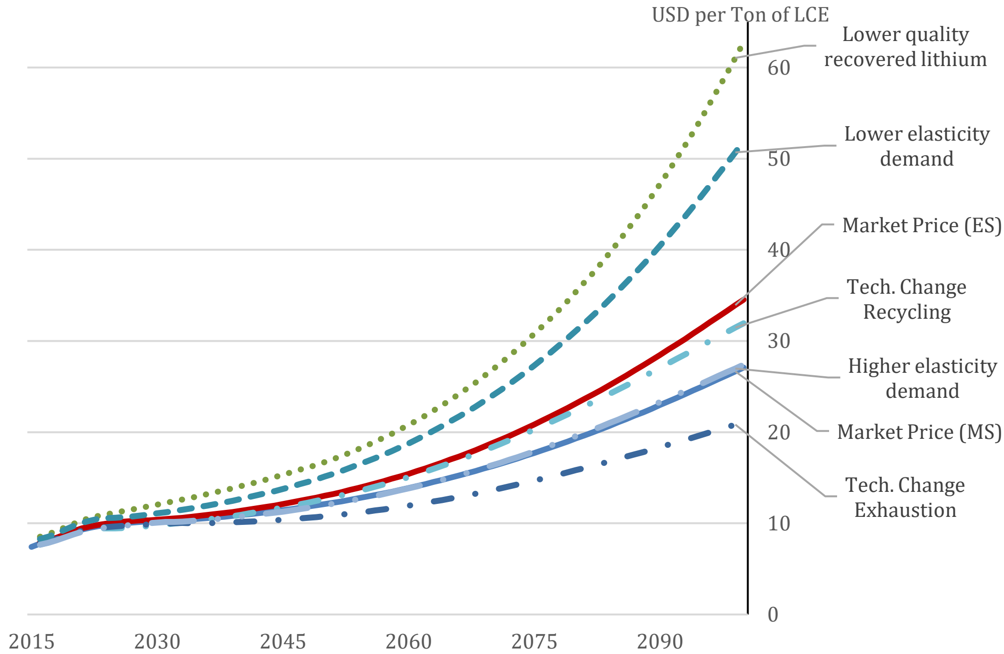
Fig. 8 shows the market lithium price development in the efficient solution across scenarios (it also shows the unregulated benchmark solution). We see that the price deviates substantially across scenarios in the second half of this century, when lithium becomes a more scarce resource. In 2100, the price varies between 21 and 63 USD per ton across scenarios. The price is lowest when technological progress in extraction of lithium increases. Technological progress in recycling has far less impact on the lithium price. The reason is as follows: On the one hand, lower recycling costs increase the supply of lithium in the market, depressing the price. On the other hand, lower recycling costs increase the value of used lithium, which in turn increase the optimal subsidies. These subsidies reflect the shadow price of used lithium. Consequently, demand increases and pushes the price upwards. The net effect is a small market price reduction.

With a lower quality-grade of recycled lithium, primary lithium prices double at the end of the century and reach the highest level among scenarios. Lower quality means less (quality-adjusted) recycled lithium supply per unit of used lithium. This further reduces lithium stocks in use ($\dot{L} = x + qw - \gamma L$), and implies less access to secondhand lithium available for recycling. Therefore, the deviation from the benchmark expands over time and reveals how the quality-grade of recycled lithium affects the future access to this resource.

Lower demand elasticity also pushes the price of primary lithium up substantially, as higher prices are needed to balance the market when demand is quite insensitive to price changes. The opposite effect is the case with higher elasticity.

Future use of lithium varies substantially across scenarios. In particular, faster technological change in recycling increases lithium demand growth and i.e. speeds up the deployment of EVs in the market. However, greater technological change is not enough to reach the EV stock levels in the two degrees scenarios illustrated in Fig. 2. Better mineral mining technologies would stimulate future demand, but to a lesser degree than greater technological change in recycling.

*Fig. 8. Market price of lithium in different efficient solution scenarios*

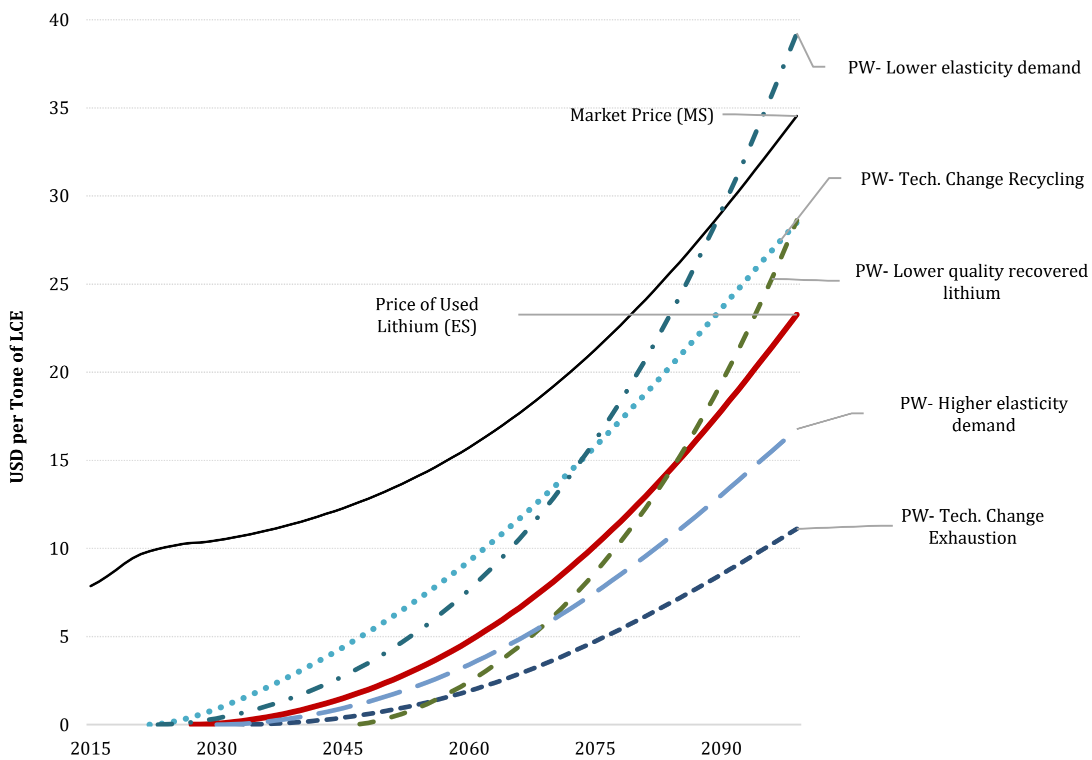



The shadow price of depreciated lithium reflects the value to society of this resource (Fig. 9). Thus, it depends positively on the price of recovered lithium, which again depends on the market price of lithium and the quality-grade of recovered lithium, and negatively on the costs of recycling. In the benchmark social planner solution in 2100, the shadow price of depreciated lithium is USD 23. At that time, one ton of primary lithium costs USD 34.

If there is no near lithium substitutes and its demand becomes more inelastic, the market prices of primary lithium and the value of depreciated lithium become much higher. Similarly, when technological changes reduce recycling costs, the value to society of depreciated lithium jumps, and the shadow price surges as well. In addition, better exhaustion technologies make primary lithium more cost competitive than recycled lithium, diminish the attractiveness of depreciated lithium, and explain why the price of depreciated lithium –PW– is the lowest here among scenarios (Fig. 9).

The first year of lithium recycling varies tremendously across scenarios (Fig. 9). In the benchmark scenario, recycling will start in 2028 in the efficient solution (2030 in the market solution). Improvements in recycling technologies or a lack of near substitutes of primary lithium (inelastic demand) make recycling activities start 7-8 years earlier. However, with a secondhand lithium of poor quality-grade recycling starts after 2048. Poorer quality of recovered lithium has two opposing effects on the shadow price of depreciated lithium. On the one hand, it reduces the price of recovered lithium vis-à-vis primary lithium. On the other hand, it reduces the overall supply of lithium, especially in the long run, which raises the market price of lithium. This latter effect seems to dominate towards the end of the century (Fig. 9).

*Fig. 9. Shadow price of used lithium across efficient solution scenarios*

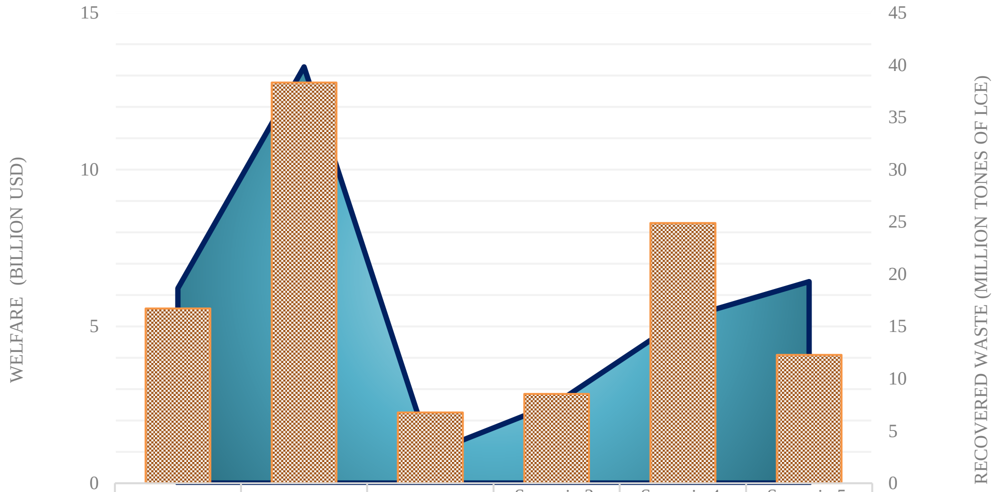



The efficient solution brings welfare benefits compared to the unregulated market solution in all simulated scenarios, but the welfare gains differ greatly (Fig. 10). Better recycling technologies offer the largest welfare gains, with 12.8 billion USD in increased net present value. This scenario also brings about the biggest increase in accumulated waste recovery when shifting from the inefficient to the efficient solution. In fact, the increase in accumulated waste recovery after introducing optimal subsidies (40 million tons) is almost as high as the currently identified reserves of lithium worldwide.

With increased technological change in extraction, an efficient market for used lithium becomes less important, and the welfare gains drop to 2.3 billion USD. The same is true with lower quality of recycled lithium, in which case the welfare gains are 2.8 billion USD. The increase in waste recovery is also much less than in the benchmark simulations.

Finally, we see that if lithium price elasticity is high, e.g., due to more substitutes available, the welfare gains from an efficient market, i.e., implementing subsidies, is reduced, whereas the opposite is the case if the elasticity is low. The changes in waste recovery are quite small after all.

*Fig. 10. Welfare and recovered waste differences between efficient and (unregulated) market solutions across scenarios*



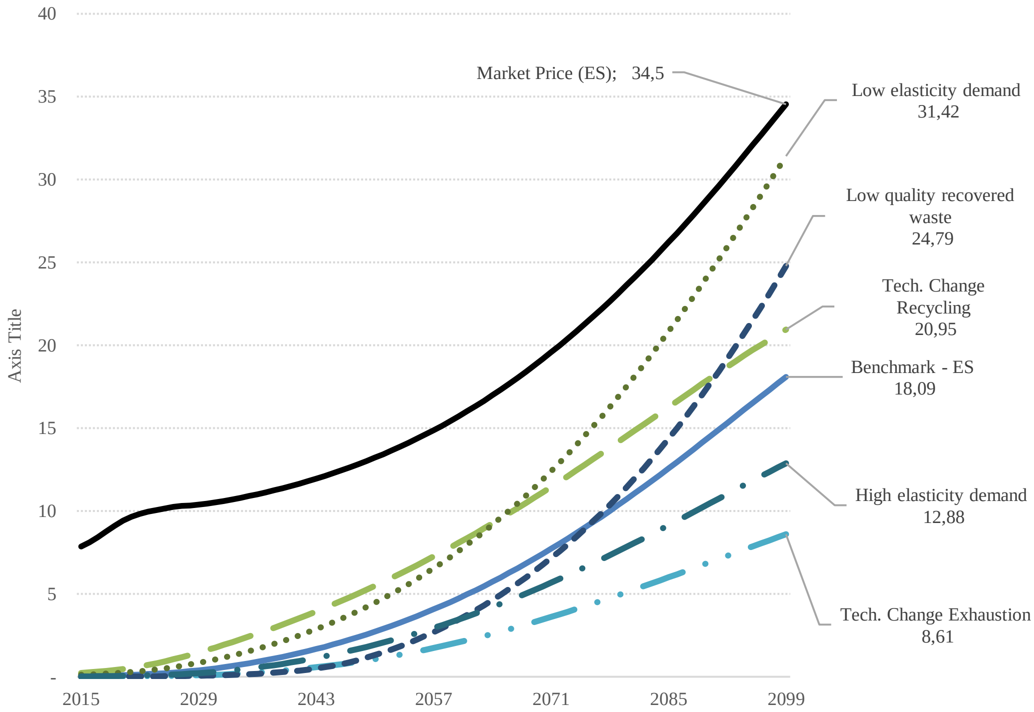

| | Benchmark | Scenario 1: Tech. Change Recycling | Scenario 2: Tech. Change Exhaustion | Scenario 3: Lower quality recovered lithium | Scenario 4: Lower elasticity demand | Scenario 5: Greater elasticity demand |
|---|---|---|---|---|---|---|
| Waste recovery | 18,6 | 39,8 | 2,9 | 7,7 | 15,7 | 19,3 |
| Welfare | 5,6 | 12,8 | 2,3 | 2,8 | 8,3 | 4,1 |

Total net present value profits for lithium producers differ substantially across scenarios, that is, between 40 and 105 billion USD. Mining profits are lowest in Scenarios 1 and 5, i.e., when there is increased technological change in recycling or greater price elasticity. Extractors obtain greatest profits with lower quality of recycled lithium (Scenario 3). Profits are also high in the low elasticity scenario, whereas increased technological change in extraction has in fact little impact on profits (lower costs are offset by lower prices).

The impact on mining firms' profits when shifting from the inefficient to the efficient solution follows the impact on welfare to a large degree. The main exception is Scenario 3 – lower quality-grade of recycled lithium. In this case lithium producers increase their net present value profits by 23 billion USD with a market intervention, whereas total welfare increases by merely 3 billion USD (see Fig. 10. ) Thus, there is a significant loss to other market participants jointly. When the quality-grade of recycled lithium is inferior to virgin lithium, the competition from recycled lithium is quite low. At the same time, optimal subsidy rates eventually become very high (see Fig. 9. ) and stimulate demand. Thus, if the quality-grade of recycled lithium is low, the effects of the subsidy on lithium supply is limited, and therefore, the market price is pushed up quite a lot.

Fig. 11 shows the optimal subsidy rates in the transport sector across scenarios. The subsidy follows, in large degree, the development of the shadow price of used lithium (Fig. 9, but are slightly smaller due to discounting, in combination with the depreciation rate of the lithium stock.[6] We see that the subsidy rates in 2100 vary between 9 and 31 USD per ton. As a comparison, the initial price of lithium is 8 USD per ton. However, until 2050 all subsidies remain below 6 USD.

*Fig. 11. Optimal subsidy rates in the Transport sector across scenarios*




## 4. Conclusions

In this paper, we investigate how effectively lithium recycling relieves resource scarcity, and whether a market intervention is desired. We have demonstrated two things: (i) the future prospects for the lithium market depend heavily upon recycled lithium supply, and (ii) unless an efficient market for depreciated lithium develops, a market intervention is desired to obtain optimal market outcomes. The paper demonstrates how lithium scarcity will be much more evident without the possibility to recycle lithium, and with prices increasing much faster. In our benchmark scenario, around half of accumulated lithium demand from today until 2100 will be met by recycled lithium.

In a free market solution, the incentives to recycle depreciated lithium will be enhanced as lithium prices rise, but lithium consumers do not necessarily take into account the shadow value of lithium waste for future recycling. In the analytical part of our paper, we showed that subsidies to either buyers or sellers of both virgin and recycled lithium may realize the optimal solution. If incentives are created, our simulations have shown that this is likely to bring greater social benefits for lithium consumers, producers and

[6] In a steady state situation with constant subsidy rates, the relationship between $\varphi$ (subsidy) and $\theta$ (shadow price of used lithium) are given by: $\varphi/\theta = \gamma/(r+\gamma)$

recyclers. The size of the optimal subsidies depends however, on a number of uncertain assumptions regarding the future lithium market development, such as technological progress to extract and recycle, the quality-grade of recovered lithium, and demand elasticity. Although our model is formulated in the lithium context, the qualitative findings should generalize to other non-renewable and recyclable resources.

We deduce policy implications from a global optimization problem. Optimal subsidies correspond to the shadow prices of the depreciated waste stock generated in a globally regulated market solution. These subsidies may of course be difficult to implement in reality. We have not examined whether single countries, or a group of countries, should implement such subsidies unilaterally. However, these issues are worthy of further research.

Technological progress in lithium recycling, as well as the quality of recycled lithium, will be crucial for the future lithium market. One could, therefore, also advocate subsidizing R&D to promote a technological push in recycling that could lower long-term recycling costs. Besides, an efficient collection system requires a mechanism to give consumers the incentive to make lithium waste available for recycling. It may be necessary for governments to intervene and create a collection system if such a solution does not exist.

Lithium has an important role in a decarbonized economy. Nonetheless, lithium mining and waste management yield critical environmental impacts and social costs. We analyze these issues in another work. In addition, the geographical concentration of lithium reserves raises a concern about market power and strategic behavior by, for instance, lithium extractors. These are all important issues that may be considered in future research.

# Appendix A

*Table 4. Lithium Demand: Other parameters*

| Description | Parameter |
|---|---|
| Recycling unit costs with 90% recovery (Based on Kushnir (2012)) | 6,08 USD/Tone |
| Lowest initial recycling unit cost ($cr_0$) | 10 USD/Tone |
| Parameter recycling cost function ($\rho$) | 2 |
| Technological change extraction ($\theta_E$) | 0.5% |
| Technological change recycling ($\theta_R$) | 0.5% |
| Discount rate | 5% |
| Global lithium price in 2015 – USD per Ton (USGS, 2017) | 7,4 |
| Long-run price elasticity | -0.5 |

## Demand growth functions

*Table 5. Annual Growth rate in lithium demand in sector i (given price in 2015)*

| | a | b | c | d |
|---|---|---|---|---|
| Until 2025 | 25 % | 15 % | 10 % | 5 % |
| from 2031 until 2050 | 7-10% | 7-10%* | 3 % | 3 % |
| from 2051 until 2100 | 5 % | 5 % | 1 % | 1 % |
| After 2101 | 1 % | 1 % | 1 % | 1 % |

We use the following functional form for the demand growth function $\sigma_{it}$:

$$\sigma_{it} = \frac{\sigma_{i1}}{\sigma_{i2} + \sigma_{i3}e^{-\sigma_{i4}t} + \sigma_{i5}e^{-\sigma_{i6}t^2}} \tag{42}$$

The calibrated parameters are displayed in the following table:

*Table 6. Parameters in the demand growth function*

| Parameter | **Transportation** | **Grid Storage** | **Consumer Electronics** | **Industrial Applications** |
|---|---|---|---|---|
| $\sigma_{i1}$ | 4982 | 2286 | 2636 | 2741 |
| $\sigma_{i2}$ | 6.07 | 6.41 | 295 | 489 |
| $\sigma_{i3}$ | 1113 | 1147 | 1229 | 2034 |
| $\sigma_{i4}$ | 0.074 | 0.072 | 0.053 | 0.053 |
| $\sigma_{i5}$ | 3863 | 1132 | 1112 | 218 |
| $\sigma_{i6}$ | 0.10 | 0.10 | 0.10 | 0.10 |

## Appendix B

The first order condition for producer j, subject to a positive outcome ($x_{jt}$) is:

$$x_{jt} \geq 0 \quad \perp \quad c_{jt} + ca_{jt}\left[\frac{x_{jt} - x_{0j}}{x_{0j}}\right] + ctrans_{jt} - \lambda_{jt} - p_t \geq 0 \tag{43}$$

Here $ca_{jt}$ is an adjustment cost parameter to consider some "institutional costs" in countries like Bolivia, where mild constraints on property rights and foreign investments are imposed and create additional costs. There is also a transport costs, $ctrans_{jt}$, since all suppliers must export its product, except from China and "rest of the world" that sells to a domestic market.

Scarcity rent ($\lambda_{jt}$) and profit levels $\pi_j$ are the free variables of our model and are paired with equations. The resource rent or "scarcity rent" develops according to:

$$\lambda_{jt} > 0 \quad \perp \quad (1 + r) * \lambda_{jt} - \lambda_{j,t+1} + (\eta_j * c_{jt} * x_{jt}) = 0 \tag{44}$$

And the net present value of lithium extraction comes from this condition:

$$\pi_j > 0 \quad \perp \quad \pi_j = \sum_{t=1}^{6} (p_t - c_{jt}) x_{jt} e^{-rt} \tag{45}$$

In our model, recycling will happen when recycling costs are competitive to extraction costs.

From the recycling costs function (41), we derive the following first order conditions:

$$\frac{\delta CR}{\delta w} = e^{-\theta_R t}\left[cr_0 - ln\left(1 - \left(\frac{w}{l}\right)^{\rho}\right)\right] + \frac{\rho e^{-\theta_R t}\left(\frac{w}{l}\right)^{\rho}}{1 - \left(\frac{w}{l}\right)^{\rho}} \tag{46}$$

$$\frac{\delta CR}{\delta l} = -\rho \frac{\left(\frac{w}{l}\right)^{\rho+1}}{1 - \left(\frac{w}{p}\right)^{\rho}} = P^W \tag{47}$$

Or equivalent to

$$\frac{\delta CR}{\delta l} = \rho w \frac{\left(\frac{w}{l}\right)^{\rho}}{\left(\left(\frac{w}{p}\right)^{\rho} - 1\right) l} = -P^W \tag{48}$$

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