Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective

Xu, C.

4 Future greenhouse gas emissions of global automotive lithium-ion battery cells and recycling potential till 2050[c]

Abstract

The global transition to electric vehicles (EVs) requires large-scale production of lithium-ion batteries which are the leading chemistry type for EV batteries (EVBs). To ensure a sustainable EV transition, greenhouse gas (GHG) emissions of EVB production have to be minimized. Given the fact that cells are the major source of life cycle GHG emissions of EVBs, we quantify the GHG emissions of global EVB cell production from 2020 to 2050. To this end, we build an integrated model that estimates the demand for EVB cells with a dynamic battery stock model, and the GHG emissions per EVB cell with a prospective life cycle assessment model. We find that GHG emissions of global EVB cell production will increase to 26-155 Mt CO2-Eq in 2030 and 58-468 Mt CO2-Eq in 2050, depending on EV demand growth, EV and related battery size, battery chemistry, and energy mix scenarios. Despite an average 8%-12% annual growth rate of global EVB cell demand between 2020 and 2050, global EVB cells GHG emissions only increase annually by 2%-10% in the same period due to the increasing use of renewable energy in EVB cell production and other factors. Decarbonization of energy used in EVB cell production and the use of small rather than big EVs are crucial factors to minimize growth in GHG emissions. EVB recycling offers potential GHG emissions reductions, however, only in the longer term after 2030.

4.1 Introduction

Transportation accounts for ~15% of global GHG emissions in 2019, making it the second-largest GHG emissions sector next to energy sector[1]. Cars for personal transport accounted in 2019 for about ~6 Gt emissions[1]. Technology developers proposed EVs, as an alternative to Internal Combustion Engine Vehicles (ICEVs), to reduce GHG emissions of transportation sector, along with reducing dependency on oil resources and (urban) air pollution[57,151]. As major deployments of EVs, the global

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light-duty EVs grew from a few thousand vehicles in 2005 to 10 million vehicles in 2021. EV fleet scenarios of the International Energy Agency[6], extended to 2050 in our previous paper[7], estimate 124-199 million EVs in 2030 and 970-1940 million EVs by 2050.

The transition to EVs reduces vehicle in-use emissions significantly due to improvements of vehicle energy efficiency[176] and use of renewable electricity[177]. However, it may increase vehicle production emissions because EVs require batteries that are carbon intensive to produce. For a 100 kWh battery, life cycle GHG emissions of the EVB cells production reach 4-9 t CO2-Eq in 2020[178] (equals to the in-use emissions of driving 16400-35600 km with a typical ICEV that emits on average 250 g CO2-eq GHG emissions per km[179]). In earlier work, we estimated the global EVB cells demand of 1.5-2.4 TWh in 2030 and 7-12 TWh in 2050[7]. This would lead to GHG emissions of 6-21 Mt CO2-Eq in 2030 and 30-104 Mt CO2-Eq in 2050 for global EVB cell production, if the life cycle emissions of EVB cell production would not change compared to 2020.

Most studies[51,52] on future GHG emissions from global EVB cell production use scenarios of future EVB demand growth and current life cycle emissions of EVB cell production[40-42]. There are few studies that take into account regional EVB demand and production and changes in battery production technology over the next decades, which strongly influence the life cycle emissions of battery production. This is due to two main challenges. First, future battery demand depends on the future EV fleet size and battery capacity per vehicle, which will both change and differ between the main EV markets (*e.g.*, US, EU, Asia). Second, regional battery production will change due to regional battery production capacity, resource constraints, and other factors. But at the same time, the climate policy and associated energy mix may differ between such regions, leading to potentially large differences in life cycle GHG emissions of battery production. Therefore, there is a need for developing future (regional) battery demand scenarios considering the development of EV fleet size and battery capacity per vehicle, and quantifying the future GHG emissions of global EV battery production considering the future distribution of battery production regions.

In this paper, we build an integrated model to estimate GHG emissions of global EVB cell production between 2020-2050. The integrated model combines a dynamic battery stock model[7] and a prospective life cycle assessment (LCA) model[178], which are both developed in our earlier work to estimate future demand for EVB cells and life cycle GHG emission per kWh capacity of EVB cell production. Considering the future (regional) EV fleet size and battery capacity per vehicle, the dynamic battery stock model includes three battery demand scenarios (low, medium, and high) specified in future demand for EVB cells in China, EU, US, and rest of world (RoW) for the period from 2020-2050. The dynamic battery stock model also includes two global-level battery chemistry scenarios: an NCX scenario (NCA and NCM batteries dominate the EV market) and an LFP scenario (LFP battery dominates the EV market). Life cycle GHG emissions for EVB cell production for the period 2020-2050 are calculated by the prospective LCA model, giving specific results by region and battery chemistry[178]. The prospective LCA model further includes two energy mix scenarios, based on the Remind Integrated Assessment Model[180], reflecting different future regional energy mixes and related carbon emissions for electricity used in cell production.

Using the integrated model, we explore hence a range of GHG emissions of global EVB cell production between 2020-2050, using three different scenarios for battery demand, two different scenarios for battery chemistry, and two different scenarios for GHG emissions from electricity production. Next to this, we perform a sensitivity analysis related to a variation of EVB production regions, on the life cycle emissions of global EVB production. In this way, this paper contributes to a better understanding of the global future environmental impacts of EVB production and options to reduce these.

4.2 Methods

4.2.1 Model framework

The integrated model (Fig. 4.1) combines a dynamic battery stock model[7] and a (2) prospective LCA model[178]. The *dynamic battery stock model* estimates the global future demand for EVB cells, considering EV fleet size, battery lifespan, and battery material compositions, as well as the end-of-life (EoL) of EVB cells. The dynamic battery stock model was developed on a global scale in our previous study[7]. Here we apply the dynamic battery stock model to a regional scale, by distinguishing the regional EV fleet share, to project EVB cells demand and EoL materials from EVB cells in China, US, EU, and RoW during 2020-2050 based on an IEA projection[6]. This projection is only available until 2030 and the regional shares are kept as in 2030 for the years after.

Further details of the dynamic battery stock model are explained in Xu et al.[7].

The *prospective LCA model* estimates future production region and battery chemistry-specific life cycle GHG emissions per EVB cell production and cell material. The model from our previous study[178] combines i) the battery cell production data is simulated based on the EverBatt model[48] and China battery industry reports[165]; and ii) the prospective life cycle inventory (LCI) background database is derived from the ecoinvent database[158], but taking into account changes in production technologies of key battery metals (nickel, cobalt, copper, and others), next to changes in energy mixes by region (decarbonization of electricity generation due to climate policy) based on outputs of Remind Integrated Assessment Model[180]. The prospective LCA model presents results for 3 production regions (China, US, and EU) and 8 types of chemistries for the period 2020-2050. For details on this prospective LCA we refer to Xu et al.[178].

Based on the outputs of the dynamic battery stock model and prospective LCA model, we calculate GHG emissions of the global EVB cells production in 2030, 2040, and 2050 without considering the effects of recycling, under various scenarios of battery demand, battery chemistry, and energy mix (see section 2.2). Further, we perform sensitivity analysis of production region and recycling with regard to GHG emissions (see section 4.2.3).

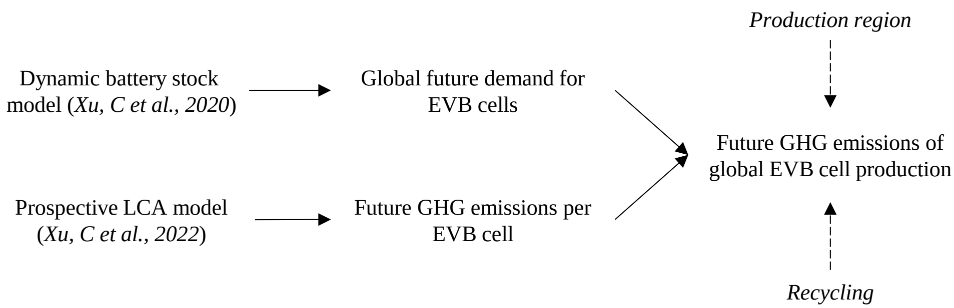


Fig. 4.1: Integrated model to estimate future GHG emissions of global EVB cell production. Dashed lines and italics indicate sensitivity analysis of GHG emissions.

4.2.2 Scenarios

The former section described how we build an integrated model to estimate the GHG emissions of global EVB cell production. We take into account 3 scenarios for EVB cell demand, 2 scenarios for battery chemistry, and 2 scenarios for energy mix between

2020-2050. This totally results in 12 scenarios.

Battery demand scenarios. We first use a medium battery demand scenario based on the EV fleet size of stated policy (STEP) scenario[7], which includes the fleet size of both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). The battery capacity per vehicle of small, mid-size, and large BEVs is assumed as 33, 66, and 100 kWh, respectively, while the average battery capacity of a PHEV is assumed as 14 kWh. The market share among small/mid-size/large is assumed as 19%, 48%, and 33% at any year between 2020-2050. We refer to Xu et al.[7] study for details of battery capacity per vehicle, share of BEVs/PHEVs, amongst others, share of small/mid-size/large BEVs.

The high battery demand scenario uses the same battery capacity per vehicle as the medium battery demand scenario, but a higher EV fleet size based on sustainable development (SD) scenario[7]. Since SD scenario suggests around double EV fleet size than STEP scenario, the high battery demand scenario indicates around two times demand for global EVBs capacity than the medium demand scenario.

The low battery demand scenario is developed based on the same EV fleet size as the medium battery demand scenario (*i.e.*, STEP scenario), but on a lower battery capacity per vehicle: we assume all BEVs are small BEVs with a 33 kWh battery capacity. This assumption is based on two arguments: first, small BEVs can provide most of the daily driving demand for consumers[181], even though they have a lower driving range than large BEVs equipped with a high-capacity battery. Second, the development of widespread EV charging infrastructure, including fast charging technology, could help to overcome the range anxiety of small BEV owners. The increasing use of small BEVs in the low battery demand scenario will reduce EVBs demand and GHG emissions significantly.

Battery chemistry scenarios. Given the uncertain battery chemistry development, we use two battery chemistry scenarios until 2050: the NCX scenario with the NCA and NCM series batteries dominating future EV market (including 1 NCA and 6 NCM batteries with X denoting manganese or aluminum, and NCX batteries will account for over 90% of EVBs market in 2030-2050), and the LFP scenario with LFP battery dominating the future EV market (LFP will reach a 60% market share in 2030-2050). We refer to the detailed descriptions of battery chemistry scenarios in our previous work[7].

We assume that battery chemistry scenarios would not differ between regions in view of limited data availability.

Energy mix scenarios. As indicated above, we take into account changes in energy mixes by region due to climate policy based on the Remind Integrated Assessment Model[180]. We apply two scenarios here, both based on Shared Socioeconomic Pathway 2 (SSP2) that indicates a 'middle-of-the-road' scenario with regard to future population and GDP growth. One is the '3.5 °C scenario' that projects the increase of global average temperature by more than 3.5 °C by 2100. Another is the 'well below 2 °C scenario' that aims to limit the cumulative global GHG emissions to 1,100 Gigatons (*i.e.*, SSP2-PkBudg1100 scenario as described in our previous paper[178]) and the increase of global average temperature by well below 2 °C by 2100. The two scenarios lead to quite different GHG intensities of electricity production per region, and as a consequence, life cycle GHG emissions of EVB production.

4.2.3 Sensitivity analyses with regard to GHG emissions

Influence of EVB production region

As shown above, we estimate the future GHG emissions of global EVB cells production during 2020-2050, based on global future demand for EVB cells and future life cycle GHG emissions per kWh capacity of EVB cell production (Fig. 4.1). However, the GHG intensities of EVB cell production differ between production regions, which are relatively high in China, medium in the US, and low in the EU. We assume China, EU, and US will produce 70%, 18%, and 12% of global EVBs during 2020-2050 while RoW is supplied by China, EU, and US proportionally. This assumption is based on predictions[182,183] of regional distribution of battery cell production capacity around the world in 2030.

It may however be that in future there will be a different production distribution mix. We, therefore, do a sensitivity analysis of battery production regions. Since EU generates the lowest energy-related GHG emissions and China generates the highest energy-related GHG emissions among three investigated battery production regions, here we perform sensitivity analysis between two extreme situations that all batteries supplied by EU producers (100% EU production) versus China producers (100% China production).

Potential benefits of closed-loop, circular recycling

In the above-mentioned scenarios (section 2.2), all life cycle GHG emissions are allocated to the use of batteries in EVs. No second uses or beneficial recycling of battery materials is assumed. We, therefore, perform a sensitivity analysis that includes a closed-loop, circular use of battery materials at their end of life. Battery recycling technologies, usually based on hydro[46]- or pyrometallurgy[48], develop fast and differ a lot according to battery chemistry, recycling volume, and other factors. This implies that using current LCI data for future battery recycling is unreliable. To avoid the use of highly uncertain estimates of environmental impacts during battery recycling, we define a 'maximum impact reduction potential by recycling': the GHG emissions of primary materials production that can be avoided if recycled materials would be used to substitute primary materials. This potential simply assumes that apart from a percentage loss in recycling all secondary materials available in EoL EVBs can be used as primary materials again, without considering *e.g.*, energy input, chemicals use, and emissions during recycling. Including reliable future-oriented LCI for recycling in future studies can promote insights into to what extent a circular use of battery materials may reduce life cycle GHG emissions of EVB production.

We calculate the maximum impact reduction potential by recycling based on global future EoL materials from EVB cells (recycled material) and future GHG emission of EVB cell materials that will be substituted by recycled materials. Calculating this recycling potential requires the match of type and quality between recycled materials and primary materials, as well as information on which and where primary materials, along the cell production chain, are substituted by recycled materials, as explained in the following.

Recycled materials amount, type, and quality. We consider two commercially available recycling technologies (pyro-[48] and hydro- recycling), and their recycled materials type, quality, recycling efficiency (Table 4.1). Although the outputs of both pyro- and hydro- recycling are industry-grade materials, the hydro- recycling can recycle more materials (such as graphite) with high recycling efficiency than pyro-recycling. The total amount of secondary/EoL materials available for re-use was calculated based on the amount of available EoL EVBs in a specific year from our dynamic battery stock model, and the recycling efficiencies in pyro- and hydrometallurgy assuming a 50%/50% market share of pyrometallurgical/hydrometallurgical recycling. Since the uncertainty around market share between pyro- and hydro- recycling technologies, we conduct **s**ensitivity analysis of 100% pyro- and 100% hydro- recycling and investigate their effects on recycling potential.

GHG emissions of primary cell materials that are substituted by recycled materials. According to our prospective model[178], EVB cell production includes five life cycle stages: mining, raw materials production, upgrading battery materials, component production, and cell production. Here we assume recycled materials will substitute primary materials at the level of 'raw materials production' since pyro- and hydro- recycling can generate battery industry-grade materials.

Besides which and where primary materials are substituted, the GHG emissions of primary materials matter for the recycling potential. However, GHG emissions of primary materials are sensitive to their production regions where energy is supplied. We assume EoL EVBs are recycled and re-used in the same region where the EVBs are used. The EoL materials from EVB cells in China will be recycled in China and substitute primary cell materials produced in China, US for US, and EU for EU. While for RoW, we assume EoL EVB cells in RoW will be exported to China for recycling since the expansion of battery recycling capacity in China, and naturally the recycled materials will substitute primary cell materials produced in China. Consequently, around 50%/32%/18% of global EoL EVB cells are recycled and reused to substitute primary materials produced in China/EU/US respectively.

Table 4.1: Recycling efficiency of battery materials by pyrometallurgical and hydrometallurgical technologies.

Materials	Pyrometallurgical[48]	Hydrometallurgical[46]
Copper	90%	100%
Aluminum foil	/	100%
Graphite	/	100%
Li+ in product	/	80%
Co2+ in product	98%	98%
Ni2+ in product	98%	98%
Mn2+ in product	/	80%
Al3+ in product	/	80%
Electrolyte organics	/	100%
Cell aluminum container	90%	90%

4.3 Results and discussion

4.3.1 Battery cells demand

The global demand for EVB cells will increase from 0.4 TWh (terawatt hour) in 2020 to 1.5 TWh in 2030, and 7 TWh in 2050 in medium battery demand scenario (Fig. 4.2), with an increasing factor of 19 and an average annual growth rate of 10% during 2020-2050. China, EU, US, and RoW account for 47%, 22%, 12%, and 19% of global demand in 2050, respectively.

Compared to the medium demand scenario, low battery demand scenario sees 42% lower EVB cells demand in 2020-2050 due to lower battery capacity per vehicle, while high battery demand scenario finds a ~70% higher EVB cells demand in 2020-2050 because of double EV fleet size. As a result, global demand for EVB cells will reach as low as 0.9 TWh (low battery demand scenario) and as high as 2.4 TWh (high battery demand scenario) in 2030 and 4-12 TWh in 2050. Global demand is expected to increase by a factor of 11-31 and average annual growth rates of 8%-12% between 2020 and 2050.

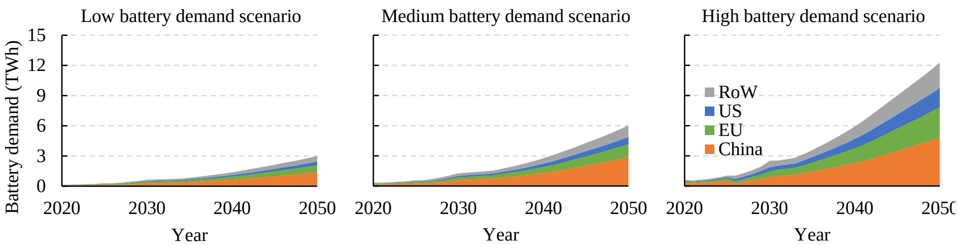


Fig. 4.2: Scenarios of global future demand for EVB cells, including China, EU, US, and RoW. 1 TWh = 10^9 kWh.

4.3.2 GHG emissions

Fig. 4.3 presents the GHG emissions of global EVB cell production in 2030, 2040, and 2050, without considering effects of recycling. Note that the figure includes also the sensitivity analyses assuming full production in China or the EU, respectively. In the medium battery demand scenario, the global GHG emission of EVB cells production will range from 44-99 Mt CO2-Eq in 2030, 54-173 Mt CO2-Eq in 2040, and 99-287 Mt CO2-Eq in 2050 (range depends on battery chemistry and energy mix scenarios). High battery demand scenario leads to 1.5-1.7 times higher annual GHG emissions than in the medium demand scenario, while low demand scenario results in 58%-59% of annual GHG emissions of the medium demand scenario. There is a factor of 2.6-2.9 for GHG emissions of global EVB cell production between the low demand scenario and the high demand scenario.

In addition to battery demand scenarios, scenarios of battery chemistry and energy mix also affect GHG emissions of global EVB cell production. Since LFP batteries generate lower GHG emissions than NCX batteries, the GHG emissions in LFP scenario are 12%-15% lower than NCX scenario (range depends on battery demand scenarios). Compared to battery chemistry, energy mix has a stronger impact on GHG emissions. The GHG emissions under well below 2 °C scenario are 48%-65% lower than under 3.5 °C scenario, because well below 2 °C scenario results in higher low-carbon energy use during battery production that can lead to over 50% reduction of GHG emission per EVB cell production. Consequently, in each battery demand scenario, GHG emissions of global EVB cell production range from low boundary in "LFP and well below 2 °C scenario" to high boundary in "NCX and 3.5 °C scenario".

Despite an 8%-12% annual growth rate of global demand for EVB cells during 2020-2050 across low-medium-high demand scenarios, associated GHG emissions only increase annually by 2%-10% in the same period. Therefore, EVB cells' GHG emissions relatively decouple, *i.e.*, emissions per kWh of battery decrease, while overall emissions continue to increase due to the fast growing demand. To illustrate this, we define a relative decoupling rate, based on[184], as the relative change of annual growth rates between GHG emissions and demand. The relative decoupling rate from 2020-2050 ranges from 19% to 70% for EVB cells, depending on battery demand, battery chemistry, and energy mix scenarios.

As indicated the region where EVBs will be produced is uncertain. Given the different GHG emission intensities of electricity production in China, US and EU this affects GHG emissions of global EVB cell production and the relative decoupling rate between GHG emissions and demand. Figure 3 shows also a sensitivity analysis assuming 100% production in China and the EU respectively. The effects are more limited in well below 2 °C scenario than in 3.5 °C scenario. The GHG emissions of global EVB cell production will increase to 61-519 Mt CO2-Eq in 2050 and the relative decoupling rate during 2020-2050 will decrease to 16%-68% if 100% China production; these numbers change to 49-333 Mt CO2-Eq and 29%-77% if 100% EU production (error bars in Fig. 4.3).

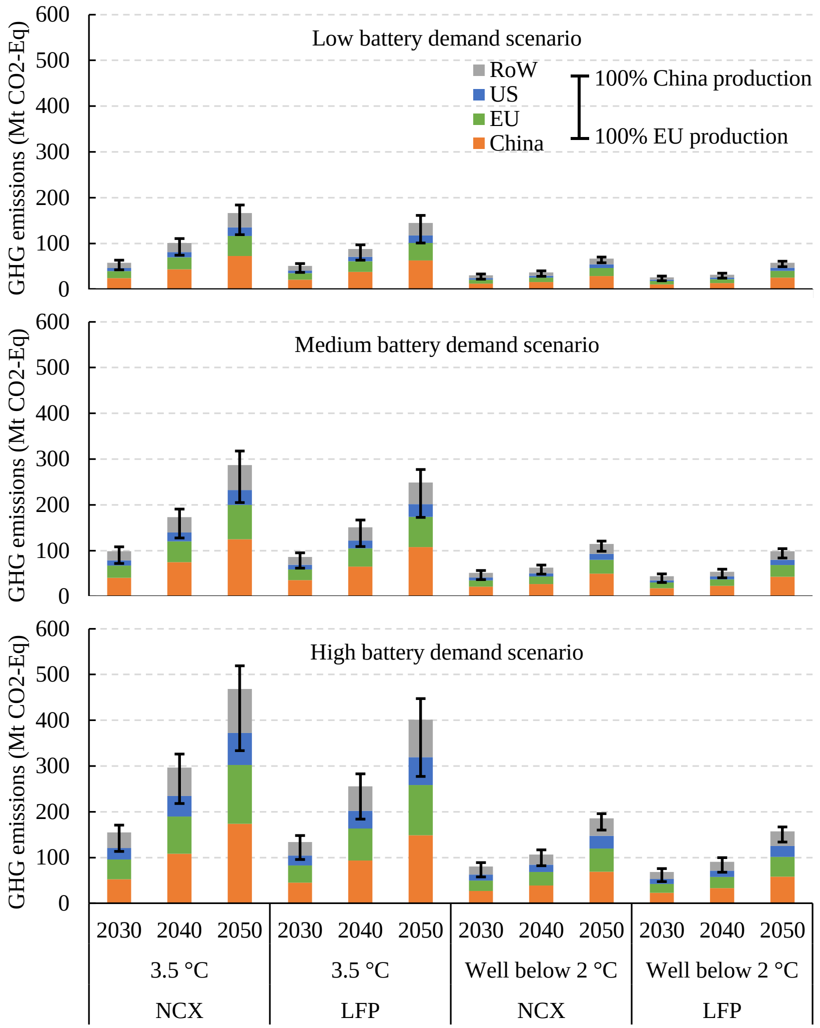


Fig. 4.3: Future GHG emissions of global EVB cells production under different battery demand, battery chemistry, and energy mix scenarios.

4.3.3 Potential benefits of closed loop recycling

EVB recycling can reduce the GHG emissions of EVB cells since recycled materials contain less embodied GHG emissions than primary materials[185]. We quantify maximum impact reduction potential by recycling, *i.e.*, avoided GHG emissions of primary materials that can be substituted by recycled materials, while at the same time neglecting the environmental impacts during recycling. The higher GHG emissions of EVB cell production, the higher maximum impact reduction potential by recycling. In other words, the highest maximum impact reduction potential by recycling exists in 'high battery demand-NCX-3.5 °C' scenario, and the lowest potential in 'low battery demand-LFP-well below 2 °C' scenario. The global maximum impact reduction potential by recycling will range from 0.4 to 1.3 Mt CO2-Eq in 2030 and from 4 to 41 Mt CO2-Eq in 2050 (see Supplementary Fig. 4.1), which is 1-2 orders of magnitude lower compared to battery production GHG emissions (Fig. 4.3).

We further investigate the relative maximum impact reduction potential by recycling for the next three decades: maximum impact reduction potential by recycling divided by battery production GHG emissions, *i.e.*, the percentage of battery production GHG emission that can be mitigated by using recycled materials to substitute primary materials (see results in Fig. 4.4). Material recycling only has a minor but increasing contribution to reduce GHG emissions. The relative maximum impact reduction potential by recycling for GHG emissions is increasing from less than 1% in 2021-2030 to 2%-5% in 2031-2040, and to 3.5%-10% in 2040-2050 (left of Fig. 4.4). This is mainly because the volume of materials entering the EoL stage in a specific year is just a fraction of the required new use (5%-30%) due to the fast growth of the EV fleet. This situation can be only partly solved once the EV battery market has reached a steady state, *i.e.*, when recycled EoL materials can almost completely meet material demand. With a hypothetical future steady state after 2050 (right of Fig. 4.4), the relative maximum impact reduction potential by recycling can improve to 8%-22% in 2021-2030 to 10%-30% in 2031-2040, and to 13%-35% in 2040-2050. These potentials are still far below 100%. The reason is that recycled materials of pyro- and hydro-recycling can substitute/be used as industry-grade primary materials whose production generates fewer GHG emissions than the further processing to battery-grade materials or components.

The recycling potential depends on not only the amount of availability of EoL battery materials, but also on which primary battery materials will be substituted by recycled materials - affected by recycled material type and quality - and what GHG emission intensity of primary battery materials will be avoided. Pyro-recycling and hydro-recycling can both recover industry-grade materials (lower quality than battery-grade materials), but hydro-recycling recovers more material types (such as graphite) than pyro- recycling. Compared to 100% pyro-recycling, 100% hydro-recycling only slightly improves the relative maximum impact reduction potential by recycling (error bars in Fig. 4.4). It is hence important to develop industrial-scale reconditioning technologies that allow the re-use of EoL battery components as components or battery-grade materials, such as direct recycling technology[186] that can recover and re-use battery cathode.

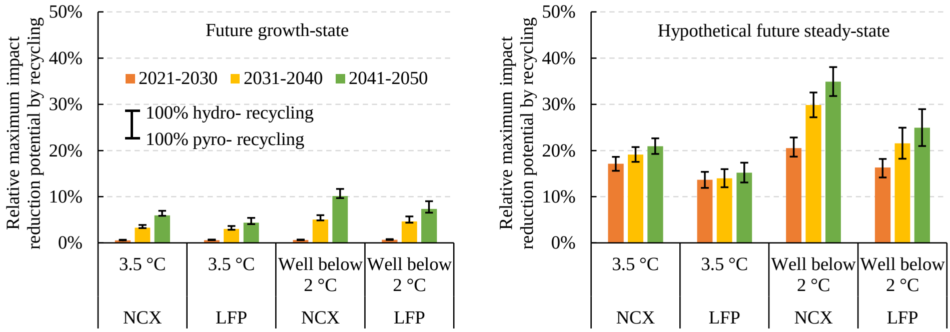


Fig. 4.4: Relative maximum impact reduction potential by recycling for GHG emissions of global EVB cells production in periods of 2021-2030, 2031-2040, and 2041-2050, with future growth-state (left) and hypothetical future steady-state (right), under medium battery demand scenario. Bar charts refer to a 50%/50% market share of pyro- /hydro- recycling. Error bars indicate 100% hydro-recycling and 100% pyro- recycling. Please see results under low and high battery demand scenarios in Supplementary Fig. 4.2 and Supplementary Fig. 4.3.

4.4 Conclusions

In this paper, we build an integrated model, consisting of a dynamic battery stock model and a prospective LCA model, to quantify future GHG emissions of global EVB cell production during 2020-2050. We further investigate the effect of different regional distributions of production and the GHG emissions reduction potential related to avoided primary material production due to closed-loop recycling. We find that:

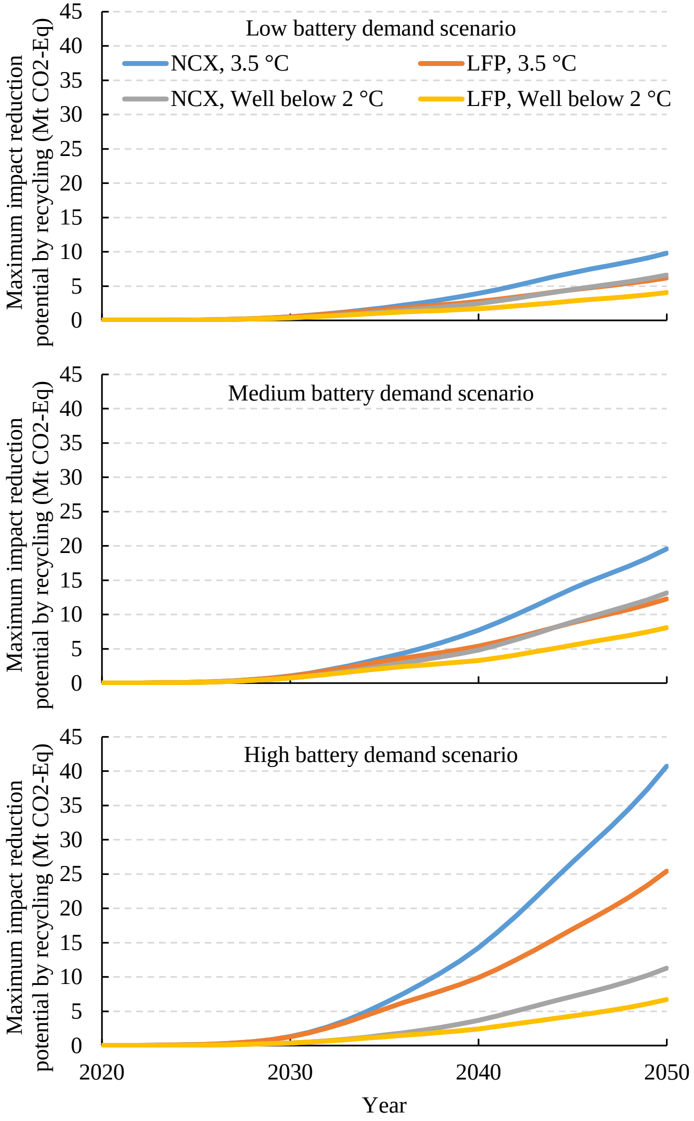
(1) Due to demand growth for EVB cells, GHG emissions of global EVB cell production will increase to 26-155 Mt CO2-Eq in 2030 and 58-468 Mt CO2-Eq in 2050, depending on battery demand, battery chemistry, and energy mix scenarios.

(2) Despite 8%-12% average annual growth rate of global demand for EVB cells during 2020-2050, associated GHG emissions only increase annually by 2%-10% in the same period. There is thus a relative decoupling of GHG emissions related to demand by 19%-70% from 2020 to 2050. This is due to a reduction of the emission intensity of battery production by over 50% that mainly results from the decarbonization of the consumed electricity during battery production, especially under the well below 2 °C scenario.

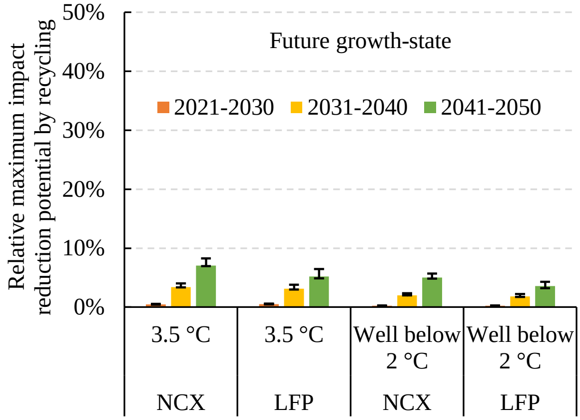
(3) Maximum impact reduction potential by recycling for GHG emissions will reach 0.4-1.3 Mt CO2-Eq in 2030 and 4-41 Mt CO2-Eq in 2050, which is 1-2 orders of magnitude lower compared to battery production GHG emissions. Recycling offers initially only a small potential to reduce GHG emissions, but the potential increases after 2030 because of the increasing availability of EoL battery materials.

In short, to avoid important GHG emissions due to battery cell production for EVs it is crucial to realize the following. First, the energy system should be decarbonized strongly, since this is the single most important factor determining GHG emissions from EVB cell production. Second, we see that using small EVs that can operate using relatively low battery capacities reduces life cycle GHG production emissions even further. Third, we see that LFP batteries have slightly lower life cycle GHG emissions than NCX batteries. Finally, we see that recycling or re-use of secondary batteries on the short term will not reduce life cycle GHG emissions a lot since building up stocks of EVBs requires much more new materials as that there are EoL batteries available. These findings give clear recommendations to policy to reduce GHG emissions from EVB production. Particularly the stimulation of use of small EVs is crucial, next to ensuring batteries are designed and developed such that easy re-use after end of life is possible. An important other development that could be stimulated is the use of self-driving cars[4] and sharing vehicles[5]. These are likely to be used much more intensively by different users, which could reduce the required battery capacity and related life cycle GHG emissions for production additionally by several factors[187].

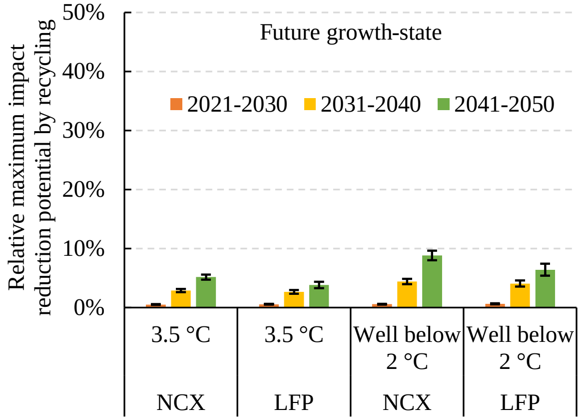
4.5 Supplementary information



Supplementary Fig. 4.1: Global maximum impact reduction potential by recycling for GHG emissions of global EVBs cells production under low, medium, and high battery demand scenarios.



Supplementary Fig. 4.2: Relative maximum impact reduction potential by recycling for GHG emissions of global EVBs cells production in periods of 2021-2030, 2031-2040, and 2041-2050, with future growth-state, under low battery demand scenario. Bar charts refer to a 50%/50% market share of pyro- /hydro- recycling. Error bars indicate 100% hydro- recycling and 100% pyro-recycling.



Supplementary Fig. 4.3: Relative maximum impact reduction potential by recycling for GHG emissions of global EVBs cells production in periods of 2021-2030, 2031-2040, and 2041-2050, with future growth-state, under high battery demand scenario. Bar charts refer to a 50%/50% market share of pyro- /hydro- recycling. Error bars indicate 100% hydro- recycling and 100% pyro-recycling.