Lithium: a major ecological challenge for low-carbon mobility

Minimal Report — 2024

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Association négaWatt – BP 16280 Alixan – 26958 Valence Cedex 9 France
contact@negawatt.org – www.negawatt.org

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The Minimal project

The fight against climate change is now a major challenge, as it is crucial for maintaining life on Earth as we know it. Yet, it is not the only environmental issue we face. Biodiversity collapse; air, water, and soil pollution; and the eutrophication of aquatic environments are all important and often interconnected. We know these problems are caused by many human activities, such as mineral extraction and metallurgy. But is it even possible to halt this extraction in the short, medium, or long term?

To limit the increase in the Earth's temperature as much as possible, we must reduce greenhouse gas (GHG) emissions. And yet, efforts to decarbonise human activities in many industries will increase the consumption of mineral resources and associated environmental impacts. This will become more of a problem in the future, as the energy transition currently contributes a tiny share of the mining and metallurgy industry's impact. To fully understand this impact, we must assess the use of metals overall, not just in the energy transition.

This raises several questions: How can we determine our true need for metals to ensure good living conditions while enacting the energy transition? How can we prioritise these needs to achieve the energy transition while reducing extraction? And how can we ensure equitable global access to mineral resources?

The Minimal project, developed by the French not-for-profit Association négaWatt, aims to answer these questions and many others. This project will take an in-depth look at possible shifts in the production and consumption of various critical metals for the energy transition and/or whose extraction is particularly damaging to the environment. The project will cover the following metals:

- **Major industrial metals:** copper, nickel, aluminium, and iron are produced in large quantities for important uses (infrastructure, construction, transport, industry, and electric power transmission) with just as significant an impact.

- **Smaller-scale metals:** lithium, neodymium, and cobalt are produced in fairly small quantities each year. However, they are considered strategic metals for certain applications in the energy transition.

- **One precious metal:** gold is produced in low volumes from very low-grade deposits. This means gold mining occurs in huge mines with major negative impacts, even though it is primarily destined for non-essential uses.

This report presents our study of the first metal in the Minimal project: lithium.

Authors: Judith Pigneur, Adrien Toledano, Stéphane Chatelin, Nicolas Taillard

Contributors: Mathilde Djelali, Adrien Jacob

Reviewers: Emile Balembois, Quentin Deforge, Julien Dezombre, Pierre De Pasquale, Natacha Gondran, Emmanuel Hache, Thierry Hanau, JeanPhilippe Hermine, Diana Huet de Guerville, Emmanuel Rauzier, Rose Rondelez, Thibaud Saint-Aubin, Marie Sauze, Thomas Van Nieuwenhuyse

Translator: Diana Huet de Guerville

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Background

Political

Electric mobility has become key to reducing GHGs. On a global scale, new policies are encouraging the transition to more sustainable transport modes. In Europe, the “Fit for 55” programme set a goal of reducing GHGs by 55% and prohibiting the sale of internal combustion (ICE) vehicles in the European Union (EU) by 2035. The United States passed the “Inflation Reduction Act”, which encourages more sustainable practices. India implemented the “Faster Adoption and Manufacture of Hybrid and Electric Vehicles Scheme”. All these measures to decarbonise mobility require changing the type of propulsion system used, which will necessarily consume additional mineral resources (lithium in particular).

Despite political efforts taken in the past few years to secure the supply of these resources, the EU’s industrial strategy has failed to consider solutions to reduce consumption and to ensure that mining projects maintain strict environmental standards. This is unfortunate because there is an opportunity to show that the energy transition can protect both human rights and the environment[1] while ensuring equity in global value chains. Indeed, an industrial strategy that is both socially and environmentally ambitious is the only way to drive truly sustainable development.

Scientific

For some metals, it is not the energy transition that has driven increased demand. Rather, there are other reasons for the rise in environmental impacts. However, in the case of lithium, transport electrification has led to a real increase in demand. Though this report focuses on the impacts of lithium production (and, therefore, indirectly on the impacts of this electrification), our goal is to present the most sustainable and realistic transition possible. However, it is important to remember that transport decarbonisation is necessary and unavoidable in a world in which the **fossil fuels** used **for passenger vehicles represented 10% of global CO_2** emissions from energy in 2018 (1, 2). And **electric vehicles (EVs) are better for the climate than vehicles that run on fossil fuels** (3). The performance of these EVs should improve with the decarbonisation of energy mixes, but they already perform better than ICE vehicles today.

Nevertheless, transport electrification is not the only solution. We must also implement measures to reduce road traffic, particularly by developing alternatives, which are featured in the various scenarios Association négaWatt presents. However, we clearly cannot suddenly eliminate cars, as they are the most widely used transport mode in the EU. Current land use planning patterns make cars essential in many cases, and going car-free would entail major lifestyle changes. As a result, EVs seem indispensable for the transition in the short term. Yet, we cannot ignore the significant social and environmental impacts of mining. Lithium, our focus here, has a very real impact. Though it currently represents a very limited share of the overall impact of mining and metallurgy, this is likely to change in the future with the expected growth in the production and consumption of this metal, and major changes in the extraction process used in new types of ore deposits.

Research questions

In this context, how can we ensure that the pathways we propose meet the most essential human needs and the needs of the energy transition, all while respecting planetary boundaries? How can we trace a path that will achieve the energy transition while maintaining high environmental standards?

To answer these questions, we suggest establishing a **sustainable consumption corridor** that defines a safe and just space for yearly lithium consumption. This sustainable consumption corridor is defined

[1]In June 2022, the UN recognised the human right to "a clean, healthy, and sustainable environment", establishing a link between respect for the environment and respect for human rights.

by possible lithium consumption values that lie between a social foundation and an ecological ceiling. **This social foundation is described in the form of a pathway between 2015 and 2050** that identifies **a social minimum regarding annual lithium needs** for mobility. This is a social minimum below which basic needs may not be met. We call the ecological ceiling the **ecological budget for lithium extraction**, which establishes consumption limits above which we risk surpassing planetary boundaries. In this report, we have set this ecological ceiling solely for 2050.

Next, we identify actions to remain within this sustainable consumption corridor. We will show how to implement a strategy based on **sufficiency, efficiency, and ecological substitution for lithium** in batteries to keep the EU within this corridor.

Abbreviations and glossary

Li_2CO_3	Lithium carbonate
$LiOH{\cdot}H_2O$	Lithium hydroxide monohydrate. The terms LiOH or lithium hydroxide are often used to simplify things, but under ambient conditions (and in its commercial form), the product is $LiOH{\cdot}H_2O$.
CRMA	The EU's Critical Raw Materials Act, which aims to reduce Europe's dependence on third countries. The regulation identifies a list of 17 strategic raw materials and an expanded list of 34 critical raw materials and sets objectives for the supply of strategic materials. Lithium is on both lists. The regulation was adopted on 18 March 2024
GHG	Greenhouse gas.
DLE	Direct Lithium Extraction.
Light-duty vehicle	Light-duty vehicle (LCV), an IEA category that includes passenger cars and light commercial vehicles (pickup trucks and delivery vans). It refers to vehicles with gross vehicle weights under 4.5 t as well as two-wheelers.
BAU	Business as Usual: a forward-looking scenario based on current patterns.
Heavy-duty vehicles	Trucks and buses.
NORM	Natural-Occurring Radioactive Materials.
IEA	The International Energy Agency is an international organisation founded by the OECD in 1974, based in Paris.
LCE	Lithium Carbonate Equivalent.
WFD	The EU Water Framework Directive.
DERA	The German Mineral Resources Agency.
EU	The European Union.

Planetary boundaries	The concept of planetary boundaries seeks to guarantee the liveability of the Earth system: crossing boundaries increases the risk of generating large-scale or abrupt irreversible environmental changes. Drastic changes will not necessarily take place overnight, but taken together, the boundaries mark a critical threshold for increasing risks to people and ecosystems. Boundaries are interrelated processes within the complex biophysical Earth system. https://www.stockholmresilience.org/research/planetary-boundaries.html
Sustainable consumption corridor	Proposal to define a safe and just operating space (according to Kate Raworth's Doughnut theory) for annual lithium consumption. This sustainable consumption corridor for lithium requires staying above the social foundation (called social minimum pathway) to ensure basic needs are met while remaining below the ecological ceiling (called ecological budget for lithium extraction), which defines the consumption level above which we risk breaching planetary boundaries.
SOH	State of health, the condition of a battery as a percentage (%) of its initial capacity (in kWh). This indicator measures the battery's loss of capacity.
BAMASI	"BAttery MAterials SImulation" is a vehicle fleet model developed by Association négaWatt to evaluate the material footprint of a transition scenario in the road transport sector. It is described in Appendix 3.
ADEME	The French Agency for Ecological Transition is a public industrial and commercial establishment created in 1991.
JRC	"Joint Research Centre" of the European Commission, which produces independent scientific knowledge and data to support EU policy.
T&E	The European Federation for Transport and Environment, also known as Transport and Environment (and the acronym T&E), is a European organisation that brings together 50 or so NGOs working in the transport and environment fields.
GDP	Gross domestic product.
CO_2	Carbon dioxide. A major GHG.
GW	Gigawatt. A unit of power equal to 1 billion watts.
kWh	Kilowatt-hour. A unit of energy delivered by 1 kilowatt of power for one hour.
kWh/cap/year	Kilowatt-hour per capita and per year.

DLS	**Decent Living Standards** are defined in academic literature that focuses on identifying the basic needs that are deemed essential for living a decent life. They cover nutrition, housing, education, health, energy, and so on. In this report, we base the minimum need for lithium on studies in the field of DLS research. We present a minimum transport need per person (in kilometres per person per year). We then translate this figure into a lithium need, as explained in Part 1.
TRL	**TRL**, or Technology Readiness Level, is a method to measure the maturity level of a given technology (material, component, peripheral device, and so on), particularly with an eye to funding research and development or integrating this technology into an operational system or subsystem.
UNEP	The United Nations Environment Programme is a UN organisation that coordinates UN activities in the environmental field and helps countries implement environmental policies. Since the emergence of the concept of sustainable development, the UNEP has sought to integrate environmental issues into broader sustainable development policies.
Primary and secondary production	Primary production comes from mining, while secondary production comes from recycling. Therefore, “primary lithium consumption” is the consumption of mined lithium.
CLEVER	CLEVER (a Collaborative Low Energy Vision for the European Region) is a scenario that proposes an ambitious and realistic decarbonisation pathway for Europe. It was created using a “bottom-up” approach that starts with national trajectories developed by 26 national partners (including Association négaWatt) from academia, research, and civil society. The scenario presents a pathway that reconciles long-term climate and sustainability imperatives with short-term energy security constraints and the practical feasibility of such a transformation. A sectoral note on mobility is available on the CLEVER website. In this report, to comply with the EU regulation prohibiting the sale of ICE light-duty vehicles by 2035, we have modified the share of light commercial vehicles in the CLEVER scenario to include only electric vehicles and exclude biogas vehicles.
IRP	The International Resource Panel is a group of independent scientific experts created by the UN in 2007 to help countries use natural resources sustainably, meaning without compromising current and future human needs. It is hosted by the UNEP.
NMC	Commonly used lithium-ion battery technology containing nickel, manganese and cobalt.
LFP/LFMP	Lithium-ion battery technology containing lithium, iron and phosphate. This technology contains more lithium than NMC and no cobalt or nickel. LMFP technology also contains manganese.

LMO	Lithium-ion battery technology containing lithium and manganese oxide. This technology contains more lithium than NMC and no cobalt.
NCA	Lithium-ion battery technology containing nickel, cobalt and aluminum.

1. Social foundation: How much lithium does Europe need?

In this report, we suggest establishing a sustainable consumption corridor that defines a safe and just space for yearly lithium consumption that meets the most essential needs for lithium while respecting planetary boundaries. This sustainable consumption corridor is defined by the possible lithium consumption values that lie between a social foundation and an ecological ceiling (called ecological budget for lithium extraction), which defines the level of consumption above which we risk breaching planetary boundaries.

In the first part of this report, we explore the social foundation concept in the form of a **pathway** that establishes a social minimum for annual lithium needs for mobility between 2015 and 2050. To do so, we must identify our **basic lithium needs**. In this part, we define the **social foundation below which it seems preferable not to drop. This is not a consumption target**. In Part 3, we will define an ideal pathway.

1.1. Scope: The main end uses taken into account to model lithium needs

Lithium consumption has increased 4.5-fold in the last eight years because of its rapidly growing use in batteries (see Figure 1). Though lithium used in batteries represented just 39% of global consumption in 2016, it now represents 90% of end uses (4).

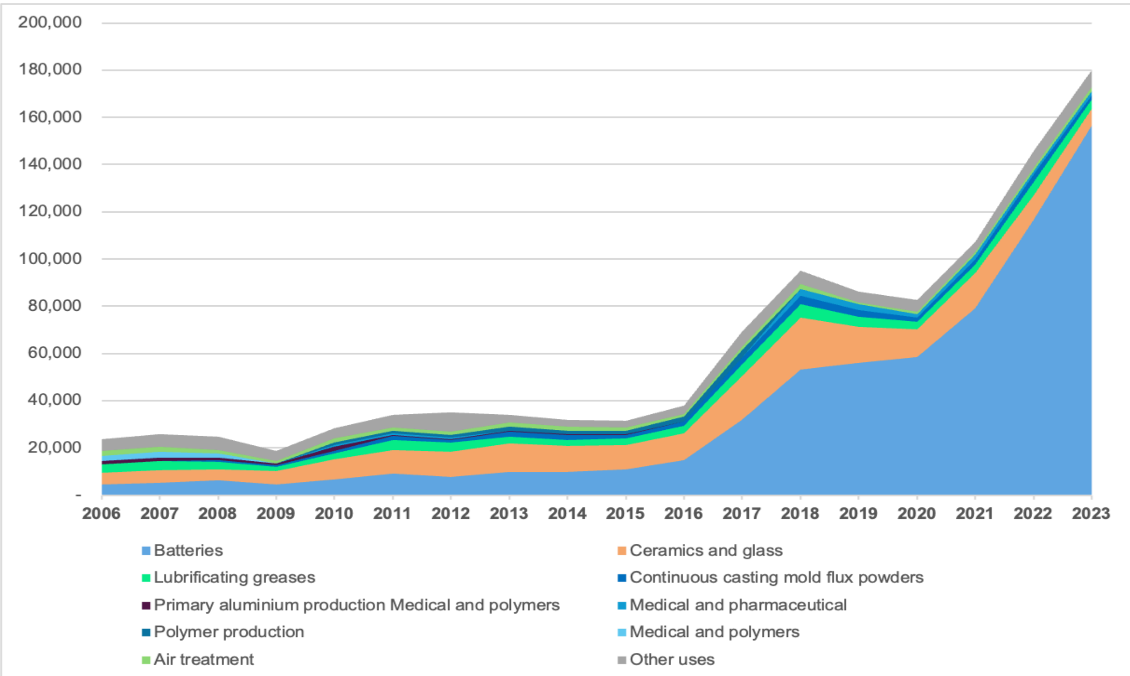

Figure 1: Evolution of global lithium end uses
in tonnes of lithium content per year (Source: USGS data (4))

Lithium batteries are used in the electronics sector in portable devices (such as smartphones and laptops), in the energy and industrial sectors for stationary storage, and the transport sector for electric mobility. In 2020, mobility consumed more than 80% of the lithium used in batteries (5), electronics represented 15%, and stationary storage was less than 5%. In the coming decades, the share of lithium used in electric and hybrid mobility will become even more dominant according to a broad range of global, European, and French scenarios: IEA, 2022 (6); JRC, 2023 (7); Eurometaux, 2022 (8); Association négaWatt, 2022 (9). Figure 2 below shows the outlook for increased demand in lithium-ion battery cells between 2022 and 2030.

Consequently, to evaluate lithium needs, we will focus primarily on the use of lithium in electric and hybrid vehicles.

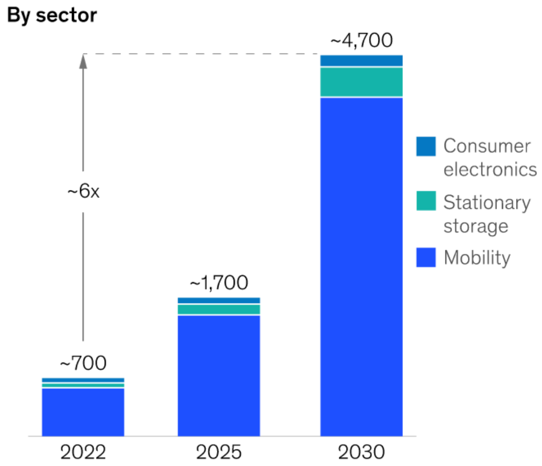

Figure 2: Expected growth in lithium-ion battery cell demand (in GWh) over the 2022–2030 period (Source: McKinsey, 2023 (10))

Reconciling sustainable lithium mining with the energy transition requires, above all, meeting the essential needs of this metal to electrify transport. This study will therefore focus on this end use. But what are these essential needs? How can we define them?

1.2. Definition of the social minimum

Our assessment of lithium needs to meet a social minimum in Europe is based on minimum mobility and freight needs as defined in the academic literature on the concept of DLS (Decent Living Standards). This literature explores the definition of the basic needs that are deemed essential for living a decent life. These needs include nutrition, housing, education, health, energy, and so on. In this study, we define the minimum need for lithium using studies that propose a minimum level of mobility per person (in kilometres per capita per year) based on DLS and low-consumption scenarios, which we then translate into material requirements.

Four studies (11–14) present a minimum level of mobility per person (in kilometres/person/year) covering all transport modes to meet essential mobility needs. This minimum incorporates various parameters, such as the urban/rural distribution in a particular area (12). It ensures that each person can go to work, buy food, access health care, and so on. The minimum mobility standards, as defined in these four studies, are presented in Table 1. Millward-Hopkins et al., in addition to establishing minimum mobility requirements per person, also disaggregate different transport modes that correspond to this minimum mobility need in a "low-energy-consumption" scenario. They also propose a vehicle occupancy rate and define a minimum need for freight transport in tonne-kilometres per capita.

	Millward-Hopkins (2020) global range	Millward-Hopkins (2020) European urban/rural ratio	Rao et al. (2019)	Grubler et al. (2018)	Kikstra et al. (2021)
Mobility requirement in kilometres per person per year	4,900–15,000	6,156	10,000	9,544–17,117	8,274

Table 1: Comparison of mobility requirements in kilometre/person/year of four major studies on DLS and low energy-consumption scenarios.

To evaluate the social minimum for Europe, we chose the mobility level of 8,000 km per capita (covering all transport modes). It is an intermediate value taken from known studies. We defined the other parameters that allowed us to evaluate minimum material requirements (such as vehicle occupancy rate or the share of active mobility) based on a study by Millward-Hopkins et al. (2020), which provided clear details about the assumptions used. We then fine-tuned these parameters during discussions with French and European foresight experts. Table 2 summarises our main assumptions for 2050. To create a scenario for 2018 to 2050, we applied linear trends between the historical and projected levels to gradually move toward a mobility level that solely meets basic needs. Regarding new vehicle sales, our scenario assumes that 100% of light-duty vehicles sold by 2035 will be electric (based on European regulations) and will have batteries with an average capacity that is slightly lower than today's average. Our scenario also assumes that half of heavy-duty vehicles (trucks and buses) will be electric and battery-powered by 2050. The other half will use other decarbonised technologies, such as bioNGV or fuel cells. All of these transport assumptions are translated into annual lithium requirements by 2050 using the BAMASI[2] ("BAttery MAterials SImulation") fleet model developed by Association négaWatt.

Indicator	Unit	Type of vehicle	Minimum scenario for 2050	Index 2018 = 100%
Mobility requirement	km per capita	Total	8,000	62%
Mobility requirement	km per capita	Passenger car	3,891	41%
Occupancy rate	person per vehicle	Passenger car	3	184%
Mobility requirement	km per capita	Bus	1,024	91%
Mobility requirement	km per capita	Motorised two-wheeler	205	84%
Freight requirement	tonnes per capita	Commercial vehicle	174	77%
Freight requirement	tonnes per capita	Trucks	1,495	38%

Table 2: Main transport assumptions for 2050 used to design the social minimum for Europe

The minimum lithium requirement for the **electronic devices** sector, though small compared to the transport sector, can be defined using a similar approach based on DLS. Vélez-Henao & Pauliuk (15)

[2] The BAMASI model is briefly described in Appendix 3.

propose 0.83 smartphones per adult per year and 0.25 laptops per capita per year to meet minimum communication needs. This represents around 0.04 kWh/cap/yr of battery capacity, a much smaller amount than the road transport sector (around 18 kWh/cap/yr).

The need for **stationary batteries** to balance the power grid depends on the change in the electricity mix, the consumption profile, and other means of flexibility and storage used. Using a conservative approach, the European Commission's S3 scenario (16) has been defined as the reference scenario (150 GW of new battery capacity installed in 2050). This value could be lower in a social minimum-type scenario, given that electricity demand and storage needs will be lower (as shown in the 2024 study conducted by ADEME (17) for France).

Still taking a conservative approach, the other **non-battery uses of lithium** (ceramics, glass, lubricants, etc.) could be considered identical between now and 2050 as part of a social minimum scenario.

1.3. Lithium needs for a social minimum scenario in Europe

All of these assumptions, generally based on the existing literature, were translated into annual lithium needs for 2018–2050. To define the need for primary lithium (meaning from mining, versus secondary lithium from recycling), we had to consider circular economy assumptions. The assumptions of our social minimum scenario go further than European regulations (18) that define a lithium recycling rate of 50% in 2027 and 80% in 2031, without setting a collection rate for end-of-life EV batteries. The social minimum scenario goes beyond current industrial and regulatory approaches to consider the following assumptions with proven technical feasibility.[3]

- All end-of-life batteries are collected based on the strategic assumption that recycling processes developed in Europe make it possible to produce high-quality lithium that can be reused in new batteries.
- The recycling rate of lithium from end-of-life batteries is 50% in 2026, 80% in 2031, and 90% in 2035. This excludes lithium recovery through downcycling (such as slag used in road foundations or to make cement).

The circular economy assumptions on the collection rate for end-of-life batteries, on recycling (and not recovery) rates, and the production of battery-grade lithium are intentionally very ambitious (while remaining technically feasible). They allow us to evaluate the amount of mined lithium needed to meet decent living standards, all while electrifying road transport.

Figure 3 below represents annual primary lithium consumption for 2018–2050 as well as cumulative primary lithium requirement for this minimum scenario. **The amount of primary lithium required to meet minimum needs in Europe is 3,000 tonnes of lithium per year in 2050 and 790,000 tonnes for the 2018–2050 period.** Given the rapid electrification of new vehicles sold compared to the more gradual reduction in mobility needs, demand for primary lithium reaches a pinnacle in 2030 before attaining much lower levels in 2050. This decrease is also underpinned by an annual rate of reincorporated recycled material that gradually increases to 85% in 2050.

[3] Lithium recycling methods, along with related challenges, limitations, and policy recommendations, are detailed in the "Recycling" section of Part 4.2 of this report.

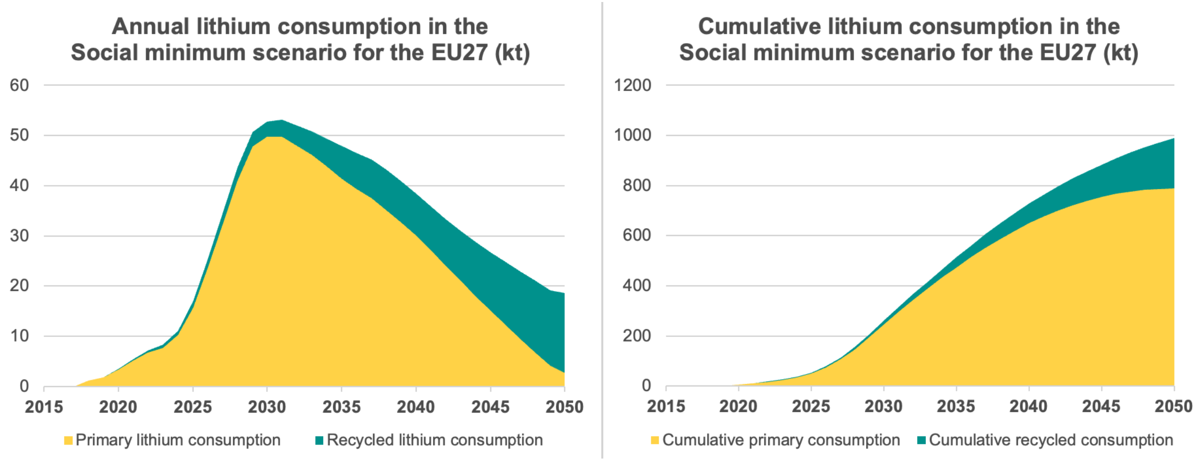

Figure 3: Annual and cumulative lithium consumption in the social minimum scenario for the EU-27 (kt)

2. Ecological ceiling: The ecological budget for lithium extraction

To establish a **sustainable consumption corridor** that defines a safe and just space for annual lithium consumption, we first identified a social foundation defined by a **social minimum pathway**. In this part, we will define an ecological ceiling in the form of an **ecological budget for lithium extraction** that establishes a consumption level above which we risk breaching planetary boundaries. In this report, we have set the ecological ceiling solely for 2050.

2.1. Why set a limit for lithium mining production?

Recycling is currently insufficient

The recycling rate is too low to halt mining in the short term because the supply of lithium in end-of-life batteries cannot meet growing needs.

Do the environmental benefits of lithium use justify overlooking its social and environmental impacts?

The EU Critical Raw Materials Act (CRMA) currently undermines the achievement of high environmental standards in mining projects by allowing operators to circumvent EU framework directives on water, habitat, and birds for strategic substances such as lithium.

The exemptions to environmental standards granted to mining operations are currently justified by the strategic nature of these metals and risks to the supply, along with the environmental benefits of their end use in the energy transition.

Nevertheless, there is a long list of mineral raw materials that could be used in the transition, and they are not all equivalent in terms of importance or volume. To ensure that the transition does not allow all industrial projects to circumvent environmental standards, we must therefore:

- **evaluate the real need for these materials in the transition on a case-by-case basis**. The concept of "real need" implies examining the possibility of implementing a strategy based on sufficiency, efficiency, and ecological substitution. We are not challenging the need for the ecological transition itself.
- **take into account the fact that human activities occur in a context of limitations**. Humans have already crossed six planetary boundaries (19) out of nine[4]. These boundaries include but are not limited to climate change, the study of which is insufficient to guarantee the sustainability of our ecosystems. As such, GHG emissions must not be the only criteria considered when planning the ecological transition and metals requirements. After all, **the habitability of planet Earth is at stake.**

The mining and metallurgy sector is putting pressure on the following boundaries: climate change, atmospheric aerosol loading, freshwater change, land system change, and biosphere integrity (20–25). Four of the five planetary boundaries impacted by mining have already been exceeded (see Figure 4).

[4] The concept of planetary boundaries seeks to guarantee the liveability of the Earth system: crossing boundaries increases the risk of generating large-scale or abrupt, irreversible environmental changes. Drastic changes will not necessarily take place overnight, but taken together, the boundaries mark a critical threshold for increasing risks to people and ecosystems. Boundaries are interrelated processes within the complex biophysical Earth system. https://www.stockholmresilience.org/research/planetary-boundaries.html

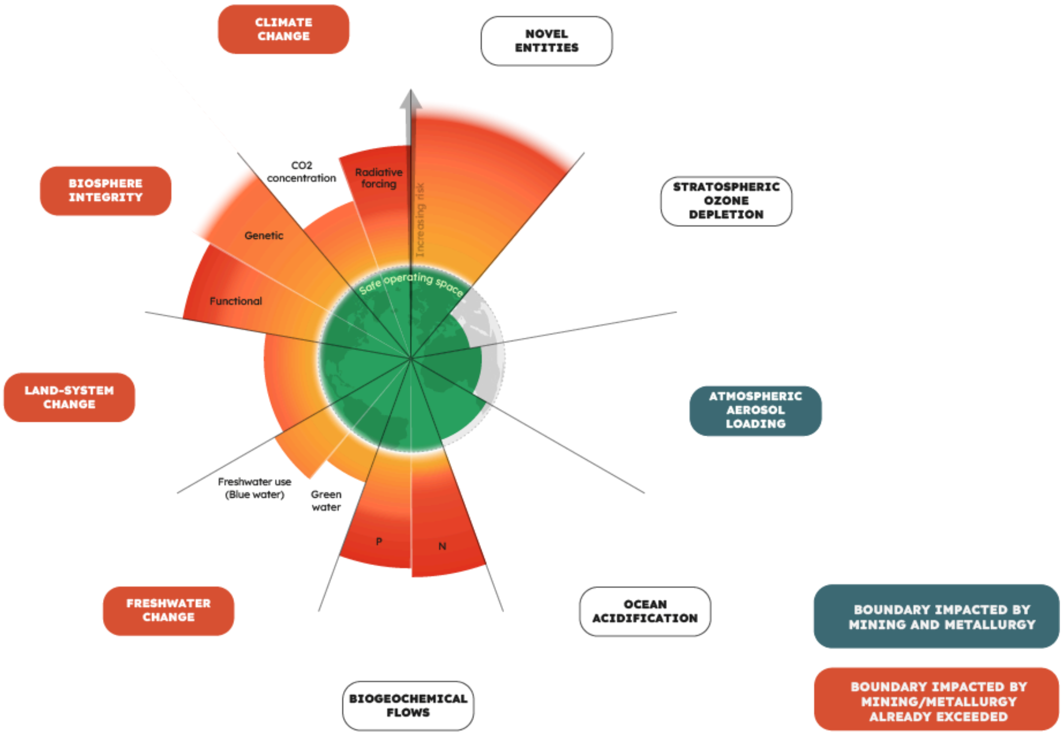

Figure 4: Planetary boundaries and the impacts of metal production
(Source: based on Richardson et al. (19))

We must not forget the impacts not considered in the planetary boundaries framework, such as irreversible soil pollution caused by mining waste storage (see Part 4.2). Pollution from mining waste remains after the mining project is completed because there is no truly effective way to treat waste rock and production tailings. Only pollution containment solutions are put in place over the long term. This results in a slow dissemination of contaminants from the waste left on site, which is currently hard to assess. An initial study on old tailings dams for lead, zinc, copper, and arsenic determined that pollution from these storage sites affected 479,200 km of waterways (or more than 70 times the length of the Amazon River), 164,000 km² of flood plains, and around 20 million people living on this contaminated land (25).

The negative consequences of the mining industry are such that its expansion could contradict stated climate action objectives and contributions to achieving the UN Sustainable Development Goals (SDGs), as shown in the report from the Columbia Center on Sustainable Investment and the Responsible Mining Foundation (RMF) (26).

In addition to these drastic environmental consequences, around 80% of global lithium reserves are located on (or very near) Indigenous land (27). *The International Labour Organisation (ILO) Indigenous and Tribal Peoples Convention (No. 169),* adopted in 1989, and the *UN Declaration on the Rights of Indigenous Peoples,* adopted by the UN General Assembly in 2007, granted some fundamental rights to these peoples, and notably their right to give free, prior, and informed consent (FPIC) on the use and development of their lands. In general (not specifically for lithium), this right has largely been ignored, namely in the EU.[5] Representatives and defenders of Indigenous Peoples (as well as non-indigenous activists) who have been fighting to defend their rights and protect their environment and way of life in

[5] Particularly regarding the Sámi people, who live on lands in Sweden and Finland (EU) and in Norway (outside the EU). See https://news.mongabay.com/2023/03/sami-rights-must-not-be-sacrificed-for-green-energy-goals-of-europe-commentary/

areas of interest for mining have been criminalised, threatened, and assassinated, as documented in the Global Witness Annual Reports since 2012.[6]

This means we cannot continue to use metals exponentially and indiscriminately without major social and environmental consequences. In attempting to mitigate climate change impacts, we run the risk of water resource overconsumption, land take, toxicity, and loss of biodiversity.

The environmental and social impacts of mining and metallurgy cannot continue to increase indefinitely. We must place an environmental limit on the volume of metal consumed to guide industrial and technological choices.

To help plan out metal needs, **we have created an ecological budget** (much like the carbon budget) **to ensure that mining falls within planetary boundaries.**

To respect these planetary boundaries, different metals will be allocated shares of this budget proportional to their potential to meet social needs and their use in the energy transition.

For lithium, this budget will not offer clear answers to discussions about environmental legislation or local impacts. Nevertheless, **it allows us to compare lithium consumption and production pathways in Europe to meet our needs while respecting planetary boundaries.**

2.2. How can we remain within planetary boundaries?

The goal is to establish an ecological budget per metal for 2050, such as a maximum tonnage mined per year whose production (mining and metallurgy) remains within planetary boundaries.

To set this limit, we based our methodology on the article by Desing et al., who sought to establish an ecological budget for metal extraction (called *ecological resource availability* in their paper, but which we refer to as the ecological budget for extraction)l (29). To calculate an ecological budget for extraction per metal for the current year, the authors took the following main steps (Association négaWatt's modifications are in blue):

1. **Translation of planetary boundaries into control variables** (one or two control variables per planetary boundary). For example, for climate change, the control variables are atmospheric CO_2 concentration and the energy imbalance at the top of the atmosphere.
2. **Define the resource segment to be studied, here the metals sector:** mineral extraction and processing, waste management (excluding recycling). The authors studied 12 metals: aluminium, copper, iron, zinc, lead, tin, nickel, gold, silver, platinum, titanium, and chromium. We added lithium, cobalt, and neodymium to this list to cover the metals studied in the Minimal project, as well as manganese, which is produced in large quantities.
3. **Allocation of a share of the planetary boundaries in the metals sector.** For each planetary boundary, Desing et al. assign a share of the safe operating space to the metal sector that corresponds to its current contribution to the environmental impacts on this boundary (method based on historical impact allocation, or grandfathering). There are several problems with this type of allocation. It is poorly suited to forecasting, as it is not proportional to efforts that can be made in various sectors. Furthermore, sectors that have made little progress in the past receive a higher allocation, which does not seem fair to sectors that have already made efforts to reduce their ecological footprint. In this report, Association négaWatt did not modify the allocation method (see Appendix 1 for more information). The grandfathering method is rather favourable to this sector if we consider that "ideal" global consumption scenarios that respect planetary boundaries and decent living standards for all allocate a much lower share to metals than the current share (as shown in an article published by Schlesier et al. in 2024

[6] Global Witness, annual reports on Land and Environmental Defenders, 2012-2023. https://www.globalwitness.org/en/campaigns/environmental-activists/land-and-environmental-defenders-annual-report-archive/

(30)). Nevertheless, we retained this choice since there is no sufficiently robust methodology to define another level of allocation to the metals sector.

The article by Desing et al. (29) reveals that in 2016, climate change (and particularly CO_2 emissions) was the boundary that most limited metal production. Here, we assume that by 2050, this planetary boundary will remain the most limiting, and we simplified the model to only calculate the budget based on this limit. If our assumption is accurate, the quantified budget will also respect the other planetary boundaries (since it is the lowest).

4. For each metal and each control variable (for example, for copper and the control variable CO_2), **a unit impact (UI) is allocated** to each kg of metal using the ecoinvent v3.5 database. For example, for copper: 3.83 kg CO_2/kg of metal. These values reflect the current situation but are likely to change over time. To adapt the results to 2050, we modified the unit impacts for seven metals (iron, aluminium, copper, zinc, lead, nickel, and manganese) to take into account efficiency improvements, ore grade decline, and changes in electricity mixes by 2050, based on the work of Van der Voet et al. (31). See Table 3.

Fe	Al	Cu	Zn	Pb	Ni	Mn
-1.44%	-42.88%	-21.95%	-30.58%	5.83%	-7.76%	-0.99%

Table 3: Modification of the unit impact (UI) for CO_2 between 2020 and 2050 based on the “Equitability First” scenario (Source: Van der Voet et al., 2019 (31))

5. **Production share of a metal in the sector.** Desing et al. used USGS production data from 2016 to define metal’s share of production (SoP) in the metals sector as a mass fraction. The ecological budget for extraction therefore depends on the different SoPs chosen for the metals (the greater the SoP allocated to metals with a large impact, the smaller the ecological budget will be). For the result for lithium in this report, we calculated the share of each metal in total production based on cumulative need between 2020 and 2050 in the négaMat scenario, which we modified to account for the change in geographic scope (the négaMat scenario focuses on France, which has different needs to Europe). This increase in lithium’s SoP (see Table 4) corresponds to a 164-fold increase in comparison to actual figures from 2022 (proportionally, not in absolute value!). This increase stems from the rising need for lithium in the energy transition and the environmental benefits associated with its use.

The share allocated to lithium to calculate the ecological budget in 2050 in % of the total gross weight of metals produced.	1.16%
The actual share of lithium in global metal production in 2022 in percentage of the total gross weight of metals produced (USGS)	0.01%

Table 4: Share of lithium in global metal production between 2022 and 2050

6. **Upscaling of resource production until violation.** The production volume of the resource mix (with SoPs chosen in the preceding step) and its impact (UI) is then gradually increased until one of the planetary boundaries is breached. The violation of the first planetary boundary determines the ecological budget for extraction. This ecological budget is defined for the entire

metals sector. Next, this budget is allocated to each metal using the SoPs defined in Step 5. The result depends on the chosen probability of violation (see Appendix 1). Association négaWatt has set this probability at 50%.

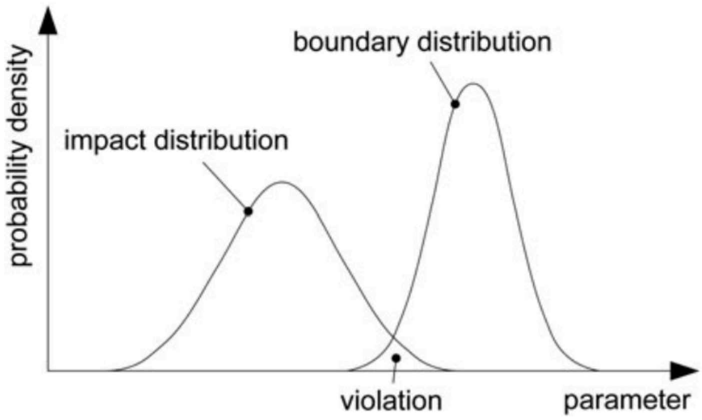

Figure 5: Schematic representation of the probability of planetary boundary violation, which results from overlap from the probability distribution of the environmental impacts with the distribution of the respective boundary (Source: Desing et al. (29))

We calculated the 2050 ecological budget for lithium as 20,000 tonnes for the EU-27, with the assumption that the EU will represent 4.36% of the global population in 2050[7] and will have access to resources proportional to its population (to ensure equity). This geographic allocation based on equity is a foundational choice for Association négaWatt (consistent with the négaMat material footprint in the 2022 négaWatt scenario). Some competing approaches are much less restrictive for the EU (using GDP or grandfathering), but they threaten the access to resources of poor and emerging countries and, ultimately, their development and energy transition. In Part 3, we present a reference scenario in which the EU consumes 88,000 tonnes of lithium in 2050, **or 4.4 times the EU's ecological budget for that year.**

This ecological budget for the EU corresponds to a budget of 459,000 tonnes of lithium for the world in 2050, or more than three times global lithium production in 2022 (4). The IEA (6) estimates that a transition to EVs without a major sufficiency assumption could lead to global annual lithium consumption of 800,000 tonnes for EVs in 2040, **or 1.7 times more than the ecological budget for mining in 2050 calculated by Association négaWatt**.

Association négaWatt calculated an ecological budget for all metal production of 39.54 million tonnes in 2050, or 43 times less than global metal production in 2022 (4). Yet current trends suggest that global production will greatly increase by 2050.

This ecological budget is therefore much less restrictive for lithium production than it is for other major industrial metals.

[7] According to World Bank data (population estimates and projections), version on 01/07/2024.

An innovative methodology to spark debate

This report is part of a series of publications as part of the Minimal project. The goal of the Minimal project is to offer a roadmap to gradually eliminate mining in the long term and offer a sustainable way of supplying mineral raw materials based on a three-pronged framework: sufficiency/efficiency/ecological substitution.[8]

This methodology based on a social minimum and an ecological ceiling will later be applied to other metals, starting with copper. Our methodology for establishing an ecological budget for a particular metal is an initial suggestion to establish a consumption limit based on scientific research. This work is innovative, and the literature has only recently started examining this question (see Appendix 1).

Association négaWatt realises that this calculation method will need to be improved and updated in the future to fine-tune this forecasting work: accounting for more efficient technologies, ore grade decline, political decisions regarding allocations to various sectors, shifting national priorities, and so on. Nevertheless, it is worth publishing these initial results to spark an important debate on a material transition that aims to limit increased mining in certain sectors and reduce it in others to ensure the planet remains habitable.

For each metal, this work will establish an ecological budget for mining (in tonnes) that can be conducted in a safe operating space (at the global scale by 2050).

[8] This framework is an adaptation to materials of négaWatt's sufficiency/ efficiency/ renewables framework developed for energy. The concepts of material sufficiency, material, efficiency, and ecological substitution are further described in Part 4 of this report.

3. Discussion of the sustainable consumption corridor

Our evaluations of the social minimum and ecological budget for lithium mining described in Parts 1 and 2 allowed us to define a sustainable consumption corridor for lithium in which Europe's essential needs are met while respecting planetary boundaries. In this part, we will make sure the corridor concept is truly applicable. In other words, will we check whether the social foundation (as defined in Part 1) is truly below the ecological ceiling as defined in Part 2. We will then examine the extent to which different scenarios respect this sustainable consumption corridor. Lastly, we will compare this corridor to existing forecasting studies.

3.1. Is the sustainable consumption corridor concept applicable?

In Parts 1 and 2, we defined the social foundation in the form of a curve (a pathway between 2015 and 2050), while the ecological budget for lithium mining was only calculated for 2050 (so far). Therefore, the sustainable consumption corridor concept is only applicable for 2050 in this report and does not allow us to confirm the sustainability of the entire proposed pathway.

For 2050, **the ecological budget for lithium mining** (calculated in Part 2) **is 20,000 tonnes of lithium for the EU** (the green dot in 2050 in Figure 7). The **social minimum** pathway, described in Part 1, revealed essential mining needs of **3,000 tonnes of lithium for the EU** in 2050 (the orange dot in 2050 in Figure 7). As a reminder, in the social minimum pathway, the EU's total lithium consumption (primary and recycled) in 2050 is 19,000 tonnes (see Figure 3 in Part 1), with 85% coming from recycling (not considered in the ecological budget). This significant share of recycling in 2050 stems from ambitious assumptions about the development of recycling, as well as the strong sufficiency approaches achieved in this scenario.

The ecological ceiling is therefore higher than the social foundation for 2050, which means the sustainable consumption corridor concept is applicable.

3.2 How do the CLEVER scenario and the reference scenario compare to the sustainable consumption corridor?

Using the BAMASI modelling tool and the set of assumptions presented in Table 5, we evaluated the primary lithium footprints of the European **CLEVER**[9] (33) scenario (based on the sufficiency/efficiency/renewables framework) and a **reference scenario**. We then compared them to the sustainable consumption corridor for lithium. Our transport and circular economy assumptions are presented in the following paragraphs.

The two scenarios, CLEVER and reference, make different assumptions about **transport, but they both meet climate targets by decarbonising the sector by 2050.** They present the same relative levels of electrification in light-duty vehicle sales (cars, light commercial vehicles, two-wheelers) but differ slightly in their mix of propulsion systems for heavy-duty vehicles (trucks and buses). **However, the two scenarios show a significant difference in absolute level of vehicle sales.**

Both assume the same technological advances in lithium batteries that we describe in Part 4. The reference scenario in our study assumes increased demand in road transport (from the European Commission's 2020 reference scenario) and stabilisation of vehicle occupancy rate and freight load factor. It also foresees a continuation of the current trend of increasing EV range (resulting in bigger

[9] CLEVER (a Collaborative Low Energy Vision for the European Region) is a scenario that proposes an ambitious and realistic decarbonisation pathway for Europe. It was created using a "bottom-up" approach that starts with national trajectories developed by 26 national partners (including Association négaWatt) from academia, research, and civil society. The scenario presents a pathway that reconciles long-term climate and sustainability imperatives with short-term energy security constraints and the practical feasibility of such a transformation. A sectoral note on mobility is available on the CLEVER website. In this report, to comply with the EU regulation (36) prohibiting the sale of ICE light-duty vehicles by 2035, we have modified the share of light commercial vehicles in the CLEVER scenario to include only electric vehicles and exclude biogas vehicles.

batteries). The CLEVER scenario presents **a general reduction in the need for mobility** and merchandise transport, **a significant shift toward other active transport modes and public transport,** an **increase in the occupancy rate of cars and load rates of trucks**, and a smaller increase in the range of battery-powered vehicles. These mobility **drivers** are part of the sufficiency measures that need to be implemented, which we **will further describe with figures in Part 4**.

Indicator	Unit	Type of vehicle	2018	2050		2050	
			Historical value	CLEVER scenario	Index 2018 = 100%	Reference scenario	Index 2018 = 100%
Occupancy rate	person per vehicle	passenger car	1.63	1.98	*121%*	1.63	*100%*
Mobility requirement	billion km	passenger car	4,254	3,105	*73%*	5,076	*119%*
Share of microcars	%	passenger car	0%	20%		0%	
Battery capacity	kWh	“conventional” passenger car	50	60		75	
Battery capacity	kWh	“micro” passenger car	7	10		15	
Mobility requirement	billion km	bus	501	705	*141%*	535	*107%*
Battery capacity	kWh	bus	650	650		650	
Mobility requirement	billion km	two-wheeler	108	195	*181%*	154	*143%*
Battery capacity	kWh	two-wheeler	5	7		12	
Freight requirement	billion km	commercial vehicle	101	98	*97%*	101	*100%*
Battery capacity	kWh	commercial vehicle	70	75		80	
Load factor	tonne per vehicle	truck	11.01	12.21	*111%*	11.01	*100%*
Freight requirement	billion km	truck	1,764	1,219	*69%*	2,458	*139%*
Battery capacity	kWh	truck	590	550		700	

Table 5: Main assumptions for transport and battery capacity in the CLEVER and the reference scenarios

As for **circular economy**[10] assumptions, CLEVER and the reference scenario follow historical trends in 2018–2021, then make assumptions that go well beyond the 2023 European regulation on waste batteries (18). This regulation calls for a lithium recovery rate of 50% in 2027 and 80% in 2031, while the CLEVER and the reference scenario make the following assumptions:

- All end-of-life batteries are collected based on the strategic assumption that recycling processes are developed in Europe that make it possible to produce high-quality lithium to be reused in new batteries.

[10] Challenges, limitations, and policy recommendations relating to the circular economy are presented in the "Recycling" section in Part 4.2 of this report.

- 50% of lithium from end-of-life batteries is recycled (and not recovered) % in 2027 and 80% in 2031. These figures exclude lithium recovery via downcycling (such as slag used as road foundations or to make cement).

The CLEVER scenario (like the social minimum pathway described in Part 1) sets a 90% recycling rate for lithium from 2035 until 2050, compared to 80% in the reference scenario.

The circular economy assumptions — on end-of-life battery and recycling rates that make it possible to produce battery-grade lithium — in this study's scenarios are very ambitious. Though they differ from current industrial practices, and the EU regulation is not strict enough on these issues, they are viable from a technical and strategic standpoint. The assumptions are also advisable if we want to strengthen the resilience of the EU's supply chain and protect the environment (see the section on recycling in Part 4 of this report). This modelling choice highlights the environmental limits of the reference scenario despite its ambitious assumptions about lithium recycling (see Figure 6 below).

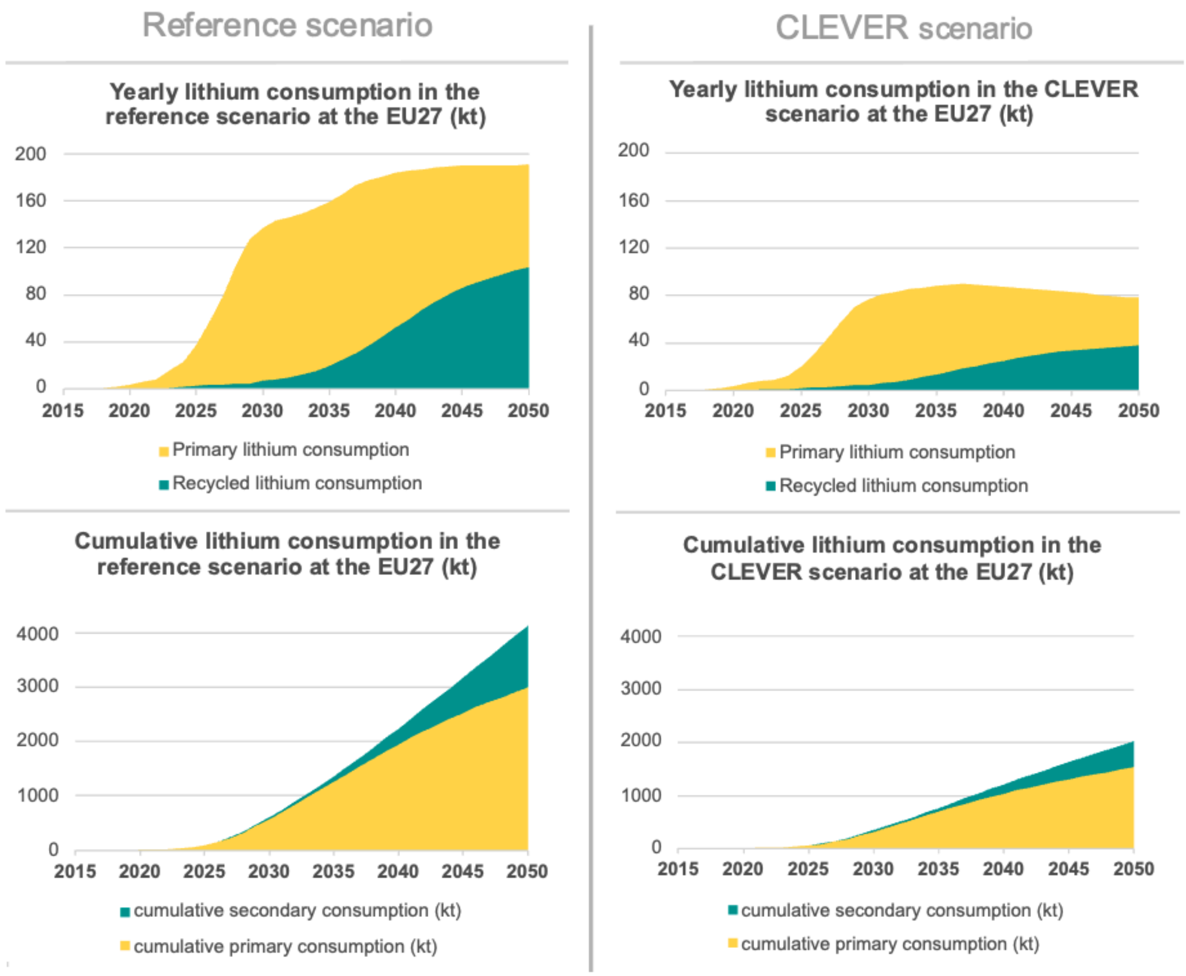

Figure 6: Change in annual and cumulative lithium demand in the reference and CLEVER scenarios for the EU

The reference scenario projects primary lithium consumption of 88,000 tonnes in 2050 and 2.99 million tonnes over the 2020–2050 period (see Figure 7). **This consumption is much higher than what is needed to meet minimum mobility requirements,** meaning the lithium consumption pathway that corresponds to the social minimum defined in Part 1 (790,000 tonnes of lithium over the 2020–2050 period, or 3.8 times less than the reference scenario). Moreover, **the reference scenario is also much higher** than the **ecological budget for lithium in 2050** (20,000 tonnes of mined lithium) that we defined in Part 2. **According to the methodology used in this report, the reference scenario does not respect planetary boundaries.**

The CLEVER scenario projects annual primary lithium consumption of 40,500 tonnes in 2050 and cumulative consumption of 1.530 million tonnes over the 2020–2050 period (see Figure 7). This scenario **fully meets minimum needs.** Unfortunately, like the reference scenario, it **does not respect the ecological ceiling of 20,000 tonnes established for 2050**. Nevertheless, it is much closer than the reference scenario: there is a 20,500-tonne gap between the CLEVER scenario and the ecological ceiling in 2050, while the reference scenario is 68,000 tonnes above this ceiling, thanks to sufficiency assumptions. The CLEVER scenario could fall below this ceiling after 2050.

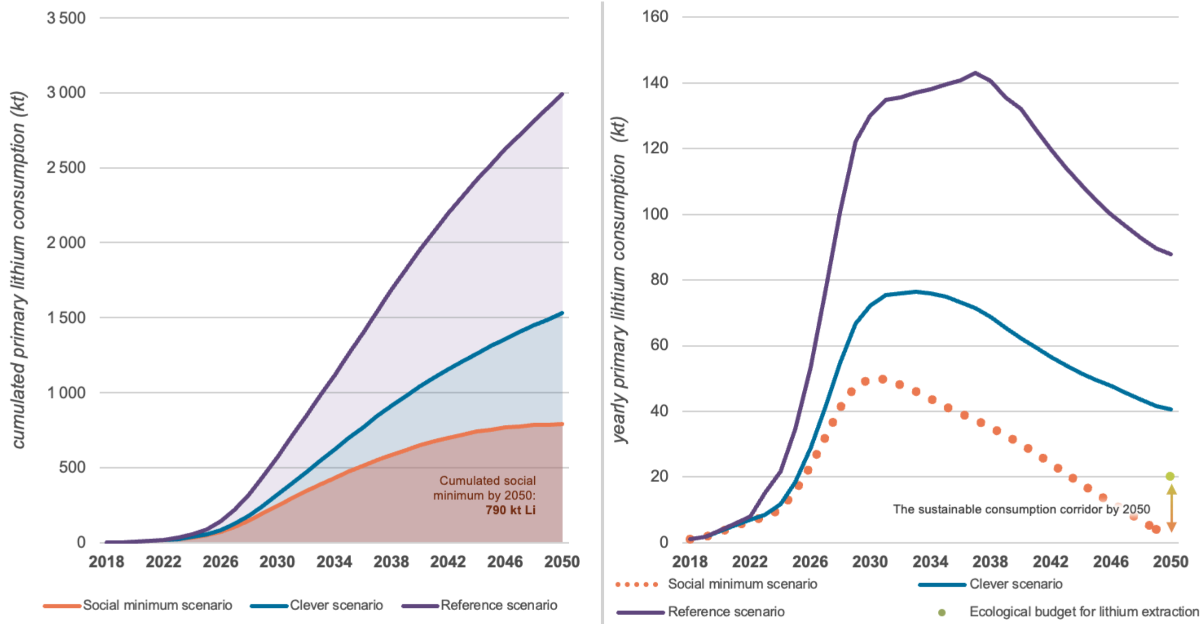

Figure 7: Cumulative primary lithium consumption in the CLEVER, reference, and social minimum scenarios (on the left) and comparison of annual consumption in these scenarios to the EU's sustainable consumption corridor in 2050 (on the right)

The fact that CLEVER — the ideal scenario because it offers the best combination of rapid electrification and moderate lithium needs based on the sufficiency/efficiency/renewables (SER) framework — is still above the ecological ceiling for 2050 raises two issues: The first issue **is the difficulty in measuring the environmental impacts of mining and metallurgy**, and the impact of resource extraction more broadly. This report offers an initial attempt to take these issues into account, so it is not surprising that previous scenarios do not fit into the sustainable consumption corridor (since it had not yet been defined). However, this further highlights the pressing need to deploy a sufficiency approach, in line with the 2024 IRP report that called for urgent action to develop demand-side measures to ensure more sustainable resource management (34).

The second issue is the need to calibrate the chosen methodology, given the difficulty in respecting the share of planetary boundaries allocated to lithium. This raises the question of how to adjust **allocations to the mining and metallurgy sector in comparison to other industries** (see Appendix 1). One option is to allocate a greater share of planetary boundaries to the mining sector relative to its current share by developing another approach besides grandfathering. However, **Association négaWatt believes that to increase this allocation, we must be able to prove that the environmental impacts of other sectors will be reduced** to ensure that increasing the share of the mining sector does not violate planetary boundaries.

3.2. How do CLEVER and the reference scenario compare to the main scenarios in the literature?

Figure 8 situates the CLEVER scenario and the reference scenario — produced using the BAMASI tool — in comparison to other scenarios in the literature that have made projections about lithium consumption. These include several European scenarios: T&E, 2023 (35); JRC, 2022 (7); Eurometaux, 2023 (8) and extrapolation of the IEA's Net Zero global scenario (3) proportional to the EU's GDP in 2020. Given the availability of data in these different scenarios, this comparison is limited to total lithium needs (primary and recycled) for 2030 and 2050. Comparing pathways is a complex endeavour that must be done carefully, given differences in scope (sometimes difficult to determine in the reports) and, above all, differences in methodology.

The comparison to 2030 allows us to evaluate the scenario's level of ambition regarding the vehicle electrification rate. The T&E, IEA, CLEVER, and reference scenarios present the highest level of annual lithium demand in 2030, which varies from 60,000 to 140,000 tonnes, revealing strong electrification ambitions. The other scenarios oscillate between 25,000 and 55,000 tonnes of lithium. For example, the CLEVER scenario, which features the most ambitious sufficiency assumptions, presents a lithium need that is 44% lower than the reference scenario in this study.

The comparison to 2050 allows us to evaluate the lithium needs of different scenarios based on the scope in question (such as passenger mobility only or all road transport, including freight). For the scope that is limited to passenger mobility, the scenarios generally present a lithium need of between 30,000 and 80,000 tonnes, which can increase to 120,000 tonnes in high demand scenarios. The CLEVER scenario is in the lower range, with 60,000 tonnes of lithium needed in 2050 thanks to its low-energy-consumption approach. For all road transport, lithium needs vary between 80,000 and 190,000 tonnes. **The CLEVER scenario represents the lower limit of this corridor, as it is nearly 60% lower than the reference scenario**.

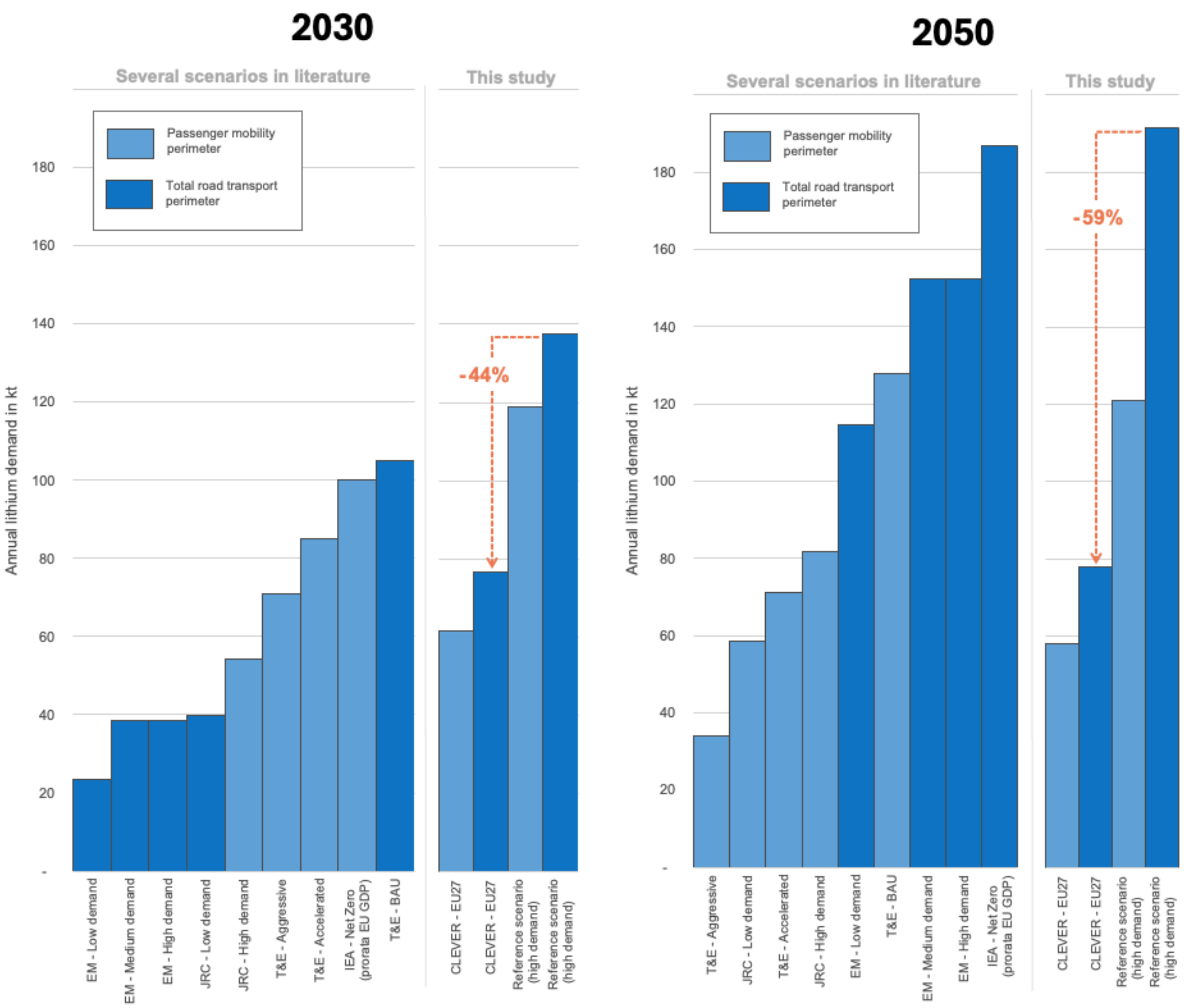

Figure 8: Comparison between total annual lithium demand (primary and secondary) in several scenarios for 2030 (left) and 2050 (right). There is a distinction between passenger mobility (light blue) and total road transport (dark blue)

Figure 9 below illustrates the EU's primary lithium demand in the CLEVER and the reference scenarios as a percentage of global lithium production in 2030 and 2035 (based on estimates by Wood Mackenzie). **In the reference scenario, the EU's lithium demand represents 27% of global production in 2030 and between 26% and 32% in 2035. In the CLEVER scenario, this demand represents 15% of global production in 2030 and between 14% and 17% in 2035.** These proportions must be contextualised with the EU's share of the global population. In 2022, the EU represented 5.6% of the global population. According to World Bank estimates, this proportion should decrease to 5.2% in 2030, 4.9% in 2035, and 4.3% in 2050.

There are real threats to the EU's lithium supply, and a gap between lithium supply and demand is expected in the coming years (36), according to many sources like the European Court of Auditors and the JRC. The 2024 CRMA attempts to limit this risk by encouraging mining projects in Europe. However, given the long lead time to develop industrial mining projects (and their inherent uncertainty), it seems unrealistic to focus solely on supply while completely ignoring demand-side policies. **Sufficiency — currently absent from the CRMA — is a major mechanism for limiting these risks. Certain measures could have an immediate impact, such as efforts to reduce vehicle size and weight.**

As such, the **sufficiency measures** we present in Part 4 would **make it possible** not only to **develop a resilient lithium supply** for transport electrification, but also to **foster global equity and allow other parts of the world to undertake this decarbonisation.** Sufficiency would also help **limit the environmental impacts of production** mentioned in Part 4.

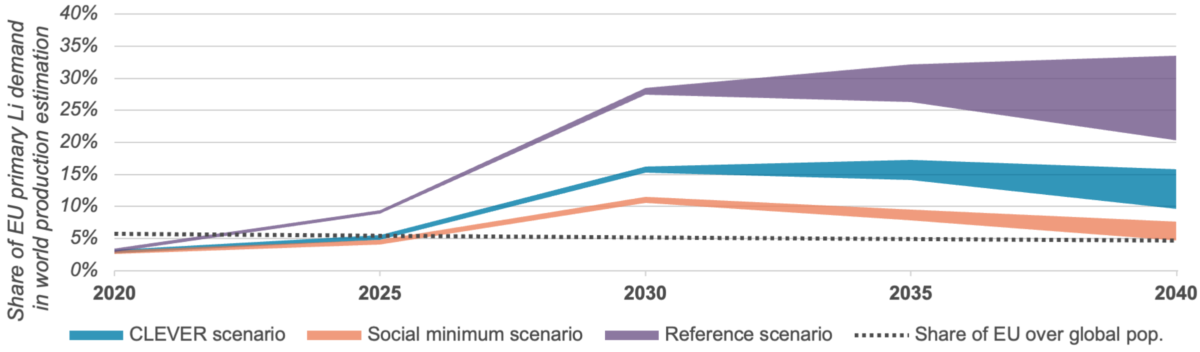

Figure 9: Comparison of primary lithium demand in the EU in different scenarios as a percentage of global production (estimated by Wood Mackenzie)

What public policy framework do we need to keep the EU's metal consumption within planetary boundaries?

Association négaWatt co-wrote an open letter signed by more than 100 organisations (NGOs, academia, think tanks, unions, and industry) addressed to several European decision-makers and demanding EU legislation on sustainable resource management. This demand was also accompanied by a more complete policy paper, Sustainable Resource Management in the EU, published in February 2024. These two publications are available on Association négaWatt's website.

This initiative calls for **binding targets for resource consumption** and highlights the need for sector-specific targets. This report and our ecological budget for lithium of **20,000 tonnes of primary production for the EU in 2050** represent an initial proposal for a binding lithium target.

4. Drivers to remain within the sustainable consumption corridor

To remain within the previously defined sustainable consumption corridor, drivers must be activated **to decrease lithium consumption**, **reduce the social and environmental impact of the consumption and production of each tonne of lithium**, and **encourage potential alternatives to lithium consumption**.

As previously mentioned, only the scenarios that activate all these drivers are likely to remain within planetary boundaries while ensuring a minimum level of provisioning needed to guarantee decent living conditions for all. This section describes these different drivers in greater detail, along with their impacts and the corresponding policies and measures that will enable Europe to respect this social minimum and ecological ceiling.

Our analysis is based on comparisons between the European CLEVER scenario and the reference scenario produced for this study presented previously in Part 3. The architecture of our BAMASI model and its level of disaggregation allow us to analyse the impact of each indicator for cumulative primary lithium consumption between 2018 and 2050.

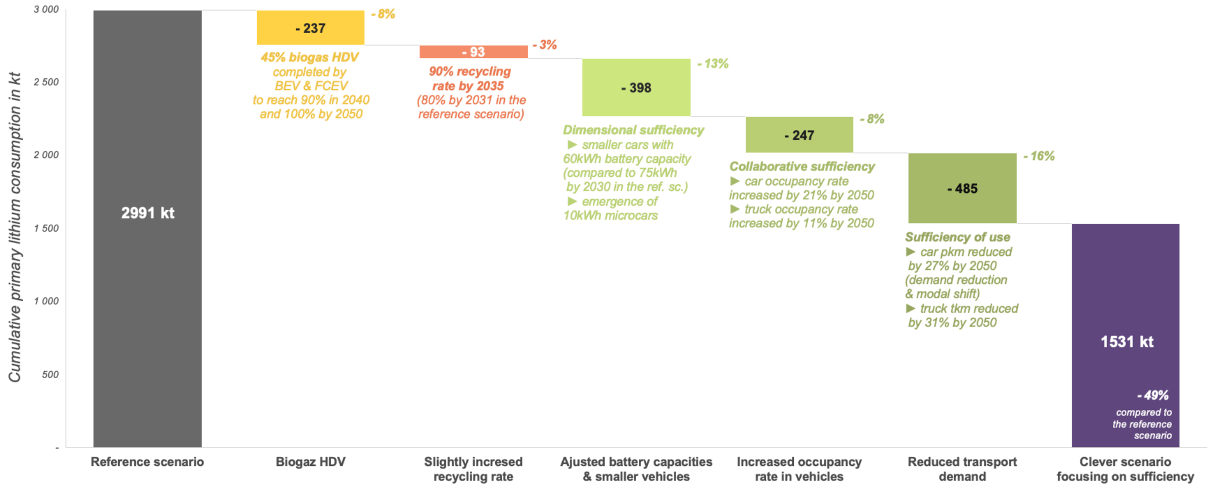

Figure 10: Contributions of each driver to reducing the EU's lithium consumption in the CLEVER scenario compared to the reference scenario, expressed in percentage of cumulative primary lithium consumption in the reference scenario between 2018 and 2050

Figure 10 above shows the impact of each driver in reducing the EU's cumulative primary lithium consumption in the CLEVER scenario versus the reference scenario. In total, all these drivers cut cumulative primary lithium consumption almost in half. Usage sufficiency reduces the need for transport; dimensional sufficiency adjusts the size and capacity of vehicle batteries; and collaborative sufficiency increases the vehicle occupancy rate, thereby reducing traffic. Taken together, these drivers have a significant impact, representing around 80% of the total reduction in lithium consumption. We further explain these sufficiency drivers in the next sections, along with policies and measures that could activate them.

4.1. Sufficiency: Consume less lithium

To reduce lithium consumption, we need to reduce consumption "at the source", which means better designing services that use lithium so they meet a specific need while consuming less. In this part, we will describe the sufficiency drivers used in the CLEVER scenario to reduce mobility needs, and therefore lithium consumption, along with the corresponding policies and measures.

Car and battery size (dimensional sufficiency)

Vehicle size and weight play a crucial role in energy consumption. In the case of EVs, these factors influence the range, or more specifically the size, of the battery needed to cover the same distance. If choosing a smaller and lighter vehicle reduces energy consumption by 20% compared to another model with the same range, the battery size will be reduced to the same extent. This directly impacts the quantity of metals used to make batteries, with a 13% reduction in cumulative lithium consumption (between 2018 and 2050) in the CLEVER versus reference scenario (see Figure 10). This is also true for all the vehicle's component materials more generally.

Reducing battery capacity also has the advantage of reducing the power needed to recharge the battery (for the same duration). Though these savings may seem marginal, they represent both dimensional and material sufficiency.

What is the difference between material sufficiency and material efficiency?

For materials, the difference between sufficiency and efficiency is fairly similar to the definitions for energy.[11]

For example:

- Choosing a smaller electric car than the previous model, working from home to limit driving (which increases the vehicle's lifespan), or taking public transport are all examples of sufficiency.
- Using a battery with a better performance (a lower weight for the same capacity), which consumes less material, is an example of efficiency.

Efficiency corresponds to the energy, material, or environmental performance of production equipment or processes. Sufficiency is related to uses and habits, which are themselves influenced by land use planning (the distance between homes and businesses); working conditions (revenues, possibility of remote work); and the development of public services (the availability of public transport). The national government, local authorities, and businesses all play a critical part in this planning and more generally in driving these changes by establishing the necessary conditions to facilitate car-free mobility.

In the scenarios advanced by Association négaWatt — the 2022 négaWatt scenario for France and the CLEVER scenario for Europe — as well as other similar scenarios, assumptions are made about reductions in the size and weight of vehicles to limit the increase in battery size that has already begun.

The IEA has also stated that "maintaining rather than increasing the current average range of electric cars would enable batteries to be 20–25% smaller than in the Net Zero Emissions (NZE) Scenario in 2030 and 2050, resulting in a 20% reduction in critical material needs for making EV batteries" (3).

[11] https://negawatt.org/sobriete-efficacite (in French)

What public policies could be implemented?

Various public policies at several levels, ranging from the European to the local scale, could be enacted to reduce vehicle size and weight, and therefore battery size.

At the European level, no regulations currently aim to reduce battery capacity. The EU could set a target value for average battery capacity for all the vehicles sold by a manufacturer, along the lines of CO_2 emissions targets.

At the national level, a bonus-penalty scheme could be developed to help limit battery size and/or vehicle weight. France has already enacted a weight-based penalty on the purchase of new vehicles, but this does not apply to EVs so has no impact on vehicle or battery size. Furthermore, this penalty only applies to vehicles over 1.6 t. To improve the efficacy of this measure, we must:

- reduce the threshold for application of this penalty to 1.2 t
- establish a weight-based bonus for vehicles below the threshold
- extend the scope of this weight-based bonus-penalty scheme to so-called zero-emission vehicles (with a threshold for application that could exclude the weight of the battery)
- combine the weight-based bonus-penalty scheme with a “battery capacity” bonus-penalty scheme

At the local level, authorities could implement progressive parking fees based on vehicle weight, following the examples of Lyon[12] and Paris (France), which already do this for ICE vehicles.

All of these measures apply to passenger mobility since electric road freight is not yet very developed. Nevertheless, new European regulations include efforts to boost its development. Public policies should also be created in this area to limit the resource consumption of these trucks, which requires limiting their battery size.

Limiting vehicle use

The more vehicles are used, the more often vehicle fleets need to be updated, increasing metal consumption. It is therefore important to reduce the number and distance of trips taken. To that end, here is a non-exhaustive list of solutions:

- Expand remote work and videoconferencing to the extent possible.
- Whenever relevant and possible for the company, employees should transfer to a site close to their home.[13]
- Choose closer holiday destinations.

What public policies could be implemented?

The first measure to implement falls under a broader initiative supported by Association négaWatt: prohibit advertisements for products/services that are particularly climate harming and incompatible with a carbon-neutral pathway. In the case of mobility, advertisements for trips longer than 1,000 km could be prohibited. As for battery size, we could prohibit

[12] https://www.lyon.fr/actualite/mobilites/stationnement-une-nouvelle-tarification-plus-juste-et-plus-progressive (in French)

[13] See this software program, for example https://www.1kmapied.com/ (in French)

advertisements for any vehicle that is subject to a penalty fee upon purchase. If the point of the penalty is to discourage the sale of certain vehicles, it is completely absurd to promote them through advertising.

Local and national public authorities could also deploy various policies to encourage the solutions cited above.

Developing alternatives to cars and road freight

Choosing active transport modes (cycling and walking), public transport, and rail freight instead of passenger vehicles and trucks would reduce reliance on the latter and delay their replacement, which consumes metals.

These modal shifts could apply to all types of mobility: commutes, occasional daily trips, long-distance leisure travel, city centre deliveries, long-distance freight transport, etc.

What public policies could be implemented?

The success of these alternatives does ultimately depend on user choices in many cases. However, their deployment is contingent upon their technical and financial accessibility, ease of use, and creation of infrastructure. This means that implementing ambitious policies is critical.

The most important measure, which applies to all levels of decision-making, is to eliminate all subsidies for roads and road transport. This entails halting the construction of new road infrastructure to funnel those resources into various alternatives. We cannot keep subsidising a transport mode that must be curtailed.

In parallel, implementing a kilometre-based fee for trucks would reduce road freight and could finance infrastructure to expand rail freight.[14] Mobility authorities also have a role to play in encouraging the development of these alternatives.

Carpooling

As previously mentioned, though some trips can be taken without cars, this transport mode will remain dominant in the decades to come due to its convenience and lack of alternatives in many cases.

And yet, though car transport will remain significant, we can decrease road traffic even more by increasing the vehicle occupancy rate. Less road traffic means fewer vehicles to replace and less metal consumed to produce them.

Carpooling can cover two main types of travel:

- Long-distance journeys, for which carpooling is already fairly well developed. The associated disadvantages (detours to pick up or drop off passengers or to meet up with a vehicle, less scheduling flexibility for the driver, etc.) are offset by financial (and environmental) gains. These disadvantages are further reduced thanks to services provided by online platforms and apps.

[14] See the case of Switzerland: https://www.negawatt.org/IMG/pdf/la_redevance_pl_en_suisse.pdf (in French)

- Short-distance journeys, where much remains to be done to increase vehicle occupancy rate. Traditional carpooling services work poorly, or not at all, for short trips since the disadvantages to users are greater than the benefits. Other services should be envisaged/deployed, such as carpooling lines developed by some authorities/operators.[15]

Public authorities can also encourage the development of carpooling at the local and national scale.[16]

Carsharing

Carsharing, or creating a pool of passenger vehicles for users who eschew car ownership (or own one vehicle instead of two), presents several advantages:

- It reduces the number of vehicles in circulation, freeing up space for other transport modes (active transport modes and public transport).
- Fewer vehicles in circulation increase the use of each one, accelerating fleet renewal and offering quicker access to the best technologies available.
- Carsharing allows users to more easily adapt the vehicle size to their needs for each trip, thereby more frequently using a smaller vehicle that consumes less metal.

What public policies could be implemented?

At the national level, several measures can be deployed:

- Similar to the carpooling bonus, create a carsharing bonus of €100 financed by schemes such as the Energy Savings Certificate in France.
- Establish or expand financial incentives for those who give up their old car to subscribe to a carsharing service.
- Promote carsharing in automotive advertisements (France already requires these ads to promote carpooling and active mobility).
- Mandate setting aside parking spaces for carsharing in various places such as train stations.
- Financially support the development of carsharing.

Other methods could also be taken at the local level, such as ensuring carsharing services have enough street parking spaces.

4.2. Efficiency: Reduce the environmental impact of the production and consumption of each tonne of lithium

Efficiency refers to the energy, material, or environmental performance of production equipment or processes.

In this part, we will examine how to reduce the environmental footprint of each tonne of lithium consumed. Since previous estimates of minimum lithium requirements show that mining will still be necessary for many more years to achieve the indispensable electrification of transport, we must ensure that this is done as sustainably as possible. What measures can be implemented to improve production?[17]

[15] https://www.ecov.fr
[16] See ecov's white paper: https://ressources.ecov.fr/livre_blanc (in French)
[17] Please note: the IEA views the design of lighter vehicles as material efficiency (3), whereas we classify it as a sufficiency driver.

To establish the ecological budget (see Part 2) for metal production in general — and lithium in particular — we used CO_2 emissions. This indicator is useful for establishing a threshold because it is the planetary boundary that is currently most limiting for production. Nevertheless, Association négaWatt wants to develop an approach that is as systemic as possible to avoid contributing to "carbon tunnel vision" (see Figure 11) by focusing solely on CO_2 emissions when planning the ecological transition.

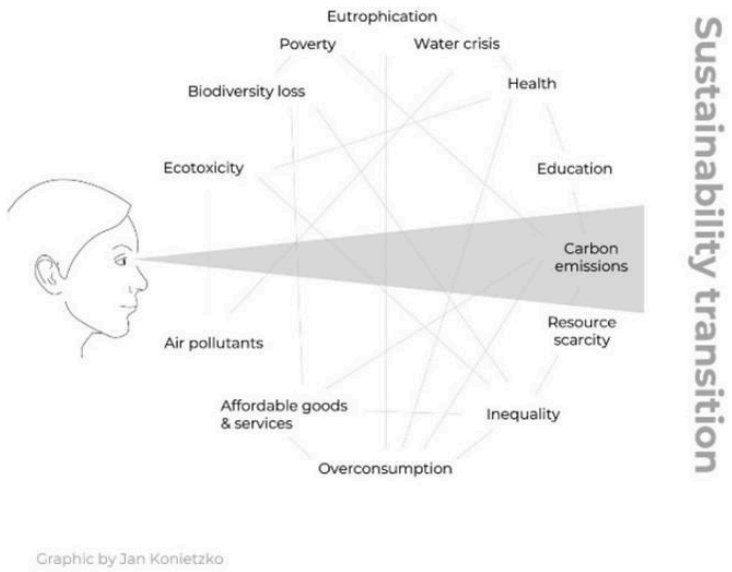

Figure 11: Illustration of "carbon tunnel vision", an expression used to describe the tendency to focus exclusively on GHGs (Source: image created by Konietzko (37))

In this section, we seek to expand the field of study and examine the main environmental impacts (both current and potential) in the lithium production chain, as well as tools to reduce them.

Our study covers impacts ranging from mining to production of the main lithium-based chemicals used to make batteries. We do not include the impact of later stages of battery production here, and we will address technological substitution in Part 4.2.

We will examine the following (non-exhaustive) environmental impacts:

- the problems of mining waste and changing land use
- the impacts on water
- GHG emissions
- the impacts on biodiversity

We will not address the consequences of acidification here. The extraction of certain metals provokes significant acid mine drainage, acidifying surface water and polluting waterways and groundwater. But lithium is generally extracted from brine[18] or pegmatites (see below), which contain none of the sulphur-bearing minerals responsible for acid mine drainage. Its occurrence in lithium extraction is therefore unlikely (38).

In each case, the goal is to determine the production routes with the lowest impact and the ones to avoid while attempting to evaluate their potential for improvement.

[18] Brine comprises water and highly concentrated salts, like common salt (NaCl). In salt flats (Argentina, Bolivia, Chile), brine contains lithium, sodium, potassium, magnesium, calcium, chlorine, sulphites, and boron.

The lithium production chain

In this section, we will explain the production chain for lithium used in batteries. Next, we will describe the corresponding impacts.

Lithium is currently extracted from two main sources (see Figure 12):

1. (left) **Salt flat production**, which pumps deep subsurface **brine** containing lithium. The largest lithium reserves are found in the salt flats of the lithium triangle, located between southern Bolivia, northern Chile, and north-west Argentina. The lithium triangle is currently the largest source of brine-based lithium, though China also boasts some production. Until recently, solar evaporation ponds were required to concentrate the lithium contained in the brine and precipitate other elements, which only works in very arid climates. The brine passes through a series of connected evaporation ponds. The ponds are designed so that, under optimal conditions, a single salt with commercial applications is crystallised per pond (gypsum, then sodium chloride, and so on) to finally form a **lithium-rich brine concentrate** (containing around 6% lithium). Certain technological improvements could make it possible to skip the evaporation step, which we will further discuss in the section on water. The brine's initial lithium content remains an important factor in the project's profitability (38).

2. (right) **Hard rock extraction**, a more traditional form of mining. Lithium is usually mined from **pegmatite** hard rocks, from which the mineral spodumene is extracted. Given its relatively low ore grade, all big mines use the open-pit method to extract lithium from hard rock deposits. Pegmatite ore is extracted using the traditional blasting and loading method. It is then hauled from the mine to the processing facility, where the rock is crushed and milled. Next, the material goes through different concentration steps to obtain a commercial product with fewer impurities: **a spodumene concentrate** (containing around 6% lithium oxide Li_2O). The most frequent concentration processes are gravity separation, flotation, and magnetic separation. Lithium-bearing pegmatites can be found all over the world, but Australia has larger quantities and higher ore grades than most other countries. Australia is currently the largest lithium mining producer, with 51% of global production (4), and has the largest production capacity in the world. However, until recently, spodumene concentrate was almost entirely refined in China. Other significant pegmatite deposits exist in Zimbabwe, the Democratic Republic of the Congo, Portugal, China, and Brazil. Lithium can also be mined concurrently with other commercially valuable substances: tantalum and tin are some of the main coproducts of lithium extraction (38).

3. Other types of resources currently being mined[19] include:
    - Lepidolite, which represented 20.12% of China's production in 2021 (39), or 11.28 kt of lithium metal produced (around 10% of global production in 2021). This is the mineral of interest in the de Beauvoir deposit in the Allier department in France (EMILI project).
    - Mineral tailings operations (mining waste), particularly in Brazil (4).

[19] Active mining operations include: seven mining operations in Australia, one mineral tailings operation in Brazil, two brine operations in both Argentina and Chile, two mineral operations in Canada, five mineral and four brine operations in China, and one mineral operation in Zimbabwe represent the majority of global lithium production. Additionally, smaller operations in Argentina, Australia, Brazil, China, Portugal, the United States and Zimbabwe also contributed to global lithium production (USGS, 2024)

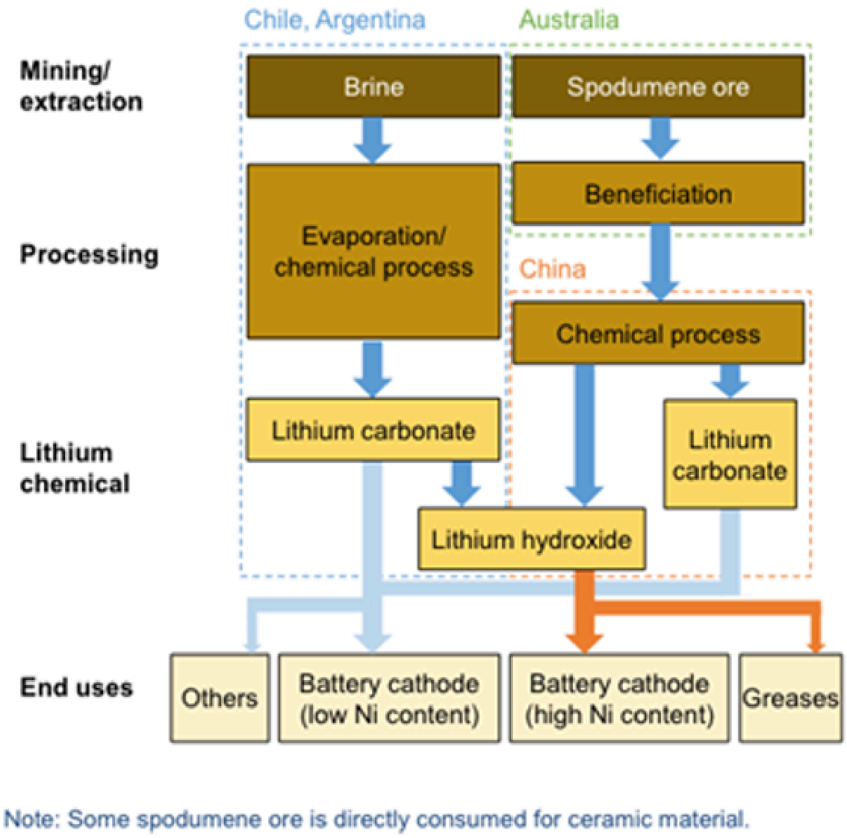

Figure 12: The lithium production chain: The two main types of extraction and the products currently used (Source: IEA, 2021 (6))

Primary lithium extraction from oil well brines and geothermal energy production are also currently being studied. Some examples are the Vulcan Energy Resources geothermal project[20] near Karlsruhe, Germany; the Eramet et Électricité de Strasbourg project in Alsace; and Lithium de France, owned by Arverne, a French group specialising in geothermal drilling (40). These projects aim to extract lithium while producing geothermal energy since brine pumped for geothermal production contains lithium. However, the concentrations are fairly weak, with less than 200 mg of lithium per litre of brine pumped. Since these regions are much less arid than salt flats, pre-concentration via evaporation is impossible. Instead, other processes have been developed: an organic solvent to selectively extract lithium from the brine, the ion exchange method, or nano-membranes to concentrate lithium under high pressure. All these technologies fall under the name direct lithium extraction (DLE). This can also be done in salt flats, which we will discuss further in the section on the impact on water resources.

Since there is greater potential for direct lithium availability in pegmatite production, it is likely to increase more than salt flat production. Additionally, salt flat production processes present greater risks, such as brine contamination or insufficient extraction volumes (38).

After the mining phase (primary production) and the ore concentration phase comes the **chemical treatment phase,** which produces refined lithium (or lithium-based chemical products). The two lithium-based chemical products most commonly used in batteries are lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$) and lithium carbonate (Li_2CO_3).

[20] According to a feasibility study published in February 2023, the company expects to produce 24,000 tons of lithium hydroxide per year starting in 2027 (39).

The treatment phase to produce lithium carbonate

With hard rock mining, the spodumene concentrate is first treated through calcination, followed by acid attack. The concentrate is calcinated at around 1,100°C to convert the minerals into a form that is soluble in sulphuric acid. Undesirable elements such as iron, manganese, aluminium, and calcium are eliminated by first adding calcium carbonate, then sodium hydroxide. The mixture goes through additional neutralisation and heating (90 °C-100 °C) steps to become lithium carbonate. Ion exchangers are used to further improve purity (38).

Chemical treatment of brine consists of eliminating boron via solvent extraction. The remaining magnesium and sulphate are precipitated using quicklime and sodium carbonate. Lithium is then extracted from the pure and concentrated liquid to form carbonate. Lastly, ion exchangers and cleaning steps are used to further improve purity (38).

The treatment phase to produce lithium hydroxide monohydrate

Brine-based hydroxide is only produced from lithium carbonate (Li_2CO_3). It reacts in several steps with a mix of quick lime and water to produce lithium hydroxide monohydrate (42).

Hydroxide from spodumene concentrate is produced using the traditional path: initial calcination of the concentrate with lime, which produces calcium silicate and lithium oxide. After calcination, hot water leaching extracts a lithium hydroxide solution, which is then concentrated and crystallised into lithium hydroxide monohydrate (43).

In 2020, production capacity was dominated by lithium carbonate of all grades (and therefore all uses), representing 68% of the global production capacity of lithium-based chemical products (44). For products used to make batteries (which require higher purity levels), battery-grade lithium carbonate represented 38% of the global production capacity, and battery-grade hydroxide represented 13%.

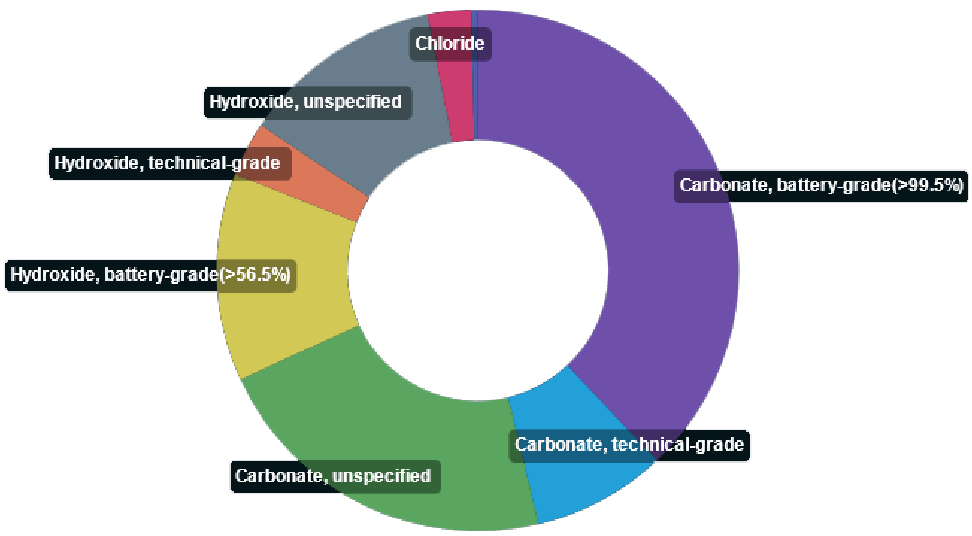

Figure 13: Refined lithium, global production capacity by product and grade in 2020, in percentage by mass (Source: European Commission (44))

However, in most of these projections, lithium hydroxide consumption is expected to increase due to its use in batteries with high nickel content. These batteries also have the highest energy density for the same number of kWh, lowering the battery weight. New installed production capacities are therefore mainly focused on lithium hydroxide (45).

In 2021, China was the leading exporter of lithium hydroxide, with around 68% of exports, while Chile was second with 11%. China produces lithium hydroxide partly from local deposits, but mainly by importing spodumene concentrate from Australia. Lithium hydroxide is then injected into local value creation or exported to other countries such as South Korea and Japan (45).

However, this situation is changing as lithium hydroxide production capacities develop. Australia will become an exporter in the future, with 100,000 tonnes of installed lithium hydroxide capacity (compared to 70,000 tonnes exported by China in 2021). The lithium triangle countries are trying to capture a bigger segment of the value chain, but investments are still lacking. However, the Bolivian government has been moving in this direction (38). Though this report does not examine geopolitical issues and international trade in depth, it should be noted that new exporting countries are not exempt from the influence of Chinese firms, as they often own shares in foreign projects.[21]

The problems of mining waste and changing land use

In the case of metals extracted from hard rock, the volume and management of mining and metallurgical waste are key determinants of the emergence of environmental, health, and social impacts.

Terminology	Description
Waste rock (*overburden, interburden*)	The mining waste (usually topsoil or coarsely ground rocks) that is removed to access the mineral deposit (ore body). There are several kinds of waste rock: overburden (the material lying above the deposit), interburden (the deposit material considered insufficiently valuable in economic terms), or a mix of both.
Tailings	Mining waste left over after mineral concentrate is produced. It can also designate waste produced in the later refining or chemical treatment phases.
Mining waste	Covers both waste rock and tailings.

[21]For example, the Kwinana project in Australia, one two big recent lithium hydroxide production projects in the country, is a joint venture, with Tianqi Lithium holding 51% of the shares.

Terminology	Description
Run-of-mine, gross ore, crude ore	Rock containing useful minerals or substances (such as metals) in a proportion of sufficient economic interest to justify extraction and which requires processing for industrial use. Ore is distinguished from interburden by its cutoff grade, the minimum grade below which extraction is not profitable. This depends on the price, operating costs, and so on. At the scale of the mining project, the size of the deposit varies according to time and place. Much like the concept of a resource, ore is a socioeconomic concept.
Ore concentrate	Ore that has been through various concentration phases: ore treatment or mineral processing. Mineral processing covers a set of physical and physicochemical treatment techniques used to obtain commercially viable products that can be subject to metallurgical processes (transformation of concentrates into metals or alloys).
Metal content and grade or net ore	The ore grade (generally in g/t or ppm) designates the metal content or net ore of the extracted crude ore: Grade = metal content of the ore/crude ore.

Table 6: Definition of mining terms (Sources available in Pigneur, 2019 (46))

Lithium is generally extracted from solid rock in open-pit mines. The extracted rock is ground to extract the mineral containing the substance of interest to produce a concentrate, which is then processed to obtain the metal (see previous section). At each of these steps, the parts of the rock with no value are discarded, creating mining waste (see Table 6). The first waste materials are produced during the extraction phase, in which construction and demolition waste and **overburden** must be removed (see left side of Figure 14) to reach the deposit. This waste is then stored in **stockpiles** that look like artificial hills. This process can also generate dust. Producing concentrate from solid rock generates tailings that are moved to settling tanks called tailing ponds (artificial lakes generally retained by a dam or raised edges — see Figure 14) (45).

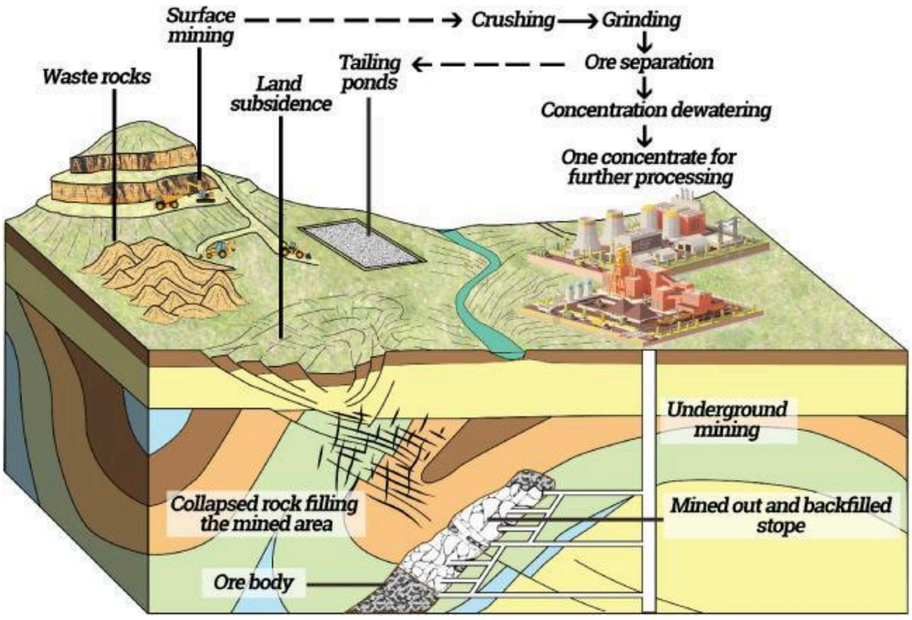

Figure 14: Stages in the generation of mining and ore processing waste (Source: Mabroum et al., 2020 (47))

This waste is usually stored outdoors, in stockpiles and tailing ponds. For certain types of mines, it can contribute to the acidification of water courses due to acid mine drainage. This waste can also disseminate toxic substances (with an impact in terms of toxicity for humans and ecotoxicity) and radioactive substances that naturally occur in the deposits. These substances can spread via storage systems, leaks, deliberate discharge (bad practices), and accidents involving the waste. These accidents, such as dam failures (48), are unfortunately much too common. There are around 3,500 of these dams in the world, which are some of the biggest civil engineering structures on the planet. Tailing dams are generally designed for long-term or permanent storage, with an estimated failure rate of twice the rate of traditional hydraulic dams (3).

These toxic or radioactive substances can naturally occur in the mined rock, but grinding, processing, and outdoor storage increase their reactivity to the environment and their dissemination. Tailings may also contain chemical inputs that have reacted with the minerals.

Since there is a low concentration of lithium in deposits, **producing lithium from hard rock requires significant volumes of rock, generating a great deal of waste**. According to the IEA (3), the rock-to-metal ratio of lithium production from hard rock mining (spodumene) is 1,600 tonnes of rock extracted per tonne of lithium produced. DERA estimates that lithium-bearing pegmatites produce between 3 and 10 tonnes of waste rock per tonne of ore (38). Based on our calculations (see Appendix 2), the IEA's rock-to-metal ratio corresponds to DERA's upper projection of the spodumene waste generated.

This figure cannot be directly translated into waste volume because it does not consider the potential commercialisation of coproducts. However, it does show that **lithium produces a great deal of mining waste compared to other metals, as shown in Figure 15.** The greater the volume of waste, the harder it becomes to contain potential pollution, all the more so given that waste storage facilities are designed to remain in place permanently once the mining operation is complete.

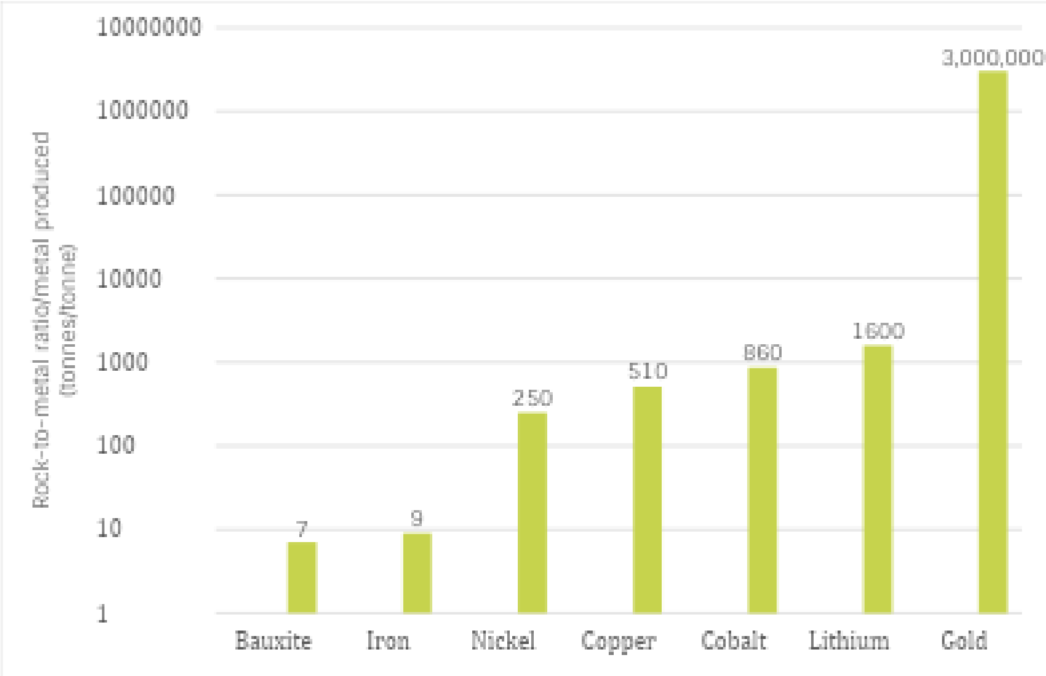

Figure 15: Rock-to-metal ratio, the quantity of rock extracted and treated to produce 1 kg of metal in tonnes/tonne, logarithmic scale (Source: IEA 2023 (3))

This significant waste volume is mainly comprised of waste rock (see Figure 16), with a small share from processing tailings. The calculations in this figure do not account for coproducts and are presented in greater detail in Appendix 2.

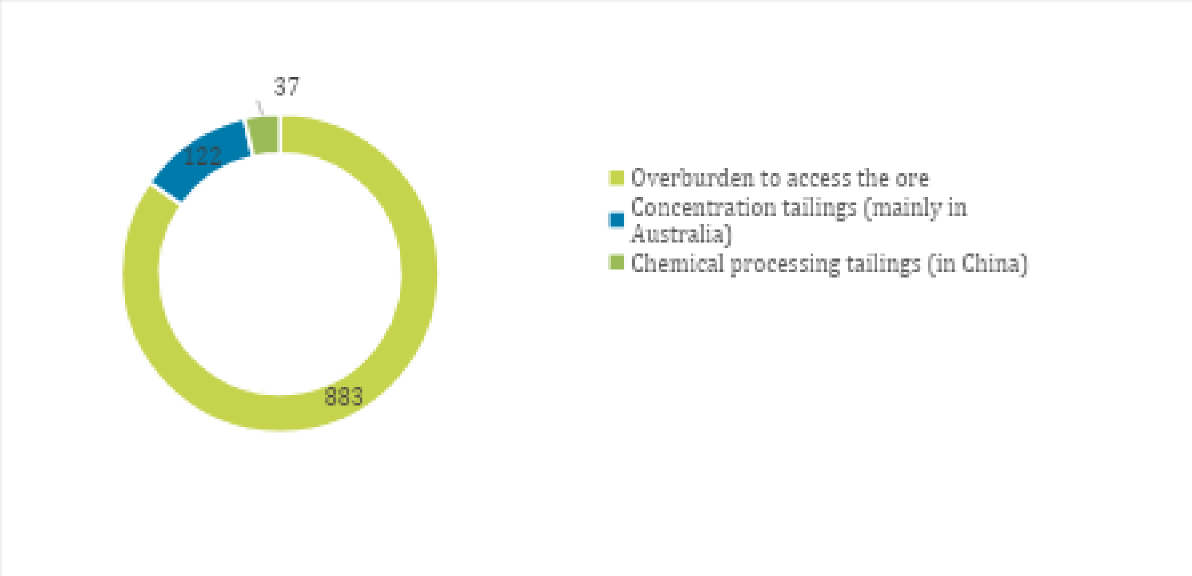

Figure 16: Mining waste produced during the different stages of spodumene processing, in tonnes per tonne of lithium (calculations based on DERA, 2023 (45) and Vignes, 2024 (43))

We can expect the volume of mining waste from lithium production to increase significantly (see Figure 17), **given the rise in demand accompanied by an increase in the share of lithium produced from hard rock extraction and diminishing ore grades** (Greenbushes, one of the largest spodumene mines in Australia, contains the highest-grade ore deposits — all other deposits have lower ore concentrations).

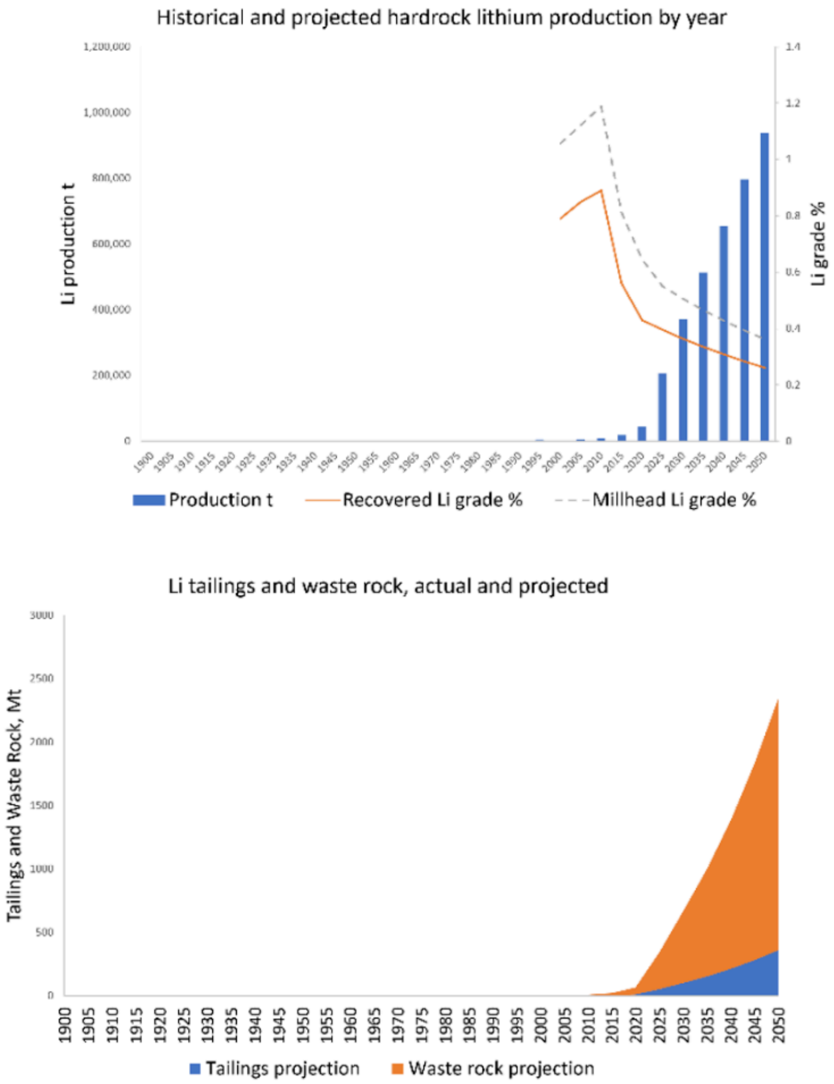

Figure 17: Estimated production of waste rock (in orange) and tailings (in blue) bottom, from global lithium production (top) (Source: Valenta et al., 2023 (49))

In the case of lithium, **waste rock from hard rock pegmatite mining does not appear to be toxic** and does not provoke acid mine drainage, given the lack of sulphide minerals in the deposits (3, 38, 50). However, we must evaluate the potential for releasing toxic or radioactive substances on a case-by-case basis since this varies according to the deposit, the local weather conditions, the technology used, and so on. For example, a study on Australian spodumene processing showed that even in the absence of sulphide minerals, the use of sulphide-based chemicals (such as sulphuric acid) during excavation and processing can cause acid mine drainage (50). In another example, the tailings storage facility of the Jiajika mine in China, which extracts pegmatite (spodumene), was responsible for disseminating arsenic, chromium, and vanadium, with arsenic values in waterways exceeding WHO values for safe drinking water in some places (51). The authors also noted the lack of studies examining the impact on surface water of waste storage from hard-rock-type lithium mines. Spodumene mines in the Chinese province of Sichuan have also been linked with pollution scandals, but the limited information available makes it impossible to determine whether this pollution is due to the presence of toxic substances in mining waste or bad practices (like toxic substances used for processing being directly discharged into waterways (52)).

We also know little about the storage of mining waste from **lepidolite deposits** being mined in China. And yet, this waste may be associated with another **risk: thallium pollution.** The company Lepidico Ltd (which sources from Namibia) conducted a study of mining tailings produced during lithium refining, revealing that **levels of thallium in these tailings were about seven times greater than Canada's reference value for soil pollution** (53). The presence of thallium in the processing tailings could explain the water pollution that occurred in the Chinese province of Jiangxi, as discussed in the next section. Using slightly acidic water to process tailings before storage could extract half of the thallium and significantly reduce the risk of it leaching into surface water and groundwater (53). **In any case, the tailings resulting from this extraction must be studied to evaluate toxicity-related risks and determine appropriate treatment and storage methods to reduce ecotoxic hazards.**

Beyond the risk of disseminating toxic substances that could impact health or ecosystems, waste storage facilities also increase the footprint of mining operations, increasing land take.[22] This land take makes it risky, or even impossible, to use waste storage areas for agricultural purposes and can create land use conflicts. On the global scale, and for all materials, mining operations have a substantial land footprint (including the mines themselves, tailings management facilities, and processing plants). And we must not forget the mining waste storage facilities that continue to accumulate over time. It is estimated that active mining sites cover 100,000 km² of the planet's surface, or the size of Iceland (24). **Mining waste can also significantly contribute to erosion and the filling of waterways, and submarine tailings disposal seems likely to damage seafloor ecosystems** (54)**.** This is particularly true for bad practices, such as deliberately discharging waste into waterways or the ocean or inadequate management that results in tailings dam failures. **Consequently, the dramatic increase in the expected volume of waste from lithium mining (see Figure 17) could cause major problems.**

Land use conflicts relating to lithium mines vary greatly depending on their location. These conflicts are less present in arid and sparsely populated regions (such as north-west Australia) than in densely populated areas. However, this can also have an insidious effect: since mining operations are often allowed to occupy larger surfaces in less inhabited regions, this can increase the impact on ecosystems. Data from feasibility studies and permit request documents published by the government of Western Australia reveal that **only 4 m² of surface area are needed to produce a tonne of lithium carbonate in the Greenbushes mine (located in a temperate zone), while the Pilgangoora and Mount Marion mines (located in semi-arid areas) use 12–13 m²/t of lithium carbonate produced.** This can partly be explained by the higher lithium grade in the Greenbushes mine, but it is also likely that the larger mining and storage areas for the Pilgangoora and Mount Marion mines were requested and approved because they are subject to fewer land use conflicts. In comparison, producing a tonne of copper requires 3–4 m²/t of land and aluminium requires 1 m²/t (45)**.**

Conflicts over land use (including the creation of waste storage facilities) can result in population displacement (55). In China, several conflicts around lithium extraction have occurred in the Sichuan region, but it is hard to know if they are specifically related to waste management (56).

There are currently few studies that evaluate the deforestation caused by lithium mining. At first glance, the impact seems negligible compared to the mining of other resources such as gold or coal. Nevertheless, it is important to remember that much larger quantities of lithium will be mined in the future, as the following countries have projects in various stages of development: Australia, Brazil, Canada, Ghana, Peru, Russia, and the United States (4). These countries are among the ten countries with the highest tendency to practise deforestation in their mining projects, representing 84% of global mining-related deforestation in the past 20 years (57).

In the salt flats, lithium is extracted by pumping brine, which does not produce mining waste (waste rock or tailings). However, these arid regions can experience extreme heat and flooding (like in Chile's

[22] Transformation of a soil of agricultural, natural or forestry character by management actions, which may result in its total or partial waterproofing. This change in land use, which is usually irreversible, has consequences which can be detrimental to the environment and agricultural production. Land take amplifies water runoff to the detriment of infiltration, thereby increasing soil erosion, muddy water flows and the risk of flooding. Runoff also contributes to the degradation of the chemical and ecological quality of the waters by intensifying the transfer of sediment laden with contaminants from the soil to the streams. Land take can also cause rapid and consequent carbon removal, which contributes to climate change when the soil is not very quickly covered (vegetation, coating). Lastly, it affects biodiversity by fragmenting natural habitats and irretrievably transforming ecosystems and landscapes (Source: INSEE).

Atacama Desert in 2015). Flooding can spread pollution from evaporation ponds, which contain debris or "gangue" comprising heavy metals such as arsenic, thallium, and chromium. Flooding can also disseminate uranium and thorium, naturally occurring radioactive elements in lithium ore (58).

Salt flats use relatively large amounts of land, mainly for evaporation ponds, but no data is available on the number of square metres per tonne of lithium carbonate. Nevertheless, salt flats are not used by other stakeholders, since they are extremely arid salty plains. Usage conflicts around lithium extraction in salt flats mostly centre around water and occur in areas outside the evaporation ponds (38) (see next section).

To apply good practices, **the priority is to avoid producing mining waste**. In this regard, sufficiency is essential (see Part 4.1). However, here we wish to discuss how to reduce the volume and danger of waste at the same production levels. To do so, we must:

- prioritise deposits with the highest lithium content (which means avoiding lepidolite mining (45)) or deposits that generate significant coproducts.
- include in the project design and environmental impact study **an analysis of the various waste products that are generated** (see below):
    - Reintegrate tailings into treatment flows to avoid losing critical materials and produce less waste. This type of process already exists and is being used by Talison Lithium Pty. Ltd. (50).
    - Commercialise as many coproducts as possible (50):
        - β-spodumene that is low in lithium after extraction could be used to extract lithium from industrial wastewater and sewage.
        - Waste rock that contains silicon and aluminium can be transformed into commercially valuable byproducts such as hydroxysodalite.
        - Lithium aluminosilicate residues can also significantly strengthen the resistance of conventional concrete mixes and can be used as a geopolymer precursor.
        - Treatment tailings can be transformed into adsorbents, catalysts, and filtration membranes to eliminate hazardous substances from wastewater.
        - In salt flats, some extraction operations focus solely on producing borates, others produce lithium carbonate, and still others sodium chloride. **Simultaneously recovering the maximum number of byproducts** in a single deposit could require fewer mining operations and produce less waste (59).

- Include in the project design and the environmental impact study **an analysis of methods used to separate the most hazardous substances from waste rock and tailings** to improve hazardous waste storage. Waiting until the end of operations to conduct an environmental assessment of soil pollution is too late since environmental remediation is often costly and involves significant waste volumes, consuming a fair amount of energy. **Anticipating and monitoring the presence of hazardous substances in waste is much more effective upstream and during operations, so methods can be designed to separate the most dangerous substances from waste rock and tailings before storage**.
    - For example, the risk of thallium contamination must be evaluated for any lepidolite mining project, and thallium treatments must be sought before waste is stored (53).

- Create a risk management plan to address dam failure.

- Alternative waste storage methods (such as dry storage, in which water is extracted from mining waste to better contain pollution), particularly for tailings management facilities, have not yet been successful and remain too cost-prohibitive (3).

The following measures would encourage better waste management:

- Create a **"European compensation fund for mining waste management"** financed by contributions from mining companies whenever they operate in Europe. This fund could be used to finance the environmental remediation of former or future mining sites (which often becomes the government's responsibility after the company fails in its duty) and research on better mining waste management. This proposal is an expanded version of the financial guarantee provision in the EU Extractive Waste Directive (2006/21/EC), which does not call for funds to support research or decontaminate old sites.

- **Expanding the human and financial resources of government agencies in charge of monitoring mining waste storage facilities**, along with a European training plan for these agencies to ensure uniform understanding across Europe of the specific environmental and health risks associated with mining waste. This measure aims to make Article 17 of the Extractive Waste Directive operational.

- Amend Annex II of the Extractive Waste Directive to **better evaluate health risks.** The directive currently calls for waste characterisation to be included in the waste management plan described in Annex II, along with a declaration of the total estimated quantity of extractive waste that will be produced during operation. This characterisation essentially evaluates the hazardous characteristics (2000/532/EC) of the mining and tailings waste. This is necessary but insufficient since it is based only on the concentration of the hazardous substance in the waste without evaluating its mobility. Yet many cases of reported health impacts around the world associated with mining waste storage demonstrate the mobility of the hazardous substances contained in this waste. **It is therefore clear that we need an approach that combines site pollution assessments as well as future-oriented evaluation of health risks. This approach is broken down into four steps:**
    - **Assess the facility's emissions.**
    - **Assess potential environmental issues and means of exposure: sources of pollution and the substances emitted, the various environments and means of transmission, the end uses, and the populations exposed.**
    - **Assess the pollution of the site to determine whether the facility's emissions contribute to environmental degradation.**
    - **Conduct a forward-looking assessment of health risks to identify real exposure risks.**

  Health risk assessments could also be improved by including mining in Annexe I of Directive 2010/75/EC on industrial emissions, the IED directive (which currently only includes concentration and metallurgical processes), and adding mining waste storage facilities.

- **The information available** in mining waste management reports transmitted by Member States (Article 18 of the EU Extractive Waste Directive) **should include** the previously mentioned health assessment as well as an **assessment of modes of dispersal and associated health risks. The deadlines to make the health information in these reports available should also be shortened**.

The impact of lithium production on water resources

Mining and metallurgy impact water quality and use significant volumes of freshwater. As in the previous section, we will distinguish between the two main processes: brine extraction and hard rock mining.

The impact of brine extraction and geothermal lithium on water

The IEA (6,60) indicates that brine extraction requires an average of 775 m^3 of water per tonne of lithium carbonate produced,[23] compared to copper (30 m^3/tonne) and cobalt (60 m^3/tonne (3)) (see Figure 18). In the figure below, the share of production in water-scarce areas represents the share of production in countries with moderate to high water scarcity risks, according to the WWF (3). In this figure, we can see that **lithium production consumes a great deal of water in areas that are vulnerable to water stress, like the Atacama Desert region.**

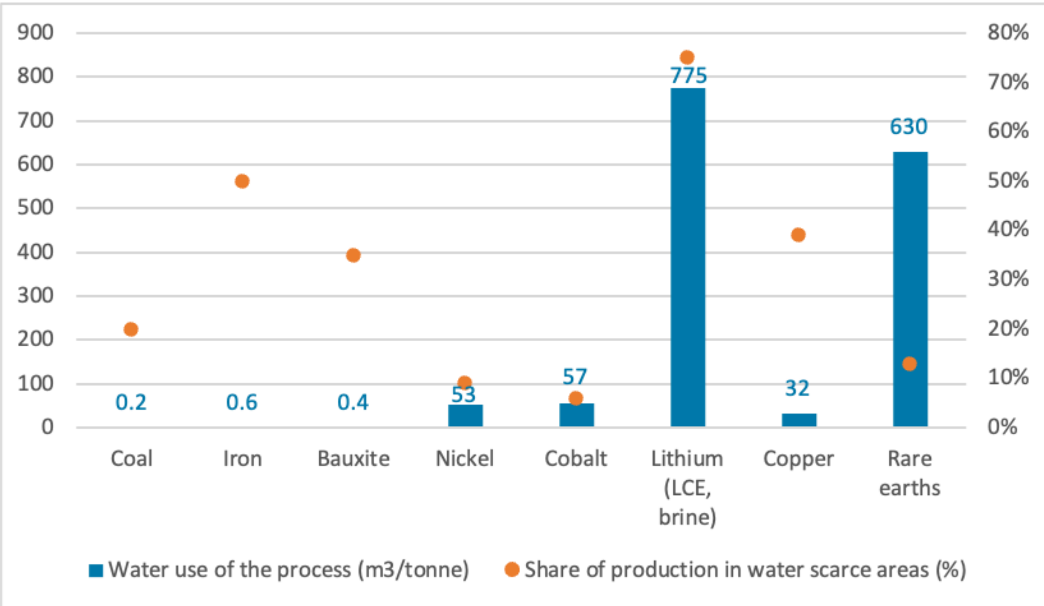

Figure 18: Apparent water consumption and share of production in water-scarce areas for various metals and coal. Data for lithium refer to brine production (Source: IEA, 2023 (3))

However, we must go beyond quantitative data to evaluate how brine extraction impacts water resources. We used the term "apparent consumption" above since the 775 m^3 of water consumed per tonne of lithium carbonate seems to include the water contained in the brine itself, which is non-potable. Current evaporation technology used to extract lithium from continental brine deposits uses solar evaporation to concentrate the brine. Significant volumes of water are lost to evaporation, from 100 m^3 to 800 m^3 per tonne of lithium carbonate, depending on the deposit (59).

The current evaporation technology uses **between 22.5 m^3 and 50 m^3 of freshwater per tonne of lithium carbonate** in the Salar de Atacama and the Salar de Olaroz salt flats, respectively (59). This volume is more comparable to the production of cobalt or copper.

It may seem obvious that freshwater consumption should be considered an environmental impact. Yet there is disagreement about whether brine volume should be included in the water footprint, as brine is unfit for human consumption or use in agriculture. What, then, is the true impact of its extraction? The answer is not obvious and is a hydrogeological question. **The volume of brine that is pumped has an impact on the quantity of freshwater that flows from the edges of the salt flat to the central zone in**

[23] The IEA's publications (3,6) are based on the article by Jiang, S., Zhang, L., Li, F., Hua, H., Liu, X., Yuan, Z., Wu, H. (2020). Environmental impacts of lithium production showing the importance of primary data of upstream processes in life-cycle assessment. Journal of Environmental Management, 262, 110253.), in which Table 2 identifies the water consumption of brine-based technology (LBT) of 773 kg water/kg of lithium carbonate, or775 m^3/tonne of lithium carbonate.

which the brine is located (see the "nucleus" in Figure 19). Freshwater is found at the edge of the salt flat basin, in the free and captive aquifers. Even in salt flats where no extraction occurs, the freshwater that infiltrates is partly mixed with the brine (in the mixing zone) or becomes brine. However, an analysis of four articles (59) suggests that brine pumping could provoke an increase in recharge from underground freshwater toward the brine deposits (see the blue arrows in Figure 19). If this recharge becomes too significant, it will impact the level of nearby freshwater lagoons, rivers, and streams, as well as the water table level in the surrounding area. This provokes **water table drawdown** (see the blue line in Figure 19).

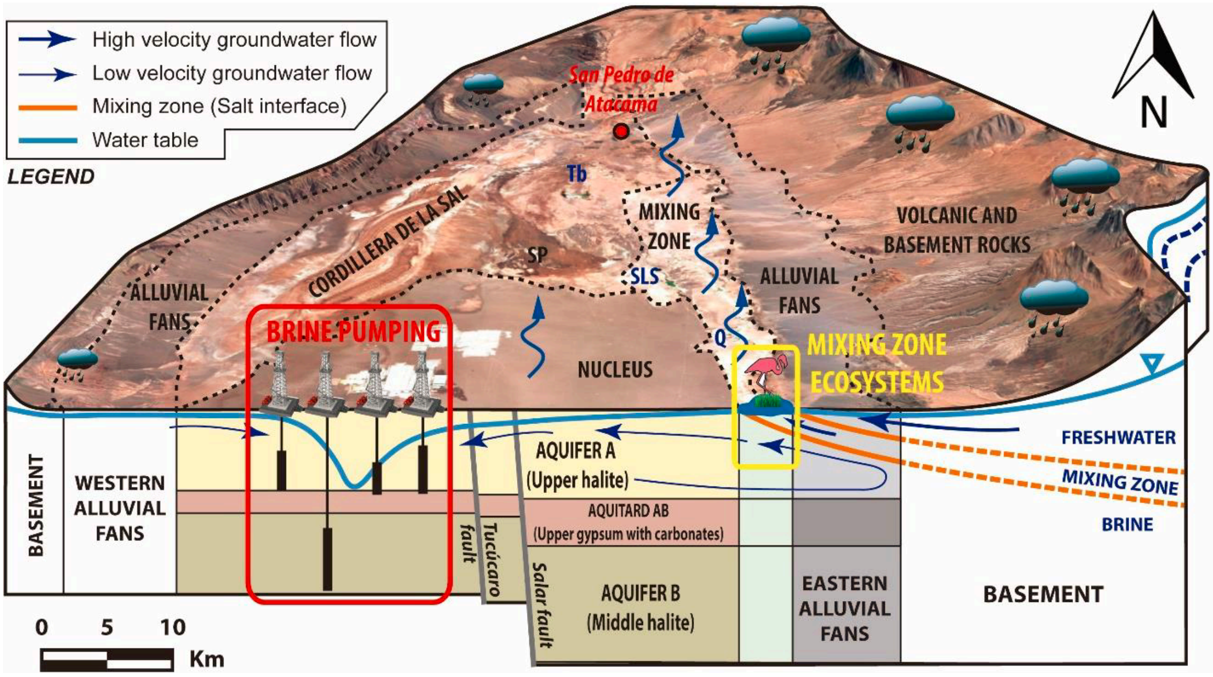

Figure 19: Illustration of the water table drawdown in the Salar de Atacama. Q is Quelana Lake, SLS is the Soncor Lake system, Tb is Tebenquiche Lake, and SP is the San Pedro alluvial fan (Source: Marazuela, 2019 (61))

Pumping the brine can therefore decrease the water table level (38). The mix of saltwater and freshwater can render this water unsuitable for drinking and for use in the traditional agricultural practices of the neighbouring communities. **A reduction in the water table has been observed in the Salar de Atacama.** Low water levels in wells have also been reported and soil humidity seems to be decreasing (38, 59).

It has become clear that lithium mining has a negative impact on water resources in the Salar de Atacama region (59). **Nevertheless, it is hard to quantify this impact and identify the specific share of responsibility that lithium mining bears for decreasing water table levels.** This is due to the complex nature of hydrogeological studies and a lack of data. Other activities also contribute to the drawdown of water tables in the region, such as copper mining (which directly extracts 15 times more freshwater from the catchment area than lithium mining (38)), reduced precipitation, and increased water stress due to tourism.

Conflicts around brine extraction and its impact on local freshwater reserves have occurred not just in Chile but in Argentina and Bolivia as well (38). These conflicts around water access have become even more worrisome as they have worsened due to the impacts of the changing climate.

The main solutions for reducing water shortages in the arid salt flat involve reducing pressures on the system. The goal is to slow down the pace of lithium extraction and copper mining (which places even more pressure on water resources). Some copper industry players in the region are looking for ways to avoid withdrawing freshwater from the salt flat catchment areas, such as using desalinated seawater instead. This solution should be evaluated for lithium. It would not solve the water table drawdown issue, but it would reduce the use of freshwater. However, there have been no techno-economic studies to examine this possibility to date.

As for the impact on water of **lithium mining combined with geothermal energy production,** there is **a risk of pumping wells becoming permeable** and geothermal water being reinjected, **potentially contaminating the aquifer** (if there is one). For example, this risk has been identified for the parts of the Rhine aquifer (one of the most significant water reserves in Europe) that are impacted by the extraction of geothermal waters, which naturally contain toxic substances (radioactive elements like lead, arsenic, and antimony (62)). A study noted that "the design of the geothermal wells involves isolating the geothermal water from the aquifer by three cemented casings. Over the lifetime of a plant, the casings should be inspected on a 3-year basis for an injection well and a 6-year basis for a production well. All these inspections must be reported to the mining authorities. In addition to these mechanical barriers, a piezometric monitoring network has been deployed… For instance… in Illkirch, an important result was that the Rhine aquifer water remained drinkable and unpolluted during all the geothermal activities" (63).

As mentioned at the beginning of this section on environmental efficiency, **DLE techniques are sometimes mentioned as a means of reducing water stress** and land stress. These techniques theoretically eliminate the need for evaporation ponds, since the lithium is directly extracted from brine. To avoid water table drawdown, the treated brine is reinjected into the geological layer where the reservoir is located. In practice, there seem to be two obstacles. Firstly, reinjecting brine that is low in lithium content dilutes the deposit, reducing the profitability of the brine extraction operation (37, 57). In the case of lithium extraction from geothermal brine, reinjection interferes with production wells in 80% of cases. Secondly, spent brine is likely to contain chemical species that are exogenous to the salt flat or the geothermal reservoir, which could contaminate the surrounding ecosystems. This spent brine is most likely to be discharged into an evaporation pond, as is currently the case. **This offers no advantages in terms of water table drawdown or land use.** Lastly, 16% of studies show that freshwater needs for DLE methods are similar to current methods, and 25% of studies estimate that these methods are more water-intensive than evaporative practices. Since DLE technologies are still under development, progress is still possible. However, an active DLE facility at the Salar del Hombre Muerto consumes more water than current evaporative processes (59). **Therefore, the advantage of DLE for freshwater consumption is still unclear. In light of this information, we can conclude that DLE remains a very uncertain solution to the problem of water stress.** Above all, this method **improves the speed (and therefore the performance)** of the lithium extraction process in arid zones such as salt flats. **It also makes it possible to extract lithium from geothermal deposits in non-arid zones where evaporation is unfeasible.**

Lithium extraction from both salt flats and geothermal resources must be subject to continued hydrogeological monitoring from the beginning of the project, since impacts on the environment can only be observed over the long term. In addition to monitoring by mine operators, **more measurements should be taken by independent experts or national authorities** (57).

The impact of spodumene extraction on water

According to DERA, the Pilgangoora mine consumes around 875,000 m³ of water to produce 5 Mt of ore per year or **around 5.3m³ of water per tonne of lithium carbonate equivalent (LCE)**. This consumption represents only water needs for mining and concentration processes, given that **the total water consumption, from spodumene mining to the production of lithium carbonate** in China, **equals 40 m³ of water/tonne of lithium carbonate.**

In hard rock mines, water is needed to mill the ore and in the concentration stages (density sorting, magnetic separation, flotation). Processing residues are deposited into tailings ponds. Some water may be reused, but the rest remains in the tailings in the form of interstitial water. **The use of thickeners and filter presses to dewater tailings could help minimise water loss, but most projects are not planning to do this yet**. According to the Pilgangoora mine's feasibility study, for an ore throughput of **5 Mt per year, around 500,000 m³ of water cannot be recovered — nearly 33% of the water required for milling and concentration** (37).

Hard rock mines have an advantage regarding water use; unlike salt flats, they are not systematically located in arid regions. Though water use is less problematic in relatively humid areas, **the location of the mine should nevertheless be chosen with these criteria in mind to limit consumption to the extent possible. This can be done by recycling water, pressing tailings, and planning for water needs.**

The impact of lepidolite extraction on water

Regarding lepidolite transformation processes, some studies in China have revealed lithium pollution in the water downstream of lithium carbonate production plants (64). As mentioned previously regarding high levels of thallium in lepidolite processing residues, several news outlets have reported the closing of lithium production sites due to thallium contamination in Yichun, Jiangxi Province, the centre of lithium mining in China (63, 64). Several Chinese scientists have called for the establishment of "stringent thallium emission standards, with a particular focus on water pollutants, prioritising lithium-related industries worldwide to address this issue on a global scale. Similar to the UNEP Minamata Convention, international management measures are necessary to mitigate global thallium emissions and reduce exposure" (67).

The impact of residual lithium on water

In China, still in Jiangxi Province, lithium pollution in the Jinjiang River Basin has also been analysed. A study shows that the concentration of lithium in aquatic plants and fish has significantly increased downstream of the lithium mine. This contamination also exposes local residents to chronic health risks, primarily due to the consumption of contaminated water and vegetables (64). At high doses (such as blood concentrations of 15–20 mg per litre), lithium is toxic to humans. It can provoke nausea, visual impairment, kidney issues, or even medical emergencies such as coma and cardiac arrest. And yet, aside from a specific concentration of 0.005 mg/litre for lithium recently proposed by the Pennsylvania Department of Environmental Protection, lithium is rarely regulated in groundwater or drinking water (68).

Though this example shows insufficient monitoring of discharge from lithium carbonate production plants in China, it also shows the value of tailings retreatment to recover as much lithium as possible (as mentioned at the end of the section on the problems of mining waste and changing land use).

The problems of mining waste and changing land use

In this part, we have shown that the direct impact of lithium carbonate production on freshwater consumption is comparable for spodumene and brine. However, **brine extraction** in salt flats also has an indirect effect on the aquifer level. **It can have a bigger impact on the availability of freshwater resources** since these mines are necessarily located in areas where water stress is even more untenable. Technical solutions to prevent water table drawdown have not yet been successful. **To**

reduce pressure on the water table in the lithium triangle salt flat, we must reduce other sources of pressure on water resources (particularly by halting copper mining in Atacama); monitor the hydrogeological impact of brine extraction; and limit the volume of brine extracted if necessary. **For hard rock mining, we should systematically examine the use of thickeners and filter presses to dewater tailings, which could help minimise water loss and limit pressure on water resources. The water requirements for DLE in geothermal fluids are harder to evaluate because this technique is fairly recent.** The following conditions seem necessary to limit DLE's impact: mining must occur in regions with greater water availability, using a method that limits the need for freshwater, and ensuring appropriate monitoring to guarantee that wells remain impermeable.

Regarding the potential contamination of water resources, more information is needed to establish and avoid the causes of lithium pollution in Jiangxi Province in China. **The presence of thallium pollution due to lepidolite extraction and processing is cause for alarm,** which means we must demonstrate the environmental feasibility of mining these deposits before new projects are launched.

Beyond monitoring, **the water needs of the mining industry should be planned out and balanced with other freshwater uses and the growing scarcity sparked by climate change,** so governments can anticipate and prioritise water requirements. At the European scale, we must ensure that potential lithium operations comply with River Basin Management Plans under the EU Water Framework Directive (WFD).

The recently adopted CRMA (EU Regulation 2024/1252) cited Article 4, Paragraph 7, of the WFD, explaining that "strategic projects" meet the WFD's criteria of overriding public interest. This article of the WFD describes exceptions to water quality standards for activities that meet several conditions, **one of which is "overriding public interest". Though the CRMA does not introduce a means of systematically bypassing the WFD for all strategic substances, the intention is certainly to help extractive industries circumvent water quality requirements. Given the significant impacts that mining and metallurgy can have on water quality,** in addition to potential health risks, **this willingness to facilitate circumvention of the WFD seems to be headed in the wrong direction.**

Greenhouse gas (GHG) emissions

This report focuses on the impacts of lithium production (and thus indirectly on the effects of the mobility transition) so we can advance the most sustainable and realistic transition possible. However, it is important to remember that decarbonising transport is necessary and unavoidable in a world where the **fossil fuels** consumed by **passenger vehicles represented 10% of global CO_2 emissions** from energy in 2018 (1,2). And we must not forget that **EVs are already better for the climate than ICE vehicles,** as the IEA clearly shows in Figure 20 below. Furthermore, the performance of EVs will improve with the decarbonisation of energy mixes.

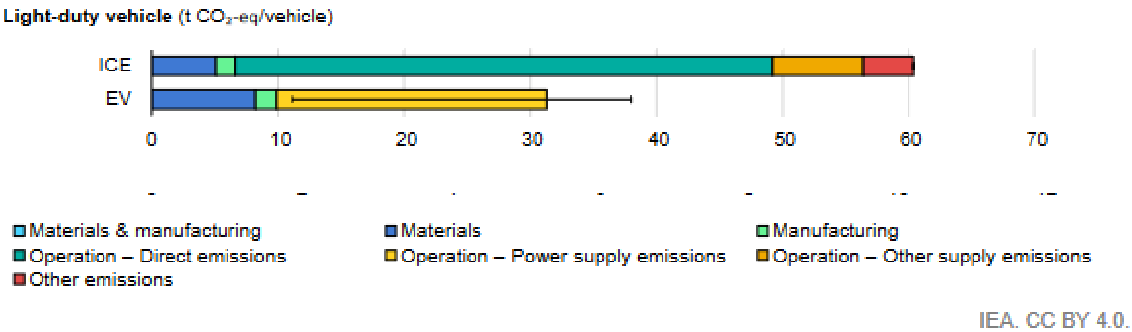

Figure 20: Global average lifecycle GHG emissions intensity of light-duty vehicles (commercial and passenger vehicles) for EVs and ICE vehicles (Source: IEA, 2023 (3))

However, Figure 20 also shows that EVs have a greater materials share of GHG emissions than ICE vehicles, both proportionally and in absolute value. This highlights the importance of sufficiency in vehicle design (using less material) and environmental efficiency in production (choosing the deposits and production methods with the lowest possible impact).

Though emissions from the production of critical materials are still relatively modest in absolute terms (representing just 0.04% of the global energy sector's emissions), **they will rapidly increase to fulfil the levels of demand in the** IEA's Net Zero global scenario. The IEA shows that at constant energy intensities and share of fuel, global CO_2 emissions from the production of the five main critical materials — copper, lithium, cobalt, nickel, and neodymium — would more than triple, with **lithium bearing the greatest responsibility for this increase**. However, the IEA contends that increased **use of these metals to electrify road transport would significantly reduce net GHG emissions compared to ICE vehicles (even when considering the entire lifecycle of these vehicles and the metals they comprise)** (3). To account for this data, we allocated a significant share of planetary boundaries to lithium (in Part 2), with a much greater share of metal production allocated to lithium than is the case today.

Emissions from lithium production

All current studies agree that the GHG emissions generated in the production of lithium products (both lithium hydroxide monohydrate and lithium carbonate) are significantly higher in the case of spodumene mining than in brine or geothermal operations (3,38,42,69). When comparing the same source (brine or ore), lithium hydroxide production is generally thought to have a greater environmental impact than carbonate production (6, 69), as shown in Figure 21. However, one article (42) found that hydroxide production generates fewer GHG emissions than carbonate production (both from spodumene).

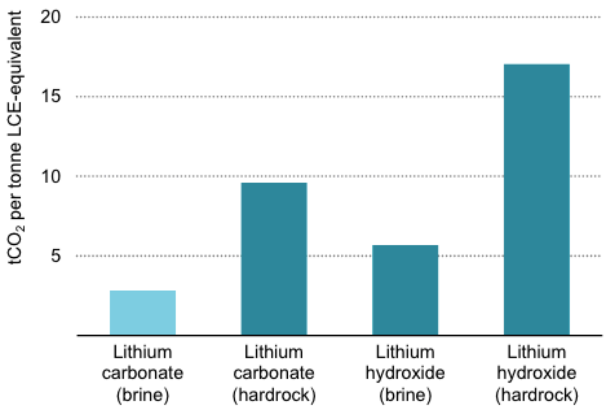

Figure 21: GHG emissions intensity (Scope 1 and 2) for lithium production (mining, processing, refining) per resource type and processing route, in tCO2eq/t LCE. For brine, figures are based on Chilean data; for mining, they are based on hard rock spodumene extraction in Australia; and for refining, they are based on Chinese figures (Source: IEA, 2022 (6))

Furthermore, an expected decline in ore quality (measured in ore grade) will mean that **new sources of lithium will require more energy to produce than current sources**. **This could lead to an increase in emissions unless mining and processing companies use lower-emission fuels.** Under the combined effect of increased demand, global market prices, and improving technologies, low-concentration reserves have become more economically viable than in the past, which has decreased average ore grade worldwide. Indirect emissions from the supply of electricity or chemical products will increase the carbon footprint even further (3).

Today, decarbonising mining and metallurgical production methods remains a major challenge. **Fossil fuels continue to represent the biggest share of the energy used in mining operations** (either via the direct use of fossil fuels or electricity production using these fuels). **As a result, mineral extraction and concentration operations generate significant CO_2 emissions**. For example, the mining and quarry sectors in Australia use fossil fuels for between 60 and 70% of their energy needs, with the rest coming from electricity. This energy is needed to power on-site trucks and the machinery used to dig and extract earth and rocks. It is also used for ventilation and crushing and separating the ore (3).

The IEA is very optimistic about mining in its Net Zero scenario, estimating that it will be completely decarbonised by 2050 (3) thanks to the electrification of drilling, digging, loading, hauling, crushing, separation, and mine ventilation, seen as “already a practical option”. The main challenges identified by the IEA include the size of mining trucks, which would require large batteries, or a shift to hydrogen and renewables, since mines are often far from the power grid. **Despite the IEA’s optimism, these challenges seem significant in terms of the investment required and the need for materials.** For example, the Swedish company Boliden uses hydroelectricity, which is not possible everywhere. We should also mention that most electrification and carbon footprint reduction projects are located in wealthy countries, which highlights the need for international cooperation in both economic and technological areas to support this progress. Furthermore, to our knowledge, no forward-looking studies examine the material footprint of this type of transition pathway for the mining industry to estimate its feasibility. For example, Anglo American’s nuGen mine haul truck, which runs on a hybrid hydrogen and battery engine, uses a 1.2 MWh battery, or the equivalent of more than 20 standard light-duty EV batteries (52 kWh) (70). It currently seems very unlikely that this decarbonisation will occur spontaneously without specific emissions regulations for the industry.

For metal refining, emissions can be reduced via technology improvements, electrification, and changes in fuel use. However, most of these technologies are not yet market ready and will initially be much more expensive (3).

The chemical treatment of spodumene concentrate requires heating at high temperatures (calcination, see the beginning of Part 4.2) and medium temperatures (for steam production). These processes are generally powered by coal (see Figure 22). Electrification of the calcination/roasting processes that occur at a temperature above 1,000 °C **does not yet seem feasible, as** technological developments were still in the pilot and research stage in 2021 (71). Fossil fuels could possibly be replaced with renewable energy or low-emission hydrogen, but little research has been conducted in this area so far (3).

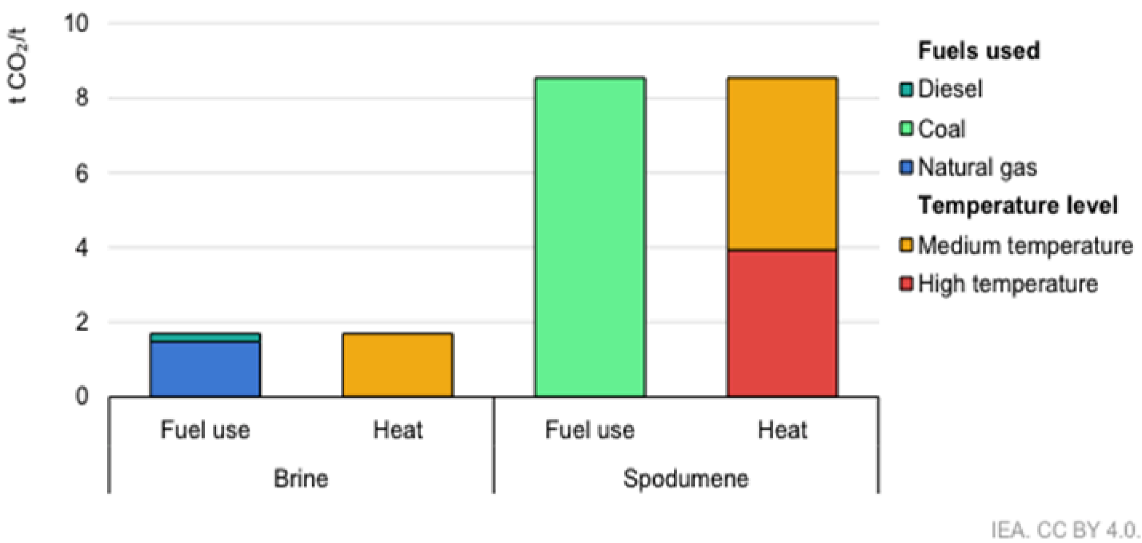

Figure 22: CO_2 emissions intensity for various hydroxide production routes by fuel used and process temperature. Only direct emissions are counted for processing; mining is not included. (Source: IEA 2023 (3))

Beyond electrification, efforts are underway to reduce the carbon footprint of these production routes. With **spodumene, the Outotec process produces lithium hydroxide using sodium carbonate instead of acid, which offers better yields but still requires high-temperature treatment** (3).

A completely different production route, such as DLE, is also an option (except for hard rock mining). As mentioned above, this technology is currently under development, particularly in the Rhine basin.

Given the difficulty in electrifying the chemical treatment of lithium ore concentrates, relocating some production sites to Europe will not automatically lessen the climate impact by immediately generating an electric mix with lower greenhouse gas emissions**. Rather, specific investments and implementation of lower-carbon processes will be required to eliminate the use of fossil fuels.**

Greenhouse gas emissions from recycling

Recycling generally has a lower ecological footprint than primary production (mining), which can primarily be seen in reduced GHG emissions. The CO_2 footprint of lithium produced from recycling is 38% lower than mined lithium (8).

To support the production of low-carbon lithium, the following measures are needed:

- **Encourage mining of deposits with the lowest impact**, such as brine (though it generates water stress, as mentioned above) or **geothermal sites**.
- **Promote investment in the research and development of low-emission processes. One option could be to require the use of fossil fuel-free technologies to access public funding for critical metals (in France and Europe)**.
- **Create and strengthen mechanisms to incite operators to use** materials with a lower carbon footprint, particularly **recycled materials**.

Biodiversity

Reduced water levels in the salt flats — partly caused by lithium extraction — impact local flora and fauna. In the Salar de Atacama, populations of James and Andes flamingos have decreased by 10% and 12%, respectively, due to diminishing surface water, especially in winter. This has also affected the reproductive success of the flamingos, putting the population size at risk. Satellite data between 1997 and 2017 showed a decrease in the size of vegetated areas. On one of the mining properties in the area, one-third of carob trees, a drought-resistant species, disappeared between 2013 and 2017, indicating a groundwater shortage (59).

Lithium is not the metal presumed to have the greatest impact on biodiversity today. The IEA claims that only 2% of global lithium production is located in biodiversity risk areas, compared to 80% for cobalt (3). However, there are two reasons to question this optimistic figure. First, measurements of the true impact of mining on biodiversity are still quite rare. Secondly, mining areas will change and expand with increased production.

To limit the impact of mining on biodiversity, the following measures are necessary:

- **Prohibit mining in protected areas and the most diverse and fragile biomes.**
- Much like the WFD, the CRMA makes it easy to circumvent the Birds and Habitats Directives. Given the current ecosystem collapse, we must ensure that laws regulating biodiversity are respected.

Recycling

Lithium recycling is still rare, as only 5 to 7% of Li-ion batteries are recycled worldwide (72). Even when batteries are recycled, lithium is not usually recovered because the pyrometallurgical process used most often primarily aims to recover nickel, cobalt, and copper. Lithium is ignored, ending up in slag (used in road foundations, to make cement, etc.). The main obstacle to lithium recycling is financial: batteries would need to be directed toward specific lithium recycling routes, which are not yet profitable given the low price of lithium.

Around 50 countries worldwide process end-of-life Li-ion batteries. The small proportion of global recycling that does recover lithium from these batteries is mainly based in China, which processes 50% of spent batteries and production tailings (73), followed by South Korea, the EU, Japan, Canada, and the United States (74). China's dominance in the recycling sector is due to the presence of plants involved in the many stages of battery manufacturing, which allows for synergy between companies.

Most recycling in China is done by battery manufacturers or metallurgical specialists using hydrometallurgical processes.[24] The majority of these companies alternate between using products generated during the pre-treatment of spent batteries (black mass), manufacturing scraps, or even concentrate from mines. The presence of many factories that produce EV batteries, which generate manufacturing scraps, provides recyclers with other materials to recycle in addition to the spent batteries. These different flows offer a partial means of overcoming barriers to lithium recycling (the variable composition of material flows, lack of material stock, etc.).

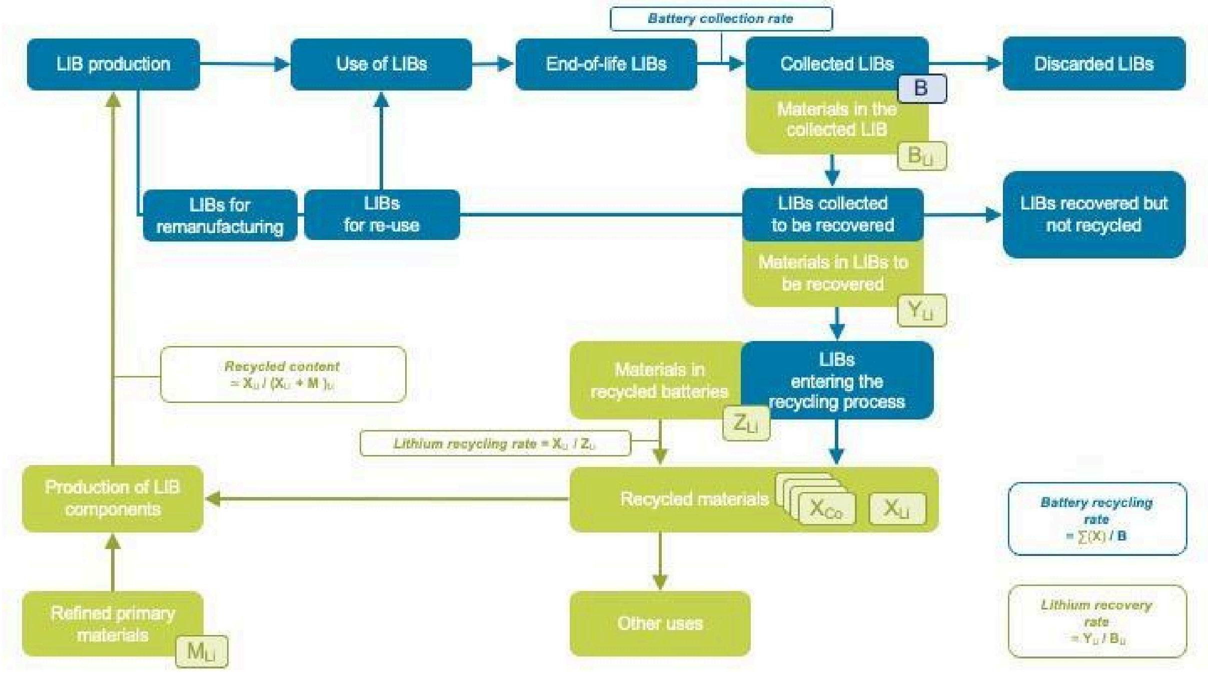

Figure 23: Diagram of Li-ion battery (LIB) collection and recycling along with lithium recycling and recovery rates

Legend:

1) Variables:
All variables are in mass quantity.
B: batteries collected
B_{Li}: lithium content in the collected batteries
Y_{Li}: lithium content in the batteries to be recovered (recycled lithium contained in reused batteries or any type of recovery process)
X_{Li}: lithium obtained (output of the recycling process)
X_{Co}: cobalt obtained (output of the recycling process)
∑(X): sum of all the materials obtained from recycling (Al, Cu, Fe, Li, Mn, Co, Ni, graphite, plastics)
Z_{Li}: lithium present in the batteries to be recycled
M_{Li}: lithium from mining

2) Various rates related to recycling:
The battery collection rate is the ratio of the mass of waste collected from identified producers to the total mass of waste generated by these producers.
The battery recycling rate is the ratio of the mass of various products recycled at the end of the recycling process to the total mass of batteries weighed upon arrival at the treatment facility. It measures the ability of the recycling system to transform waste into secondary raw materials.
The substance recycling rate is the yield of the recycling process for a specific substance.

[24] Almost all the companies in China use hydrometallurgical processes. The main reason is the ability to recover larger quantities of battery components and reach very high purities. In the EU, the most common recovery methods are pyrometallurgy, hydrometallurgy, and combinations of both (74).

The recovery rate is the ratio of the mass of a recovered substance[25] to its collected mass.
The recycled lithium content, also called the reuse rate of a Li-ion battery, is the percentage by mass of recycled lithium in the battery relative to the total mass of lithium.

With the increase in lithium demand, recycling may become more common in Europe, as shown by many industrial initiatives in progress. Nevertheless, some obstacles to recycling remain: the gradual decline in cobalt content, which has reduced recyclers' interest in material flows from pyrometallurgy (black mass); the need for highly qualified labour to dismantle EV batteries; and the lack of battery standardisation. Another problem is that lithium refiners launching operations in Europe are not interested in recycling since it is less profitable than processing other raw materials, such as salts extracted from brine in Argentina and Chile. It might therefore be necessary for French and European public authorities to improve incentives to encourage recycling. In this vein, the EU has approved legislation establishing requirements for battery recycling (18). **As for requirements for end-of-life battery collection (see Table 7), it is unfortunate that they do not apply to EVs, which are expected to become the main consumer of Li-ion batteries in the coming years.** We should also set specific recycling objectives for lithium and each substance. For example, the CLEVER scenario set a target lithium recycling rate of 80% in 2030 (see Figure 23 above and Table 7). In contrast, current recycling requirements (see Figure 23) are set for the sum of recycled materials from batteries and not specifically for each substance, bringing down recycling quality.

We applaud the emergence of European targets for recycled lithium content in new batteries. The initial target of a minimum level of **recycled lithium content** in batteries of 4% in 2030 and 10% in 2035 was revised upwards to **6% by 2031 and 12%** by 2036 (18). **However, it is unfortunate that the trilogue agreement put recycled lithium in end-of-life batteries on the same level as lithium from "pre-consumption"**, i.e., battery manufacturing scraps. While both types of recycling are worth considering, since they are mutually reinforcing, we should avoid reaching the target for recycled lithium content in new batteries solely using production scraps, which are harder to track and monitor. Furthermore, these targets seem low given the need to encourage recycling of future spent batteries. First, for environmental reasons: recycling the components of end-of-life Li-ion batteries could reduce energy consumption and CO_2 emissions (72). Secondly, to limit resource depletion: since resources such as lithium are finite, we must preserve those that have already been extracted. To do so, we need specific recycling channels. Until these are developed, this lithium must be stored rather than lost to landfills (72) or road foundations and concrete production (the current practice).

[25] "Recovery means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" (Directive 2008/98/EC, Article 3, p. 10). In other words, virtually any use that avoids landfilling. For lithium, even pyrometallurgically processed lithium that is not technically recycled and ends up in slag (used in road foundations or to make concrete) is classified as "recovered".

	CLEVER scenario	European targets
Battery collection rate	In 2030: 99% In 2050: 99%	**For LMT[26]:** In Dec. 2028: 51% In Dec. 2031: 61% **For spent portable batteries:** In Dec. 2023: 45% In Dec. 2027: 63% In Dec. 2030: 73%
Battery recycling rate	n/a[27]	In Dec. 2025: 65% In Dec. 2030: 70%
Lithium recycling rate	In 2030: 80% In 2035: 90%	n/a
Lithium recovery rate	n/a	In Dec. 2027: 50% In Dec. 2031: 80%
Recycled lithium content in new batteries	In 2030: 6% In 2035: 15% In 2050: 48%	In 2031: 6% In 2036: 12%

Table 7: Comparison of EU targets and CLEVER scenario assumptions for Li-ion battery collection and recycling as well as lithium recycling and recovery in treatment processes (Sources: created by Association négaWatt based on our data and those of the 2023 EU Battery Regulation (18))

Furthermore, we must support research and development on lithium recycling to reach a battery-quality lithium recycling rate above 90%. For example, a study of early-stage lithium recovery upstream of pyrometallurgical or hydrometallurgical recycling facilities[28] by RWTH Aachen University suggests lithium recovery rates above 90% could be achieved (75). This energy-efficient process, based on CO_2-assisted leaching from “black mass”, does not require modifying current lithium recycling techniques using pyrometallurgy or hydrometallurgy, nor does it reduce the ability to recover high-value metals such as nickel or cobalt. Another example is electrochemical recycling, which has yields above 90% (76) in the laboratory with lower energy and reagent costs than pyrometallurgical and hydrometallurgical technologies (77). New processes must prove their feasibility at an industrial scale before 2035, the year in which vast massive quantities of end-of-life batteries will need to be recycled (from EVs sold in 2020–2025).

[26] LMT, "light means of transport", are wheeled vehicles equipped with an electric motor of less than 750 watts, on which passengers are seated while the vehicle is in motion and which can be propelled by the electric motor alone or by a combination of motor and human power. These are broadly defined as electric two-wheelers.

[27] The BAMASI model takes into account a share of battery remanufacturing in the material balance. However, there is no target for battery recycling rates as such, mainly because not all battery materials are included in the material model.

[28] Conventional hydrometallurgical processes theoretically can recycle lithium with very high yields by using solutions (such as sulfuric acid) and precipitating agents (such as sodium carbonate). However, it is generally recycled at the end of a long extraction chain using a solvent or precipitating agent in which the metals of high commercial value, such as nickel, cobalt, and copper are recovered first, resulting in losses of lithium and lower yields.

And it is important to remember that we can only recycle the quantity available in the waste stock, meaning end-of-life batteries. In a growing economy, this stock is necessarily inferior to current consumption, and the content of recycled material is necessarily limited. **Consequently, the volume of raw materials recycled from batteries is decreasing even as the rate of consumption is increasing! Sufficiency is therefore critical for achieving high recycling targets.** When developed alongside sufficiency drivers, recycling is an essential tool to reduce pressure on mining and avoid wasting the resources contained in end-of-life goods.

Lastly, it is also important to take action upstream of recycling by encouraging solutions such as battery reuse and remanufacturing. One idea is to replace only degraded cells (SOH[29]<70–80%) to limit lithium needs and avoid discarding battery components that still work. Battery remanufacturing (called direct recycling), in which cathode or anode material is removed to be reconditioned and reused in a refurbished battery, is a step in the right direction — though lithium must often be added to compensate for material degradation during the battery's use (78). However, these methods have not yet reached large-scale industrial maturity and will face technical, economic, and time-based constraints. This is because waste stock only becomes available for remanufacturing after 10 to 15 years, while battery cathode technologies change very quickly. A specific and uniform description of each battery produced will therefore be necessary.

The following measures are needed to encourage efficient lithium recycling:

- Improve traceability and knowledge about the future of end-of-life vehicles (ELVs). Set ambitious collection targets for ELVs in EU regulations (no specific collection rate is currently mentioned). Strengthen policies to curtail the illegal export of ELVs to Eastern Europe and Africa (a current practice).
- Set specific targets for recycling lithium versus recovery (excluding downcycling-type uses).
- Establish governance for the recycling industry to ensure better visibility and activate investment capacity among recycling operators.
- Develop systems to trace materials in the metallurgical industry. Create an industrial policy to promote optimised and efficient recycling that includes specific pre- and post-consumer targets for lithium (beyond high-value metals such as nickel, cobalt, and copper).
- Strengthen targets for including recycled materials that encourage recycling of battery-quality lithium.
- Support research and development on innovative recycling technologies, such as early-stage lithium recovery or electrochemical recycling.

[29] SOH: State of health, the condition of a battery as a percentage (%) of its initial capacity (in kWh). This indicator measures the battery's loss of capacity.

4.3. Ecological substitution

The sufficiency/efficiency/ecological substitution framework adapts Association négaWatt's sufficiency/efficiency/renewables framework to the topic of materials.

The section on sufficiency looked at ways to adjust mobility services to reduce lithium consumption while meeting mobility needs. Efficiency aims to reduce environmental impacts for each tonne of lithium produced. Ecological substitution entails looking for ways to replace the lithium used in mobility with other materials while considering the feasibility of technological changes this would require. Whenever possible, it also involves studying the environmental advantages or disadvantages of using various alternatives to lithium.

We can think about lithium substitution at several levels:

1. in the propulsion system (electric or not);
2. in the battery:
    - by reducing the lithium content in the same battery technology, such as Li-ion batteries with nickel, manganese, and cobalt oxides (Li-NMC).
    - by using another type of battery with lower or zero lithium content, such as the sodium-ion battery.

The following sections will describe these two types of substitutions, their main environmental impacts, and the role they can play in minimising lithium use.

What role will EVs play? Are there suitable alternatives for reducing battery needs and therefore lithium consumption?

The role of EVs will depend greatly on the type of vehicle in question. Road vehicles with the greatest influence on lithium needs are cars, light commercial vehicles (LCVs), and trucks. The total or partial electrification of buses and motorised two-wheelers has a limited influence on lithium needs because of much lower sales volumes and much smaller battery capacity in the case of two-wheelers. Since electric bicycles and other two-wheelers, such as kick scooters and unicycles, consume very little energy, they have a negligible impact on total lithium demand and will not be covered in this report. For example, the battery capacity of an electric bicycle is around 300 to 800 Wh, 100 times less than an electric car (30 kWh to 80 kWh). Outside road transport, battery-powered vehicle electrification has so far been limited:

- Aviation and maritime/river transport: electric applications remain limited to very short distances,[30,31] representing a small share.
- Rail: in many cases, it is not economically viable to install overhead lines. So non-electrified rail lines can be decarbonised in several ways: battery-powered electric engines, decarbonised hydrogen fuel cells, or ICEs running on renewable gas. However, these technologies are unlikely to have a significant impact on lithium consumption.

In the next section, we will examine the utility and associated difficulties of electrifying the vehicles with the biggest influence on lithium demand: passenger cars, trucks, and LCVs.

Passenger cars

Electric cars present many advantages: significant efficiency improvement compared to ICEs, no tailpipe emissions (though they generate tyre and road wear particles), a sharp reduction in noise pollution, and a better GHG emissions footprint (see the paragraph on GHGs in Part 4.2). The main disadvantages are battery-related: the environmental impacts of mining the resources needed for

[30] Electric aircraft have a low TRL (4/5), and even with technological maturity, they are "Unlikely to become available for medium or long haul flights, more suitable for short-haul flights with maximum distances of 500-1200 km" https://www.incarbzero.com/etp-clean-energy-technolgies/battery-electric-plane

[31] "battery electric ships will mostly find applications on short-distance routes" https://www.incarbzero.com/etp-clean-energy-technolgies/battery-electric-ship

electric engines and batteries, the carbon footprint of manufacturing, the price, range limitations, and strategic dependence on countries that mine and refine critical raw materials or battery-producing countries. Beyond the impact of lithium mining (we will address other metals in subsequent publications), electric cars are a much better alternative than diesel/petrol-powered cars based on the above criteria. What's more, measures are being taken and progress made to overcome the limitations of electric cars: recent technological advances to improve the energy density of batteries; efforts to

onshore some of the battery and metal production, particularly by expanding recycling (which needs to be combined with a sufficiency policy to guarantee strategic independence); and lowering costs.

Recent EU regulations prohibiting the sale of ICE light-duty vehicles by 2035 also send a clear message to all stakeholders. The only alternatives to EVs that will be permitted are hydrogen cars, which are much more expensive to purchase and use. Hydrogen also has a much lower overall efficiency than direct electrification of battery-powered vehicles (33% vs 77%)[32] since the engine is much less efficient and 25% of the electricity used to produce hydrogen is lost through the electrolysis process. Developing hydrogen also raises questions about supply, given the need for a specific network and fuel delivery by truck. Massive hydrogen development could also pose problems regarding platinum consumption. Current studies suggest that the use of hydrogen-powered vehicles will remain niche.

The CLEVER scenario projects 100% electric cars in 2050.

Trucks

Electric propulsion in trucks presents many advantages, particularly for energy efficiency. Electric trucks are well adapted to short-distance transport and require little power, which is why the CLEVER scenario sees them as a good option for distances up to 150 km, perhaps even 300 km. We could even define this category of trucks as urban and regional delivery vehicles with a gross vehicle weight (GVW) below 26 t and a daily range under 400 km. A sufficiency scenario like CLEVER estimates that in 2050, 30% of tkm[33] will be under 150 km (50% <300 km) and can therefore be electrified (see p. 74 (33)).

Battery-based electrification for longer distances raises many questions about range (and therefore battery capacity), charging infrastructure, technical feasibility, and costs.

Electrification through overhead lines — a promising alternative with the advantages of electrification minus the limitations of batteries — will remain limited, given the massive need for infrastructure deployment (in addition to new railway infrastructure also considered in the scenarios). The primary transition scenarios assume they will be used in less than 5% of tkm.

Although hydrogen trucks present the same limitations as those mentioned for cars (efficiency, supply, and materials), they are more suitable for long distances. For this truck segment, it may be worth equipping major road networks with hydrogen fuelling stations. The cost of long-haul hydrogen trucks is similar to other propulsion systems.

Trucks that run on biogas are also a great solution since this method is mature and costs less than zero-emission alternatives. The biogas transport and distribution network already covers much of Europe. In a sufficiency scenario, there are enough sustainable biogas resources to fuel road transport and other sectors that are hard to decarbonise (33). Nevertheless, the EU regulation, which focuses on tailpipe emissions, currently excludes biogas technology from the definition of zero-emission trucks.

The CLEVER scenario includes 45% electric trucks in the 2050 fleet, with the rest split between hydrogen and biogas. This scenario considers that distances under 150 km should be electrified via batteries.

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[32] p.29 https://www.transportenvironment.org/uploads/files/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf

[33] tkm or tonne-kilometre is a unit of measurement for transport quantities that corresponds to the transportation of one tonne over one kilometre. The transport quantity can also be described as transport volume.

LCVs

From an industrial perspective, LCV production lines are often closely aligned with cars. As a result, a 100% electric vision for cars will probably go hand in hand with a 100% electric vision for LCVs. However, some segments are more similar to trucks, and certain LCV uses may require power or ranges that could justify the use of hydrogen or biogas, much like trucks.

Are sustainable liquid fuels a solution for reducing lithium needs?

When talking about transport decarbonisation, the potential role of biofuels or e-fuels is sometimes mentioned as a solution to replace the petroleum-based petrol and diesel fuels used in ICEs (for the same vehicles).

However, biofuel resources are quite limited and should be channelled toward end uses with fewer alternatives (aviation and maritime, even tractors).

The production of e-fuels or liquid synthetic fuels (made from electricity and CO_2) is not yet very mature (TRL of 5/6). The volumes produced will likely remain low by 2050, making it risky to build a truck decarbonisation policy based on the massive production of e-fuels. Furthermore, this technology has low efficiency rates (55% for production and 40–50% for tank-to-wheel). And we have yet to identify sustainable sources of CO_2 for high-volume production.

How can we reduce lithium content while maintaining battery capacity?

Several drivers can be activated to reduce the lithium content in batteries (see the glossary for the acronyms).

First, we can optimise the material content in batteries for existing Li-ion battery cathode technology. The industrial development of NMC (nickel-manganese-cobalt) technology is the most advanced in Europe. The latest chemistry to hit the market, "NMC811" (80% nickel/10% manganese/10% cobalt), contains 19% less lithium per kWh of capacity than the first "NMC333" (33% nickel/33% manganese/33% cobalt) batteries, primarily because of improved specific energy. Using NMC batteries with high nickel content, such as "NMC811" or even "NMC95" (95% nickel/2.5% manganese/2.5% cobalt), could reduce lithium needs. This shift toward increasing nickel content while reducing manganese and cobalt use is already underway, mainly due to increased cobalt prices and the social impacts of cobalt mining in the Democratic Republic of the Congo. Nevertheless, the increased use of nickel in batteries will need to be balanced with a decrease in other end uses, given the impact of mining new nickel deposits, particularly in Indonesia, where NGOs have denounced deforestation and human rights violations.

Another useful technology is LFP, "lithium-iron-phosphate". This cathode technology has lower specific energy than NMC, which makes it slightly less suited to mobile uses. However, it has become popular thanks to its lower cost since it does not contain certain expensive critical materials like cobalt or nickel. It also presents the lowest lithium content per kWh of capacity, according to Argonne National Laboratory (see Figure 23 below). Though LFP technology presents many advantages, it also consumes the most copper and is less profitable to recycle than NMC batteries, given the absence of nickel and cobalt. Nevertheless, the EU regulation contains binding targets on battery recycling and the company ABEE is opening a facility in Belgium to recycle LFP-type batteries. Compromises and strategic choices will need to be made, all while considering future inertial effects associated with industrial development.

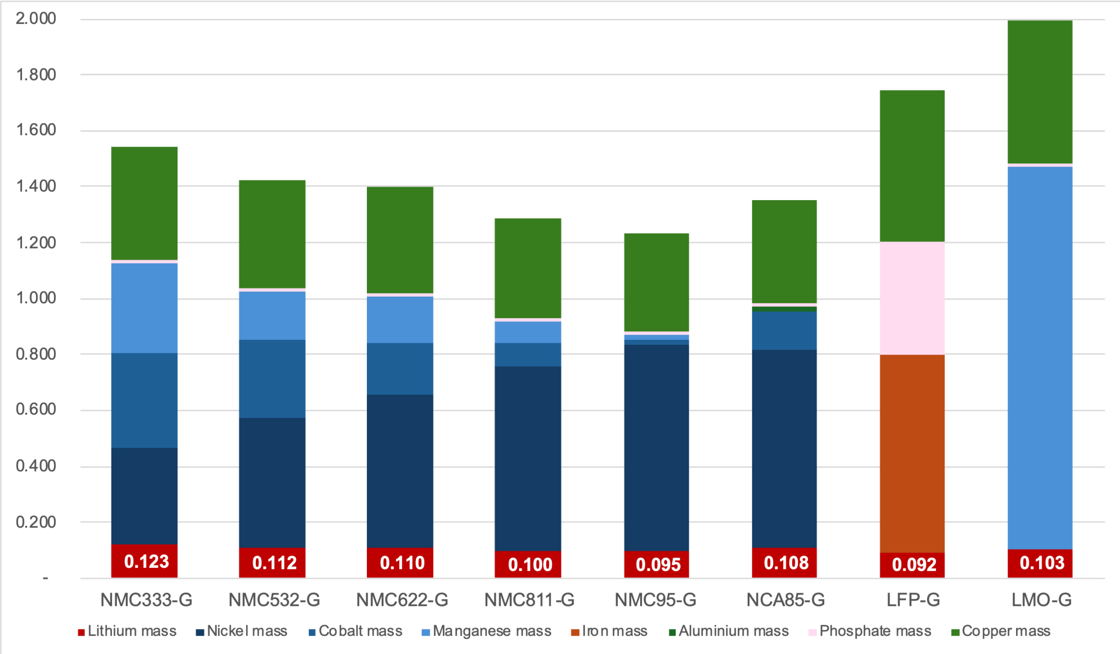

Figure 24: Quantities (kg) of lithium and other metals per kWh of battery capacity for several technologies in 2022 (Source: calculations based on data from BatPaC model v 5.1 (79))

The battery sector is evolving extremely quickly in response to continuous technical progress and economic fluctuations, and has already experienced several major upheavals in the space of several years and even several months. After the emergence of NMC technology, which dominated European gigafactory projects in 2020–2022, LFP technology (initially deemed unfeasible) is now popular because of its lower cost. In 2023, Chinese manufacturer CATL shook up the battery sector when it announced the sale of an EV using a sodium-ion battery.

Making predictions about battery technology is extremely challenging. As with previous projections, very long-term predictions will likely become obsolete in the coming years. Nevertheless, they help us understand market trends, the challenges associated with various technologies, and the impact of a particular pathway on material needs. The evolution of each battery type in the share of future sales is presented in Figure 25 below, guided by several principles:

- Technological maturity: for example, though solid-state batteries are quite promising thanks to much higher energy density and reduced material requirements (except for lithium), they are still in the prototype stage (TRL of 5/6). We therefore consider their development to be limited in our proposed pathway, and only over the very long term.
- Resilience: we prioritised diversity to avoid overdependence on a single battery technology.
- Environmental impacts: we prioritised technologies that consume fewer critical materials, particularly lithium, but also nickel, cobalt, and copper (to a lesser extent).
- Industrial inertia: the European battery industry has already invested in specific cathode technologies, and conversion to another technology would be subject to a certain inertia. This inertia would likely be even more significant regarding conversion to another battery type, such as sodium-ion.

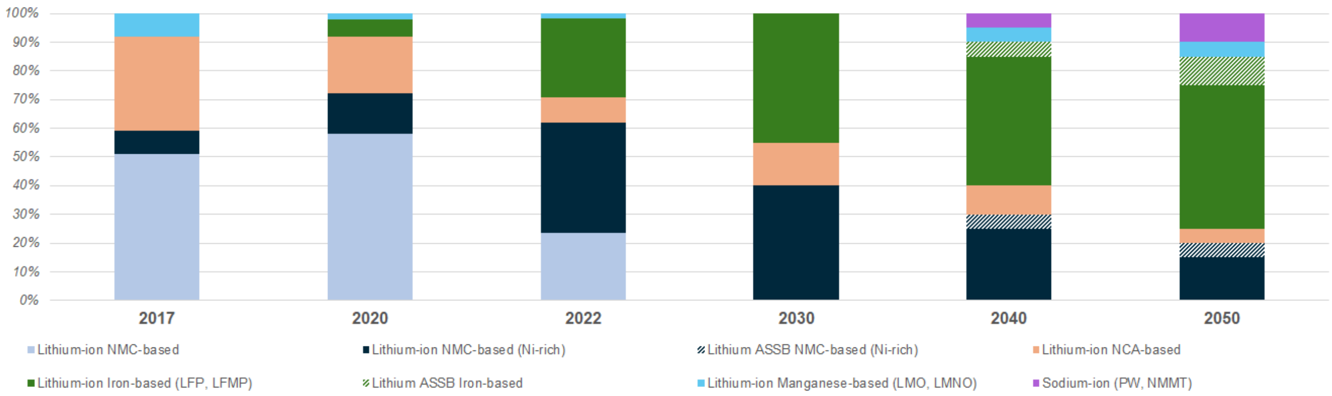

Figure 25: Evolution of technology combinations considered in the BAMASI model up to 2050 for the EU-27

A closer look at sodium-ion batteries

Sodium-ion batteries are of particular interest, as they could be 20 to 30% cheaper (since they contain less expensive and less critical materials) and may have less environmental impact. They function similarly to Li-ion batteries, but lithium is replaced by sodium, which is less expensive, less sought-after, and potentially much easier to extract — reducing both environmental and supply risks.

Additionally, this technology has made impressive leaps in maturity, increasing from TRL 3/4 (early prototype) to TRL 8 (first-of-a-kind commercial) between 2021 and 2023, according to the IEA. However, the energy density (Wh/kg) of sodium-ion batteries is 40% lower than their Li-ion counterparts, which is a significant drawback for mobility. To be on the safe side, our projections assume limited long-term development of this technology in Europe. Nevertheless, it is worth closely monitoring the development of this technology, given that it may strongly disrupt the EV battery market.

Our modelling approach therefore focuses on **resilience:** the goal is to develop several technologies to reduce the risks of depending on a single one and to avoid replacing Li-ion batteries with just one other technology. We can do this by promoting LFP-type chemistries that are less expensive, are just as recyclable, and consume fewer critical metals such as lithium, cobalt, manganese, and nickel.[34] In this approach, diversifying the types of batteries will contribute more to resilience than replacing a particular metal with another equivalent technology**.** As shown in Figure 26 below, changes in the mix of battery types and technological progress in each battery family will lead to a strong reduction in the quantity of lithium needed for the same battery capacity (-32%) between 2020 and 2050.

34 Nevertheless, LFP technology contains a larger quantity of copper (another critical metal) per kilowatt-hour of capacity than NMC technology. A compromise between lithium/nickel/cobalt/manganese, on the one hand, and copper on the other needs to be found. We will examine this question in depth in the next Minimal study on copper. That study will also enrich our analysis of lithium in this report, and could potentially modify our forward-looking assumptions about battery technology choices.

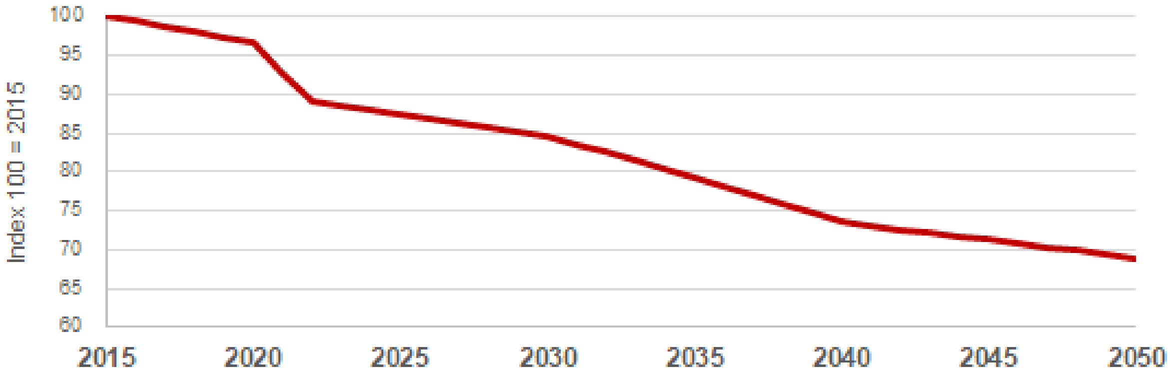

Figure 26: Evolution in average lithium content per kWh of battery capacity up to 2050 used in the BAMASI model (Source: calculation using data from the BatPac model v5.1 (79))

Conclusion

This report takes an innovative approach, charting a path for limiting the overconsumption of lithium in the coming years, all while successfully achieving the energy transition.

To do so, we suggest establishing a **sustainable consumption corridor** that defines a safe and just space for lithium consumption in 2050. This sustainable consumption corridor is defined by an **ecological budget for lithium extraction** (that cannot be surpassed if we are to respect planetary boundaries) of **20,000 tonnes of lithium for the EU** in 2050 and a **social minimum** (below which we cannot fall without compromising essential functions of our economy) of **3,000 tonnes of lithium for the EU** in 2050.

If current trends continue (increased road transport demand, stabilisation of vehicle occupancy rates and freight load factor, and a race to extend the range of EVs — and therefore battery size), **the ecological ceiling defined in the study (representing planetary boundaries) will be severely transgressed.** The reference scenario corresponds to 4.4 times the ecological budget for lithium mining in 2050.

The CLEVER scenario — the ideal scenario for mobility based on the sufficiency/efficiency/renewables framework, born of a collaboration between 26 European partners — presents much lower lithium consumption. Even so, it **does not respect the ecological ceiling of 20,000 tonnes set for 2050, with primary lithium consumption corresponding to twice the ecological budget for mining in 2050**.

The fact that the CLEVER scenario remains above the ecological ceiling for 2050 that we calculated in this report raises several issues.

The first issue is **the major difficulty of accounting for the environmental impacts of metal extraction and processing** (and the impact of resource extraction in general). It has become clear that **sufficiency measures are critical for limiting threats to planetary boundaries**. The CLEVER scenario consumes half as much mined lithium between 2018 and 2050 than the reference scenario. Several drivers are essential for limiting consumption: usage sufficiency to reduce transport demand; dimensional sufficiency to adjust the size and capacity of vehicle batteries; and collaborative sufficiency to increase the vehicle occupancy rate, thereby reducing traffic. **All sufficiency-related drivers taken together play a major role, representing around 80% of the total reduction in consumption in the CLEVER scenario compared to the reference scenario.**

Deploying a sufficiency policy aligns with the latest IRP report, which highlighted the urgency of developing “demand-side measures” to manage resources more sustainably (34). Enacting a sufficiency policy for lithium consumption will also improve the resilience of our supply chains. According to sources like the European Court of Auditors and the JRC, **there are real threats to the EU’s lithium supply, and a gap between lithium supply and demand is expected in the coming years** (36). Though the 2024 CRMA attempts to limit this risk by encouraging European mining projects, given the lead time to develop industrial mining projects and their inherent uncertainty, **it seems unrealistic to focus solely on supply while ignoring public policies to reduce demand. Sufficiency — currently absent from the 2024 CRMA — is an important means of limiting these risks. Some measures could have an immediate effect, such as efforts to reduce vehicle size and weight.**

The second issue is the calibration of our methodology to calculate the environmental ceiling, given that both European scenarios studied (CLEVER and reference) are outside the sustainable consumption corridor. This raises questions about **allocations to the mineral extraction and processing sector compared to other industries**. One alternative could be to allocate a greater share of planetary boundaries to the mining sector relative to its current share. Even so, **Association négaWatt believes that to increase this allocation, we must be able to demonstrate a real reduction in the environmental impacts of other sectors.** Otherwise, increasing the mining sector’s share may undermine respect for planetary boundaries.

More generally, our methodology for establishing an ecological budget for a particular metal is an initial proposal to create a consumption limit based on scientific research. This work is innovative, and researchers have only recently begun exploring this question. Association négaWatt realises that this calculation method will need to be improved and updated to fine-tune this forecasting work: accounting for more efficient technologies, ore grade decline, political decisions regarding allocations to various sectors, shifting national priorities, and so on. **Nevertheless, it seems crucial to publish these initial results to spark an important discussion on how to achieve a material transition that limits increased mining in certain areas and reduces it in others to ensure the planet remains habitable.**

Respecting the ecological budget for mining will be a major challenge for the EU. Even in the case of lithium — a metal with a relatively large allocation in the overall ecological metals budget for 2050 — immediate changes in transport modes will be required to meet these targets. This points to **the magnitude of the challenge we face in ensuring that consumption of the main industrial metals remains within planetary boundaries!**

To that end, Association négaWatt co-wrote an open letter to several European decision-makers signed by more than 100 organisations (NGOs, academia, think tanks, unions, and industries) to demand EU legislation on sustainable resource management. We also drafted a more complete proposal in the form of a white paper, Sustainable Resource Management in the EU, published in 2024. This open letter calls for binding resource consumption targets and highlights the need for sector-specific roadmaps. This report and the ecological budget for lithium aim to inform discussions on these binding targets.

Lastly, this report also addresses various means to improve the environmental efficiency of battery-grade lithium. More efficient production processes and better selection of deposits to mine would help reduce local impacts. Among other measures, **mining should be prohibited in protected areas and the most diverse and fragile biomes.** We should also **prevent the generation of mining waste by prioritising deposits with the highest ore grades and producing as many commercially viable coproducts as possible.** To curtail the hazardous impacts of mining waste, public authorities should **require an accurate evaluation of the presence of any naturally occurring toxic and radioactive substances in the deposits during the exploration phase.**

At the EU level, to ensure environmental efficiency in waste management, we must also **improve the characterisation of mining waste under the Extractive Waste Directive** (2006/21/EC) by better assessing health risks, particularly regarding the mobility of toxic substances. Another idea is to create a **"European compensation fund for mining waste management"** financed by mining companies that want to operate on European soil. As for water resources, it seems there is no way to eliminate the impact of brine extraction, and new techniques such as DLE do not appear to prevent water table drawdown. In contrast, though hard rock extraction currently consumes a lot of water, this consumption can be reduced by pressing tailings and recycling water during processing. Nevertheless, a significant amount of water does remain trapped in mining tailings. **For the EU to prevent potential water usage conflicts, we recommend removing the articles in the CRMA that introduced exceptions to the WFD and ensuring that potential lithium mines comply with River Basin Management Plans and the WFD** to anticipate and prioritise water needs.

Lastly, **promoting recycling is an important means of reducing the ecological footprint** of lithium consumption. **To do so, Association négaWatt suggests setting a collection target for car batteries, setting targets for lithium focused on recycling rather than recovery** (excluding downcycling-type uses), and **adding specific pre-consumer and post-consumer targets**. We must also **strengthen targets for the use of recycled materials** to encourage recycling of battery-quality lithium.

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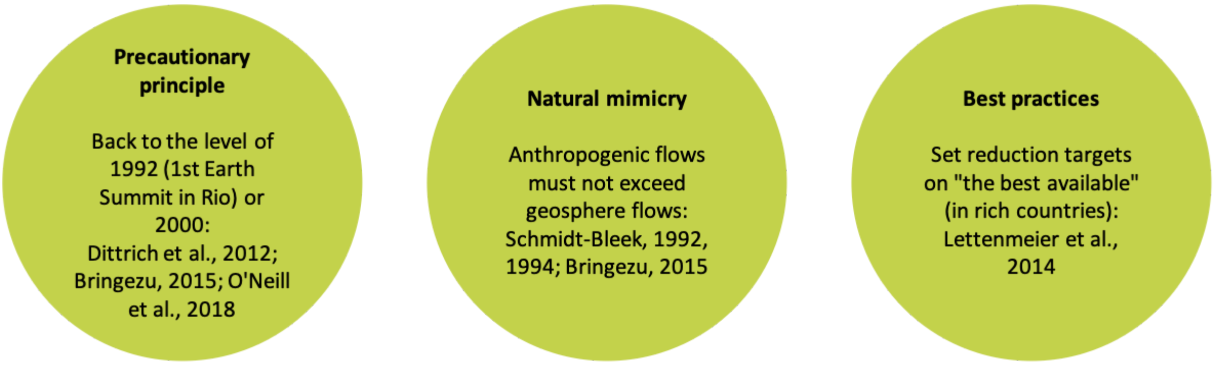
Appendix 1: Methodology for determining the ecological budget of metals — assumptions and possible improvements

Existing research on limiting resource consumption for ecological reasons

There is a consensus in environmental research on the need to reduce the overall level of resource consumption. However, few published studies have focused on setting ecological limits for global metal production to remain within planetary boundaries. A 2015 meta-analysis (80) that was cited more than 180 times discussed setting resource consumption limits for both biotic resources (fishery, forest, and agricultural) and abiotic resources (fossil fuels, metals, industrial minerals, construction minerals). In the study, the author sets a resource consumption reduction target of 50 Gt/yr for the global use of biotic and abiotic resources (raw material consumption — RMC). Though this global target seems necessary, the article and others (81,82) use a very aggregate scale and ignore planetary boundaries. Instead, they base their calculations on the precautionary principle, natural mimicry (the idea that anthropogenic processes should not overrun natural processes), or a pragmatic approach based on best practices (see below).



We therefore wanted to conduct complementary research to define an ecological budget per metal that is more specific to each industry and based on environmental criteria from the literature. To our knowledge, only two articles consider setting metal production limits based on indicators relating to planetary boundaries (29, 83). Furthermore, the lack of data measuring the impact of mining and metallurgy on planetary boundaries made it even harder to define this ecological budget. It is thanks to the work of Desing et al. (29) that we were able to develop the budget concept in this report.

Assumptions

- By 2050, the future metal supply will not be limited by physical availability (lack of resources). In other words, the ecological ceiling will be reached well before the physical resource runs out.
- The article by Desing et al. reveals that in 2016, the boundary that most limited metal production was climate change (particularly CO_2 emissions). We assume here that this planetary boundary will remain the most limiting in 2050. We have therefore simplified the model to calculate the budget solely based on this limit. If this assumption is correct, the quantified budget will also respect other planetary boundaries.

- The share of the planetary boundary allocated to the mining and metals sector overall (the segment) will not change between now and 2050 (grandfathering). This assumption is rather favourable to this sector if we consider that in "ideal" global consumption scenarios that respect planetary boundaries and decent living standards for all, the share allocated to metals is much lower than the current share (as shown in an article published by Schlesier et al. in 2024 (30)).
- The calculation of the share of production applied to the total ecological budget of the metals sector to obtain a specific budget for each metal is based on the cumulative needs identified in the négaMat scenario between 2022 and 2050. We slightly modified this figure to account for the difference in geographic scale — this report focuses on Europe, while the négaMat scenario focuses on France.
- Desing et al. set a probability of violating planetary boundaries (P_v) of 1% for the metals sector. In our model, we chose to set this P_v at 50%. In comparison, IPCC reports calculate the likelihood of staying below 1.5°C or 2°C using 17%, 33%, 50%, 67%, and 83%.[35] With the same assumptions we described above, but using a P_v of 1% like Desing et al., we obtain an ecological budget for metals that is 1.87 times smaller than our initial calculation with a P_v of 50%.

What is not taken into account

- Recycling is not part of the scope of this report. This means we did not set an ecological ceiling for recycling, which is simply limited by the available stock (as well as collection rate and recycling efficiency).
- Cumulative production to reach the 2050 milestone. In reality, the shape of the curve to 2050 should be considered. In other words, we should determine how cumulative production between 2022 and 2050 allows us to respect planetary boundaries, rather than production solely in 2050.

What could be improved

- The allocation of Europe's ecological budget per metal could include stocks already present on the continent, which would be more equitable. In the case of lithium resources, which are not yet very substantial, the difference would probably be minimal.
- The share of production applied to the total ecological budget of the metals sector may potentially be revised and corrected to better account for the specific needs of each sector and the different geographic areas.
- The unit impacts considered for each metal: ore grade decline, energy efficiency improvements in the primary production chain, and the decarbonisation of electric systems (which reduces indirect emissions) were accounted for in rather approximate terms (assuming that CO_2 follows the same pattern as all GHGs) and only for seven metals, based on the work of Van der Voet et al. (31).
- Make the model dynamic to create yearly pathways and be able to evaluate whether planetary boundaries are respected for cumulative production and not just for a milestone to 2050. To do so, we must create scenarios for future environmental impacts, like what is being done for the climate with science-based targets (84).
- The model could be changed to allocate a planetary boundary segment to each metal rather than an overall allocation for the metals sector. This method would make it easier to generate different results for each metal and would undoubtedly encourage better consideration of the

[35] See Table SPM.2 de https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

various planetary boundaries. However, this would increase the risk of double counting and make it harder to develop a consistent method that applies to the global economy.

- An easier option would be to add the other planetary boundaries using this calculation method based on Desing et al.'s model. However, the results would surely be identical.
- The same calculation could also apply to metal recycling. This study focuses on determining the ecological budget for mining, but we could do the same thing for recycling.
- And the same calculation could be used for non-metallic raw materials.

Appendix 2: Details on the calculation used to determine mining waste production in the different stages of spodumene processing

The calculation does not account for potential coproduct recovery.

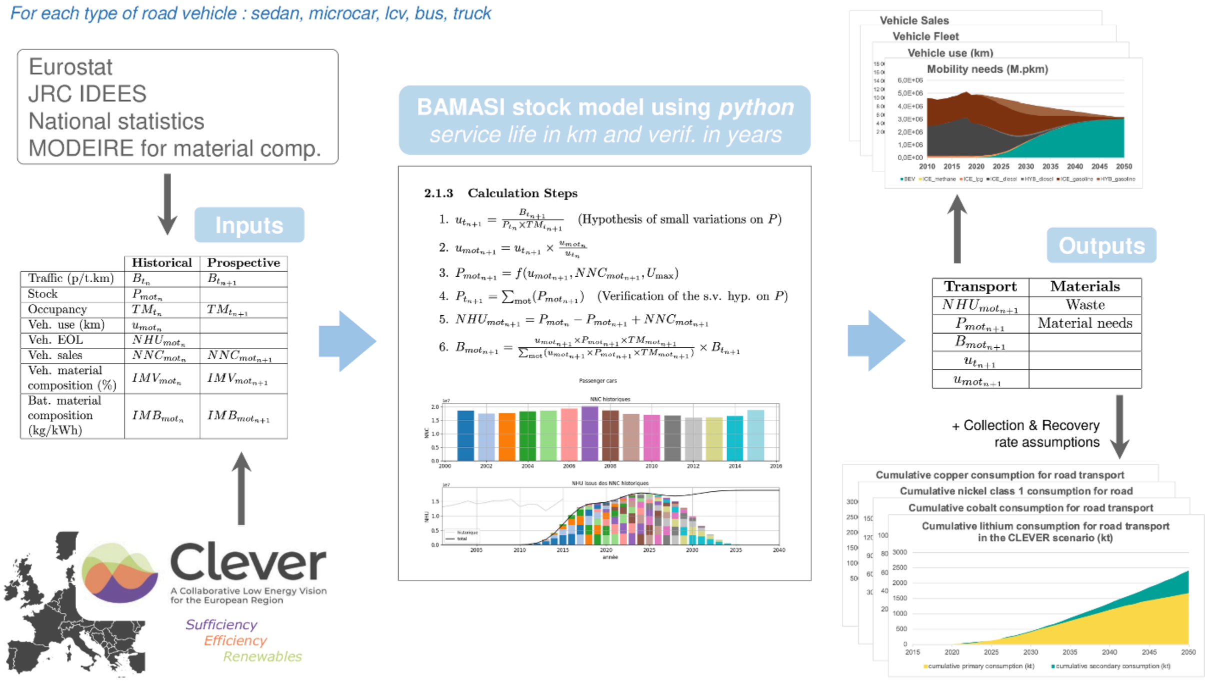
	Unit	Source	
Concentrate grade	%	Vignes, J.-L. Lithium (Elementarium). Société chimique de France.	6%
Ore grade	%		1.43%
Lithium production	tonnes	Schmidt, M. (2023). Rohstoffrisikobewertung – Lithium. DERA.	41,800
Concentration factor from ore to concentrate	-	Calculation	4
Production of concentrate in Australia	tonnes	Schmidt, M. (2023). Rohstoffrisikobewertung – Lithium. DERA.	1,600,000
Corresponding ore production in Australia (excluding waste)	tonnes	Calculation	6,713,287
Rock needed to produce 1 tonne of ore (high estimate)	tonnes	Schmidt, M. (2023). Rohstoffrisikobewertung – Lithium. DERA.	10
Rock needed to produce 1 tonne of ore (low estimate)	tonnes		3
Rock needed to produce 1 tonne of ore (average)	tonnes		6.5
Total rock extraction (high estimate)	tonnes	Calculation	67,132,867
Total rock extraction (low estimate)	tonnes	Calculation	20,139,860
Total rock extraction (average)	tonnes	Calculation	43,636,364
Rock-to-metal ratio (high estimate)	tonnes waste/tonne Li	Calculation	1,606
Rock-to-metal ratio (low estimate)	tonnes waste/tonne Li	Calculation	482
Rock-to-metal ratio (average)	tonnes waste/tonne Li	Calculation	1,044
Table in Figure 15: waste (including potential coproducts) produced during the different stages (average estimate)			
Overburden to access the ore	tonnes per tonne of lithium	Calculation = (average total rock extracted — ore production in Australia)/lithium production	883
Concentration tailings (primarily in Australia)	tonnes per tonne of lithium	Calculation = (ore production in Australia — concentrate production)/lithium production	122
Chemical processing tailings (primarily in China)	tonnes per tonne of lithium	Calculation = (concentrate production — lithium production)/lithium production	37
Total waste corresponding to Figure 15	tonnes per tonne of lithium	Calculation	1,043

Appendix 3: The BAMASI model

Association négaWatt developed a model to quantify the mineral raw materials needed in an energy transition scenario for 2050 in the road transport sector.

The BAMASI model is a vehicle fleet model in which lifespan is defined in kilometres (such as 195,000 km for a passenger car) rather than years. The goal is to better reflect sufficiency assumptions in the mobility and road freight sectors that lead to a reduction in the annual distance travelled by vehicles.

The model is presented below:



In this model, the historical lifespan in kilometres is determined to ensure strict alignment with historical data on vehicle fleets, new vehicle registrations, and end-of-life vehicles (ELVs) provided by various databases, such as Eurostat, the European Commission’s “New Mobility Patterns” (NMP) survey, and JRC IDEES.

Input data:

	Historical value	Projected value
Traffic (pkm or tkm)[36] **[B]**	Traffic here is defined by mobility or freight requirements for year X	Traffic here is defined by mobility or freight requirements for year X+1
Fleet **[P]**	Vehicle fleet by propulsion type	
Occupancy rate or load factor **[TM]**	Occupancy rate is defined by passengers per vehicle and freight load factor is defined by tonnes per vehicle in year X	Occupancy rate is defined by passengers per vehicle and freight load factor is defined by tonnes per vehicle in year X +1
Use (km) **[u]**	Vehicle use by propulsion type in year X corresponding to the distance travelled per vehicle per year	
End-of-life vehicles **[NHU]**	ELVs by propulsion type in year X	
New car registrations **[NNC]**	Sale of new vehicles by propulsion type in year X	Sale of new vehicles by propulsion type in year X+1
Material composition of vehicles, excluding batteries (%)	Material composition of vehicles by propulsion type, excluding batteries, in year X	Material composition of vehicles by propulsion type, excluding batteries, in year X+1
Material composition of lithium batteries (kg/kWh)	Material composition of batteries in year X	Material composition of batteries in year X+1

Output data:

Transport data	Material data
End-of-life vehicles by propulsion type in year X+1	Annual stock of ELVs and batteries
Vehicle fleet by propulsion type in year X+1	Annual raw material needs
Traffic by propulsion type in year X+1	
Total vehicle use and by propulsion type in year X+1	

[36] Pkm (passenger-kilometres) and tkm (tonne-kilometres).