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Study of the potential for reduced greenhouse gas emissions and the transition to a low-emission society through circular economy strategies

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ABSTRACT

Abstract heading
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Executive summary

Circular economics is about making the most out of our resources, ensuring sustainability and value creation in both short and long term. Attempts are made to close the material loops to prevent resources being lost and at the same time prolong their lifetime, so that the value and quality of the resources remain as high as possible for as long as possible. The products and materials that our society relies on lead to greenhouse gas emissions in different parts of their value chain, either at manufacturing or use stage or at the end of the life cycle. At the same time, the green shift and conversion to the low-emission community lead to the use of more scarce resources, which affects the resource situation.

This study focuses on circular economic opportunities that are expected to have a large potential for reducing the climate gas emissions associated with Norwegian consumption and production. Over a dozen circular strategies were selected and analysed as case studies with both the consumer perspective and the industry perspectives and their potential impact on reduction of green house gas emissions investigated. The study found that implementing the studied strategies could have a significant effect on reducing Norwegian greenhouse gas emissions, both within Norway and outside of Norway as Norwegian consumption is heavily dependent on global production and supply chains.

Total GHG emissions in Norway in 2018 were approximately 54Mt CO_2e. We estimate that between approximately 6 – 10 Mt CO_2e of emissions in Norway and abroad can be saved through the selected circular strategies analysed in this report alone with further savings possible should Norway adopt a fully encompassing national circular economic model.

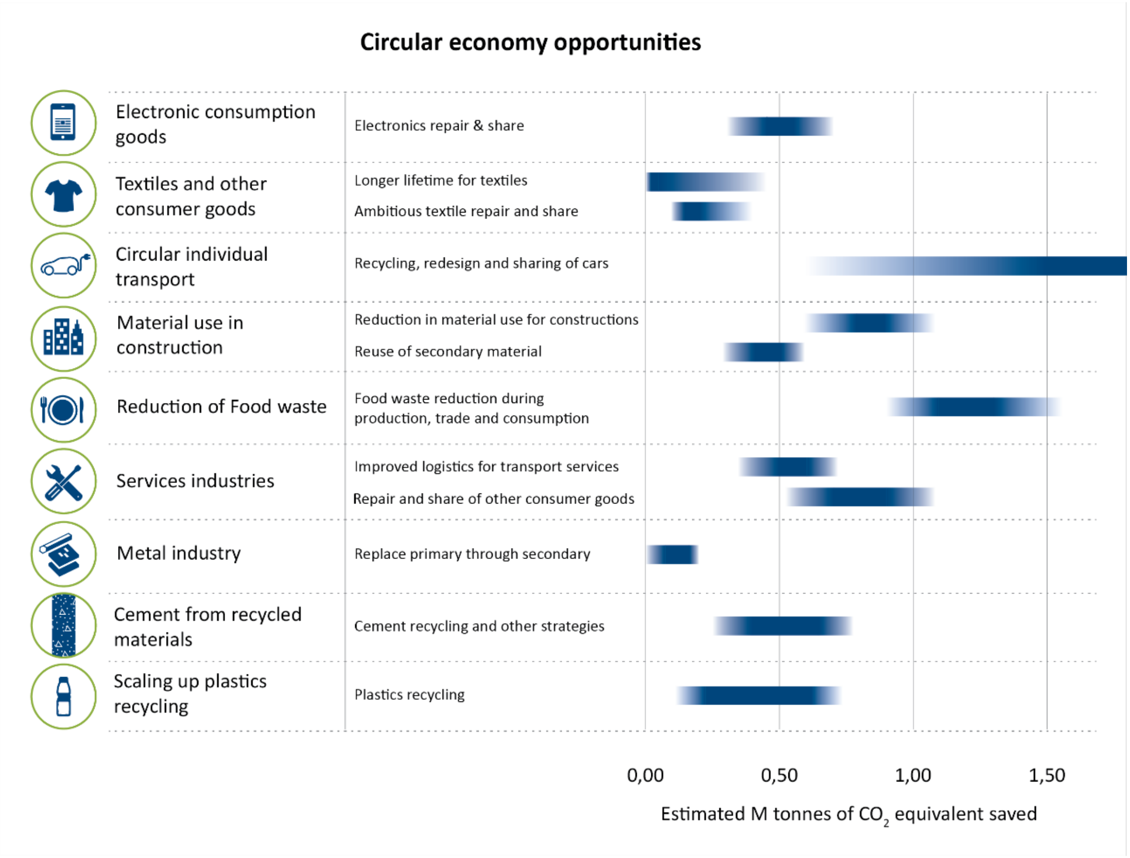


Figure 1. Estimated GHG emission reduction potentials through selected circular strategies based on case studies dependant on given assumptions.

The report also summaries the barriers that are preventing these circular strategies today and how they might be resolved such as the use of digital tools that can provide an information platform are a prevalent need as are regulatory incentives for increased use of secondary materials, and to make share and repair of consumer goods more economically attractive. Recurring enablers for many of the circular strategies are:

- Strengthened requirements for sorting of waste and increased collaboration across the value chain to improve on product recyclability
- Improved production planning and decision support across the supply chains
- Long-term public and private RD&D investments in new circular economy enabling innovations
- Reform of tax system, prolonging economic lifetime of capital goods and penalising the use of materials and non-renewable energy instead of labour
- Focusing on consumer education and changing public attitudes towards waste minimisation
- Stimulation of the markets for secondary materials and products
- Digitalization for improved logistics, embedded information about materials, and platforms for sharing, and better utilization of side-streams and by-products

The Circular Economy will also be a critical enabler of the transition to a low emission society, which will demand a large volume of materials, including critical elements. Establishing large infrastructure projects will increase the need for basic materials for construction and energy projects, such as concrete, steel, and aluminium. In addition, the production of low-carbon technologies depends on critical materials such as platinum-group and rare-earth metals, for which future prices and availability are uncertain.

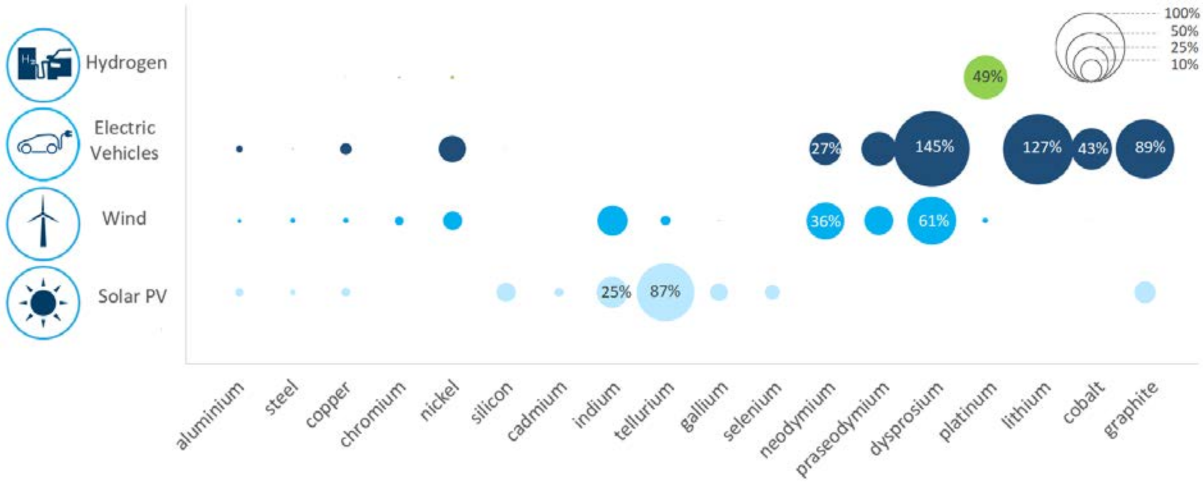


Figure 2. Average annualised cumulative global demand of strategic and critical materials needed by 2040 for the growth of low-carbon technologies, compared to current primary material production rates. The annualised cumulative global demand corresponds to total global cumulative demand of materials between 2019 and 2040, distributed equally in each year throughout the period.

The large amount of critical materials are needed for the growth of low-carbon technology in the next decades – representing a significant share of current primary production capacity – highlights the need for circular economy measures for critical materials. These include increasing recycling rates and the use of secondary materials, improving material efficiency, and extending the lifetime of in-use stocks. Despite increasing research and development in the recovery and recycling of critical materials from electronic waste, solar cells, permanent magnets, fuel cells, and Li-ion batteries, the technology is yet mostly immature and has limited commercial availability.

This study concludes that to achieve emission reduction via circular economic principles consumption must be reduced and channelled towards more sustainable, higher quality and longer lasting products. Producers and wholesale/retail trade services must offer and promote the more sustainable options. This includes not only goods that are designed for repair and reuse and to reduce material use and emissions, but also new business models offering leasing, repair and share services. Material reuse and recycling strategies must become the norm rather than the exception, this is especially important in the context of new low-carbon technologies.

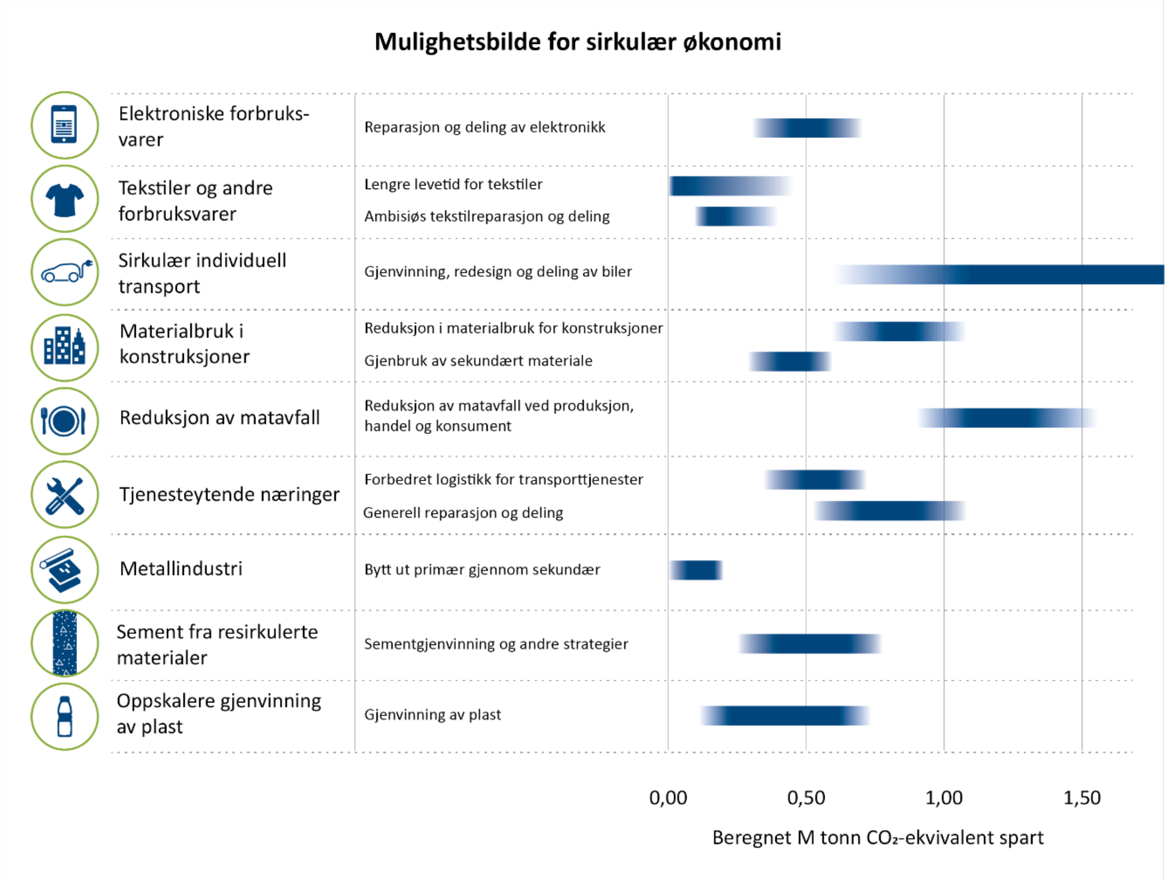
The transition to a circular economy entails a system change, with wide ranging environmental, societal and economic impact along global supply chains. This study highlights the impact the circular economy opportunities can have on greenhouse gas emissions and further analysis should be carried out to find the impact of the case studied on economic value creation, job creation, waste generation, ecological impact and more. Achieving the adoption of a circular economic model requires participative and collaborative inter-disciplinary actions across various levels which need to be fostered and supported across branches and sectors.

Norsk sammendrag

Sirkulær økonomi handler om å utnytte ressursene våre best mulig, sikre bærekraft og verdiskaping på både kort og lang sikt. Det forsøkes å lukke de materielle sløyfene for å forhindre at ressurser går tapt og samtidig forlenge levetid, slik at verdien og kvaliteten på ressursene forblir så høye som mulig så lenge som mulig. Produktene og materialene som samfunnet vårt er avhengig av fører til utslipp av klimagasser i forskjellige deler av verdikjeden, enten på produksjons- eller bruksstadium eller på slutten av livssyklusen. Samtidig fører det grønne skiftet og overgangen til lavutslippssamfunnet til økt bruk av knappe ressurser, noe som påvirker den totale ressurssituasjonen.

Denne studien har identifisert sirkulærøkonomiske muligheter som anses å ha et stort potensial for å redusere klimagassutslippene knyttet til norsk forbruk og produksjon. Case-studiene som er undersøkt fokuserer på sirkulære strategier for å redusere ressursbruk og utslipp i verdikjeder, og fra forbrukerperspektiv og fra industriperspektiv. Implementering av disse strategiene kan ha en betydelig effekt på reduksjon av norske klimagassutslipp, både i Norge og utenfor Norge, ettersom norsk forbruk er sterkt avhengig av globale verdikjeder, noe som fører til betydelig utslippsreduksjoner også i utlandet.

De totale utslippene av drivhusgasser i Norge i 2018 var omtrent 54Mt CO_2e. Vi anslår at mellom 6 - 10 Mt CO_2e av totale utslipp kan spares gjennom de utvalgte sirkulære strategiene analysert i denne rapporten alene, og med mulighet for ytterligere besparelser dersom Norge vedtar en fullstendig altomfattende nasjonal sirkulærøkonomisk modell.

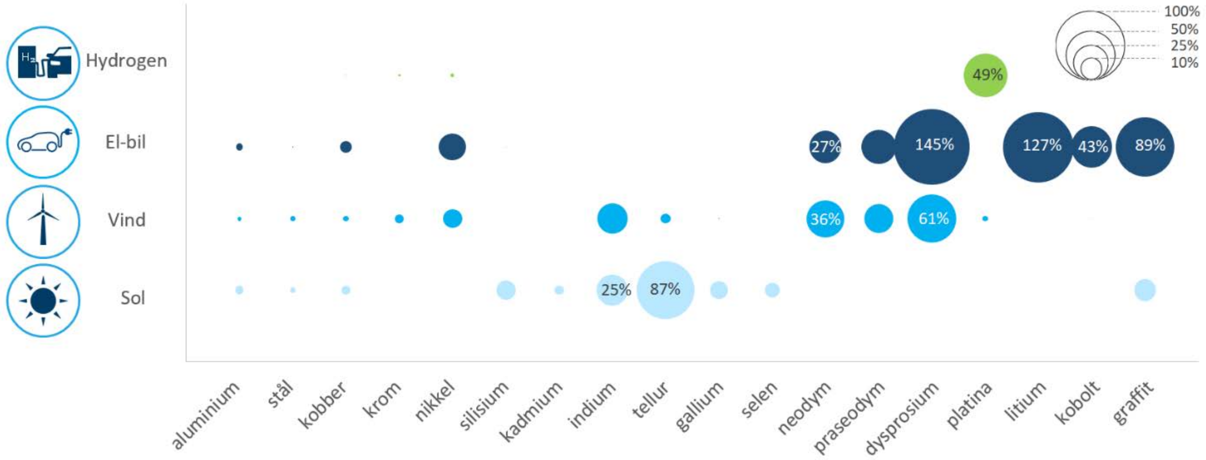


Figur 1. Estimert potensial for reduksjon av klimagasser gjennom utvalgte sirkulære strategier basert på casestudier med deres gitte forutsetninger.

Rapporten oppsummerer også barrierer som forhindrer gjennomføring av disse sirkulære strategiene i dag, og hvordan de kan løses. For eksempel er digitale verktøy som kan gi en informasjonsplattform et utbredt behov, så vel som regulatoriske insentiver for økt bruk av sekundært materiale, og for å gjøre deling og reparasjon av forbruksvarer mer økonomisk attraktivt. Muliggjørende tiltak som gjentar seg for mange av de sirkulære strategiene er:

- Styrket og strengere krav til sortering av avfall og økt samarbeid på tvers av verdikjedene for å forbedre gjenvinnbarheten av produkt
- Forbedret produksjonsplanlegging og beslutningsstøtte på tvers av verdikjedene
- Langsiktige offentlige og private FoU-investeringer i ny sirkulær økonomi som muliggjør innovasjoner
- Reform av skattesystemet, forlengelse av forbruksvarers økonomiske levetid og økonomisk straff (skatter/avgifter) for bruk av nye materialer og ikke-fornybar energi i stedet for bruk av arbeidskraft
- Fokus på opplysning og opplæring av forbrukere og endring av forbrukeres holdninger til avfallsminimering
- Stimulering av markedene for sekundære materialer og produkter
- Digitalisering for forbedret logistikk, innebygd informasjon tilstand/kvalitet materialer og sporing, og plattformer for deling av informasjon og data som kan brukes for å få bedre utnyttelse av sidestrømmer og biprodukter

Sirkulær økonomi vil også være en kritisk og sentral muliggjøre for overgangen til et lavutslippssamfunn med teknologier som vil kreve et stort volum av materialer inkludert kritiske ressurser. Etablering av store infrastrukturprosjekter vil øke behovet for basismaterialer til bygg- og energiprosjekter, som betong, stål og aluminium. Videre avhenger produksjonen av null- og lavutslipps-teknologier av kritiske materialer slik som platinagruppen og sjeldne jordartsmetaller osv. hvor fremtidige priser og tilgjengelighet er usikre.



Figur 2. Gjennomsnittlig årlig kumulativ global etterspørsel av strategiske og kritiske materialer som trengs innen 2040 for veksten i lavutslippsteknologier, sammenlignet med nåværende produksjonsrater for primærmaterialer. Den årlige kumulative globale etterspørselen tilsvarer den totale globale kumulative etterspørselen etter materialer mellom 2019 og 2040, fordelt likt utover for hvert år i hele perioden.

Den store mengden kritiske materialer som er nødvendig for veksten i lavutslippsteknologier i de neste tiårene - som representerer en betydelig andel av dagens produksjonskapasitet av primære materialer - fremhever behovet for sirkulærøkonomiske tiltak for de kritiske materialene. Disse inkluderer økende resirkuleringsgrad og bruk av sekundære materialer, forbedring av materialeffektivitet og forlengelse av levetiden til materialer som er i bruk. Til tross for en økende forskning og utvikling innen utvinning og gjenvinning av kritiske materialer fra elektronisk avfall, solceller, permanente magneter, brenselceller og Li-ion-batterier, er teknologien stort sett ennå umoden og har begrenset kommersiell tilgjengelighet.

Denne studien konkluderer med at for å oppnå utslippsreduksjoner ved hjelp av sirkulærøkonomiske prinsipper må forbruk reduseres og endres til utvikling av mer bærekraftige produkter, med høy kvalitet og lang levetid. Produsenter og forhandlere må tilby og promoter mer bærekraftige alternativer. Dette innebærer produksjon og salg av varer som er designet for reparasjon og gjenbruk, redusert materialbruk og utslipp, og også nye forretningsmodeller som tilbyr reparasjon, utleie og deling. Gjenbruk av materialer og strategier for resirkulering må bli normen og ikke unntaket, og dette er spesielt viktig når det gjelder de nye lavutslippsteknologiene i det grønne skiftet.

Overgangen til en sirkulær økonomi er et fullstendig systemskifte, og vil ha omfattende miljømessige, samfunnsmessige og økonomiske konsekvenser langs globale verdikjeder. Dette studiet belyser effektene sirkulærøkonomiske strategier og muligheter kan ha på utslipp av klimagasser. Videre analyser bør utføres for å avdekke virkningene på f.eks verdiskaping, sysselsetting, avfallsproduksjon, og økologiske effekter på hav og land av de analyserte case-studiene og teknologiene. For å oppnå at sirkulærøkonomiske modeller tas i bruk krever det deltakelse og interdisiplinært samarbeid på ulike nivå, og dette må fremmes og støttes på tvers av bransjer og sektorer og i et privat-offentlig samarbeid. Det vil være essensielt for å muliggjøre omstillingen fra en lineær til en sirkulær norsk økonomi.

Study of the potential for reduced greenhouse gas emissions and the transition to a low-emission society through circular economy strategies

Susie Jahren, Vibeke S. Nørstebø, Moana S. Simas and Kirsten S. Wiebe SINTEF

Contents

This Study was commissioned and financed by ENOVA

The following SINTEF researchers also contributed expertise to the report
Eivind Kristoffersen, Ida Kero, Birgit Ryningen, Frode Rømo, Kyrre Sundseth, Harald Justnes, Marit Aursand, Sidsel Meli Hanetho

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Study of the potential for reduced greenhouse gas emissions and conversion to the low-emission community through more efficient use of resources

1 Introduction

Circular economics is about making the most of our resources, ensuring sustainability and value creation in both short and long term. Attempts are made to close the material loops to prevent possible resources being lost and at the same time prolong their lifetime, so that the value and quality of the resources remain as high as possible for as long as possible. This can happen in a variety of different ways, well summarized in the 10 Rs [1]: R0 refuse, R1 rethink, R2 reduce, R3 reuse, R4 repair, R5 refurbish, R6 remanufacture, R7 repurpose, R8 recycle and R9 recover as energy.

The products and materials that our society relies on lead to greenhouse gas emissions in different parts of the value chain, either at manufacturing or use stage or at the end of the life cycle. At the same time, the green shift and conversion to the low-emission community lead to the use of more scarce resources (such as rare earth metals), which affects the resource situation (and can have geopolitical effects).

There is a need to identify potentials for reduced greenhouse gas emissions and conversion of the low-emission society through more efficient use of resources [2,3]. Here it is important to understand the potential of utilizing in a better way the materials and resources that have already been extracted or produced. The EU's New Circular Economy Action Plan as part of the European Green Deal states [2,p.20]:

In order to achieve climate neutrality, the synergies between circularity and reduction of greenhouse gas emissions need to be stepped up. The Commission will:

- *analyse how the impact of circularity on climate change mitigation and adaptation can be measured in a systematic way;*
- *improve modelling tools to capture the benefits of the circular economy on greenhouse gas emission reduction at EU and national levels;*

Furthermore, the transition to a low-carbon economy requires a large-scale investment on both mature and new technologies, which will pose substantial pressures on material demand [4]. Besides commonly used infrastructure materials – such as cement, steel, aluminium, and copper - low-carbon technologies rely on materials which are currently produced in lower volumes and have potentially high supply risks. These critical materials can become bottlenecks for a green shift to a low-carbon society, especially in regions with a high import reliance, as it is the case for Europe. Circular economy measures can help alleviate the pressure on these critical materials.

This investigation is in two parts:

- In part 1: How can circular economy strategies and solutions contribute to reduced greenhouse gas emissions, and where is the potential greatest?
- In part 2: In what way can circular economy solutions play a long-term role in the transition to the low-emission society in terms of minimizing the pressure on strategic resources?

In the first part of this report we will give an overview on industries and value chains, that due to volume or emission intensity have the potential for large emission reductions (Section 2). This will be followed by an in-depth analysis of individual value chains and materials, answering the following questions:

- What technological or physical characteristics represent the most important obstacles or opportunities for more optimal use or recycling within the relevant value chains?
- How large are the potential for emission reductions associated with more optimal material / resource use?
- What characterises the markets that are in line with the relevant value chains and material flows?
- What public regulations and other framework conditions are central to the relevant value chains, and how are these aligned to circular economic principles?
- What social innovations (public, market) could most effectively contribute to more efficient use of materials and emissions reductions in the selected value chains?
- In what areas will technology and market development be decisive for success in the circular transition?

Here, we differentiate between the use side of materials in goods and services (Section 3), and the production side of materials (Section 4), more specifically, the process industry transforming virgin or secondary raw materials into new materials as well as biomass production.

In the second part of the report we look at the demand for materials for transitioning to a low-carbon energy system in the next two decades, focusing on the demand for critical materials (Section 5), and what are the opportunities and barriers for the circular economy to alleviate the pressure on these resources (Section 6). This part of the report aims at answering the following questions:

- What are the key materials demanded for low-carbon technologies, and what are the risks for these technologies in terms of future access to resources?
- How can circular economy solutions help minimize the pressure on strategic resources, and what will be the most important barriers to circular material use for these technologies?
- In a global context, what tools can contribute to the development of circularity in the use of strategically important resources?

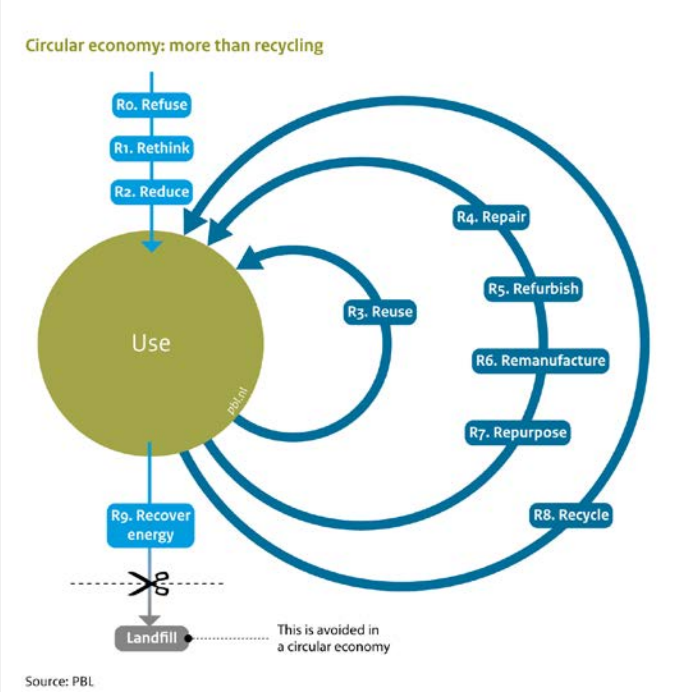
Finally, in section 7 we present the main conclusions, as well as limitations and future research needs.

The mandate of this study is to provide a knowledge base on how circular economy strategies can contribute to reduced greenhouse gas emissions and more efficient use of resources in the transition to the low-emission community. The report does not include in depth analysis of the other environmental impacts of circular strategies, such as resource depletion, waste reduction or ecological impact although the same strategies would be broadly expected to have positive impacts. Similarly, the report does not cover social and economic impact of the studied circular strategies.

The commissioned study scope does also not cover the complex interactions of the circular - bioeconomy and regenerative biological systems as part of our analysis.

The transition to a circular economic have wide ranging environmental, societal and economic impact with complex interacting global value chains and industries. Further studies on the impact of a circular economic model in Norway could provide supporting insight and guidance for public and private bodies to enable the restructuring from a linear to Circular Norwegian Economy.

Box 1: Circular strategies – The 10 R's.
Source: PBL Netherlands Environmental Assessment Agency: Potting et al. [205]



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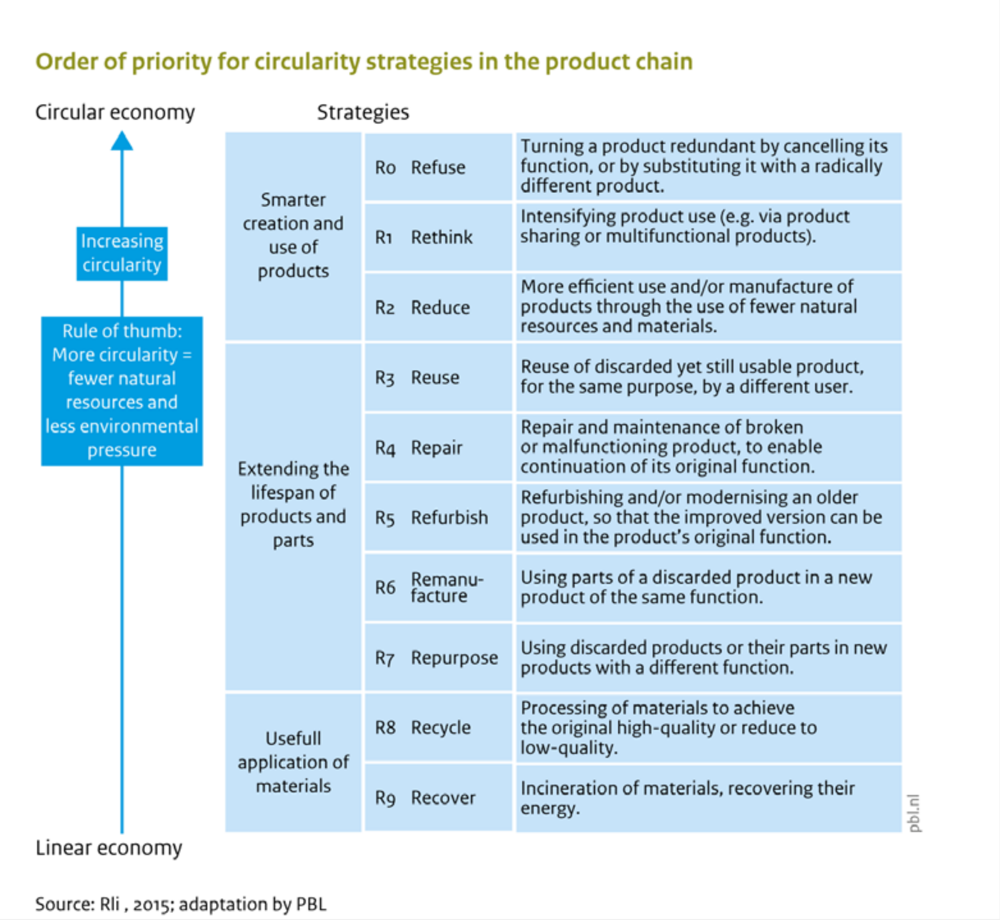

Order of priority for circularity strategies in the product chain

Circular economy

Increasing circularity

Rule of thumb: More circularity = fewer natural resources and less environmental pressure

Linear economy

Strategies			
Smarter creation and use of products	R0	Refuse	Turning a product redundant by cancelling its function, or by substituting it with a radically different product.
	R1	Rethink	Intensifying product use (e.g. via product sharing or multifunctional products).
	R2	Reduce	More efficient use and/or manufacture of products through the use of fewer natural resources and materials.
Extending the lifespan of products and parts	R3	Reuse	Reuse of discarded yet still usable product, for the same purpose, by a different user.
	R4	Repair	Repair and maintenance of broken or malfunctioning product, to enable continuation of its original function.
	R5	Refurbish	Refurbishing and/or modernising an older product, so that the improved version can be used in the product's original function.
	R6	Remanufacture	Using parts of a discarded product in a new product of the same function.
	R7	Repurpose	Using discarded products or their parts in new products with a different function.
Usefull application of materials	R8	Recycle	Processing of materials to achieve the original high-quality or reduce to low-quality.
	R9	Recover	Incineration of materials, recovering their energy.

pbl.nl

Source: Rli , 2015; adaptation by PBL

Part 1: How can circular economy strategies and solutions contribute to reduced greenhouse gas emissions, and where is the potential greatest?

2 Emissions in current material flows and value chains

The transition from an economy based on the linear extract – produce – use – discard model, heavily relying on the extraction and processing of virgin materials will be challenging, but at the same time offer new possibilities for Norway. This is linked to some of the underlying characteristics of the Norwegian economy:

i) For a long time, we have had large trade surpluses, and several of our key industries are based on natural resources. Holding resources in the economy for as long as possible requires innovation in value creation in these hitherto commodity-focused industries, so that we get more out of nature's benefits. On the one hand, this dependence on natural resources can be challenging. On the other hand, Norway has managed to build highly competent industry around some of its natural resources, such as the process industry, oil and gas and aquaculture industries, which can strengthen the basis for sustainable innovation in several areas.
ii) The total value creation in Norway depends on the value creation in the districts. Norway has managed to curb strong centralization forces and maintain a dispersed settlement and value creation pattern. We have the world's second longest coast, with great distance from north to south. The fact that resources are widely distributed constitutes an important premise for value creation based on sustainable utilization of resources. Circular principles can provide new opportunities for local interaction and entrepreneurship in the districts, while the large distances can provide high transport costs and restrict access to larger markets.
iii) Another characteristic of the circular economy is that energy consumption must be covered as much as possible by renewable energy. We in Norway have a unique access to renewable hydropower. This has led to the development of a large energy-intensive industry, and Norway certainly has a large competitive advantage in this field globally. These are aspects that are important in terms of innovation and value creation around this industry in a circular economy.

Figure 1 and Figure 2 show CO_2 equivalent (CO_2e)emissions by industry in Norway, using different accounting perspectives. Figure 1 displays direct emissions by economic activities for 2018 for six greenhouse gases (CO_2, CH_4, N_2O, HFK, PFK, SF_6). While CO_2 is dominating in most industries, some industries stick out: CO_2 emissions are very low compared to CH_4 and N_2O for agriculture; compared to CH_4, HFK and N_2O for waste treatment; compared to CH_4 for the wood industry; compared to HFK for Accomodation and food services, Education, and Social work; and compared to N_2O and HFK for Health services. This needs to be kept in mind when taking the value chain perspective below (Ref. Figure 2), as only data for CO_2 emissions is available.

Direct emissions are highest for international shipping and extraction of crude oil and natural gas, including services and pipeline transport. These will not be further analysed, as the expected potential for emission reduction through especially circular economy policies is low. Direct emissions from household are the next highest emissions (Figure 1). These are mainly emissions from fuel use for transport and heating (CO_2), but also from cooling (HFK). Circular economy measures for reducing private transport emissions are discussed in Section 3.1.3. The process industry, including chemicals, metals, and non-metallic minerals, is responsible for about 20% of direct emissions. It plays a central role for realizing circular economy potentials due to its unique position in the material value chain. Emission reduction potentials in many value chains depend on the material processing stage, so that in Section 3.4 emission reduction potentials for parts of the process industry are analysed specifically.

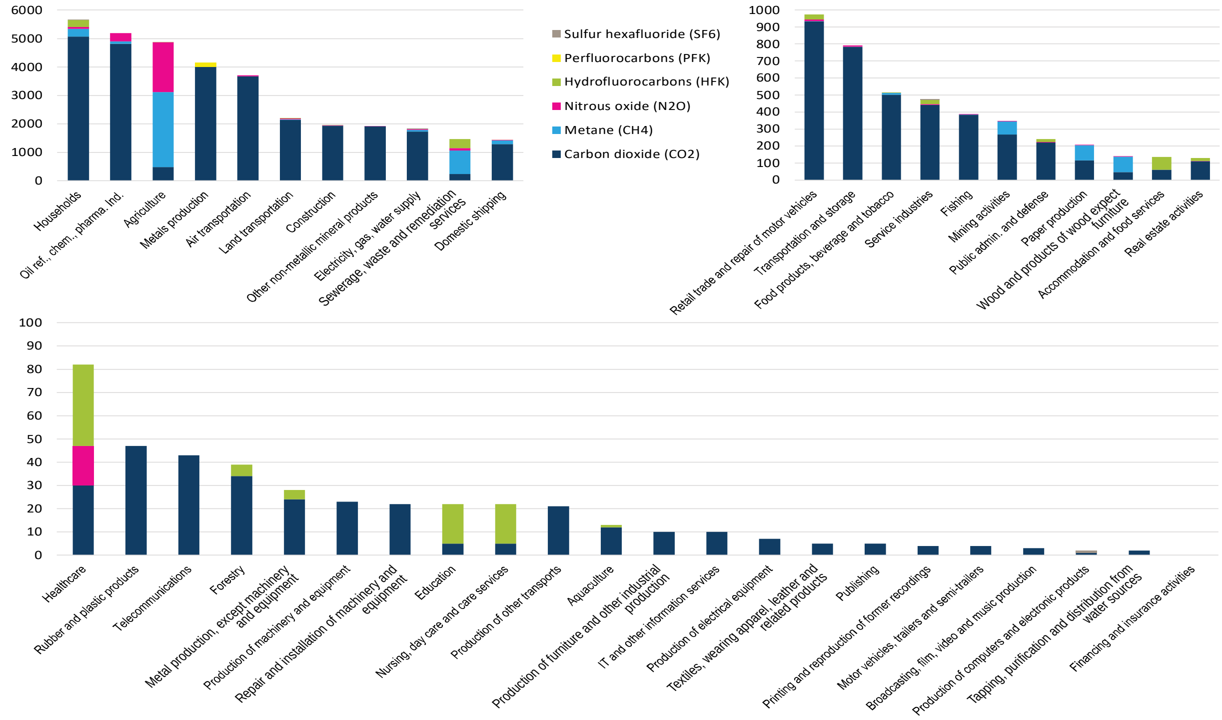

Figure 1: Greenhouse gas emissions (in 1000t CO_2-equivalents) by industry in 2018. Source: Own representation based on SSB table 09288. Note, the two largest industries International shipping (20mt) & extraction of crude oil and natural gas, incl. services and pipeline transport (15mt) are not included.

Figure 2 displays direct and indirect CO_2 emissions as well as consumption-based CO_2 emissions for Norway. These consider not only the direct emissions, but all emissions that occur along upstream production chains in other industries within but also outside Norway, from the producing industry's perspective (direct and indirect) and from the final consumers' perspective [6].

While the service industries (e.g. wholesale and retail trade, other business sector services, or real estate activities) have very low direct emissions (3% of total Norwegian emissions), due to the use of other goods and services, especially transport services, the service industries have a high share in total indirect emissions (about a third of indirect emissions). Here, analysing circular economic measures from a value chain perspective are essential. In Section 3.4, we will look at both upstream (mostly transport services) and downstream (waste) value chains of the service industry to identify emission reduction potentials, showing that there is no clear separation of upstream and downstream measures, but that the entire system needs to be analysed from a holistic point of view.

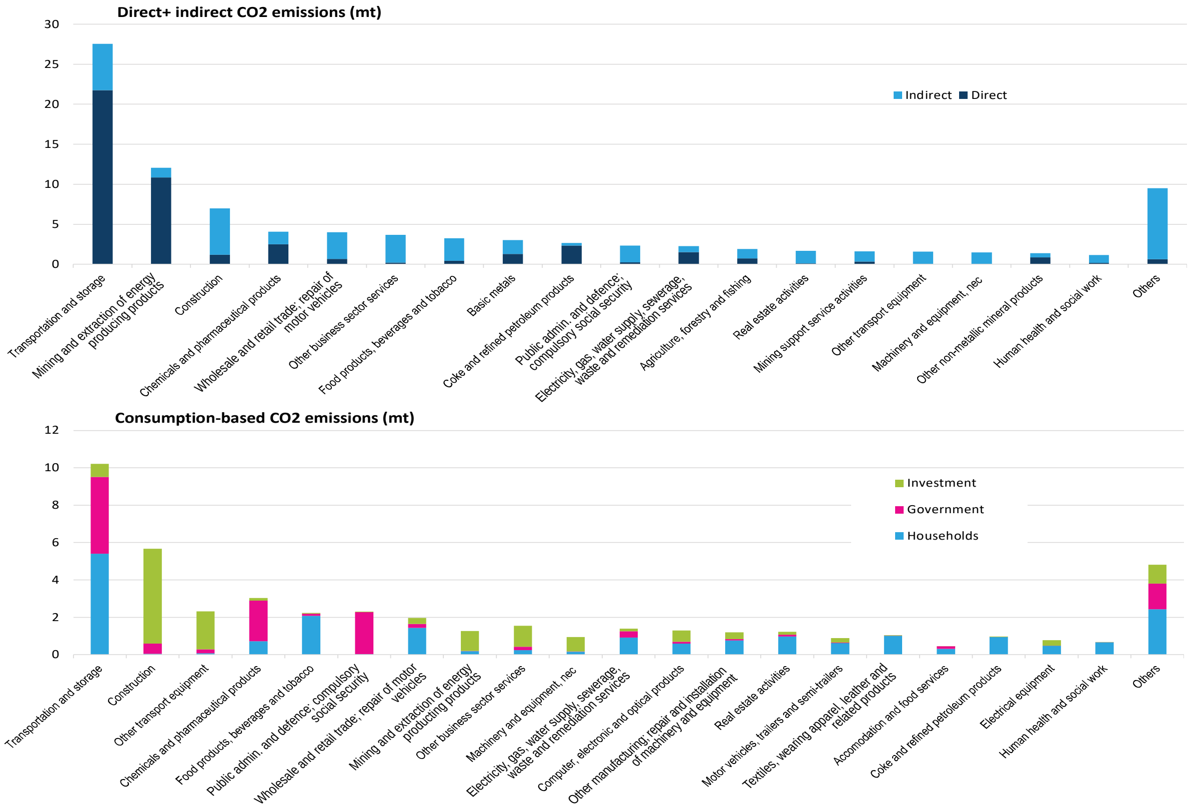

Figure 2: CO_2 emissions (in mt CO_2-equivalents) along value chains by industry in 2015[1]. Source: Own calculations based on OECD ICIO [5–7]

The construction industry has, together with real estate activities, very high upstream emissions from both the production (doing the work) and the consumption (investing in buildings and other infrastructure) perspective. These can be traced back to the large material as well as transport requirements. Section 3.2 analyses possibilities for emission reduction through more circular organization in these value chains.

From the consumer perspective (households in Figure 2) a large share of emissions are embodied in final consumption goods, such as computers and other electronic and electrical equipment, textiles or and motor vehicles. The possibilities for reducing emissions through circular actions along the value chains of different consumer goods are described in more detail in Section 3.1.

Materials are extracted and processed and then further used in the production of intermediate and final goods by all industries. At the end-of-life goods are disposed and should, optimally, be fully recycled. At each step in the value chain, circular strategies can help reducing GHG emissions. Below, we analyse different options for this from the material user and the material producer perspective.

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[1] The latest available data from OECD for these calculations is from 2015. Comparing total and relative values for CO_2 emissions per industry indicates that the 2015 numbers are still a good representation of the state in 2018 and can be used for this analysis.

Box 2: Emission accounting concepts and relevant terms and definitions

What is an *'industry'*?
We use the industry classifications based on Statistical Classification of Economic Activities in the European Community (NACE) Revision 2. Greenhouse gas (GHG) emission data from Statistics Norway (Statistisk sentralbyrå – SSB) is available for 43 industries plus direct emissions from private households, e.g. from transportation fuel use or fuel use for heating. CO_2 emission data from OECD is available for 36 industries plus direct emissions from final demand/households. An example for an industry is "Agriculture, hunting, fishing and forestry" in the OECD classification, while these are 4 separate industries in the SSB data: Agriculture and hunting; Forestry; Fishing; Aquaculture.

Direct emissions (taken from SSB Table 09288)
Emissions that occur during the production of goods/services in the industry itself, e.g. when burning fossil fuels or through processes such as reduction in metal production or natural emissions from livestock. These are often referred to as Scope 1 emissions. These are the emissions that are addressed under the UNFCCC climate agreements, i.e. those that were addressed under the Kyoto Protocol and those that are currently addressed under the Paris Agreement.

Trade and emissions along national and global value chains
However, through international trade, Norway is also inducing emissions elsewhere in the world. Here we can differentiate between emissions that occur elsewhere through production of goods and services in Norway (*indirect emissions*) and those emissions that occur elsewhere through the consumption of goods and services in Norway (*consumption-based emissions*). Total indirect and consumption-based emissions include emissions within Norway in other industries and outside Norway. Neither indirect nor consumption-based emissions are reflected in Norwegian statistics or climate goals, but emissions outside Norway are about half of each indirect and consumption-based emissions, so that changes in production and consumption-behaviour in Norway can have a significant impact not only on those climate gasses that are emitted within Norwegian territory, but also in the rest of the world.

Indirect emissions (estimated from OECD ICIO and CO_2 extensions)
Indirect emissions are those emissions that occur during the production of intermediate goods and services that are used as inputs into production in the industry, e.g. electricity or the individual parts that go into a mobile phone or financial services needed. Indirect emissions include Scope 2 and parts of Scope 3 emissions. Scope 2 emissions are emissions from the generation of energy that is purchased. Scope 3 emissions include all other indirect emissions upstream and downstream, while we only show indirect upstream emissions here.

Consumption-based emissions – CBA (estimated from OECD ICIO and CO_2 extensions)
Consumption-based emissions (CBA) allocate emissions that occur during the production of the goods or services and all intermediate goods and services to the consumers of the final products, that is households (HH), government (gov) and investment (inv). Consumption-based emissions related to final demand for electrical equipment (households appliances such as lamps, laundry machines, microwaves) by Norwegian households for example includes all emissions that occur during the final assembly of the product, the transportation of all the individual parts and the intermediate goods and services needed for producing the individual parts. These emissions do not only occur in Norway, but also abroad where most of the goods and all the intermediate goods are produced.

Mt CO2 equivalents	SSB 2018 09288: Climate gasses from Norwegian Economic Activity							OECD 2015 OECD ICIO + CO2						
	Carbon Dioxide (CO2)	Methane (CH4)	Nitrousoxide (N2O)	Hydrofluorocarbons (HFK)	Perfluorocarbons (PFK)	Sulgur hexafluoride (SF6)	total direct GHG	direct CO2	indirect CO2	direct + indirect CO2	CBA	CBA HH	CBA gov	CBA Inv
Total	66	5	3	1	0	0	74							
International shipping	20	0	0	0	0	0	20							
Total excl. intl shipping	46	5	2	1	0	0	54	46	46	92	53	20	12	14

Further reading: Consumption-based emissions: http://oe.cd/io-co2; Scope 1, 2, and 3 emissions: https://ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf

3 The user side of materials

A new study by UNEP Resource efficiency and climate change: Material Efficiency Strategies for a Low-Carbon Future, published in December 2019, summarizes emission reduction potentials through more efficient use of materials as

> *"An estimated 80% of emissions from material production were associated with material use in construction and manufactured goods. Here, materials are understood as solid materials including metals, wood, construction minerals, and plastics. Fuel, food, or chemicals are not included. Reducing the GHG emissions for materials required for homes and cars, the most important products of the construction and manufacturing sectors, can cut cumulative life cycle CO_2e emissions in the period of 2016-2060 by up to 25 Gt in G7 countries. The technologies to increase material efficiency are available today."* [3, p.7]

This confirms our findings from analysing emission on the macro-level in Section 2. We will therefore look further into consumer products, using the example of electronic and electrical equipment (EEE), textiles and private mobility, transport in the service industry and summarize findings from the literature on the construction sector, i.e. housing. Further we look at circular possibilities to avoid food waste.

3.1 Consumer goods

Consumers play a significant role in the transition to a circular economy. In the end, goods are used and consumed by people and their demand determines what is produced in the world. Figure 3 shows consumption-based emissions of Norwegian households by consumption category. Direct emissions from households, e.g. from driving or heating, as well as upstream emissions from other energy consumption and emissions from transport are tackled by energy policies and not further analysed here. Emissions related to the consumption of services and emissions related to food, agricultural production and fishery are discussed in other sections. The consumption of durable (in use for longer than 3 years) and non-durable goods is responsible for more than 20% of households' annual consumption-based emissions, thus offering potential for emission reduction.

Circular strategies available for consumers are mainly related to the first six of the ten Rs: refuse, rethink, reduce, re-use, repair, refurbish. The main outcomes of these are reducing consumption through simply using fewer things or using goods more intense (refuse, rethink, reduce) or reducing consumption by using goods longer (re-use, repair, refurbish). But, producers also play a significant role in enhancing the circularity of consumer products. They can ensure product design that minimizes resources use and GHG emissions, make them more durable and easier, or even possible to repair. Furthermore, retailers can adapt their business models for enabling more circularity in the value chains [8], for example offering repair services, collecting broken goods for refurbishment, remanufacture and possibly repurpose (into other products) and resell and actively using reverse logistics.

3.1.1 Consumption-based emissions

The consumption of goods and services by households in Norway accounted for about 25Mt CO_2 emissions in 2015, which is almost 40% of consumption-based emissions of Norway. About half of these are energy (electricity and heat) and transport (individual transport by car as well as transport services). 10% are related to food and 18% to the consumption of services. More than 20% of the consumption-based emissions occur along global production chains of durable and non-durable consumer goods. Most non-durable consumer goods, such as batteries, light bulbs, or bike parts are consumed and not shareable or re-useable (however, the materials could be recycled and used in new products).

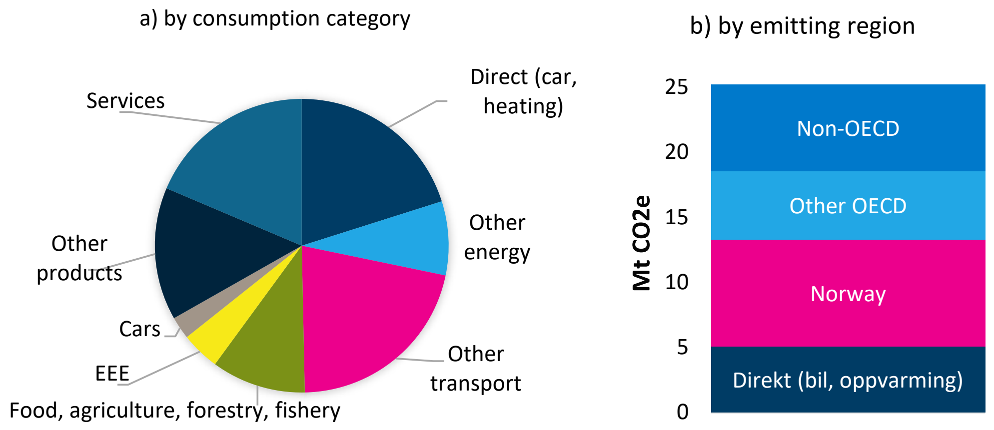


Figure 3: Consumption-based CO_2 emissions of Norwegian households in 2015. Source: Own calculations based on OECD ICIO [5–7]

3.1.1.1 Sharing and renting

Sharing and renting of goods intensifies the use of products. Rather than being idle in everyone's homes or storage, neighbours could share garden tools and lawnmowers, local supermarkets could rent out bicycle trailer. Using average numbers for savings potential from sharing and renting from a study for the EU [9] and adapting it to Norwegian expenditure shares, we get savings potentials for consumer goods as shown in Table 1 (column Sharing). While the authors assume a 10% sharing scenario to be realistic, to show the full emission savings potential the shares in Table 1 are based on a 100% sharing scenario, i.e. that all durable and sharable goods that can be shared, will be shared. The sharing potential for shoes for example is assumed to be zero, while cameras or garden tools can be shared to a large extend. Assuming the full utilization of the sharing potential, consumption-based emissions of Norwegian households could be reduced by 5% (Figure 4, panel b, Total). Most of the emission savings however would occur outside Norway, with the largest effects in the non-OECD, especially Asian countries. This is because the consumer goods manufacturing industry in Norway is very small and a large share of consumer goods are imported. Electrical and electronic products have a high potential for being shared (see column "Sharing" in Table 1), and related circularity strategies are analysed in Section 3.1.2.

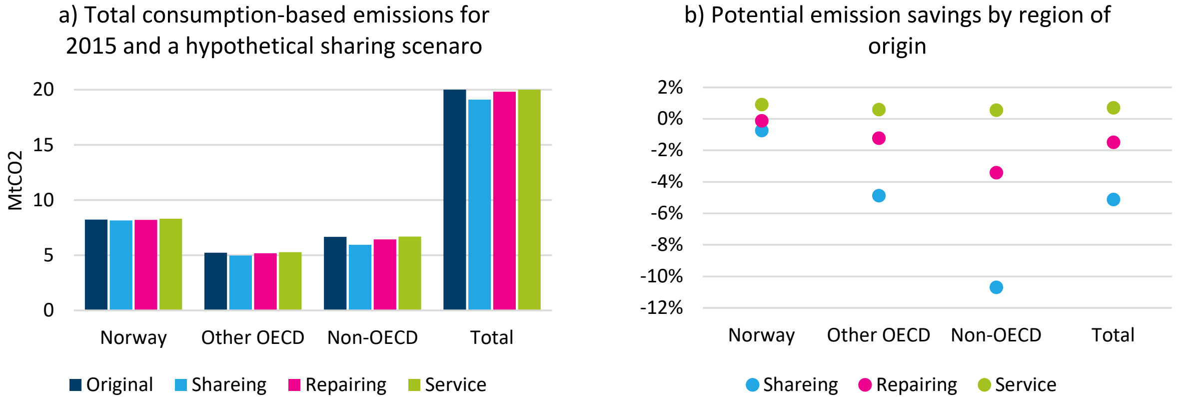
3.1.1.2 Extended product lifetime

Life-cycle assessment studies, dealing with individual products, have for example found that a 10% increase in toaster life-time globally results in 4000 t CO_2 equivalents (CO_2e) annually and in t-shirt life-time globally to 100000 t CO_2e annually [10]. Of course, not all consumer goods can easily be used 10% longer, light bulbs are usually used until they break, while there is a large potential for goods that are exposed to fashion trends, such as clothes or mobile phones, and some potential for other household electronics. For a rough estimation, we assume a 10% increase in lifetime of selected consumption goods categories, see Table 1 (column Repairing), resulting in about a 10% decrease in spending on these. At the same time the demand for repair services increases. Industries that are most likely to gain from these are Other manufacturing, Waste collection, Other service, Rental and leasing, repair of computers and household goods [10]. In our model (based on the OECD data) , these industries are subset of larger industry aggregates. Neither Renting and installation of machinery and equipment nor Scientific research and development activities are relevant services for households. The last column in Table 1 (last column: Services increase) specifies the assumption of an increase in demand for these services by Norwegian households, combining assumption at the detailed level (grey shaded) with increases at the aggregated level.

Table 1: Emission savings potentials through renting and sharing, and extended lifetime of consumer goods

Industry	**HH shares**	**Sharing** (and renting)	**Repairing** (extended life time)	**Services increase**
Textiles, wearing apparel, leather and related products	1.8 %	-18 %	-10 %	
Paper products and printing	1.1 %	-13 %		
Other non-metallic mineral products	0.3 %	-18 %		
Computer, electronic and optical products	1.3 %	-34 %	-10 %	
Electrical equipment	0.8 %	-47 %	-10 %	
Machinery and equipment, nec	0.4 %	-73 %	-10 %	
Other manufacturing; repair and installation of machinery and equipment	1.8 %	-29 %	-10 %	
Electricity, gas, water supply, sewerage, waste and remediation services	3.0 %			13 %
Waste collection, treatment and disposal activities	0.8 %			50 %
Other business sector services	2.1 %			6.2 %
Rental and leasing activities	0.1 %			100 %
Arts, entertainment, recreation and other service activities	2.9 %			1.7 %
Repair of computers and personal and household goods	0.1 %			100 %

**HH shares = Shares in total household expenditures in 2015, based on OECD ICIO, grey shaded based on SSB*



Source: Own estimation based on data for 2015 from OECD ICIO and estimated savings potentials from Table 1.

Figure 4: Consumption-based emissions of Norwegian households (excluding direct emissions) in hypothetical sharing and repairing scenarios

3.1.1.3 Rebound effects

Rebound effects are adverse effects on emissions that occur when emission reduction actions by households also lead to monetary saving in consumption expenditures, thus freeing up money to spend on other goods and services. These additional purchases then lead to additional emissions that partly, fully or more than offset original emission reductions [11–13]. We can differentiate between direct rebound effects, that is more consumption of the same product if price decreases, and indirect rebound effects, that is the consumption of other products if spending on one product is decreased [9]. In this context, both direct and indirect rebound effects are relevant. A product might get cheaper if fewer raw materials are used in the production decreasing also related emissions (direct). If people spend less on a certain product, e.g. through sharing, they might consume more of other products (indirect). This latter is especially relevant in the context of car/ride sharing as well as decreasing costs of accommodation through sharing platforms, when these savings are spent on additional (air) travel. One possibility to at least partly avoid this type of rebound effect is an equal pricing of emissions across all goods and services, clearly showing the price of emissions to the consumer, as stated by Skjelvik et al. [13]: *"Since almost all human activities cause some CO_2e emissions through production, consumption and waste handling, it is important that all emissions are priced so that producers and consumers can take this into account when they make their choices. The case with the sharing economy also illustrates that when using taxes, they would have to be adjusted over time as we get richer to avoid overall emissions to increase. In an emission trading system the CO_2 price will automatically adjust to increases in emissions through increased demand for emission allowances."* [13]

3.1.2 Household electronics, electronic waste and critical raw materials

The market characteristics

Computer, electronic and optical products, and electrical equipment together account for about 2.2% of Norwegian household spending (Table 1). But the value chain of household electronics includes all production, processing and trading stages and thus spans from the extraction of critical raw materials and fossil-based raw materials for plastics production, via intermediate electronics production to the production of the actual electrical and electronic household goods, wholesale and retail trade of these, as well as related leasing, renting and repair services, see Figure 5.

In Norway, wholesale and retail trade has by far the largest share of value creation and employment in this value chain. The market for selling electronics to final consumers is concentrated around two big players creating almost 80% of the value and employing about 75% of the workers[2], while the remaining are working in mostly locally active SMEs. Businesses renting out or repairing goods are significantly smaller, a lot of them being one-man businesses with no employees (the number of employees – Ansatte in Figure 5 – excludes the owner).

Businesses selling, renting or repairing household electronics are spread over the entire country, thus providing a good base for an increasing sharing and repairing economy all over Norway. However, for sharing to work efficiently, local activities at neighbour level (consumer-to-consumer) need to be established, maybe through online platforms such as finn.no.

Norwegian businesses are not involved to a large extend in the production of electronic and electrical equipment (EEE), so that circularity measures at those stages are not easy to implement from a Norwegian perspective. However, especially when it comes to the extraction and processing of minerals needed for EEE, the process industry and research and development activities are necessary[14], see also Section 4 and part 2 of this report.

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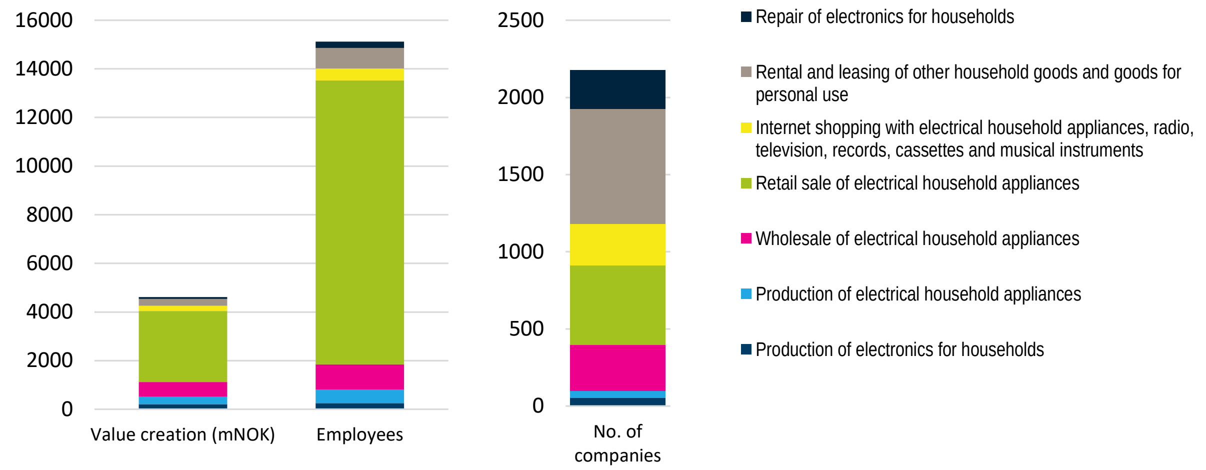
[2] Elkjøp (95 out pf the 518 businesses) employs about half of the 11678 employees in electronic retail trade, Power (67 out of the 518 businesses) about a quarter



Source: Own estimation based on data for 2017 from ProffForvalt.

Figure 5: Value creation, employment and number of businesses in industries along the electronics value chain in 2017, for Norway

The technological or physical obstacles

More than 50% of critical raw materials (CRM) extracted around the globe are used in the production of electrical and electronic equipment annually. This includes not only consumer electronics, but also electrical and electronic components for machinery, equipment and other technologies, such as for example renewable energy technologies [15]. The use of CRM in consumer electronics is increasingly competing with the use of CRMs for low carbon energy technologies, making it ever more important to decrease the use of new raw materials through material efficiency improvements, longer use of products and efficient recycling. Part 2 of this study highlights the future risk to the supply of critical raw materials and the need to recover more of the in-use stocks. In addition to CRM, plastics are up to 37% of the content in small household appliances and up to 7% in large household appliances [16].

Technological change in consumer products has been ever increasing in the last decades, making entire technologies, such as CD players, FM radios or old-fashioned mobile phones, obsolete [17], cutting their life-time shorter than technically necessary. While those technologies were still designed for repair or at least exchanging parts such as rechargeable batteries, the newer generation of smartphones are not easily repairable[17]. Though exceptions exist, such as the Fairphone, which is often used as an exemplary case for circular thinking in consumer electronics. Another important factor for extending the lifetime is the use of more durable parts and components [8].

Barriers to recycling occur during the collection and the technical recycling stage. Collection can be hampered by hoarding (consumers keep old no longer in use or partly broken electronics at home for various reasons) or an unsuitable waste collection system [15,17]. The Norwegian system of collecting WEEE where EEE is sold ensures easy access and results in one of the highest WEEE collection rates in the world. For the technical recycling stage barriers can be technical feasibility, economic costs or a combination of these [15]. Technical barriers occur due to the product design, e.g. making it hard to separate metals from plastics as well as different types of plastics or metals from each other [18,19]. Three companies are approved in Norway, Norsirk, ERP Norway AS, and RENAS AS and in 2017 85% of the WEEE was recovered [20].

The magnitude of emission reductions

Through intensifying and prolonging the use of electrical and electronic products, about 500000 tonnes CO_2 could have been saved along global value chains of Computer, electronic and optical products (ISIC code 26) and Electrical equipment (ISIC code 27) consumed by Norwegian households in 2015, that is about 2.3% of total consumption-based emissions (based on our rough estimates using assumptions from Table 1 and the OECD ICIO data for 2015). However, since most emissions occur during the production phase, about ¾ of the savings occur in non-OECD countries. Remember, these numbers assume that everything that can be shared, is shared and consumption is reduced by an additional 10% through extended product lifetime. Not only will CO_2 emissions along global value chains be reduced, but also consumers will spend less on these products, making more money available for other consumption. This consumption needs to be channelled to low-emission goods and services, in order to not have negative rebound effects, where total emissions increase, because consumers buy more of these goods or switch to even worse products (from an environmental perspective) such as flight travel [11,13].

This emission savings potential does not include emission reduction possibilities through changes in product design or the use of recycled rather than primary raw materials. However, studies claim that the potential for emission reduction for electrical and electronic products through redesign is relatively limited [21], while this strategy has larger potentials for mobility (see Section 3.1.3) or housing (see Section 3.2).

Relevant public regulations and other framework conditions

There are an increasing amount of EU directives and guidelines for ensuring circularity of consumer goods. The most relevant for household electronics are summarized in the Circular Economy Action Plan [2] of the European Green Deal as follows:

- Regulatory measures for electronics and ICT under the Ecodesign Directive (2009/125/EC)
- Electronics and ICT as a priority sector for implementing ‘right to repair’ and 'right to update obsolete software'
- Enhancing durability and introduction of common design for chargers
- Improving collection and treatment of WEEE through updating Directives 2002/96/EC & 2012/19/EU, including a possible EU-wide take back scheme to return or sell back old mobile phones, tablets and chargers
- Review and possible update of regulation regarding hazardous substances in electrical and electronic equipment (Directive 2011/65/EU)
- Extending warranties

In Norway, regulations regarding the treatment of waste can be found in the *Forskrift om gjenvinning og behandling av avfall (avfallsforskriften [22]*. Retailers, such as Elkjøp and Power, are obliged to offer return services for old and broken WEEE. Norway has amongst the highest return rates of WEEE in the world, 19.6kg per capita in 2016 [23], and with that surpassed the target 45% WEEE collection (i.e. collecting at least 45% of the weight sold of EEE in the same year). While the delivery to the return station works, a large problem is theft from these stations and illegal export of old and broken consumer electronics to Africa, as reported by NRK in the documentary *Søppelsmuglerne*[3].

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[3] Available online at https://www.nrk.no/dokumentar/xl/blir-drapstruet-av-folk-som-stjeler-soppel-1.14723377

Effective social innovations

Societal changes and innovations can be achieved through government regulations or incentives, new business models and through a change of values in the society. The latter requires "rethinking" by individuals and social groups and an active participation of society in the transition to a more circular economy. Rethinking can be achieved through information, such as empower the consumer with more information about repair and recycling[4], and global movements such as Fridays4future, which has brought climate and environmental problems, and through this, also Circular Economy into the news, daily conversations and onto political agendas. Rethinking and changes in consumer behaviour are essential for a circular economy and today pose one of the largest barriers to the transition [24].

Some examples for rethinking in the context of consumer electronics are the insight that one does not always have to have the newest electronic gimmick or buy a new mobile phone every year [25], while the old one is still working, an increase in demand for goods that are designed for repair and recyclability and a culture for using share, repair and recycling services [17,26]. Especially for the latter, a whole range of new business opportunities arise, offering for example local repair and share (leasing, pooling) services [8]. The introduction of these can be incentivized by rules and regulations [13], by for example making such services tax free or including maintenance contracts in the original costs of the product, possibly together with an extension of the economic lifetime of goods, through changes in tax deduction regulations [8,15]. The aim is to make it cheaper to share and repair than to buy new. Another important factor for this is ease of access through decentralization of such services, such that transport costs (monetary and time) remain lower than those for buying new.

In addition, Norway is in a unique position to be a relatively small and highly digitalized society with a centralized market for second-hand goods around two actors: finn.no and Fretex. This enhances the accessibility of reuse opportunities [8]. Currently [17.03.2020], more than 116000 items are offered in "Elektronikk og hvitevarer" on finn.no, which is about 7% of the total items offered in the second-hand market "Finn torget". However, it is important that this second-hand market does not result in increased consumption (and production), since easy access to selling used goods might increase the buying of new goods. Another example of circular activities is Norsk Ombruk, which repairs about 6000 units of large household appliances per year[5].

Critical market and technology developments

Electronic and electrical household equipment are just one example for explaining the role of households in a circular economy to explain necessary changes in their consumption behaviour and in the design and production of household goods. Societal barriers and necessary innovations are similar for other durable goods, while technological characteristics may differ significantly. While metals and plastics can be recovered multiple times from old electronic and electrical equipment and the production of new products from recovered materials is generally less energy and thus also less emission intense, this is not true for textiles.

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[4] For example, https://sortere.no/privat/avfallstype/29/Elektrisk%20og%20elektronisk%20avfall

[5] According to information from an interview with Virke.

Opportunity: Electronic consumption goods	
Emission reduction potential	• **Approx. 0.5 Mt CO2** (~2.5% of consumption-based emissions) based on an ambitious 100% repair & share replacing goods purchases scenario • **Unknown** through resource efficiency and design strategies, but expected that emissions reduction of those would occur outside Norway
Key Barriers	• Circularity still is too expensive: labour costs too high, natural resources and manufactured goods too cheap • *Consumption culture** • Consumption levels
Enabling innovations	• *Repair and share culture** + easy access to related services with regards to location and costs • Design for repair and recycling • Urban mining possibilities, both for the consumer at the end-of-life of the product, and for the producer to get the critical materials, possibly through reversed logistics • Changes in tax systems (Lower taxes on repair and other services) • Digitalization for improved logistics, better tracing of raw materials, and easy access to repair and share options

* Here, we refer to the "*consumption culture*" in contrast to the desired circular "*repair and share culture*" as being the current prevailing behaviour in the population: we rather buy new goods than getting old/broken things repaired or renting/sharing goods that we do not use on a daily basis.

3.1.3 Textiles

The market characteristics

The garment and textile industry has experienced enormous growth with doubling of clothing sales in the last 15 years alone. But a trend for 'fast' or 'throw away' fashion also means that clothes are worn 36% less now after the same 15-year period. Less than 1% of clothing is recycled, representing a loss of over $100 billion globally each year. According to Fretex, each Norwegian on average purchases 15kg Clothing and disposes of 8-10Kg, totalling 40-50 tonnes textile waste each year in Norway from consumers [27].

Poor decision support in the textile supply chain and designed obsolescence result in large over production with 30% of all garments never meeting the consumer.

The magnitude of emission reductions

Extending the life of 50% of clothes by an extra nine months of active use would reduce carbon, water and waste footprints by around 4-10% each. To increase durability producers need to use better quality materials and design (physical durability) and so called 'emotional durability' for example for consumer involved design initiatives. Consumption-based CO_2 emissions in Norway were about 1Mt for textiles in 2015 (based on own calculations using the OECD ICIO data). Decreasing emissions of half of this by 4-10% results into a potential emission reduction of 0.02-0.05 Mt CO_2 along the global supply chain of textiles that are consumed in Norway. With an ambitious repair and share scenario as described in Table 1, these emissions could be reduced by about 20%, i.e. 0.2Mt CO_2.

Relevant public regulations and other framework conditions

In the Norwegian market the cost of new clothing is relatively low compared to the cost of labour meaning that repair services struggle to be economically sustainable. To address the economic imbalance there has arisen an industry led call to remove VAT on repair services.

Leasing clothing through subscription services such as from providers Fjong or Parkdress.no. But clothing rental services are struggling with upscaling especially economically effective operations and logistics and consumer acceptance.

In Norway there is solid infrastructure for the collection and sorting of textiles, often organised by charities such as The Salvation Army to fund their charitable activities. Around three quarters of these textiles are sold on global markets. These activities markedly increase the usage of a garment although at a global level, used textiles tend to flow from richer countries to poorer ones in the search for buyers in a cascade of quality and value [28] . The circular economy package, adopted in 2018, will for the first time require Member States to ensure that member states are required to collect textiles separately [29] and the EU Green deal will develop a new EU Strategy for Textiles to strengthen competitiveness and innovation in the sector and boost the EU market for textile reuse.

The technological or physical obstacles

While metals and plastics can be recovered multiple times from old electronic and electrical equipment and the production of new products from recovered materials is generally less energy and thus also less emission intense, this is not true for textiles. Textiles loose quality fast through recycling cycles and fibre recycling does not avoid the energy intense and harmful production stages [30], so that the overall environmental benefit really depends on which part of the production processes can be avoided by circular strategies [30]. In addition, only mono-material textiles, that are made of one or two fibre compositions can be recycled, but these amount to about 24% of textiles ending up with collectors and sorters [31]. The most important technological innovation is the production of higher quality and more durable clothes, that are recyclable. However, to be successful, this must come with a change in the "fast fashion" culture and an increase in the textiles returned for reuse and recycling [32]. Here, societal innovations changing the demand side are inevitable.

Effective social innovations

The most important innovations both regarding technology and market development for establishing circularity in the garment and textile sector are;

- Eliminate over production (estimated 30% of all fashion never gets sold [33].
- Reduce the ' fast fashion ' effect by increased by improving longevity in garments through higher quality materials, stimulation of the repair industry and changing consumers relationship with garment by for example, consumer involved design processes.
- Stimulate resale and clothing leasing services for example public procurement for example workwear and uniforms
- Improving recyclability through improved design and increasing the share of garments recycled post-consumer textile fibres to stimulate the market for secondary fibres.

Critical market and technology developments

Key barriers and enabling innovations are more or less the same across all consumer goods. Thus, much of what is true for electronics also holds for textiles. Consumers need to use fewer, high-quality and longer-lasting products, that can be repaired and where consumers are willing to repair them.

Opportunity: Increased circularity for consumer textiles	
Emission reduction potential	• **0.02-0.05 Mt CO2** (~0.5% of consumption-based emissions by Norwegian households) based on an assumption of a nine months longer lifetime • **Around 0.2 Mt CO2** based on an ambitious repair and share scenario • **Unknown** potential based on the textiles that are imported into Norway but never sold (more data is necessary)
Key Barriers	• Circularity still is too expensive: labour costs too high, natural resources and manufactured goods too cheap • Fast fashion *consumption culture** leading to high consumption levels
Enabling innovations	• Eliminate overproduction • *Repair and share culture** + easy access to related services with regards to location and costs • Design for repair • Stimulation of market for secondary fibres • Changes in tax systems (Lower taxes on repair and other services) • Digitalization for improved logistics and easy access to repair and share options, e.g. resale and leasing services

** see Table above on EEE*

3.1.4 Circularity in individual transport

Transport is one of the largest sources of GHG emissions from households, see Figure 3. While the decarbonization of the transport sector is already part of the climate policy discussion, circular economy measures can help reduce emissions even further [13].

The technological obstacles

Cars are material intense, using different metallic and non-metallic minerals, plastics and rubber products, as well as electronic and electrical equipment and textiles. Scrapping cars and reusing the raw materials has a long history and is still improving as better recycling technologies become available, especially regarding the non-metallic components. Increasing digitalization and dependence of the functioning of the car on software makes it easier to identify broken parts in a car, but can also make a technically functioning car unusable if the software itself introduces an error. In addition, this makes it harder to do do-it-yourself repairs of the cars at home. For example, we see an increasing number of cars driving with only one headlight as changing the light bulb needs to be done in a repair shop and is no longer possible using general tools at home.

In addition, especially in Norway, the share of electric vehicles has been and still is increasing significantly. Not only the production, but also routines and technologies for recycling car batteries are still on the steep part of learning curves, with high cost decreases and efficiency increases expected over the next years. Part 2 of this report summarizes technology development and recycling opportunities.

The magnitude of possible emission reductions

Optimizing the use of materials and resources here does not only include the actual design of a car, but also a more intense use of the car fleet. Most privately owned cars are idle for more than 90% of the time [34]. If each car was used more intensely, fewer cars would be needed. Hence, for passenger vehicles, two major sources of better resource use can be differentiated: less material per car and fewer cars. The former can be achieved through more durable parts and components and lower repair/replacement needs [8,13] as well as a lighter design, which decreases material requirements [21], or which can be achieved through switching materials or demand for smaller cars. A switch from e.g. steel to aluminium, high-strength steel or carbon fibre may result in higher emissions during the production phase, but a lighter design results in significantly lower use of energy of the cars during the use phase. Unfortunately, the global trend is to have ever bigger cars, which offset efficiency improvement in in-use emissions of the average car in the past decades and threatens to offset emission reductions through the use of electric vehicles [35]. The number of cars can be reduced through more intense use of the vehicle fleet by ride-sharing and car-sharing [3,9,21].

The 2019 UNEP report [3,21] estimates potential emission savings through material efficiency improvements both in the production, use and end-of-life stage of passenger vehicles to be more than 50% in 2050 in G7 countries and more than 30% in countries like India and China. Translating this into tonnes CO_2 saving potentials is challenging. Given the calculations for Norway visualized in Figure 3, and assuming that about 3 Mt of the direct emissions are related to fuel use private road transport plus 0.6mt CO_2 emissions related to car purchases (consumption-based emissions), then 50% of total emissions are 1.5-2 Mt CO_2 (this is a very uncertain and approximate value that should be used with care).

Potential reduction of emissions due to ride sharing strongly depends on assumption about the average occupancy of cars [9]. If occupancy rates go up from 1.6 persons (European average) to 2.8 persons on the average ride, the climate impact per person km is reduced accordingly. Ride-sharing has a larger potential for reducing climate impacts than car sharing, as most emissions during the life cycle of a car (with internal combustion engine) occur during operation [9]. However, the penetration of electric vehicles in Norway today is much larger than the EU average of 2015, thus car sharing with electric cars (that have higher share of emissions during the production rather than the operational life phase) can yield benefits. In addition, a more intense use of cars will speed up the renewal of the car fleet so that new low-emission alternatives penetrate the market faster [9,13].

The potential of reducing emissions from transport is strongly depended on the uptake of collaborative transport and that people who already use low-emission transport options, cycling, walking, public transport, do not switch to higher emission transport in shared internal combustion vehicles because access to those rides becomes easier [9]. For that, it is important that emissions are universally taxed to reflect the environmentally costs in the best possible way [13].

The market characteristics

Norway is not a producer of cars or other land transport equipment. Only 0.1% of Norwegian value added and employment in 2017 was related to the production of motor vehicles, trailers and semitrailers (ISIC Rev 4 industry 29). Wholesale and retail trade and repair services of motor vehicles and motorcycles (ISIC Rev 4 industry 45) is more important for the Norwegian industry, with about 1.7% of employees and 1.4% of value added. [Own calculations based on SSB IOT and table 09174: Lønn, sysselsetting og produktivitet, etter næring, statistikkvariabel og år.]

The Norwegian process industry, however, produces a number of materials for export (e.g. aluminium) that are used in the production of cars, in e.g. Germany, but emissions are relatively low compared to similar materials produced in other countries [36].

The global trend towards bigger and heavier cars [35] is also visible in Norway, and can only be partly explained by the harsh climate and road conditions in some parts of Norway. And, while Norway has one of the highest number of electric vehicles (EVs) in the world (in absolute number and by far the highest in per capita terms), which are generally smaller than the average internal combustion engine

(ICE) car, the share of Teslas, which are bigger cars than the average EV, among the EVs is also comparatively high.

While generally urban and rural densification or regional and national centralization are seen as options to reduce transport demand [37], the population density in some Norwegian regions is very low, so that with the current transport system the ownership of a car is inevitable. In addition, regional policy in Norway is meant to support all regions and avoid an increasing centralization of the country [38].

Relevant public regulations and other framework conditions

> "*However, in models based on a scenario with unchanged framework conditions, the environmental impacts are only marginal, suggesting that measures supporting public transport and cycling are the main drivers of the positive environmental impacts revealed by the study, and not the increase in car sharing in isolation (without rebound effects explicitly considered).*" [9]

This shows the importance of the public regulations and framework conditions as well as the importance of a systems perspective on transport, considering the interplay between transport modes and not each one separately. It therefore important to design the entire transport system in a way that allows flexible switch between different modes with e.g. universally available tickets (combining long distance trains, regional busses and local bike sharing), a higher frequency of transport (especially in rural areas, possibly with lower capacity), and a uniform pricing of emissions to foster the choice of low carbon alternatives (cycling rather than taking the car share option). In addition, the accessibility of the public shared transport system needs to be attractive enough (both in terms of costs and logistics) that people prefer it over owning their own car. Of course, the low population density and geographical challenges in some regions in Norway makes this more demanding than in other countries. Especially in areas with hills and mountains, a better support for electric bikes and flexible public transport systems would be desirable. EVs in Norway profited and still profit from huge tax advantages, while people must pay the full VAT on e-bikes, which are actually more expensive than old used cars.

Prevailing rules and regulations for the road transport sector are general fuel and vehicle taxes as well as the emission trading system that indirectly influences electricity prices for EVs [13], but those are not directed at or fostered by circular economy thinking. Less material intense, easier to repair vehicles with more durable parts should be made more affordable compared to other cars and a tax system fostering life-time extension could be introduced. City tolls or general road tolls, which already exist all over Norway, foster ride sharing to some extent. A study from 2004 showed a decrease of 3% in the number of vehicles going into the Bergen toll ring [39]. While car sharing, and to a lesser extent, ride-sharing options exist in Norway (e.g. Bilkollektiv, Nabobil, GoMore), regulations especially regarding insurance should be reviewed and adapted so that these C2C (consumer-to-consumer) options as well as establishing sharing service businesses becomes easier.

The Norwegian Centre for Transport research [37] lists a whole range of other policy instruments for reducing emissions: Continuously sharpened CO_2 component in the vehicle purchase tax; Subsidies or tax relief for plug-in hybrid vehicles, especially those with high electric range; Vehicle recharging facilities in residential areas, as well as on the job; Subsidies and infrastructure directed at electric bicycles; Result-oriented support schemes for public transport, encouraging, e. g., BRT and the construction of ordinary bus lanes; Strongly increased capacity in the Oslo rail tunnel; Strongly increased capacity and coverage in the Oslo metro network; Double track railway lines in the inner intercity triangle around Oslo (i. e., Skien-HamarFredrikstad); Marginal cost pricing at tolling points, covering road wear, noise, emissions, accidents, and congestion; Climate friendly procurement of public transport and ferry services, favouring electrically powered or (bio)gas driven vehicles and vessels. Those most relevant in terms of a circular economy are: Regulation mandating *taxis (and other car and ride sharing services)* to use cutting-edge, low emission technology; Strict parking regulation in urban centres *to foster the choice of sharing options*: Attractive park-and-ride facilities at public transport nodes *for a better combination of different transport modes*. (Comments in italic were added by the authors, not by the Norwegian Centre for Transport research.)

Effective social innovations

Societal innovations related to a more holistic and circular transport system are closely related to the framework conditions discussed above. The current individualistic private car transport culture [40] must change, with more people choosing shared and low-carbon options. Giving pedestrians and cyclists more space, not only within cities but also around cities and supporting e-bike purchases could transform regional transport choices, not only those in the city centre. The trend towards bigger and heavier cars (SUVs) [41] needs to be reversed.

Car sharing options (and related research [42]) in Norway are currently limited to the central parts of larger cities (e.g. Bilkollektiv in Trondheim), but should also be made available to those living in suburban or rural areas. Especially in large regions with a very low population density, such as most of Norway, society needs to become more creative regarding transport solutions. Digitalization could enable this through informing and reporting about availability as well as making coordination of the services possible in real time. In the currently prevailing transport system with roads and private vehicles, for ride sharing in rural areas with infrequent public transport, apps could life track cars and available seats, so that one can basically go anywhere at almost any time. This could maybe best be described as an organized and formalized form of hitch-hiking. For this to work, safety through traceability and identification as well as clear rules on insurance are necessary. In addition, a relatively large participation rate of the population is necessary.

Even more creativity is needed to find solutions for the mountain hiking, camping and skiing trips, that are very common Norway. An additional challenge here is the necessity of transporting equipment.

Critical market and technology developments

Circular economy measures are based on systems thinking [43]. For private transport, holistic systems thinking is inevitable. Technological development, both for transport means themselves, but also for an interplay between individual and collectives transport are necessary for a successful transition. Digital solutions are an enabler for a more efficient and better accessible transport system.

Opportunity: Circular Mobility	
Emission reduction potential	• Up to **50% emission reduction** in the entire material cycle of cars, considering use of recycled materials, better design (lighter and for easier repair and recyclability) and car and ride sharing options (if Norway is comparable to the G7 average), which can be approximately translated to **1.5-2Mt CO_2 ±large uncertainties** • Varying, depending on the assumptions taken for the uptake of shared public and private transport and the entire organization of the transport system
Key Barriers	• SUV trend • Individualized transport culture
Enabling innovations	• Sharing culture + easy access to related services with regards to location and costs • We need creative solutions for rural areas and "fjellturer" • A tax system reflecting environmental pollution, while considering equal access to transport for all • Digitization of information around share services

3.2 Construction

The construction sector in Norway – which includes new buildings, refurbishment and demolition of buildings and infrastructure – is responsible around 14% of direct and indirect Norwegian emissions, almost two thirds of it for the production and transport of materials [44]. It is estimated that, in the Nordic countries, circular economy measures in the construction sector can save up to 20% of building material use, leading to a reduction in greenhouse gas emissions of up to 10 million tonnes CO_2e when considering the extraction, production and transport of building materials [45].

The technological or physical obstacles

Circular economy measures should be applied through the entire value chain of constructions activities, from the material production, building and materials design, construction phase, use of buildings, and end-of-life [46]. They can be summarized as actions to maintain, re-use, refurbish, and recycle resources and materials in the supply chain of buildings and infrastructures. Here, we do not quantify materials or emissions reductions associated to the design of buildings, such as design for disassembly, but we focus on the construction materials, construction activities, use of the building stock, and end-of-life and waste recovery. We have focused circular economy strategies for the construction sector regarding efficiency in the use of building materials and reduction and recovery of construction waste (covering material production, construction and end-of-life phases). A more efficient use of the building stock is shortly discussed in the conclusion.

Three material groups are responsible for 83% of the emissions associated with materials [44]: cement, lime and gypsum (34%), iron and steel (32%), and aluminium (16%). The remaining of the emissions are mostly due to plastics (6%), other mineral products (5%) and wood products (3%).

The construction sector was responsible for about one fourth of all waste generated in Norway in 2017. Regarding waste types, the construction sector generated over 80% of all discarded concrete and bricks, around one third of all wood waste, and around 10% of all discarded metals, according to SSB table 10514. Figure 7 shows the flows of waste from construction activities (new buildings, refurbishing, and demolition) per waste type, into different waste treatments (sent to recycling, energy recovery, landfill, and other/unspecified). It can be noted that demolition is responsible for 40% of all waste from the construction sector, while refurbishing accounts for 25%. At the same time, only one third of all waste from the construction sector is recycled, mostly concrete and bricks (40% of recycled waste), asphalt (31%) and metals (15%). About one third of all waste from construction activities is sent to landfills, and it mostly consists of concrete and bricks, both contaminated with other materials such as plastics, glass or metals (25%) and uncontaminated (64%).

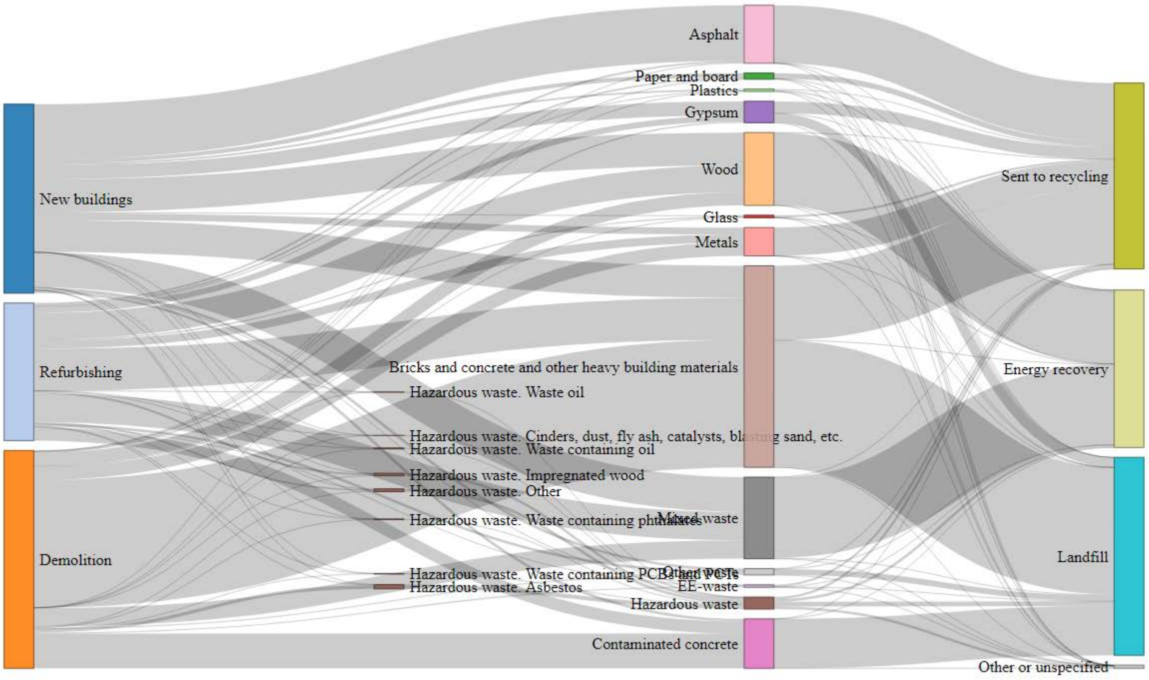

Figure 6: Waste flows from the construction sector, split into construction activity (new buildings, refurbishing, and demolition, on the left), type of waste (middle) and waste treatment destination (sent to recycling, energy recovery, landfill, and other/unspecified, on the left). Source: own elaboration based on SSB tables 09247 and 09781.

Not only the amount of waste that is re-used or recycled is important, one of the aims of circular economy measures is to maintain not only the amount of materials in the economy, but also retain as much as possible of their value. Therefore, despite the high recycling rates of concrete, the materials are usually downcycled, which means that the application of the recycled material leads to lower overall value, such as using recycled aggregates in road sub-bases [46]. Here we identify the potential of more re-use and recycle of materials regardless of further use, as well as strategies to re-use and recycle construction waste avoiding downcycling.

The magnitude of possible emission reductions

In 2017, 63% of all bricks, concrete and other heavy building materials (and 100% of concrete contaminated with other materials) were sent to landfills. This percentage is higher in Norway than for the average European Union, of only 11%, as shown in Figure 8[6].

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[6] The statistics presented in the European Environmental Agency (EEA) report *"Construction and Demolition Waste: challenges and opportunities in a circular economy"* [46] are different from those in SSB. The EEA uses data from Eurostat (statistics on waste generation and treatment – tables env_wasgen and env_wastrt), and reports that only 31% of all mineral waste from construction and demolition are sent to landfills. There are some possibilities for the differences. First, they use different base year – 2016 in the EEA report, 2017 in data from

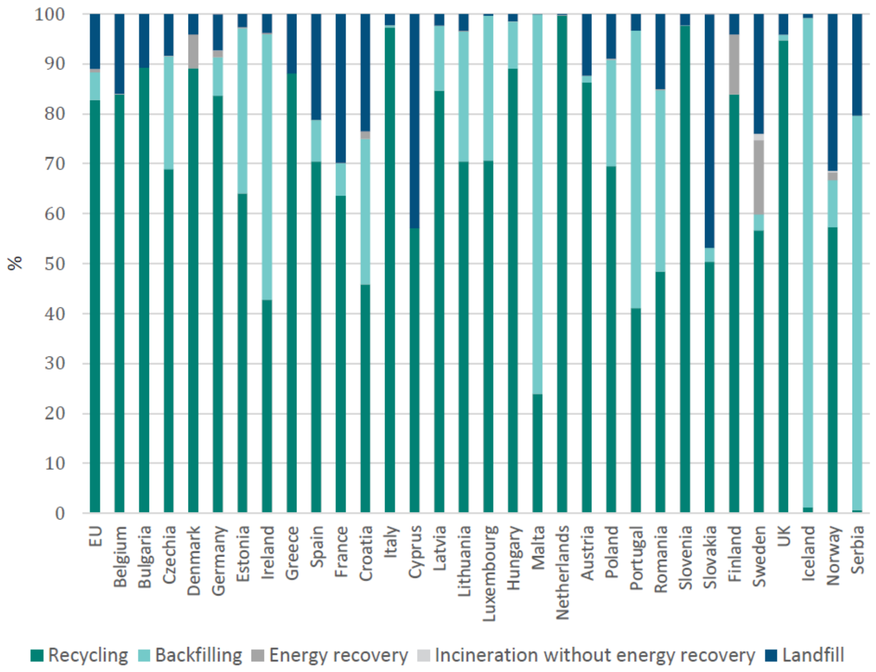

Figure 7. Treatment of mineral waste from construction and demolition in the European Union and countries in the European Economic Area. Source: Wahlström et al., 2020 [46].

From 2013 to 2017, the amount of waste from construction activities increased by 4%. However, the amount of waste sent to recycling decreased by 40% and waste sent to landfills more than tripled. The higher landfilling of waste was driven mainly by the increase of concrete waste sent to landfills, largely by demolition activities. The share of concrete, bricks and other heavy building materials sent to recycling decreased from 81% in 2013 to 37% in 2017 (79% to 30% if included concrete contaminated with other materials).

It is estimated that the construction sector uses around 4.4 million m^3 of concrete products [47], or around 10,5 million tonnes. This is a large discrepancy between the amount of materials used in Norway and the reported statistics for waste from SSB. Nordby [48] points to differences between estimates for domestic production plus imports, and reported waste from the construction sector in 2016 for wood, concrete, glass and steel, and show that the values reported for waste correspond to 5%, 6%, 13% and 33%, respectively. While it is possible that the waste of construction activities generates around 1/3 of the amount of steel used per year, the amount of wood and concrete waste it is likely underreported. In fact, SSB statistics report only on buildings which are required to have a waste plan [48], and other construction projects (other than buildings and associated roads etc) are not included [49].

A 20% of reduced material consumption [50] and a 10% re-use rate [48] in the building sector is estimated to be possible to achieve with efficient material use and proper sorting and design to

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SSB. Second, the statistics from Eurostat include other types of waste. According to Eurostat, "*Mineral waste from construction and demolition are for instance concrete, bricks, and gypsum waste; insulation materials; mixed construction wastes containing glass, plastics and wood; and waste hydro-carbonised road-surfacing material (legal definition is given in the EWC-Stat)*", which includes categories which are separated in SSB, namely asphalt (100% sent to recycling), mixed waste (100% incinerated) and gypsum (50% sent to recycling). Some countries might also include soil as a mineral waste in this category.

disassembly. By assuming an equal distribution among material types, a 20% reduction in the use of the main materials would yield savings of around 830 000 tonnes CO_2e, and a re-use rate of 10% would yield emissions savings of around 415 000 tonnes of CO_2e.

Refurbishment of buildings has a high potential for emission reduction. FME ZEN (Research Centre on Zero Emission Neighbourhood)[7] has carried out a study on life cycle assessment of buildings. For the investigated projects in this study, the CO_2 impact of refurbished buildings equals 2,3 $kgCO_2e/m^2/yr$, whereas the reference buildings have a average footprint of 6,3 $kgCO_2e/m^2/yr$ and 4,9 $kgCO_2e/m^2/yr$ for older and new buildings respectively[8]. The new buildings use materials that are lighter, have lower emissions and more robust, in itself circular measures. The refurbished buildings have, to a large degree, reuse of groundings and substructures, which are made of materials with high CO_2 footprint (steel and concrete materials).

The market characteristics

Improving circularity in the building sector should take into account the decentralised nature of the industry. Norway has a building stock of 4.2 million buildings, an increase of around 3% since 2015. 37% of the Norwegian building stock is comprised of residential buildings, a share that has remained stable for the past two decades. Around 57% of all building stock is located in four counties, according to SSB table 03158: Viken (21%), Innlandet (14%), Vestland (12%) and Trøndelag (10%).

Energy efficiency requirements will lead to a demand for refurbishment of the existing building stock. At the same time, the increase in zero-emission buildings (ZEB) and nearly zero-emission buildings (NZEB) will result in the demand for more different materials for insulation and energy generation [51], and the decrease in the demand for emission-intensive materials such as concrete towards less emission-intensive such as wood [52] might affect the domestic demand for production of non-metallic minerals and for forestry products.

Relevant public regulations and other framework conditions

Norwegian building regulations require the collection of information on components in buildings that can result in hazardous waste as these need to be removed before demolition starts [53]. The same data collection principles, and, possibly, database could also be used to also collect information on all other materials used in the building, thus making information about material contents easily accessible. In addition to the lack of information/data available, regulations regarding the reuse of construction waste pose barriers, especially if the reuse requires extensive paperwork, extensive testing, or if materials are not approved for reuse and recycling. The environmental authorities though are aware of the current limitations in the regulations and aim to further develop these to increase effective and environmentally responsible use of waste, also taking into account regulations from the EU and the European Economic Area [53]. Special attention needs to be paid to wood waste from buildings (of which currently 99% is used for energy recovery and only 1% for material recovery), concrete and mixed waste. The current national action plan for building and construction waste (Nasjonal handlingsplan for bygg- og anleggsavfall, NHP, [54]) is valid until 2020, so that the new version will take into account not only the EU Circular Economy strategy, but also the European Green Deal.

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[7] https://fmezen.no/

[8] https://www.sintef.no/siste-nytt/norge-bor-satse-pa-rehabilitering-framfor-nybygg/

Effective social innovations

There are some enabling innovations for improving the documentation and trust regarding origin and quality of waste from building activities. Material passports (also referred to as building passports or circularity passports) can give the necessary (standardized) methodology and data structure for collecting, handling and disseminating information on the material composition of the building stock and related products [55]. During a recent Horizon2020 project called Buildings as Material Banks (BAMB), over 300 material passports for products, components or materials were developed in order to map their potential for recovery, reuse and recycling to a range of stakeholders, such as product manufacturers, building owners, dismantlers, urban miners and material suppliers [46]. Madaster, a company based on the Netherlands, compiles information in a material passport for entire buildings. It includes information on materials characteristics, quantities, quality, location and monetary and circular value in an online and public platform with the aim to facilitate the reuse and minimization of waste [56].

Two enabling innovations in the recovery of waste materials are the design for disassembly (DfD) approach and selective demolition. Design for disassembly is a design approach that aims to build structures and products that are easy to disassemble into their individual components so they can be reused, reassembled, reconfigured or recycled. This design approach has been applied to the retrofitting of eight existing student housing regarding internal partitioning and façade, which can be transformed into other functional spaces without the need of further materials or generate construction and demolition waste. In addition, selective demolition has the goal to recover high-quality materials for reuse or recycling, based on information from pre-demolition audits. These audits serve to identify hazardous substances to be removed prior to demolition and assess the recycling potential of materials. Although selective demolition does not reduce the amount of waste generated by demolition activities, it can increase the volume of materials that can be reused or recycled, reducing the waste share that is destined to incineration or landfilling [46].

Critical market and technology developments

There are certainly barriers to companies to implement circular economy measures in the building sector. The lack of documentation and trust regarding of origin and quality of waste from building activities [46], of value chain integration [57] and of economy of scale [50] are some of the main barriers for early adopters. Thus, there is a need for regulatory and financial incentives for improving information on materials and for linking different actors in the value chain (product and building designers, constructors, demolition companies, and waste managers), coupled with better logistics and warehousing for heavy materials.

Circular material use in construction	
Emission reduction potential	- Reducing 20% material use in new buildings could lead to emission reductions of around **0.8-0.9Mt CO_2e** ± large uncertainties throughout the life cycle of construction materials. These savings relate to both direct and indirect emissions in Norway or abroad. - A rate of 10% of re-use of secondary material in new constructions and refurbishments, instead of primary materials, could reduce emissions by **0.4-0.5 Mt CO_2e** throughout the life cycle of construction materials. These savings relate to both direct and indirect emissions in Norway or abroad.
Key Barriers	- Documentation and information regarding the content and quality of building materials, such as technical performance, recycling rate and traceability of the materials
Enabling innovations	- Digitalization and Material passports to enable information sharing about materials embodied in components - Design to disassembly - Selective demolition - Material developments – lighter and more durable

3.3 Food waste

According to the Ellen Mc Arthur Foundation six garbage trucks of edible food are thrown away around the world each second. A circular economy strategy for tackling food waste could reduce emissions by sequestering carbon in soil and minimising carbon emissions in the supply chain – by designing out waste, keeping materials in use, and regenerating natural systems [58]. The forthcoming EU Food to Fork strategy will outline plans to achieve a circular economy for food that will aim to reduce the environmental impact of the food processing and retail sectors by taking action on transport, storage, packaging and food waste [59,60].

Østfoldforskning report that in 2017 over 385thousand tonnes of edible food, the equivalent of 73Kg with a value of just over 4000kr per Norwegian was thrown away. The emissions associated with the wasted food are 1.3 Mt CO2 equivalent yearly. The losses are spread along the value chain with the biggest food waste occurring during production (24%), in the shop (13%) and in the hands of the consumer (58%). The reasons that food waste occur vary along the value chain. In industry over production is a major cause with additionally some production errors and damage. The majority of food waste occurs in households with consumers citing limited shelf life of the foods as the top reason for throwing away food with bread in particular being a product that gets often wasted as consumers have a demand for high quality fresh products [61].

To reduce food waste in Norway there is in place an industry agreement on reduced food waste. The agreement, which was signed in June 2017, obliges the Norwegian authorities and the food industry to halve food waste in Norway by 2030, compared with 2015. The halving is to be achieved through the sub-targets 15% reduction by 2020 and 30% reduction by 2025.

In the trade agreement [62], food waste is defined as follows: "*Food waste includes all useful parts of food produced for humans, but which are either thrown or taken out of the food chain for purposes other than human consumption, from the time when animals and plants are slaughtered or harvested." In other words, food waste includes only edible parts of food that are thrown away, which means that* *inedible parts such as bones, cores, shells and the like. is not considered food waste. Food waste also includes food that is utilized as animal feed*.''

Within the food value chain bi products of production from agriculture and fisheries occur and these are discussed in more detail in Section 4.4.

Within the food production industry overproduction can arise due swings and variations in product demands. But demand adjusted decision support tools such as digital measuring for feedback loops through the supply chain can be used avoid overproduction and unexpected variation in sales by improved prognosis across value chains.

Food sharing such as toogoodtogo.no and holdbart.no, are alternative distribution channel for still edible food waste services. However, although growing these services need to be upscaled do this they need information sharing, knowledge about and systems to ensure food security, necessary infrastructure, supportive legislative framework as well as funding or financial incentives. There also needs to be financial or legislative incentive for shops and restaurants to donate rather than throw away food and currently food safety regulations hinder donation of food waste from private homes. France implemented 'Loi Garot' legislation in 2016 making the disposal of food from large supermarkets illegal, increased the number of supermarkets donating food from 33% to 93% within two years.

Empowering consumers to reduce food waste will have a significant impact with a reduction of 223kt of food equivalent of 0.75Mt CO_2e. Consumers have been successfully targeted in campaigns such as being more savvy regarding using food after the 'best before' dates marked on packaging. Actions such as providing consumers with more information about food durability and solutions such as storage can shift purchasing decisions and behaviour at home towards more sustainable choices with reduced food waste.

Ultimately in in Norway about 30% of all wet organic waste including municipal food waste and industrial food waste and biproducts are used to produce biogas with the remainder being sent to composting or incineration.

Opportunity:	**Reduction of Food waste**
Emission reduction potential	• **Approx. 1.1-1.3 Mt CO_2** equivalent total reduction (0.3 Mt CO_2e in production, 0.1-0.2 Mt CO_2e in transport and shops and 0.7-0.8 Mt CO_2e by the consumer). The food loss related to production and transport happens both in Norway and abroad, while the loss related to shops and consumers
Key Barriers	• Lack of cross supply chain production planning tools • Consumer behaviour
Enabling innovations	• Improved production planning and decision support across the supply chain • Incentivising food donations from supermarkets, restaurants and other industries. • Focusing on consumer education and changing public attitudes towards waste minimisation.

3.4 Services as an enabler for the circular economy

The service industry in Norway employs three quarters of the workforce, entails 80% of all registered businesses, is responsible for 18% of exports (mostly related to tourism and wholesale and retail trade services), 30% of intermediate imports and 40% of final imports (whereof 90% are related to

Norwegians traveling abroad). The service industry mostly consists of SMEs, i.e. businesses with less than 250 employees, see

Figure 88. Especially for wholesale and retail trade and repair of motor vehicles (Varehandel, reparasjon av motovogn), the high number of SMEs is driven by the fact that business chains such as the above mentioned Elkjøp and Power, but also car dealer chains are registered locally with their individual stores.

Especially the wholesale and retail trade industry, as well as repair and leasing services are central for a circular economy, as those are services needed for lifetime extension of products. Possible policy interventions are a lower value added tax on repair and renting services compared to selling new products and the product itself, as well as the introduction of a tax or other type of fee reflecting the actual GHG emissions associated with the product. If developed together with the players in the market, the former can result in a larger number of businesses offering these services as the options become economically profitable. The latter however is, unfortunately, beyond today's data availability. Scientific methods for a precise estimation of the associated GHG emissions exist, but the data for a robust estimation are not available.

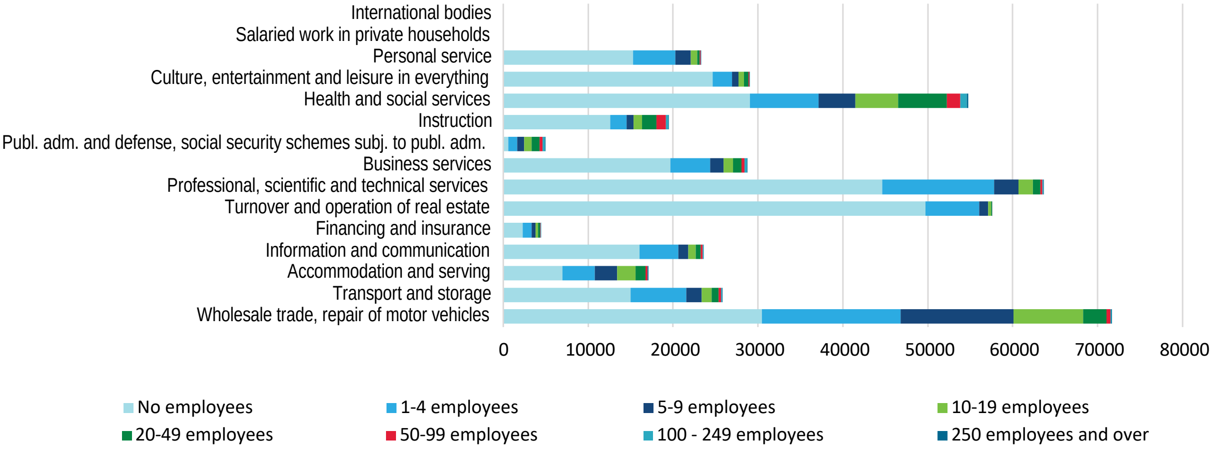


Figure 8: Virksomheter etter størrelse og næring. Source: https://www.ssb.no/291603/virksomheter-etter-storrelse-og-naering

However, an increase in demand for services goes hand in hand with an increase in related emissions, material use, and waste. Thus, when increasing the availability and use of services in the context of a more circular economy, it is important to consider possible increases in associated environmental impacts and put counter measures in place early, to avoid negative indirect consequences. Two aspects stand out when analysing environmental impacts of the service industry from a value chain perspective (see figure 9):

First, the service industry produces about 18% of total waste in Norway, but about a third is mixed waste, and not sorted or recycled, resulting in about 550000 t CO_2 emissions [63]. According to an analysis of Avfall Norge [64], the largest part of this mixed waste is plastics. See Section 4.3 for emission reduction potentials from improved plastics recycling. But, also for other types of waste there is potential for a better sorting and recycling system, not restricted to only the service industry, but also other industries, public institutions and private households. Technological and regulatory systems must be put in place to facilitate the uptake of urban mining possibilities as inputs into industry, e.g. food waste as an input into aquaculture and fisheries [65].

Second, while the service industries (excluding transport) only have a share of 3% in direct emissions, they have a share of 35% in Norway's indirect emission. About one fifth of this is related to upstream use of transport services. More than a quarter of all kilometres driven by trucks in Norway are driven without cargo [66], making room for large improvements in emissions from transport services through optimised logistics. Based on direct emissions from land transport of about 2.2 Mt CO_2e in 2018, see Figure 1, this could amount to about 0.5-0.6 Mt CO_2e emissions reduction potential. These can for example be delivery services that collect packaging waste or goods to be repaired, remanufactured or recycled. Minimizing transport packaging by e.g. using higher quality reusable containers is another example that simultaneously reduces transport needs as well as waste. Klimakur 2030 [67, Table T04] for example shows that through optimised logistics and higher efficiency up to 200000 t CO_2 can be saved annually in 2030. Given the international character of freight, and the commitments made by Norway through the EEA agreement, the list of policy options open to Norwegian authorities on the freight side includes for example [37]: Enhanced railway and cargo handling capacity with indiscriminate access for all operators; Enhanced priority for freight trains in existing network; Foreseeable, gradually sharpened biofuel regulation, ensuring predictability for private investors; Support for transfer of shipments from road to sea or rail; Support for common freight distribution trial schemes in major cities. Other existing ideas are a reduction of fossil-fuel-based transport at the beginning and end of transportation routes, by using e.g. electro-scooter or electric cargo-bikes as envisioned by e.g. DHL and already implemented as Armadillos by https://www.velove.se/. In addition, regulations for transport routes and the means of transport used for certain waste categories such as electronics or hazardous mixed waste could be re-evaluated [53].

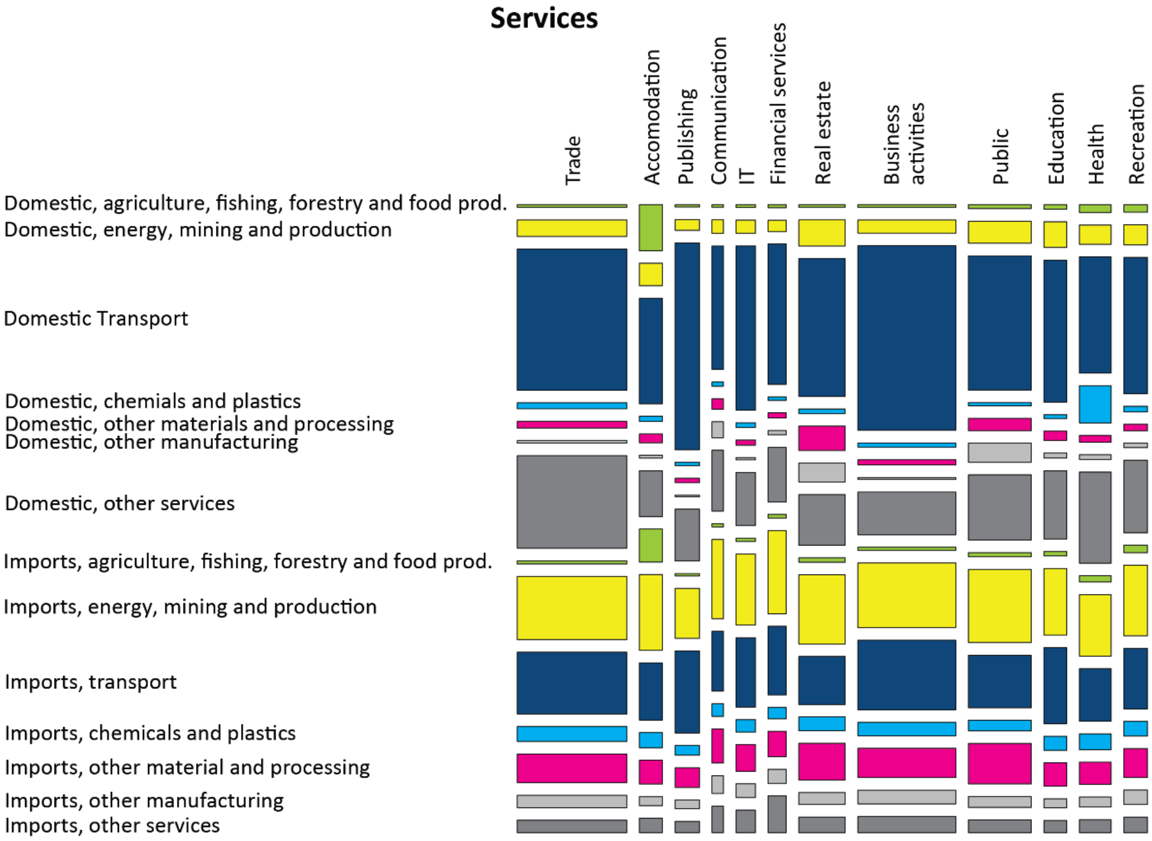


Figure 9: Origin of direct (domestic) and indirect (imports) emissions CO_2 emissions of the service industries in 2015. Source: Own calculations based on OECD ICIO [5–7]

The wholesale and retail trade industry can support the transition to a circular economy through the implementation of new business models and strategies to support consumers in more environmentally friendly and sustainable choices. The Norwegian government envisions Norway to be at the forefront of the transition to a more sustainable development. This requires further [68]

- An introduction of regulations supporting the industry to develop and adopt new business model
- That the Norwegian trading industry is equipped to meet the competition from foreign players and to exploit the opportunities offered by e-commerce to compete in the international market
- That the focus on digital competence - both in education and in continuing education - continues, so that Norwegian business and trade can develop and apply new technology
- A strict competition law that is effectively enforced by the competition authorities
- An innovation policy that contributes to new solutions that would not otherwise have been developed and that stimulate increased competition and innovation.

Opportunity: Services industries	
Emission reduction potential	• Use of optimised logistic including sharing of transport space and using transport means for different purposes to avoid empty driving, fully avoiding empty driving has the potential to reduce emissions by **0.5-0.6 Mt CO_2e** • Similar calculations (as those for electronics and textiles) for other consumer products and increasing the demand for repair and share service, results in an emission reduction potential is close to **5% (approx. 0.7-0.9 Mt)** of consumption-based emissions, with least savings in Norway and most in non-OECD countries
Key Barriers	• Changes in consumer behaviour • Incentives in the tax system are not designed for the circular economy • Taxing labour and not materials and (dirty) energy
Enabling innovations	• Taxing materials and non-renewable energy instead for labour • Reform of tax deduction system, prolonging economic lifetime of capital goods • Maintenance contracts, training contracts, leasing, renting, pooling • Digitization of information around share services • Digital (tracing and) information about materials embodied in in goods and related repair possibilities

3.5 Summary of emission reduction potential in use side of materials in goods and services

We have examined the cases related to consumer products, using the example of electronic and electrical equipment (EEE), textiles, and private mobility; transport in the service industry; construction sector, i.e. housing; food waste; and services as an enabler. The cases are selected based on macro-level analyses of emission in Norway and on the study by UNEP Resource efficiency and climate change. The UNEP study summarizes emission reduction potentials through more efficient use of materials and estimates that 80% of emissions from material production were associated with material use in construction and manufactured goods.

The total potential for reductions in CO_2e emissions from the use side based on the cases examined here are about 5-6.5Mt CO_2e. This can be compared to direct Norwegian CO_2 emissions (according to the OECD data) of about 45Mt CO_2, indirect emissions of about 46Mt CO_2, total consumption-based emissions (household, government and investment) of about 53Mt CO_2 and households' consumption-based emissions of about 20Mt CO_2 (25Mt when including direct household emissions). The selected cases mix the consumption-based perspective with the production-based direct and indirect emission accounts, making it difficult to summarize the impact on either one of these perspectives in relative terms. However, our macro-level analysis shows that we cover almost 20% of consumption-based emissions of Norwegian households (EEE and textiles each for about 5%, motor vehicles and fuel for about 9%). We find that through consumer goods repair and share strategies, also covering other goods like furniture and tools, can save up to 5% of consumption-based emissions annually. This does not include the first, refuse, and third, reduce, of the circularity strategies [1] from a consumer perspective. While Norwegian consumption has increased slower in the last years than previously [25], there is large potential to actual reduce the consumption of goods and, thus, emissions related to these. The construction sector is responsible for 3% of direct, 12% of indirect emissions and more than a third of emissions related to Norwegian investment activities from the consumption-based perspective. Here, circularity strategies from the producer perspective are vital, e.g. replacing virgin materials in concrete production by secondary and waste materials, see Section 4.2. The service industries play a vital role as an enabler for the circular economy by providing repair and share services. While only about 4% of direct emissions occur during the economic activities of the different service industries (excluding the transport industry), these account for 35% of indirect emissions and these are dominated by transport services. Here, a better usage of transport capacity through circularity strategies, such as sharing, is essential and has untapped potential in Norway.

Box 3: Digitalization and the Circular Economy

Despite the growing interest for the circular economy, resources are reused at volumes far below what is *actually* possible. If this system were to be improved, loss of value, dependence on volatile commodity markets, and environmental pollution could be avoided [206]. An increased drive towards digitalizing the circular economy could make this happen, paving the way for a more efficient and effective circular economy, the *Smart Circular Economy* [207,208]. Hence, correctly leveraging digital technologies may enable a step change that goes beyond incremental efficiency gains towards a more sustainable mode of business operation and low-carbon society development.

A new digital roadmap for the circular economy

Acknowledging the potential of the smart circular economy, various sources have voiced calls for work that links digitalization and the circular economy. For instance, a number of studies [209–213] aim to raise awareness of the potential of digital technologies to support circular economy strategies through calling for research and innovation. Focus has also been put towards investigating how digitalization relate to product-service systems through usage- and performance-based business models {214–216]. Policy initiatives are also underway such as the Digital Roadmap for the Circular Economy by the European Policy Centre [211] and the Circular Economy Action Plan by the European Commission [191,217], which includes a call for the creation of an architectural and governance infrastructure in the form of a dataspace for smart circular applications.

Circular economy implementation is a problem of information logistics

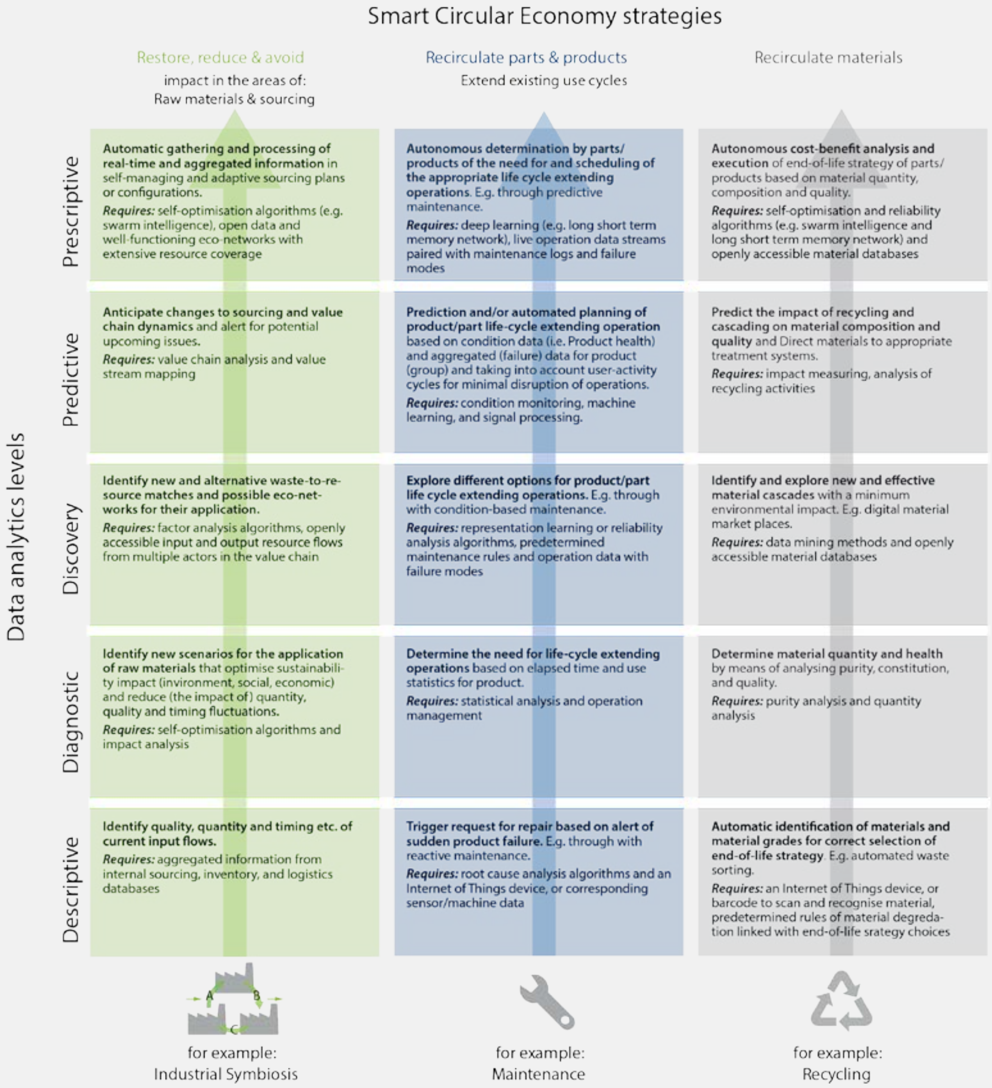
Central to the failed operation of current closed-loop system is the observation that this has primarily failed as a result of missing, or lack of integration, of information [206]. In particular, information pertinent to the location, availability, and condition of products, components, and materials that allow for the effective cascading or extension of its lifecycle [209]. Hence, the transition towards a circular economy will require enhanced coordination of material and information flows. It is crucial that information about the quantity and quality of products and the raw materials they contain are kept together with the physical materials in the cycle.

Digital technologies form the building blocks

In other words, digital technologies such as IoT, Big Data, AI, and Blockchain form the operational building blocks of the *smart* circular economy; increasing the efficiency, enhancing the effectiveness, and facilitating the adoption of circular economy concepts at scale. See Figure 10 and Figure 11 below for building blocks and examples of data analytics optimizing industrial symbiosis, maintenance, and recycling.

Figure 10 Building blocks of the Smart Circular Economy

Box 3: Digitalization and the Circular Economy cont.



Data analytics levels	Restore, reduce & avoid impact in the areas of: Raw materials & sourcing	Recirculate parts & products Extend existing use cycles	Recirculate materials
Prescriptive	**Automatic gathering and processing of real-time and aggregated information** in self-managing and adaptive sourcing plans or configurations. *Requires:* self-optimisation algorithms (e.g. swarm intelligence), open data and well-functioning eco-networks with extensive resource coverage	**Autonomous determination by parts/products of the need for and scheduling of the appropriate life cycle extending operations**. E.g. through predictive maintenance. *Requires:* deep learning (e.g. long short term memory network), live operation data streams paired with maintenance logs and failure modes	**Autonomous cost-benefit analysis and execution** of end-of-life strategy of parts/products based on material quantity, composition and quality. *Requires:* self-optimisation and reliability algorithms (e.g. swarm intelligence and long short term memory network) and openly accessible material databases
Predictive	**Anticipate changes to sourcing and value chain dynamics** and alert for potential upcoming issues. *Requires:* value chain analysis and value stream mapping	**Prediction and/or automated planning of product/part life-cycle extending operation** based on condition data (i.e. Product health) and aggregated (failure) data for product (group) and taking into account user-activity cycles for minimal disruption of operations. *Requires:* condition monitoring, machine learning, and signal processing.	**Predict the impact of recycling and cascading on material composition and quality** and Direct materials to appropriate treatment systems. *Requires:* impact measuring, analysis of recycling activities
Discovery	**Identify new and alternative waste-to-resource matches and possible eco-networks for their application.** *Requires:* factor analysis algorithms, openly accessible input and output resource flows from multiple actors in the value chain	**Explore different options for product/part life cycle extending operations.** E.g. through with condition-based maintenance. *Requires:* representation learning or reliability analysis algorithms, predetermined maintenance rules and operation data with failure modes	**Identify and explore new and effective material cascades** with a minimum environmental impact. E.g. digital material market places. *Requires:* data mining methods and openly accessible material databases
Diagnostic	**Identify new scenarios for the application of raw materials** that optimise sustainability impact (invironment, social, economic) and reduce (the impact of) quantity, **quality and timing fluctuations.** *Requires:* self-optimisation algorithms and impact analysis	**Determine the need for life-cycle extending operations** based on elapsed time and use statistics for product. *Requires:* statistical analysis and operation management	**Determine material quantity and health** by means of analysing purity, constitution, and quality. *Requires:* purity analysis and quantity analysis
Descriptive	**Identify quality, quantity and timing etc. of current input flows.** *Requires:* aggregated information from internal sourcing, inventory, and logistics databases	**Trigger request for repair based on alert of sudden product failure.** E.g. through with reactive maintenance. *Requires:* root cause analysis algorithms and an Internet of Things device, or corresponding sensor/machine data	**Automatic identification of materials and material grades for correct selection of end-of-life strategy**. E.g. automated waste sorting. *Requires:* an Internet of Things device, or barcode to scan and recognise material, predetermined rules of material degredation linked with end-of-life srategy choices
	for example: Industrial Symbiosis	for example: Maintenance	for example: Recycling

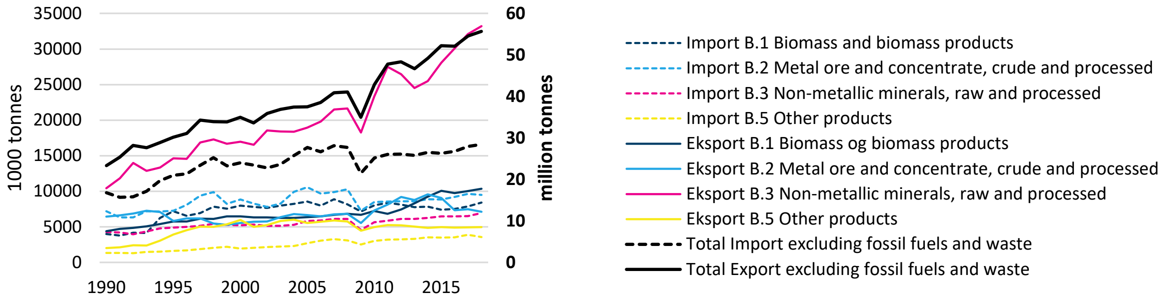
Figure 11 Example smart circular economy strategies using different levels of data analytics. Source: Kristoffersen et al., 2020 [208]

Further reading, "The Smart Circular Economy Workbook":
https://orbit.dtu.dk/files/210455530/WB4_CIRCit_double.pdf

4 Material production, emissions, and recycling opportunities

Material production and processing is central in a circular economy. Norway has, over the past decades, been a materials net-exporter, even when excluding oil and gas products. Figure 11 shows that this has been and is still driven by raw and processed non-metallic mineral products. In addition, in the last years biomass exports became increasingly important. The trade balance of metal ores is fluctuating. Iron ores as well as raw and processed iron and steel have a large export surplus, while the share of non-ferrous metal imports increases[9].

Figure 12: Material imports and exports excluding fossil fuels and waste. Source: SSB table 10321



The circular economy transition will bring about changes in the material flows, increasingly replacing primary raw materials with secondary materials recycled from waste, both industrial and household, and a better utilization of by-products from industrial production. The Ellen MacArthur Foundation [69] estimates that global CO_2 emissions from key materials, steel, aluminium, plastics and cement, can be reduced by 40% by 2050 through increased waste elimination, product reuse and materials recirculation, see figure 13

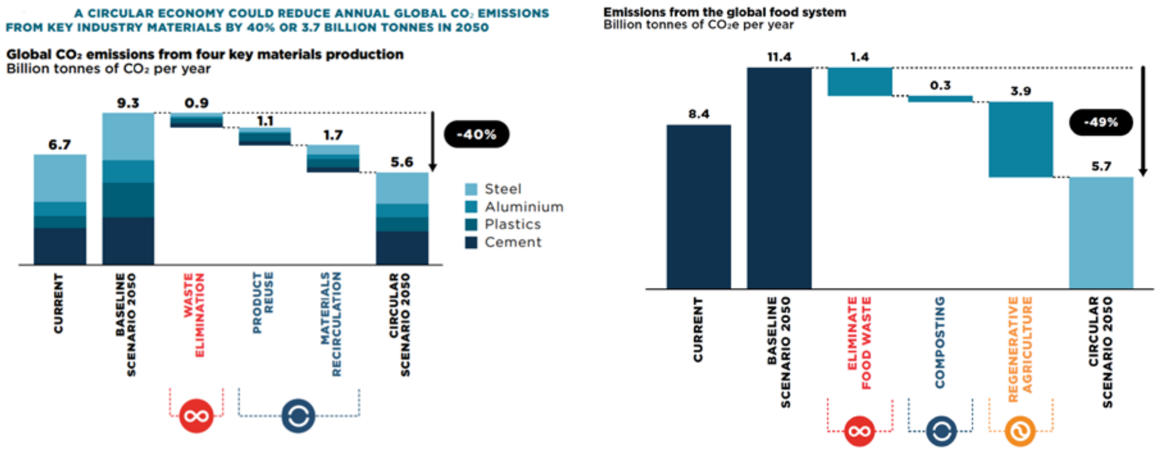


Figure 13: Possible emission reductions by material in a circular economy. Source: Ellen MacArthur Foundation [69],

While iron and steel production in Norway is relatively small, Norway produces almost 3% of global aluminium, 4% of global silicon and ferrosilicon and more that 3% of global ferromanganese [70]. Emissions in the process industry subject to the European ETS are dominated by emissions from ferroalloy and aluminium production [71], Panel b) in Figure 13. These emissions are, for the most part, process emissions and not related to the burning of fossil fuels for energy (Section 4.1). A large share

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[9] Note that data from SSB (table 10221) for the extraction of non-ferrous metals is not available for the years after 2015, thus related production and trade data should be analysed with care.

of the emissions from mineral production is related to cement (Section 4.2). While plastics production in Norway is a relatively small industry, the use of plastics and, thus, related emissions are just as high as in other countries (Section 4.3). But also emissions related to biomass can be reduced significantly through circular economy actions, amounting to 49% emission reduction through circular economy strategies in the global food-system alone [69] (see Figure 13 and Section 4.4).

a) Emissions from ETS and non-ETS sectors

b) Emissions from material production under ETS

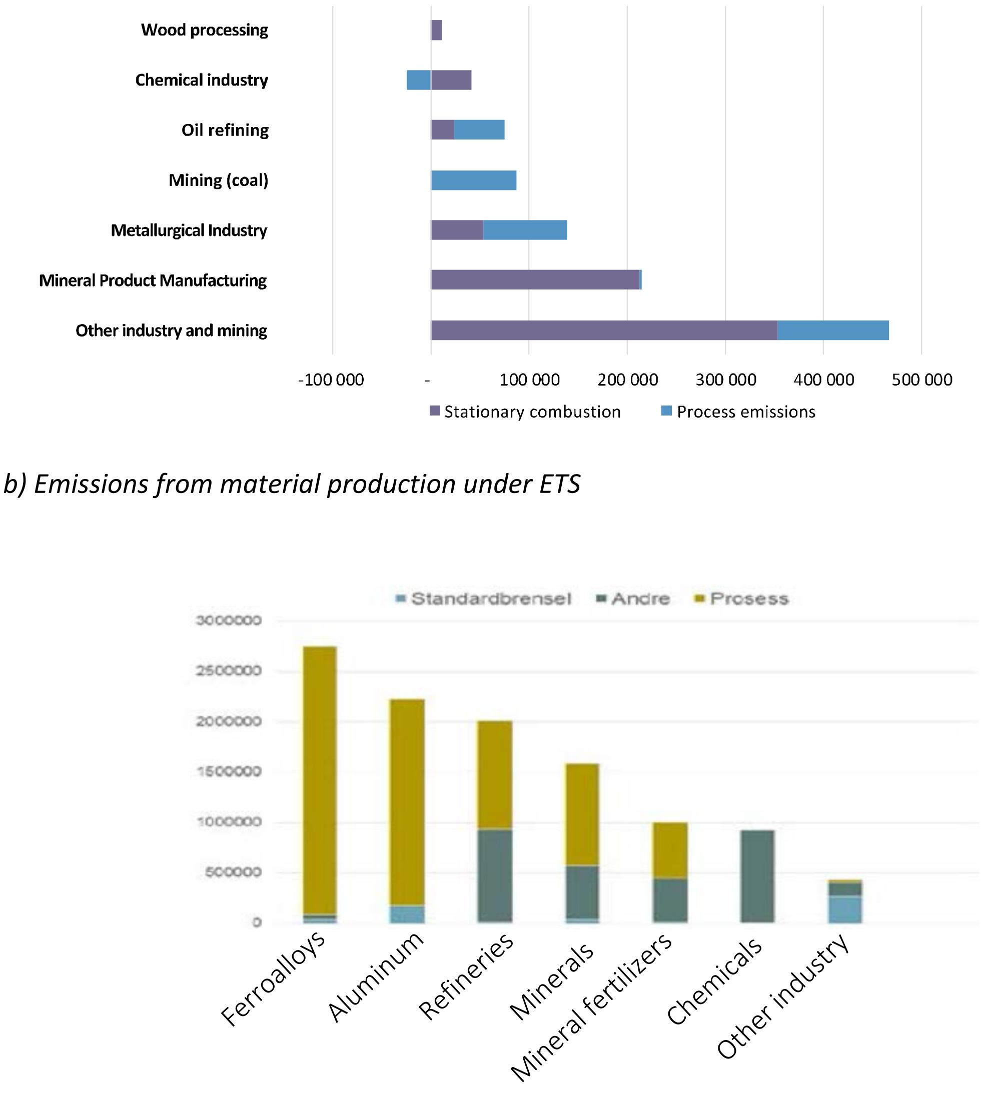

Figure 14: Emissions from industrial production. Source: Klimakur 2030 [67], Norsk Industri [71]

4.1 Metals and metalloids: aluminium, steel and ferroalloys

Norway is producing between 3% and 4% each of global aluminium and of ferroalloys such as silicon, ferrosilicon and ferromanganese. In 2014, emissions from ferroalloys and aluminium dominated emissions from the process industry subject to emission quotas in the European Emission Trading System (ETS)[10], Panel b) in Figure 14. These emissions are primarily related to using fossil reduction

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[10] For more information on the EU ETS, see: https://ec.europa.eu/clima/policies/ets_en

agents in metal production for removing oxygen from the ores. In the case of aluminium, for example, carbon is used as an electrode in electrolysis. Emissions related to energy use subject to ETS quotas in this energy intense industry are low in Norway compared to other countries due to the abundance of renewable energy sources such as hydropower, historically, and increasingly also wind. Though, the share of emissions from stationary combustion increases to about a third of total emissions, when also accounting for non-ETS emissions, Panel a) in Figure 13.

The technological obstacles

Aluminium can theoretically be recycled endlessly without compromising its properties, though some small quality decreases are present [72,73]. Together with a readily available recycling technologies for aluminium, about two thirds of aluminium produced globally is still in use. Aluminium is strong, durable and lighter than other metals, thus opening room for replacing steel or other materials in different contexts. If e.g. used in transport means such as cars but also trains or ferries, those will need less fuel/energy over their operational lifetime [74]. One challenge when it comes to recycling of aluminium is the plastic/aluminium laminates, often found in food packing. An estimate of 700 tonnes aluminium is wasted yearly in Norway as packing waste. In Europe, the estimate is 24 000 tonnes and the estimated potential reduction in emissions if the aluminium from the packages are recycled is 40 000 tonnes CO_2e in Europe [75–77]. Steel and ferroalloys, while recyclable, loose quality in their properties faster than aluminium. Nonetheless, they have a high recyclability when compared to other material such as paper or wood.

In addition, by-products of metal production should be used as resources rather than discarded as waste. However, today, several technological and physical barriers exist:

- The elements of interest are always mixed with other unwanted elements.
- Existing methods for separating the elements are often complex and of multi-step nature.
- Existing methods of separation/refining are often sensitive for variations in the composition and conditions.
- The level of dilution has come too far, the cost of recycling is larger than the value of recycled materials with current technologies.
- Unwanted elements from one industry might be an interesting raw material for another but current cross value chain collaboration and symbiosis is immature or lacking.
- The volumes at one site may be too small for economical treatment, but economy of scale at one central site may improve the situation.

Hydrogen, for example, has potential to be used a reducing agent in metal processing and is a by-product of several industrial processes. However, full exploitation of the available hydrogen today is not possible due to challenges especially regarding transport, storage and safety. [78]

For other materials, such as EAF dust, better collection, identification and sorting technology will help more waste, including hazardous waste, to be sorted for material recycling and biological treatment. This provides the opportunity for financial benefits and reduced environmental impact in the process industry, which can utilize recycled raw material that meets company specifications and quality requirements.

The magnitude of possible emission reductions

Producing aluminium from recycled materials uses only 5% of the energy that is necessary for aluminium production from virgin materials (at global average). Recycling the 400 million tonnes of aluminium that are in the global building stock over and over again therefore has large potentials for emission reductions. [74] In Norway however, the aluminium industry uses primarily hydropower, so that non-process emissions are already low. With all non-process energy coming from hydro-power and the newest technology in place, CO_2 emissions per kg of primary aluminium produced at Hydro's plant in Karmøy are 3.5kg, which is less than 20% of the global average of aluminium production based on coal [79]. ETS missions from primary aluminium production in Norway currently are about 330 000 tonnes, that is 9% of total ETS-emissions, see Table 2. A complete switch in Norway from primary to secondary aluminium production has a much lower effect on global emissions that the switch to secondary aluminium production other countries. In a global systems perspective, Norway should continue producing primary aluminium as the gains for switching to secondary aluminium production are low, whilst the world continues to need a certain supply of primary aluminium. Something that should be produced in Norway, rather than in other countries. A complete switch in Norway from primary to secondary aluminium production has a much lower effect on global emissions that the switch to secondary aluminium production other countries. In a global systems perspective, Norway should continue producing primary aluminium as the gains for switching to secondary aluminium production are low, whilst the world continues to need a certain supply of primary aluminium. The overall global emissions would be improved by a larger adoption of Norwegian Primary aluminium compared to primary aluminium for other production land with fossil-based energy processes.

While globally, steel production has a significant emission reduction potential, this is not the case for Norway. Celsa Steel Service is Norway's largest recycling company[11], producing about 700 000 tonnes of steel 100% from scrap metals every year. Their process for manufacturing reinforcement steel is Europe's cleanest with only 360kg CO_2e / tonne of steel[12] [80]. "*In the next five to ten years, CO_2 emissions reductions can most easily be achieved by accelerating deployment of energy efficiency measures and best available technologies. This includes increasing secondary production by improving scrap collection and sorting.*" [81] There is a large market potential especially for reinforcement steel as, currently, only 50% of related scrap metal is collected. TiZir Titanium & Iron produces a high-purity pig iron as a co-product of their titanium slag production [82]. This use of co-products is completely in line with circular economy strategies.

Klimakur 2030 visualizes emission reduction potentials for the process industry, Figure 14. Energy efficiency, heat recovery and conversion to renewable alternatives are measures that reduce emissions from stationary combustion of fuels. It is the measures for conversion to renewable energy carriers that together constitute the greatest potential for emission reductions [67]. Reducing process emissions often requires new technologies to replace carbon in the reduction process. If available at all, these technologies currently have a very low technology readiness level (TRL -ie. are immature), and need significant amounts of further research and development activities [78]. In addition, process differ significantly for different materials and through different steps in the processes, so that these technologies or opportunities cannot be generalized.

But circularity strategies in the metal industry are not only the recycling of individual metals, but also a better use of raw and secondary materials. The materials in the side streams can be utilized regardless of whether these are classified as waste or by-product. Given the low level of technological development for a better use of these by-streams, possibly the best short-term strategy for reducing emissions related to materials from the process industry is an increased life-time of products [78]. Given the low level of technological development for a better use of these by-streams, possibly the

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[11] See also: https://celsa-steelservice.no/hvem-er-vi/celsa-armerongsstal-var-leverandor/

[12] See also: https://celsa-steelservice.no/produkter/

best short-term strategy for reducing emissions related to materials from the process industry is an increased life-time of products [78].

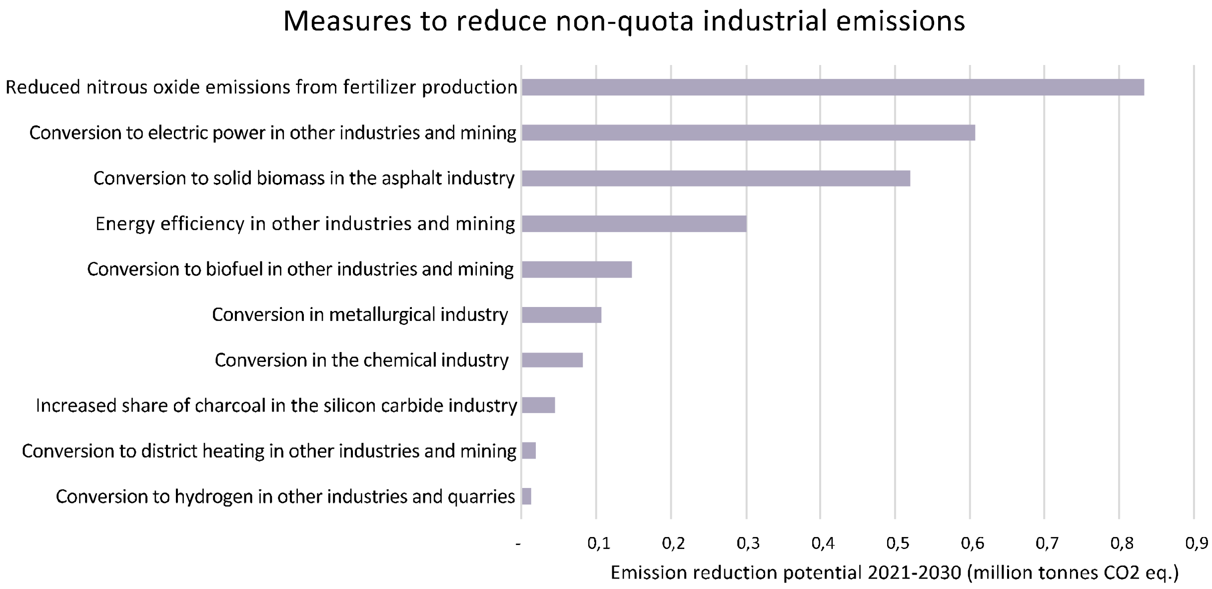


Figure 15: Emissions reduction potential for non-ETS emissions. Source: Klimakur 2030 [67]

The market characteristics

The Norwegian process industry produces 30% of Norwegian exports, but only 20% of emissions, it is energy- intensive, but has access to renewable hydropower, is geographically spread (value creation happens in the districts where the raw materials are located) and is raw material based.

In 2018, the metallurgical industry accounted for just under 15% of non-quota industrial emissions. The emissions come from the production of iron, steel, ferro alloys, aluminum, anodes and other metals. There are five companies that we find worth mentioning, and all of which annually have non-quota emissions of more than 15,000 tonnes of CO_2 equivalents. These five are: Yara Porsgrunn (kunstgjødselfabrikken), Fiven Norge Lillesand, REC Solar, Hydro Aluminium Holmestrand og Elkem Carbon [67]. Several plants from ferroalloy, iron and steel and primary aluminium production exceeded according to data from norskeutslipp.no [83]

Urban mining is the term used when extracting materials from spent products building and waste. Today there is limited recovery of resources from many complex products. Sound recovery of these materials is still a global challenge the importance of which is illustrated particularly in part 2 of this report. It is known that manufacturing from recycled materials requires much less energy than producing the same products from natural resources, in average 17 times less [84]. Water usage and emissions are also usually much higher in primary production than in recovery and recycling processes. Norway's industry, with a high proportion of renewable hydroelectric energy, could beneficially provide recovery and recycling services with lower energy intensity leading to good international competitiveness in a greener future. An example is electronic equipment, as mentioned in section 3.1.2, recovery and recycling offer a substantial resource as well as economic benefits. Urban mining with recovery of particularly critical raw materials form secondary products and further technology development in Norway and Europe would be lessen our dependency on imports in a resource scarce future market. The challenge is how to effectively and sustainable regain as much as possible of these complex materials.

Relevant public regulations and other framework conditions

A feasibility study on circular economy in the process industry has shown that harmonization and simplification of EU legislation is important. Imperative is also to continue to have a good dialogue with Norwegian environmental entities and the process industry [85]. Research and development will promote circular economy, especially if the focus shifts to industrial research and development. The research should have a long-term focus, preferentially 4-8 years. Commercialization of products with a low environmental footprint should be given special attention. Even though the total amount of waste from the process industry has been reduced and that the industry is able to utilize more bi-products, the process industry is faced with more financial, market, regulatory and technical barriers that challenge the work with a circular economy. Norwegian industry has identified frameworks and means of measures that will further promote a circular economy in the process industry.

Two Norwegian laws that are relevant for the process industry in the context of a circular economy and require revisions to support the transition to a more circular economy are the pollution act (Lov om vern mot forurensninger og om avfall [86]) and the competition act (Lov om konkurranse mellom foretak og kontroll med foretakssammenslutninger [87]). Relevant revisions of the former relate to a re-classification of waste for better transport, usage and recycling opportunities, an increase in the costs for waste disposal and possibly an introduction of deposits on certain materials, so that returning materials becomes economically cheaper than disposing them (following the slogan: Give waste a value). The latter (competition law) needs to make it possible to provide by-products such as waste heat at low prices to the users of waste heat, even if this means competitive advantages for those located in the proximity as e.g. in the case of vegetable growing in greenhouses that use the excess heat from the nearby processing plant.

Effective social innovations

An increase in the demand for environmentally friendly industrial products is a crucial market force for fostering the circular transition in the process industry, including waste reduction and better resource utilization. However, there is, no active responsible institution for better utilization and recirculation of metals in Norway and therefore there is no knowledge of where the materials are or who may use the material and thus, also a lack of suitable processes, both administrative, organizational and technological. Again, digital platforms for information collection and sharing are a crucial enabler for this. These could report on the availability (amount and location) of by-products and excess heat, as well as collecting information on transport possibilities. The national infrastructure for transport, would of course need to be adjusted to facilitate this through available rail and pipeline infrastructure, related logistics and regulations, including safety issues for e.g. general and hazardous waste management, hydrogen, and CCS. On the local level, programs for supporting a closer collaboration in industry clusters, such as Eyde or Thamsklyngen, could be developed together with the industry. Public support programs for green investments can foster the faster uptake of circular technologies. In addition, research programs for the process industry need to have a longer time horizon as the currently available ideas for environmentally friendly production technologies are at a very low Technology Readiness Level and need several more years of development [78].

Critical market and technology developments

In the Norwegian metal producing industry, where electricity comes mostly from hydropower, the reductant materials used are the key to reducing greenhouse gas emissions. The currently used fossil carbon may in the future be replaced by 1) biocarbon or 2) alternative reductants, such as hydrogen. Both of these would increase the circularity of the industry. Biocarbon represents the high-TRL option as currently used furnaces could continue to operate with biocarbon. Hydrogen is the low-TRL option as most metals and metalloids produced in Norway today do not have hydrogen-based alternatives available at industrially mature technology (TiZir being the main exception). In the long-term, hydrogen is nonetheless a prime candidate as it is currently produced in the chemical industry but largely emitted as a waste-product (due to safety and technical issues with respect to handling, transport and storage) [78,88,89].

In metallurgical industries, there are several types of by-products with significant potential for increased use and circularity. Prime candidates include different types of slags, dusts and sludges from electric arc furnaces as well as electrolytic cells. Slags represent inert, ceramic materials with the potential to replace certain minerals and construction materials in at least some applications in the future. Dusts and sludges are more complex, granular materials which often contain valuable compounds, including metal oxides with the potential to be extracted (urban mining) [89–93].

Opportunity: Circularity for emission reduction in the metal industry	

Emission reduction potential	• **Limited** emission reduction potentials in iron and steel industry: Celsa and TiZir are producing steel from scrap metal and steel as a co-product, see next section.
	• Some 0.2 Mt CO_2 emission reduction potential by switching from primary to secondary aluminium production. However, considering the entire global production system, the switch to secondary aluminium production should occur in other countries, while Norway can be among the few that continue producing primary aluminium.
	• **Unknown** emission reduction potential through better use of by- and waste products
	    • By-product hydrogen for reduced use of fossil-based reducing agents
	    • Heat for other processes, agriculture (in greenhouses), and housing
	    • Rare metals and possibly hazardous by-products

Key Barriers	• Steel and aluminium production should be seen in the global context • Low to very low TRL for technologies that reduce process emissions • Varying TRL for technologies for a better utilization of by-products • Economically costly due to highly specialized equipment needed combined with too little quantities for recycling • Regulatory barriers for utilization of by-products, e.g. those that are classified as waste or those that might result in competitive advantages • Regulatory barriers for transport of by-products • Safety issues for transport and storage of hydrogen
Enabling innovations	• Digitization for a better utilization of side-streams and by-products • Technologies for safe transport and storage of hydrogen • Better collaboration possibilities in industry clusters, through enabling rules and regulations, digitization of information, shifts in business models, prioritizing • Long-term public and private RD&D investments • Public support for investments in climate and environmental technologies

4.2 Cement

The technological obstacles

Emissions during cement production occur through energy use for the processes and the processes itself. While on the energy side, coal can be replaced by other materials, not only renewables, but also waste products from industrial production or other waste. Norcem for example uses food waste, fuel blends from hazardous waste, carbon anode coal from aluminium production, and animal meal to replace fossil energy carriers. On the material input side, they replace virgin materials such as silicon, iron and aluminium with by-products and waste products of processes that have high contents of these materials. Some of these secondary materials are imported from example Germany, while others are available in Norway. [85,p.16]

The magnitude of possible emission reductions

Although the cement content of concrete is only between 7–20%, it amounts to 90-95% or more of the CO_2 footprint [69,94]. The major cement producer in Norway is Norcem, producing about 2.5% of total Norwegian emissions [95]. While the market for cement, thus, is easily manageable for public authorities, there is a large number of concrete producers. And it is that stage where "new" cement should partly replaced by broken concrete for concrete production.

The Mission Possible Report [96, Exhibit 5.6] estimates a 35% emission reduction potential from cement in buildings use through circular strategies. Applying this to the about 2.5% of Norwegian emissions that are due to cement production in Norway, results in a reduction potential of 0.6-0.65Mt CO_2 emissions (35% * 2.5% * 74Mt). Assuming that Norwegian cement production also relies on hydropower, the reduction potential of 35% might be very high. To correct for this, we assume some uncertainty and conclude that there might be a total emission reduction potential of 0.4-0.65Mt CO_2.

However, emission reduction potential outside Norway is substantial. Research from a Norwegian project [97] for example showed that when replacing coal by plastic and other waste in Chinese cement production, up to 100Mt CO_2 can be saved annually, that is more than all of Norway's emissions in one year. However, burning plastic waste is only the very last of the R-strategies "R9 recover energy" (see Box 1). This research has now been scaled up and extended to a large number of Asian countries [98], where parts of Norwegian plastic waste is exported to. This shows the importance of looking beyond Norwegian borders for identifying circular economy potentials for reducing GHG emissions. It is also of note that whilst concrete waste is largely environmentally inert the large volume of concrete waste generated by building demolition is large and difficult for landfills to accommodate.

Relevant public regulations and other framework conditions

The goal for 2020 is to reuse/recycle 70% of construction waste. Two regulations are crucial for cement [94]: First, the regulation for Chrome 6 (Cr6+) needs to be changed for an easier reuse of concrete and other demolition waste. And, second, todays standard for concrete production (NS-EM 206, tilleg E) has a restriction on the content share of broken concrete in the aggregate (maximal 30%), which need to be increased to allow for higher rates. In addition, the Norwegian environmental authorities are currently considering the introduction of a new chapter on the proper (re)use of lightly contaminated concrete in the waste regulation (Lov om vern mot forurensninger og om avfall [86]) [53].

Effective social innovations

In the UK, the introduction of a fee of 1 £/tonne on raw materials such as sand or gravel resulted in higher production and use of secondary materials such as broken concrete [99]. This could be tested in Norway as well, possibly with introducing additional incentives for reusing secondary materials (introducing 'green' certificates), by developing higher demand for this from both private households, but even more so as a precondition for public procurement.

A large-scale information and education program for workers at construction sites and their supervisors can help with a better understanding of circular economy principles and aid the identification of circularity options at the local level. This can support the introduction of new business models, but even entirely new businesses specializing in the collection of (information on) available secondary construction material.

Opportunity: Cement from recycled materials	
Emission reduction potential	- Estimation with high uncertainties, based on emission shares, total emission and reduction possibilities at different geographical levels and years **0.4-0.65Mt CO_2e**, but it could be significantly higher
Key Barriers	- Regulatory issues with waste classification - Regulatory issues putting a maximum on the share of secondary concrete in new concrete production - The construction industry is very decentralized with a work force that may not be well educated in environment and climate issues or circular economy strategies
Enabling innovations	- Create a market for concrete with high secondary material content through e.g. public procurement standards - Incentives for private investors to use concrete with high recycled material content (green certification) - Information, availability and affordability of environmentally friendly concrete for private households - Education and information programs about circular economy strategies for workers in the construction industry

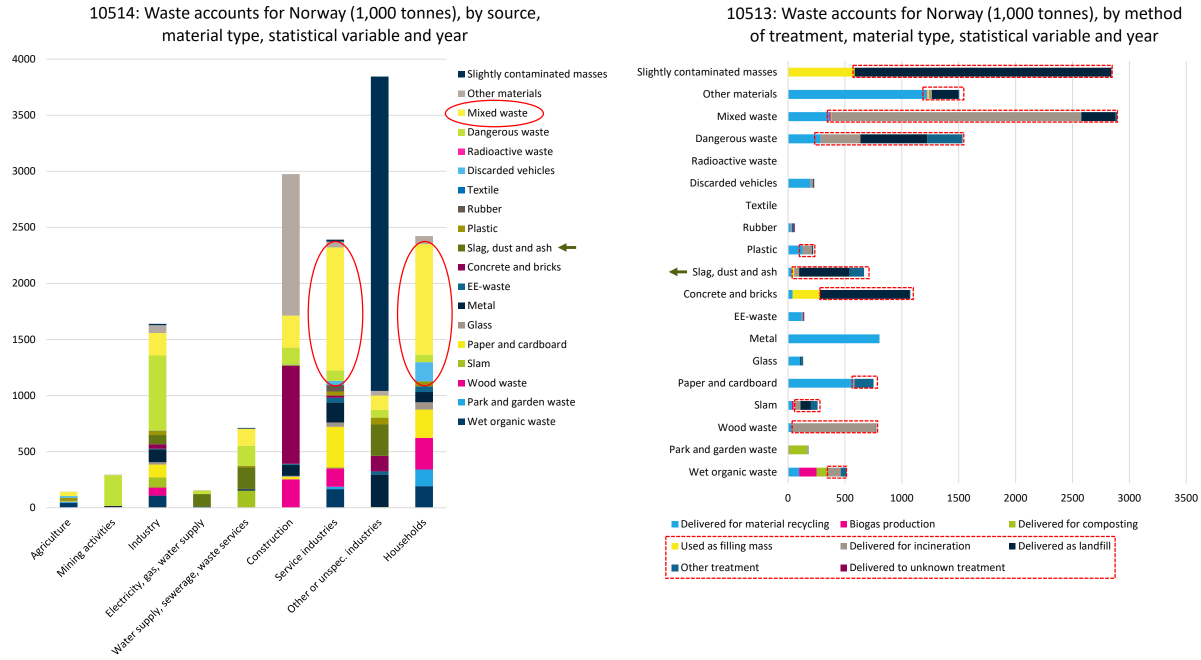
4.3 Plastics

Plastics come in various forms, shapes and compositions. There is not one single "plastics" product or one plastics recycling strategy that fits all. But, on average, producing 1 tonne of plastics from recycled materials can reduce emissions by 1.1–3.0 tonnes of CO_2e compared to producing the same tonne of plastics from virgin fossil feedstock [100].

Consumer and political pressure have led to a stimulation of plastic waste handling as a future market with much focus on plastic packaging. In 2018, China introduced a ban on imports of several types of waste products including secondary plastics, Malaysia, Thailand and Vietnam soon also closed the streets. Soon after, the EU 'Single Use Plastic Directive' [101], which imposes extended manufacturers responsibility on a range of products. And in 2019, following proposals from Norway, it was decided today to tighten control of international trade in plastic waste under the Basel Convention. These events in addition to the EU recycling targets (see below) stimulate the industry to initiate measures for plastic waste

Norwegian household use about 220kT plastic packaging such as food packaging yearly [102], which makes up more than half of the plastic waste in Norway. Other types of waste include 15-30k tonnes of plastic waste from the aquaculture industry (cages, for pipes, etc.), 10kT from the automotive industry, 5.5kT electronics plastic waste and 1kT from the agricultural industry. Waste prevention is the most important step that must be taken to reduce the volumes of plastic waste produced each year. But plastic products also have an important function especially food packaging, and will continue to be ubiquitous in the future.

Waste from households and services such as schools, offices etc produce large amounts of waste categorised as 'mixed waste' (see Figure 16), and much of this is unsorted plastic waste which is incinerated for municipal energy in large quantities. Improving the sorting and collection of plastic waste into from both household and services such as supermarkets, offices, schools could greatly increase the recycling rate.


10514: Waste accounts for Norway (1,000 tonnes), by source, material type, statistical variable and year

10513: Waste accounts for Norway (1,000 tonnes), by method of treatment, material type, statistical variable and year

Figure 16a). Volumes of waste from Norwegian sources categorised by sector and material type, 15b) the destination of Norwegian wate categorised by material type and handling. Source: Own calculations based on SSB.

Avfall Norge has analysed household and industry waste including the volumes that are typically categorised as 'mixed waste' [64]. They estimated the volume of plastic waste material that will need to be sorted and recycled to meet these targets. In this scenario Norway will have to recycle 204kt more plastics in 2035 than in a business-as-usual scenario (where it will only recycle 52kt), to meet the EU recycling target of 65% in 2035 [103].

This results in an estimated emission savings potential of plastics recycling of 224-612kt CO_2e, which is approximately equivalent to today's direct and indirect CO_2 emissions of the Norwegian rubber and plastics industry. Note that, the Norwegian industry only produces a very small fraction of the plastics in and around products sold in Norway and the plastic ending up in the Norwegian waste system. Thus, the emissions savings potential includes not only emission savings potential within Norway, but along in a large degree, those in global value chains.

The EU Waste Framework directive lays out EU Municipal waste recycling target for waste from households and businesses:

55% by 2025, 60% by 2030 and 65% by 2035. 65% of packaging materials will have to be recycled by 2025, and 70% by 2030. Separate targets are set for specific packaging materials, such as paper and cardboard, plastics, glass, metal and wood

4.3.1 Plastic packaging

The market characteristics

Each year, 222,000 tonnes of plastic packaging are supplied to the Norwegian market, Packaging is about 65% of all plastic waste [104], and as described earlier a large part of the mixed waste will be plastic coming from municipal plastic waste (household plastics), and industrial plastics (which include industrial waste but also household type waste for example from office buildings, hospitals, schools, etc.), as well as other fractions such as agricultural foil [105].

Relevant public regulations and other framework conditions

The ambitious targets described in the EU Waste Framework Directive are reinforced as part of the EU Circular Economy Action Plan which in addition proposes to stimulate the market for secondary plastics by mandatory requirements for recycled content and waste reduction measures for key products such as packaging, construction materials and vehicles. Other initiatives named specifically for packaging are

- reducing (over)packaging and packaging waste, including by setting targets and other waste prevention measures
- driving design for re-use and recyclability of packaging
- considering reducing the complexity of packaging materials, including the number of materials and polymers used.
- assess the feasibility of EU-wide labelling that facilitates the correct separation of packaging waste at source
- also establish rules for the safe recycling into food contact materials of plastic materials other than PET.

In Norway the Forum for Circular Plastic Packaging, led by Orkla and the Norwegian Packaging Association, has in 2019 started the process of creating an industry road map to meet the EU requirements.

Effective social innovations

The New Plastics Economy report from the Ellen Mc Arthur Foundation [106] estimate that optimized handling of plastic collection could have a value-added potential of USD 190-290 per tonne. If Norway reaches 65% collection requirements in 2030 this may amount to a profit potential of USD 27-42M per year from Norwegian plastic packaging alone. The report identifies two important levers to achieve the potential of shipment a) harmonization and upscaling of collection and sorting, b) improved packaging design before increased recyclability.

At present, about 30% of Norwegian plastic packaging is recycled, which corresponds to 67 tonnes per year. Packaging from commercial and service industries and industry is not specially collected and sorted accounting for the large amount of plastic that coms under the category mixed waste and not sorted for recyling. Drink bottles and agricultural foil have established systems and are well sorted and recycled today. Excluding these, only 24% of plastic packaging is recycled with the biggest loss being at the sorting stage with 53% of plastic packaging is not collected and sorted in a manner to enable subsequent recycling. Reasons for this are technical, regulatory and economical [107] with few incentivisation mechanisms to stimulate effective sorting.

Critical market and technology developments

Technical challenges include difficult to sort or recycle packaging design and limitations to today's technology for sorting, washing and recycling. Currently the recycling capacity in Norway and Europe is not dimensioned to enable the scale of collecting, sorting and recycling of plastics with the capacity far below that necessary to reach the current EU targets.

But several municipalities are now investing or considering building a central sorting facility. A central sorting facility automatically sorts waste into different fractions that have a higher value, an example today found in ROAF in the municipality of Romerike. A similar plant IVAR began pilot testing in host 2018 in Stavanger, Trondheim municipality assessing Sesame plants and Fredrikstad Frevar. In addition, Fortum is considering building similar to a private facility in Oslo.

The economic changes of upscaling plastic recycling are substantial. If Norway achieves a 65% recycling target, it is equivalent to 145T of recycled secondary plastic that must be absorbed by the market. However per today there is very limited demand for secondary plastics due to limited and unstable supply concerns about contamination and quality and largely strong competition from virgin plastics.

4.3.2 Plastics in products

The plastic waste challenge is particularly salient in aquaculture because the industry is envisioned to grow substantially in coming decades. Norwegian aquaculture currently produces 15-30 kt of plastics waste (secondary plastics) annually. This includes ropes and nets comprising of PA , PE or PE/PP blends (~7kt per year), Cages (~8.1kt) and food pipes (~2.7kt) made of HDPE [108]. The materials used for equipment are of high quality, and therefore suitable as raw materials for new production in e.g. furniture, construction and automotive industries, or back into aquaculture. Despite this, producers struggle to gain access to robust, transparent and long-term stable supplies of secondary materials[109].

Waste from the household electronics covered earlier in the report but EE waste accounts for 5.5kt of hard plastic waste per year. The plastic content of waste of electrical and electronic equipment varies between about 7% for large household appliances and 37% for small household appliances [110]. Separating the plastics used in electronics is difficult and challenging to make economically viable in addition electronics often contain substances such as chlorine and brominated flame retardants that could contaminate a recycling stream and must be sorted carefully and separately [111].

A multitude of organisational, technological and regulatory barriers currently hinder development of a market for secondary plastic. In their study on the Nordic countries, Henlock et al. [109] see two main types of market failures: one relating to producers' choice of input materials, production process and product design, and the other in form of asymmetric information about quality and specifications of the secondary plastics and their availability.

Within the Norwegian aquaculture industry there is increasing interest in CE, with e.g. new actors such as Norwegian Recycling AS establishing market activities based on collecting and granulating hard plastics and other materials. However, the market is young and fragile. Supply stability is seen to hamper demand, and recycling targets for PCP from aquaculture are currently non-existent. As per now, recycled plastic is largely exported, but international restrictions on plastic wate imports have created an unstable market situation. Recycling of hard plastics from aquaculture and other industries is limited, but there are large potentials to be gained.

Opportunity:	**Scaling up plastics recycling**
Emission reduction potential	- **0.2-0.6Mt CO_2e** saved with 65% plastic recycling rate, primarily outside of Norway during the materials production phase and in Norway during the end of life phase in the case of incineration.
Key Barriers	- The plastics recycling market is economically not competitive with virgin plastics - Norway and Europe lack the infrastructure for large scale plastic collecting, sorting and recycling
Enabling innovations	- Increased collaboration across the value chain to improve on product recyclability - Strengthened requirements for sorting of plastic from services and industry - Dimensioning of regional infrastructure for increased plastic recycling - Improving the markets for secondary plastics to be competitive with virgin

4.4 Bio-based services and industry

"*The circular economy favours the use of renewable resources and aims to enhance natural systems by returning valuable nutrients to the soil. This regenerative approach offers opportunities for carbon sequestration.*" Ellen MacArthur Foundation [69]

Biological resources are part of nature's own regenerative cycle and thus circular in themselves. CO_2 emitted by the combustion and degradation of biological material is absorbed by other organisms in growth. The bioeconomy and the circular economy are therefore closely linked, and sustainable growth within biobased value chains can create new products and materials to replace non-renewable and fossil-based products.

The scope of this commissioned study is not intended to cover the complex interactions of the circular –bioeconomy. Nevertheless, both regenerative biological systems and the use of selected resources in the industries using biological resources; agriculture, forestry, fisheries and aquaculture are important to consider in the transition to a circular model. This report will not include studies of biological systems, but we have highlighted some of the cases using biological resources that have high potential for implementation of circular economic strategies in the bio-based sector and recommend further studies to deeper understand the potential for emission reduction.

Emissions from agriculture, forestry and fishing are about 10% of Norwegian emissions (when excluding emissions from international shipping). Emissions from agriculture are 8,6% [112], as shown in Figure 1, consisting mainly of methane and nitrous oxides. Aquaculture has relatively low emissions, however, when including transport and feed, the main contributors to emissions in this sector, this increases significantly [113]. Emission reduction potential is difficult to estimate due to the possibilities of natural carbon sequestration, and also the high share of international trade, both for export (e.g. fish and wood) as well as for import (e.g. soy-based fodder, fertilizers).

The UN Climate Panel's special report on climate change and land areas [114] shows that today's human activity in land areas, such as forestry, agriculture and land use changes, contributes to both the absorption and emission of CO_2. During the period 2007-2016, agriculture, forestry and land use changes accounted for around 23% of total net man-made greenhouse gas emissions. On average, we eat one third more calories each than in 1961 and twice as much vegetable oil and meat. Two billion adults are overweight and suffer from obesity. At the same time, over 821 million people are still malnourished. About 25-30% of all food produced for humans is not eaten.

Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2 , 44% of methane (CH_4), and 81% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, representing 23% (12.0 ± 2.9 $GtCO_2$ eq/y) of total net anthropogenic emissions of GHGs (medium confidence). The natural response of land to human-induced environmental change caused a net sink of around 11.2 $GtCO_2$/y during 2007–2016 (equivalent to 29% of total CO_2 emissions) (medium confidence); the persistence of the sink is uncertain due to climate change (high confidence). If emissions associated with pre- and post-production activities in the global food system[13] are included, the emissions are estimated to be 21–37% of total net anthropogenic GHG emissions (medium confidence) [[114]].

In a low-emission society, the use of biologically renewable resources from land, forest and sea will increase significantly. Prosperity growth and growing population will require more food and feed, while renewable resources will both supplement and replace consumption of fossil resources in chemicals, materials, biopharmaceuticals and bioenergy. The bioeconomy will have a bigger place.

Through implementing circular strategies related to food loss and waste along the food value chain (see chapter 3.3), a large part of associated GHG emissions can be saved. But also, at the first production stage of biomass and bio-based products, emission reductions through circular strategies are possible and necessary. The circular strategies following the 10 Rs [[1]] are adapted for biomass as follows [[115]]:

- R1 (rethink): the optimal use of natural resources (e.g. soil, water and biodiversity). Another possibility is that of producing products that will replace those with a large environmental impact.
- R2 (reduce): reduction in food loss and waste
- R8 (recycle): the reuse of residual flows of residual raw materials, food, feed, materials and fertiliser/compost: 1. Residual flow used in food products and animal feed, 2. Residual flow used as a resource in industry, 3. Residual flow used as fertiliser and compost
- R9 (recover energy): the use of residual flows to generate energy.

For the last two, it is important that minerals are returned to the agricultural cycle (in the form of fertiliser or animal feed) after the organic compounds in products have been used or converted. R2 "Reduction of food loss and waste", which amounts to about a quarter of GHG reduction potentials in the food value chain (Figure 13), is analysed in Section 3.3. Other reduction potentials are related to composting and a better use of residual flows, regenerative agriculture, and energetic use of waste materials, and discussed in more detail below.

4.4.1 Forestry

Forestry is a key sector to control and reduce CO_2-emissions. The sector includes forests, cultivated land, pasture, water and marshes, and how land use changes over time. In addition, carbon storage is included in wood products. Projections of net greenhouse gas uptake in the sector show a downward trend towards 2050. This is due to a combination of an increasing proportion of old forests (forests

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[13] Global food system in the IPCC-report is defined as ‘all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socioeconomic and environmental outcomes at the global level’. These emissions data are not directly comparable to the national inventories prepared according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

that are no longer in their most productive phase), increased harvesting as more mature volumes become available in the future, and lower investments in forest culture in recent decades [67].

Today, less than 54% [116] of the annual biomass growth in Norwegian forests are taken out for utilisation/ product processing. Therefore, the forestry and wood-based industries have resource and market opportunities for growth and development. Increased environmental awareness and knowledge about the importance of forests in relation to the Green shift and the circular economy increase demand for the use of wood and opportunities for new wood-based products.

Barriers and opportunities

The complexity of the forest sector is large with a variety of challenges and opportunities both horizontally and vertically in the value chains. This is acknowledged by the actors in the sector, while the recent establishment of regional clusters represents a determination to improvement through increased and strategic cooperation.[14]

The challenges are related to the necessity for more vertical cooperation and information sharing in the value chains to achieve a higher outtake of the primary resources and more efficient resource utilization. Due to asymmetric incentives among the involved actors, new business models and network cooperation models are needed to adequately address these challenges. It is also very important to understand potential barriers preventing a full exploitation of the potential and which instruments and incentives could be used to reduce or remove these barriers. Today, full utilization of the biomass from forests is limited due to production and logistics cost. The technology to utilize the forest-based biomass for energy is well known, but not very profitable.

Potential Climate Impact

The forests in Norway expect to have a net CO_2-uptake of 20 million tonnes CO_2-equivalent in the decades ahead [67]. The net development might be on the negative side due to new use/construction on new areas (roads, buildings/industry) and an increased fraction of old forests. This is important to be aware of in a long-time perspective.

The forest in the Nordic countries areas is growing slowly, so most forest climate measures will have full effect only in the long term, towards the end of a cycle of 60-120 years depending on the forest quality [67]. It will be important to implement measures as quickly as possible for the forests to fulfil its roles as carbon sequestration and as a biomass resource for long-lived products and for bioenergy as a substitute for fossil resources. Planting of forests in new areas and overgrown areas, rejuvenation with the right wood species and high density, stands out as the measures that have the greatest potential for increasing the absorption of greenhouse gases in the sector.

Technology and market development

Forestry is a complex chain including different actors and markets. One important enabler to increase efficiency and potential market value is related to information sharing. On the market side, increased climate conscious consumers are getting more eager to know the climate footprint for different goods. That will strengthen the market position to wood-based products over for instance metals and concrete in buildings. That might increase outtake of mature forest and increase the uptake of CO_2 in forests and products.

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[14] See for instance WoodWorks Cluster: https://woodworkscluster.no/english-info/

Other technology and market developments in forestry that have a potential of increasing use of the forest biomass and reduce emissions in Norway are:

- Increased use of logging waste, both in existing industries and products, as well as in new products. This might replace other raw materials (for instance fossil) with larger negative environmental impact. Increased transportation is a side effect that needs to be carefully considered.
- Increased production of bio-degradable polymers (plastic, proteins, cellulose) that can be used as input in plastic or pharmaceutical and food products.
- Biomass for bio fuel production
- Bio-refinery for microbial food and feed.

Both to be able to trace volumes and qualities, enabling technologies as digitalization and robotics will be important along the value chains to enable a predictable and strong commitment and mutual interest between the forest owners, logging companies, transporters, and the industry along the value chain.

4.4.2 Agriculture

The change in agriculture to reduce carbon footprint from the sector, will probably come from a change in demand for red meat. It is quite controversial, but the consequences for the agricultural sector will most likely be significant. The biggest potential is related to reduced meat production, with a decline in the number of animals almost 70 percent compared to today's level [67]. At the same time, an increase is expected production of fruits, vegetables and cereals [117]. For some, a change in relative profitability will lead to change to production of grains / vegetables if land areas can be used for this.

Large parts of the forage-based livestock farms take place in parts of the country where the climatic conditions make such a change challenging. In these districts, in such a scenario it is likely that a significant proportion of the farms must reduce or stop their production. It is room to produce the increase in cereals and cereal products, fruits and vegetables in Norway on available areas, but this will require both market demand and increased research and testing of new products. It also requires a strong focus on R&D related to product variety, technology for cultivation and storage of products beyond the current growing season and significant investments in the value chain.

Emission reduction potentials

The potential is estimated to 2.7 million tonnes annually over the next decade if food waste is improved and limited to a minimum and the trend for lower demand for red meat will continue in the future. [67]

The transition from red meat to plant-based diet and fish will inevitably result in emission reductions from the sector. The composition of Norwegian agricultural production changes as consumers change their diet in the direction of food with lower climate footprint.

Technology and market development

Some of the technology and market developments in Norwegian agriculture that have a potential of reduce emissions and a better use of land and biomass in are:

- Robot-based production technology, decreasing use of machinery equipment, and increasing efficiency

- Precision agriculture[15], reducing the need for fertilizers, increasing efficiency and crop production
- Genetic precision breeding and crop
- Production and development of meat substitutes
- New and higher-quality animal feed with a lower environmental impact
- Capturing and utilizing GHG emissions from sheds
- Increasing quality of fertilizers and storage of fertilizers

4.4.3 Aquaculture

In addition to their role within the climate system, such as the uptake and redistribution of natural and anthropogenic carbon dioxide (CO_2) and heat, as well as ecosystem support, services provided to people by the ocean and/or cryosphere include food and water supply, renewable energy, and benefits for health and well-being, cultural values, tourism, trade, and transport [118].

A full study of the carbon footprint of the Norwegian seafood industry has been completed in 2017 and revised in 2020 [119]. The report highlights feed as an important strategy where circular economic models can have a positive impact on the industry's emissions. One of the major challenges in Norwegian animal food production is access to protein-rich feed. This is an issue that concerns both the feed industry, the food industry and the agricultural organizations, but not at least the aquaculture industry. Soy-based feed, for instance, is a major concern [120].

Salmon is dependent on omega-3 fatty acids and amino acids in the feed to grow. In the 1990s, feed for farmed salmon consisted of 90% fishmeal and fish oil [121]. In order to counter the formidable growth of the industry and prevent over-consumption of wild fish, the feed today has a significantly larger element of vegetable proteins and oils. Norway produced 1.2 million tonnes of salmon in 2017 [122], which corresponds to a need for approx. 1.6 million tonnes of fish oil-based feed. New and sustainable sources of feed, especially omega-3 fatty acids, will be a prerequisite for meeting the ongoing growth in the aquaculture industry.

Feed accounts for just over 80 percent of Norwegian salmon's greenhouse gas emissions [119]. This is mainly related to the fact that fish feed contains vegetable ingredients such as soy. A significant share of the soy in feed in the aquaculture sector comes from Brazil. Although Norwegian importers can buy soya certified as deforestation-free, there is a problem that the total soybean production in Brazil is associated with deforestation, which means that Norwegian demand also contributes to higher greenhouse gas emissions [123,124]. If we could produce the feed based on local biomass, we also avoid the emissions related to transport of millions of tonnes soy worldwide.

It is a potential to increase feed production by utilizing biomass from the agricultural sector. In addition to reach feed quality measures, the production must also be sustainable in terms of climate, environment and economy. A lot of research[16] is already being done on technology that uses biomass from, for example, forests and sea (wood, seaweed and kelp) and animal residues for feed production.

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[15] See for instance: https://www.yara.com/crop-nutrition/products-and-solutions/precision-farming/ and https://www.landbruk.no/biookonomi/presisjonslandbruk-gir-mer-klima-og-miljovennlig-norsk-mat/

[16] See for instance: https://www.nibio.no/nyheter/fiskeoppdrett-og-planter-i-samme-system, https://www.sintef.no/prosjekter/biocycles/ and https://www.sintef.no/ocean/satsinger/norsk-senter-for-tang-og-tareteknologi/

Emission reduction potentials

The reduction potential related to climate gases in aquaculture operations as is, is mainly related to electrifying the vessel fleet and increase utilisation of residuals. If all Norwegian aquaculture installations implement the green shift over to electric or hybrid power, CO_2 emissions can be reduced by 360,000 tonnes per year [[125]].

This is a significant contribution, but as stated above, the big climate problem is related to the fish feed, deforestation related to soy production and global transport. Feed is responsible for more than 80% of emissions related to the industry [[119]]. It is, however, important to carefully evaluate the full supply chain effects of replacing feed ingredients. Shifting to lower input ingredients may not necessarily lower the carbon footprint of the product if e.g. the feed conversion ratio increases, or fish growth is reduced [[119]].

Regulations

The aquaculture sector is heavily regulated, both related to farming permits, production areas and development permit rules. The Aquaculture Act, the Pollution Act, the Port and Waters Act and the Food Act regulates the activity. The requirements for the operation of aquaculture is very much related to pollution and disease control. None of these regulations are related to circular economic principles as such, but environmental standards are one of the main motivations from the authorities.

Innovations

To succeed in transforming the feed production value chains, based on local ingredients instead of soy from overseas, research and development related to both Biorefinery and Agriculture cultivation is needed. Chips from the Norwegian spruce industry can be made into protein in fish feed, and the technology is at a medium to high technology readiness and maturity level. Several research projects are ongoing for example to convert brown algae into fish feed protein[17], and a pilot plant for growing seaweed and kelp has started outside Frøya in Trøndelag. In Sunnmøre, they are already engaged in insect farming for feed production[18].

4.5 Summary of emission reduction potential at the producer side of materials

While the Ellen MacArthur Foundation [[69]] estimates that global CO_2 emissions from key materials, steel, aluminium, plastics and cement, can be reduced by 40% by 2050 through circularity strategies, we find that the potential in Norway is significantly lower. This is mainly due to very emission efficient aluminium and ferroalloys production that have emission intensities of up to 75% below world average. For concrete/cement and plastics emission saving potentials through circular strategies are higher. Here, it is important to differentiate emission savings potentials in Norway (in e.g. the case of replacing primary with secondary materials in concrete) and outside Norway (in the case of plastics, where plastics are used a lot, but not produced in Norway). Here, we can nonetheless save emissions not only in Norway but also along global value chains that amount to about 1-1.5% of direct emissions in Norway.

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[17] See for instance, BIOFEED project: https://www.nmbu.no/en/projects/node/35598

[18] See: https://nifes.hi.no/prosjekt/insektdyrking-og-romsdal/

Part 2: In what way can circular economy solutions play a long-term role in the transition to the low-emission society in terms of minimizing the pressure on strategic resources?

5 Material demand for the transition to a low-carbon society

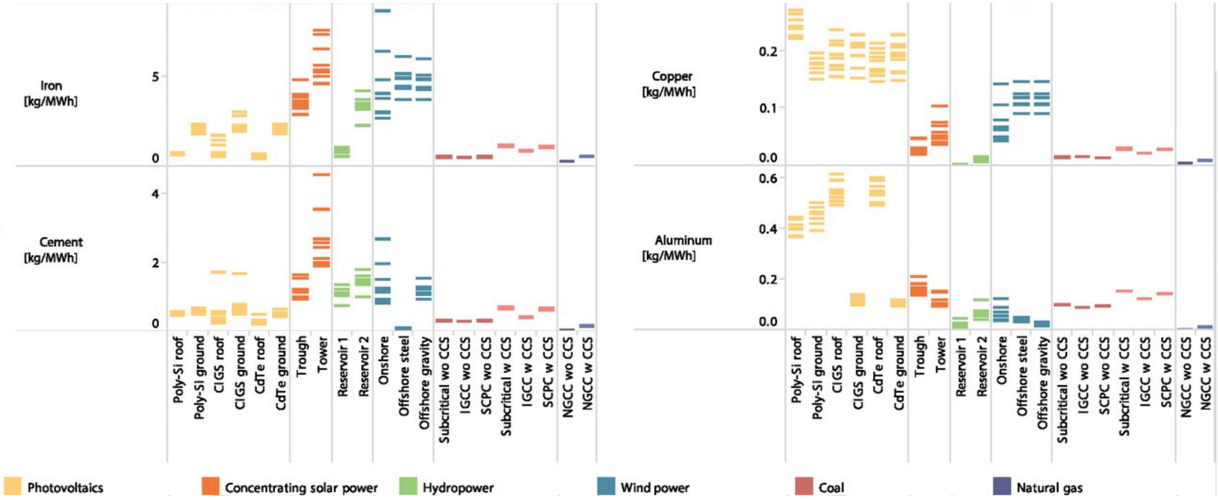
The transition to a low-carbon economy will require a significant restructuring of the energy, production, and transport systems. Every scenario for emissions reduction to stay within or below a 2°C increase in temperature relative to pre-industrial levels [126] will require large and rapid investments in both mature technology, such as wind and solar power, as well as new technologies which have recently become or are in the path to become commercially feasible, such as electric and hybrid vehicles, carbon capture, utilisation and storage (CCUS) in industrial processes, batteries, hydrogen, and large-scale use of biofuels for aviation. Regardless of the mix of technologies used for the transition to a low-carbon economy, what is certain is that this transition will pose large pressure on material demand [4]. This pressure will be exerted not only on commonly used infrastructure materials (such as cement, steel, aluminium and copper) but will result in new applications for materials which are today produced in a relatively low volume (such as lithium, cobalt, platinum-group metals, and rare earth metals).

This second part of the report discusses future global demand of materials for different low-carbon technologies, and how more effective use of resources and circular economy strategies can lower the pressure on strategic resources needed for a low-carbon transition.

5.1 Electricity sector

Electricity production is responsible for around one quarter of total annual greenhouse gas emissions [126]. Substantial investments in renewable energy technologies for the power sector are forecasted for the next decades. These technologies will demand materials not only to produce the technology itself (for example, wind turbines and solar panels), but also for building and operating large electricity infrastructure. This infrastructure includes, for example, roads and foundations for wind power; mounting structures, inverters and transformers for solar photovoltaics (PV); dams for hydropower; and transmission and distribution of electricity. Renewable energy sources are more material intensive than fossil fuel power plants when accounting for copper, aluminium, steel and cement [4]. The share of energy technologies addition of the global demand of these materials is likely to increase in the future. In scenarios of intensive adoption of renewable technologies, consistent with climate targets of maintaining the global temperature changes below 2°C, the demand of new electricity infrastructure could account for around 4% of global steel demand (mostly driven by additions of wind and solar), over 2% of aluminium (mostly due to solar), and almost 1% of global cement demand (mostly due to additions of hydro, wind and solar) [127]. Copper demand, however, might pose future availability problems due to its widespread use in electricity generation, transmission and distribution [4].

The amount of iron (steel), cement, copper and aluminium needed per unit of electricity generated for different energy technologies is illustrated in Figure 15 [128]. The technologies assessed are different types of solar PV, mounted on residential or commercial rooftops and as power plants on the ground, ion yellow; two types of concentrating solar power (CSP), in orange; hydropower plants with different reservoir sizes, in green; onshore and offshore wind power with concrete or steel foundations, in blue; and fossil fuel with and without CCUS, in pink and purple. Overall, renewable energy technologies are several times more intensive in the use of these materials than fossil fuel plants, and fossil fuel with CCUS uses around twice as much materials than those without CCUS. The installation of solar PV demands a considerable amount of materials. The high demand of copper arises from the installation of inverters and transformers. In addition, roof-mounted PV systems require a large amount of aluminium, while ground-based PV power plants demand large volumes of steel. CSP plants, especially those based on solar tower technologies, require high amount of steel and cement, but also considerable volume of copper and aluminium. Wind power – both onshore and offshore – demands a large volume of steel for turbines towers, while foundations require large amounts of steel and concrete. The high demand for copper from wind power plants arise from electrical substations and, in the case of offshore wind, long distances covered by submarine cables. While offshore wind power plants are more material- and energy-intensive than the onshore ones, they benefit from higher wind speeds and more favourable wind conditions, which makes their material requirements per energy produced similar or lower than land-based wind power plants.



Material use indicators for iron, copper, cement and aluminium. CCS, CO_2 capture and storage; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; IGCC, integrated gasification combined cycle coal-fired power plant; NGCC, natural gas combined cycle power plant; offshore gravity, offshore wind power with gravity-based foundation; offshore steel, offshore wind power with steel-based foundation; reservoir 2, type of hydropower reservoir used as a higher estimate; SCPC, supercritical pulverized coal-fired power plant.

Figure 17. A comparison of life-cycle material use per unit of electricity generated (kg/MWh) by different power-generation technologies in nine world regions. Source: Adapted from Hertwich et al. [128].

A key technology for reducing emissions in fossil fuel electricity production and in industrial processes is carbon capture, utilisation and storage (CCUS). Most of the current CCUS applications is in industrial processes, while the use of CCUS in power generation is still low and off-track to provide substantial contribution to low-carbon energy systems compared to scenarios consistent with climate targets. In 2019, 35 million tonnes of CO_2 were captured from power generation and industrial processes. Of these, only 2,4 million tonnes were captured from large-scale capture from fossil fuel power plants. Including projects in early development stage, the capture capacity from fossil fuel power plants rises to 18 million tonnes of CO_2 per year [129]. CCUS systems demand infrastructure for CO_2 capture and compression, and pipelines and wells for transport and storage.

Concerns have been raised about the availability of materials for a rapid deployment of renewable energy technologies, especially materials which are considered critical due to risks in future supply [130–

[132]. This is the case for rare earth metals for thin-film solar PV [133], for permanent magnets in direct-drive wind turbines [134], or platinum-group and rare earth metals in hydrogen fuel cells [135]. These materials are further discussed in detail in section 6, and could present bottlenecks for the growth of these technologies, requiring material substitution, changes in technology mix favouring those without materials with risks of supply, or higher recycling and recovery of materials in-stock, putting lower pressure on increased demand of primary resources.

Electricity grid and energy storage

The generation of electricity by power plants is one side of the electricity system. On the opposite side, the demand for electricity by electric appliances. To transport the electricity from the supply to the demand, there are transmission and distribution lines, transformers, converters and storage units. The addition of power plants to meet additional energy demand and to decarbonize the electricity system will generate large additional demand for aluminium, steel, concrete and copper for transmission lines, transformers, converters and circuit breakers [136,137]. Furthermore, except in the case of rooftop solar photovoltaic, renewable energy generation is often located far from consumption and spread in larger areas. In the cased of offshore wind farms, additional underwater transmission is required through distances ranging from a few kilometres to up to 80 kilometres [138] between the wind farm and onshore transmission lines.

The expansion of cables and transmission lines require a significant amount of materials: aluminium and copper for conducting electricity, and iron, steel and concrete for building the towers and foundations. The expansion of each kilometre of overhead transmission lines require between 130-290 tonnes of concrete, 20-60 tons of steel, 7-18 tonnes of aluminium, and 6-15 tonnes of iron, depending on voltage. The production of each kilometre of underground and offshore cables require between 8-15 tonnes of copper, 14 tons of lead, a variable amount of steel depending on whether cables are land-based (around 3 tons of steel) or offshore (13-16 tonnes) [136]. In addition, transformers and high voltage components also demand large amounts of copper, steel and aluminium [137].

A larger share of renewable energy technologies in the electricity mix pose a challenge. Wind and solar PV are estimated to represent the largest additions of renewable in the upcoming decades. These sources represent a variable source of energy – dependent on wind blowing and sun shining – and need to be balanced with larger grid systems, energy storage, flexible demand and/or flexible operation of fossil-based power. Energy storage will play a significant role in providing a smooth balance between supply and demand of electricity in an electricity system with significant share of variable renewable energy. Common storage solutions are utility-scale technologies that can store energy from hours to months, such as pumped-storage hydroelectricity and compressed air energy storage; hydrogen production, which can also store energy from hours to months; and batteries, which can store energy for seconds to days, depending on the technology and size [4].

The production of hydrogen through electrolysis can be used to balance variable renewable energy by using the excess electricity from peaks of oversupply (for example, when there is more production of electricity from wind or solar power plants than what is demanded by consumers) to produce a low-carbon fuel. Hydrogen can be used to produce electricity in fuel cells, both in stationary power plants and in vehicles. Furthermore, low-carbon hydrogen can substitute natural gas. The use of natural gas distribution grids – which are estimated to go through significant expansions in the next decades – can lower the cost of low-carbon gas such as hydrogen and biogas, and decrease overall carbon intensity of gaseous fuels [127]. In addition, low-carbon hydrogen can be used as a substitution for coal as a reduction agent in the iron and steel process industry or used as a feedstock for the chemical industry [139].

5.2 Low-carbon mobility

Besides the increased share of renewables in the electricity sector, the transition to a low carbon society necessarily passes through the decarbonisation of the transport sector. In places with a low-carbon electricity system, such as Norway, the electrification of passenger and freight transport will lead to significant decrease not only in greenhouse gas emissions, but also in other air pollutants and environmental impacts. Besides the electrification of transport, switching from liquid or gaseous fossil fuels to alternatives such as biofuels and hydrogen can play an important role in transitioning to a low-carbon mobility system.

Considering current material efficiency in the production and supply chains of vehicles and batteries, the high penetration of electric vehicles for personal transport will result in an increase in metal demand, especially steel and aluminium [127] for car manufacturing, rare earth metals for electric traction motors [140], and lithium, graphite and cobalt for batteries [141].

Currently, road vehicles (including passenger and freight) account for 12% of global demand for steel and 14% of global demand for aluminium [127]. Light-weighting can reduce the demand for steel for passenger vehicles, while increasing the demand for aluminium, plastics and composites. Similarly, the shift from internal combustion engine vehicles towards electric and, in a lower scale, hydrogen fuel cell vehicles will shift the requirements for materials for vehicle manufacturing, since internal combustion engine vehicles contain more steel and less aluminium than the low-carbon alternatives [127].

Further reduction of greenhouse gas emissions from the transportation sector, for both passengers and freight, is highly dependent on fuel efficiency and changes in transport mode. It is estimated that additional rail infrastructure could lead to an additional demand of about 35% of steel and cement by 2040 [127]. Another important strategy is the increased use of biofuels in transport. Biofuels are important to decrease the carbon emissions of liquid fuel supply chains in transport modes which are today more challenging or even infeasible to electrify, such as heavy-duty vehicles, air transport, and ships. Under European regulations, the share of renewable sources should be of, at least, 14% of final energy consumption in the transport sector, and fuel suppliers should reduce by at least life cycle GHG emissions per unit of energy of fuels used by road vehicles, partly by using blending of biofuels in liquid fossil fuels. Additionally, there is a concern on indirect land-use change, which put a restriction on biofuels, bioliquids and biomass fuels for which production crops lead to occupation of land with high carbon stock, as well as those that pose competition with food crops [142].

In this circular economy study, however, we focus on metal demand for electrification of the transport fleet. There are high uncertainties in estimating the material needs for hybridization of mass transit such as busses. In addition, there has been a growing interest on the material needs for the high estimated penetration of electric passenger vehicles in the market, especially in developed economies. In Europe, several countries have signalized the phasing out of gasoline and diesel cars, including Denmark, Ireland, France, the Netherlands, Norway, Slovenia, and the United Kingdom. However, these commitments are yet to be translated into policies.

5.3 Critical materials for low-carbon technologies

Although the increased demand of materials such as aluminium, steel and cement from future technology deployment is important, there have been significant concerns on the availability of critical materials for the steep growth of new technologies. The European Commission keeps a list of critical raw materials for the European economy, for which the criticality is assessed every three years, reflecting the development of production, markets and technology [143]. Raw materials are considered critical if they have (1) economic importance in terms of end-use application and participation in the value added of EU industries; and (2) risks of disruption in supply due to availability and concentration of primary supply from producing countries, as shown by Figure 16. Besides publishing the list and risk of 27 critical raw materials, the European Commission also provides a detailed analysis of important non-critical raw materials use, supply risk, value chain, and recycling rates and challenges.

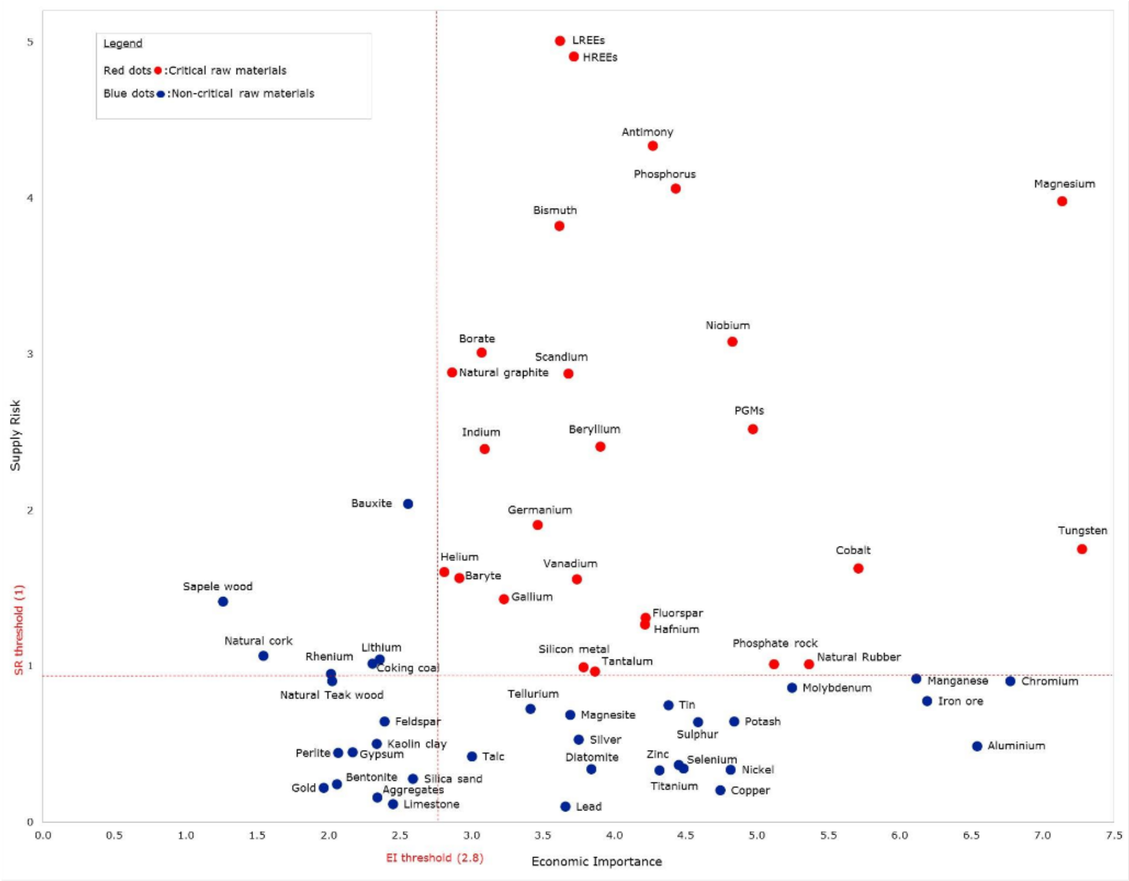


Figure 18. Critical and non-critical strategic raw materials classified according to economic importance and supply risk. Strategic materials which are currently considered critic are in red, and non-critical raw materials in blue. Non-critical materials can change their status in the future if their demand grows faster than expansion of supply. Source: European Commission [143].

Figure 17 shows the concentration of global suppliers of critical raw materials according to the 2017 assessment. China accounts for around 70% of global supply of critical raw materials (and 62% of supply of critical raw materials to the European Union), and it accounts for most of the global supply of critical materials indispensable for low carbon technologies, such as gallium, indium, magnesium, natural graphite, silicon metal, and rare earth elements (REEs). As China dominates both the extraction of rare earth elements and a large market share of wind and solar energy industries, export restrictions of these elements may pose higher costs and barriers to technology industries in other countries [144]. In fact, there are concerns over the availability of REEs from China since 2010, when China restricted the export of these metals, causing a shortage of these metals in the international market and a price surge [145]. Besides China, strategic materials for renewable energy technologies are also concentrated in the Democratic Republic of Congo (cobalt) and South Africa (platinum group metals). The concentration of critical materials in politically unstable countries pose a risk of disruption in supply due to internal conflicts. In the 1970s, Zaire and Zambia produce around two thirds of global cobalt supply, when a rebellion in Zaire caused a 380% price increase in cobalt prices [146]. In addition to high concentration of production in few countries, the high-risk status is, in many cases, complemented by high expected demand growth, restricted possibilities for production expansion, low substitution options and low recycling rates [130].

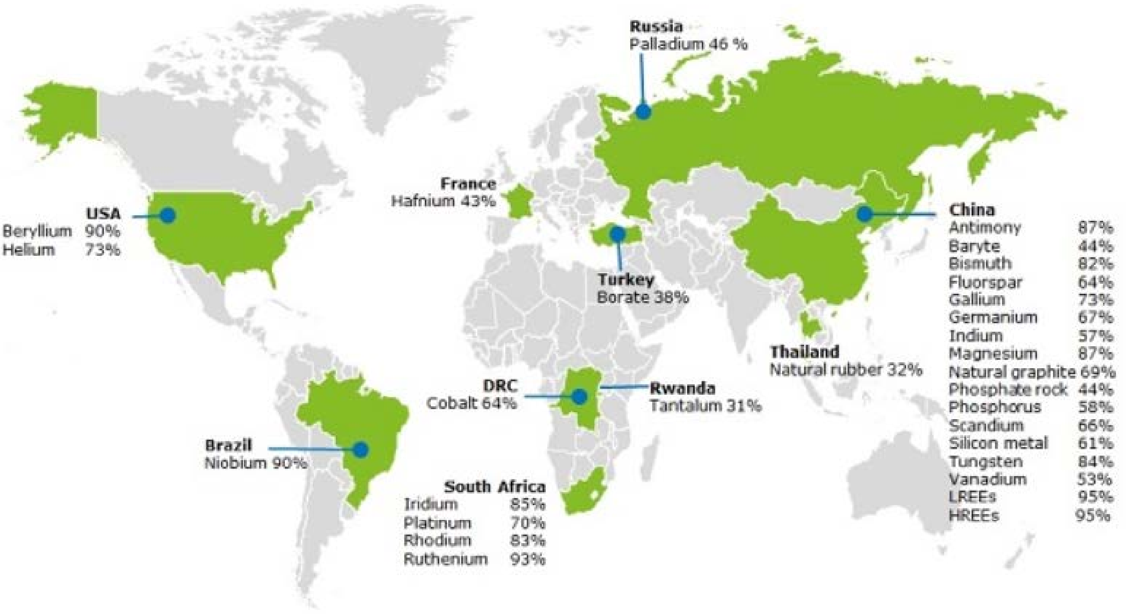


Figure 19. Countries accounting for the largest share of global supply of critical raw materials. Source: European Commission [147].

5.4 Demand for strategic materials in scenarios for low-carbon energy systems

In the most recent assessment of the International Energy Agency [127], total primary energy demand in the world is expected to increase in about a fourth by 2040 under the current and stated policies. There are substantial changes in the configuration of the future energy system. It is expected a decreased role of fossil fuels in total energy demand, led by a flattening out of the demand for oil and a decrease of coal, while the demand for natural gas will increase. In addition, the electricity sector is expected to go through major transformations. First, the increasing electrification of energy use, for example in the heating and transportation sector, will lift the participation of electricity in final energy demand, and electricity generation is expected to grow by around 55% between 2019 and 2040. Second, this growth in electricity demand is expected to be met increasingly by renewable energy, mostly by increasing the share of wind and solar photovoltaics (PV) in the global electricity mix. However, these stated policies still fail to meet climate targets and Sustainable Development Goals of universal energy access, and even more aggressive policies of energy efficiency, and more aggressive policies for energy efficiency and renewable energy deployment should be expected soon. Furthermore, coal power plants installed in the last two decades – 90% of those in Asia – provide an emission lock-in that demands either retrofitting of these plants with CCU/CCS, repurposing them to provide system adequacy and flexible load instead of base electricity load, or early retirement.

Here, we refer to the World Energy Outlook (WEO) Sustainable Development Scenario (SDS) for the energy sector as possible pathways for a low-carbon society. The WEO SDS fills the gap between the stated policies scenario and a scenario where sustainable energy goals would be met in full. The stated policies scenario comprises the current policies in action in 2018, plus stated policy intentions and targets, some of which are already in place in 2020. It includes, for example: the individual countries' Nationally Determined Contributions (NDCs) for the Paris Agreement, which are their post-2020 climate actions; individual countries' recent pledges to phase out coal and nuclear power plants, and to phase out the commercialization of new internal combustion vehicles; and the European Green Deal. The SDS includes providing universal access to modern energy for all, within the climate boundaries of keeping the temperature changes well below 2°C.

The additional installed and retired capacity for the two scenarios is illustrated in Figure 18. In addition, the stated policies scenario estimates that, by 2040, there will be 330 million EVs on the road, versus a much higher electrification of transport in the SDS, which include 900 million EVs in 2040. For hydrogen, we use estimates of hydrogen demand from the International Renewable Energy Agency (IRENA) Renewable Energy Roadmap (REmap) scenario [148]. In this report, we illustrate the material demand for the SDS only.

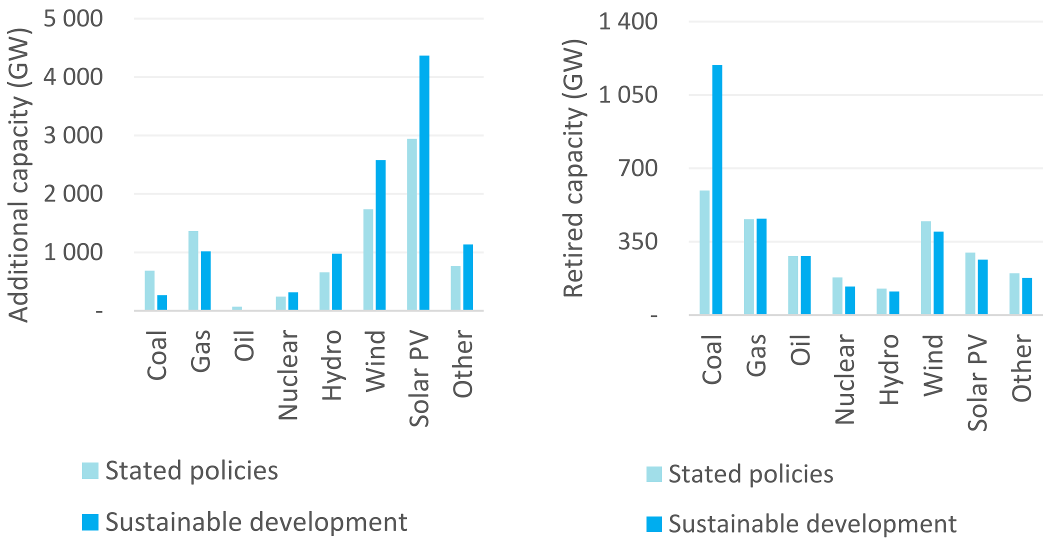


Figure 20. Cumulative electricity capacity installed (left) and retired (right) between 2019 and 2040 in the WEO State Policies Scenario and in the WEO Sustainable Development Scenario. Source: Own elaboration based on IEA [127]

Below we provide a summary on sources for material intensities used to estimate future material demand for low-carbon technologies. This study combined different data sources for assessing material demand for low-carbon scenarios. It used a bottom-up methodology to estimate material demand for low-carbon energy technology under the SDS described above. In this study, the materials needed to manufacture and install 1 unit (e.g. 1 MW) of each technology were scaled up to meet global new additions up to 2040[19]. A simplifying assumption was that material requirements per unit were assumed to be linear, and material intensity to remain the same as in the base-year. The main sources for physical material requirements in different technologies were life cycle inventories (LCI), detailed below.

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[19] For the analysis, only manufacture and installation were taken into account. We do not consider materials used for operation and maintenance, substitution of spare parts, or recovery of materials for end-of-life treatment.

The market share of different technologies has a direct effect on future material demand. For example, a larger share of mono-Si and poly-Si PV cells would increase the demand for silicon metal, a higher adoption of thin-film would increase the demand for critical metals, and a large amount of utility scale PV would require higher volumes of concrete, aluminium and steel. Likewise, the different wind turbine technologies and where they are located (onshore or offshore) exert pressures on different materials. The assumptions for the distribution of the technologies in the different scenarios are also detailed.

Solar energy: LCI for crystalline silicon (c-Si, consisting of monocrystalline silicon - mono-Si - and polycrystalline silicon - poly-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIS/CIGS) photovoltaic (PV) cells include production of raw materials, production of the PV cells and module, installation (rooftop and open ground) and electric components [149]. In the case of mono-Si and poly-Si, it includes refining of silicon from silica sand to mono-Si and poly-Si silicon. For the refining of silicon and for the production of cells and the PV module, it includes the materials directly used in the processes, whether they are embodied in the final product (e.g. frames and cables) or if they are used as auxiliary materials (e.g. petroleum coke and chemicals). The share of different solar technologies was based on current distribution of PV cell production in 2017 [150]. The current distribution of PV cells produced in 2017 were of 62,4% poly-Si, 33% mono-Si, and 4,6% thin-film PVs, of which 2,4% CdTe, 1,9% CIS/CIGS, and 0,3% amorfous-Si (a-Si). The distribution of utility and rooftop PV installed was based on IRENA's report "Future of Solar Photovoltaics" [151]. In its REMap scenario, IRENA estimates that rooftop PV capacity by 2050 would be of 40%, and 60% utility scale. This study assumes same distribution for the IEA's scenario for 2040.

Wind energy: LCI for wind turbines include production of wind turbines and construction of wind power plants, foundations, cables and transformers [4]. These inventories are complemented with information on precious, rare and critical metals from dedicated studies [134,152,153]. Although offshore wind power accounted for only 4% of installed capacity 2018, in the report "The Future of Wind" (2019), IRENA estimates it will account for 17% of global installed capacity in 2050 [138]. This study assumed the same distribution between onshore and offshore wind for new additions by 2040, of 83% and 17% respectively. A major difference in material requirements for wind turbines is the used magnets – electromagnet generators versus permanent magnets generators. Permanent magnets contain rare earth metals and were estimated to compose 23% of global installed capacity in 2015 [154]. The share of permanent magnets are expected to rise to 100% for new offshore additions, and are likely to account for over 30% of new onshore power plants [130]. In this study, we assume that new wind energy additions will consist of 30% onshore and 100% offshore turbines with permanent magnet.

Hydrogen and fuel cells: LCI for hydrogen systems included the production and installation of the electrolyser [155], of the hydrogen storage tank, and of the fuel cells [131,156]. We considered that most of the hydrogen would be used for uses other than electricity production, and 10% of the hydrogen would be used in fuel cells. There is no distinction in the application of fuel cells.

Electric and hybrid vehicles: LCI data for battery packs for electric vehicles include not only the battery itself, but also the packaging and cooling system [157]. The amount of lithium, cobalt and graphite for battery packs and rare earth metals for electric traction motors were based on average for current vehicle models sold in Europe [130].

The transition to a low-carbon energy system will demand a large amount of materials. In terms of weight, the manufacture and installation of solar photovoltaics, wind power and electrolyser plants, and the manufacture of fuel cells, batteries and permanent magnets for electric traction motors will demand over 3 billion tonnes of materials. Most of the new demand for materials are of common infrastructure materials, such as iron and steel, concrete, and aluminium, as shown in Figure 19.

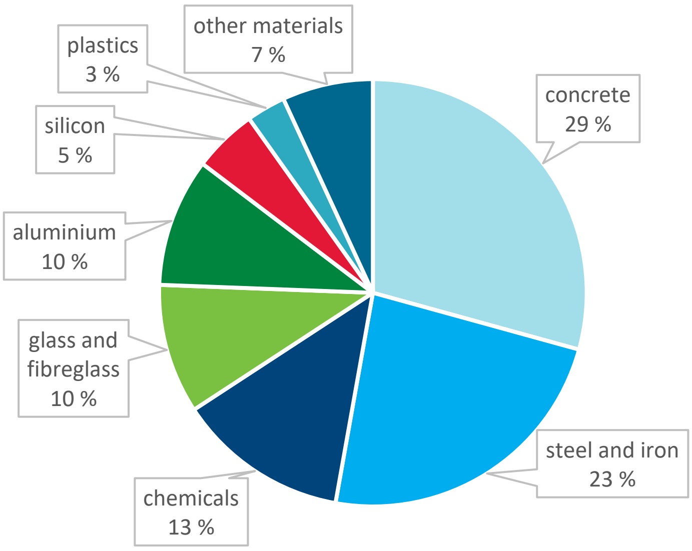

Figure 21. Distribution of main materials demanded for low-carbon energy technologies between 20198 and 2040 in the World Energy Outlook Sustainable Development Scenario. Source: Own elaboration.

However, there will be substantial pressure on strategic and critical materials by the growth of these technologies. Here we focus on the demand for critical materials identified in section 1.4. In this section, we will present the demand for critical materials and a review of the potential bottlenecks for the transition to a low-carbon energy system.

5.4.1 Major metals and alloys: Aluminium, steel, copper and alloying metals

Aluminium and steel correspond to around one third of all future material demand for the transition to a low-carbon energy system. The estimated annual demand for aluminium and steel for the additional electricity capacity correspond to 3-4% and 2-3% of annual production capacity, respectively [[127]]. Although these metals are not considered critical, they are important for the circular economy due to two aspects. First, these metals have a high recycling rate, and they are central for economic activities. One third of global production of aluminium and steel come from recycled scrap [[158,159]], and the recycling technologies, logistics and markets are mature, and thus not explored further in this report. The growing demand for steel or aluminium by low-carbon technologies are not considered to present challenges or bottlenecks for a low-carbon society.

Secondly, alloying metals for steel used in low-carbon technologies are either considered critical or close to the criticality threshold. The most common alloying metals for steel for wind turbines are chromium, nickel, molybdenum and manganese [[153]]. Nickel and manganese are also used for the production of Li-ion battery packs for electric vehicles [[157]]. The breakdown for these metals between the low-carbon technologies is illustrated in Figure 20.

Recycling of metals from end-of-life products has become more challenging due to complex composition of final products. Alloying metals provide different properties depending on the demands of the final product, such as resistance to corrosion, conductivity or lightweight. These alloys cannot be recovered separately in the recycling of steel scrap, and the recovery of these metals depends on a proper sorting and recycling of steel aiming to generate steel with close composition as needed. Proper sorting and recycling of steel alloys aim to reduce the losses of alloying elements, reduce the need to dilute the recycled steel from undesired elements, and to reduce the pressure on primary production of alloying elements [160,161].

Chromium is an alloying metal widely used in stainless steel, together with nickel. The production of primary chromium is highly concentrated in Kazakhstan and South Africa, and there are low constraints to expansion of primary chromium production [162]. Although future demand is estimated to grow, the additional average annualised cumulative demand[20] for low-carbon technologies correspond to around 2% of annual production in 2019. There is no substitute for chromium in stainless steel or other steel alloys, and secondary use of chromium is restricted to recycling of steel alloys. The main use of nickel, on the other hand, is on nickel-based batteries – in particular, NiMH rechargeable batteries, which are being increasingly substituted by Li-ion. Although the additional average annualised cumulative demand for nickel is high – over 20% of annual primary production in 2019 – it is not considered to become a bottleneck for low-carbon technologies. Nickel has a high end-of-life recycling rate, of over 60% [163], and nearly around half of all apparent nickel consumption comes from new or end-of-life recycled scrap. In addition, the growing substitution of nickel-based batteries for Li-ion and the use of stainless steel varieties with low or no nickel will likely lead to a lower competition from new low-carbon technologies [162]. Manganese is an irreplaceable material in the production of steel, and due to its high economic importance, it is just below the threshold of criticality in the EU classification. Due to its economic significance, over 50% of end-of-life manganese is recycled [164]. Most of the demand for manganese by low-carbon technologies comes from batteries for EVs. Although the demand is rising, there are low constraints to the expansion of manganese production, and the average annualised cumulative additional demand corresponds to less than 3% of total primary production in 2019. Finally, molybdenum is an important steel alloy for the wind power industry. Like chromium, its main application is in steel alloys, and recovery of molybdenum is restricted to steel recycling. Currently, around one third of global supply of molybdenum comes from secondary metal from new and old steel scrap. Although it has a high demand growth – average annualised cumulative demand for wind power until 2040 represents over 15% of global primary production in 2019 – there are little concerns over the future expansion of molybdenum production [162].

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[20] The average annualised cumulative demand for materials is estimated to be the cumulative global demand for the entire 22-years period (2019-2040) split equally between the years. It is likely to overestimate the annual material demand for years of slower growth in the beginning of the time series and to underestimate for years of rapid growth in the end of the time series.

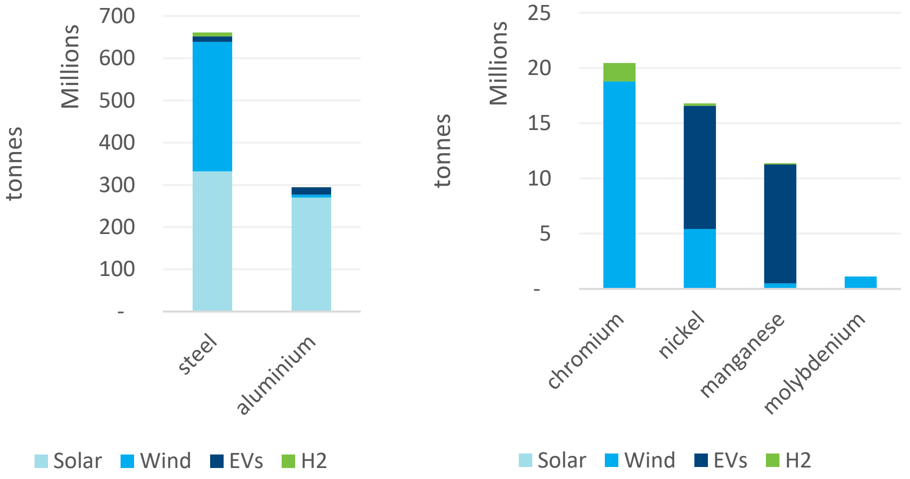

Figure 22. Cumulative demand of steel and aluminium (left) and steel alloys chromium, nickel, manganese and molybdenum (right) between 2019 and 2020 for the four technologies assessed. EVs = electric vehicles. H_2 = hydrogen. Source: Own elaboration

Copper constitutes one of the main metals for the expansion energy system, not only for low-carbon technologies. Copper is also an essential metal for electric and electronic products communication, infrastructure, and transportation. The global demand for copper has more than doubled between 1990 and 2015, and is further expected to increase another 250% by 2050 compared to 2010 demand [165]. It is estimated Furthermore, around half of all end-of-life copper is recycled, and over one third of total copper supply is from recycling [166]. Additional annualised cumulative copper demand from low-carbon technologies corresponds to around 5% of primary copper production in 2019 [162]. However, this additional demand is estimated to be low compared to other uses [167].

5.4.2 Minor metals: demand for critical materials for the green energy shift

The key role of critical materials for renewable energy and low-carbon technologies raises the question whether the availability of these materials will pose a constraint to the transition to a low-carbon energy system [131,153,168]. This is the case for rare earth metals for wind turbines and for electric vehicles (EVs); tellurium, indium, gallium and selenium for thin-film solar PV; platinum-group metals for hydrogen fuel cells; and lithium, graphite and cobalt for electric vehicles. A study on the criticality and potential bottlenecks for clean energy technologies growth in Europe identified rare earth metals (wind, EVs), gallium and tellurium (solar PV) as most critical supply chains for the growth of low-carbon energy technologies in Europe, as shown in Figure 21 [131]. Following in decreasing criticality rankings, indium (solar PV), platinum (fuel cells) and graphite (EVs) were identified as high-medium criticality; cobalt (EVs) as medium criticality; and lithium (EVs), cadmium, lead, selenium and silver (solar PV), were considered low or medium-low criticality.

High	High-Medium	Medium	Medium-Low	Low
REE: Dy, Eu, Tb, Y	Graphite	REE: La, Ce, Sm, Gd	Lithium	Nickel
REE: Pr, Nd	Rhenium	Cobalt	Molybdenum	Lead
Gallium	Hafnium	Tantalum	Selenium	Gold
Tellurium	Germanium	Niobium	Silver	Cadmium
	Platinum	Vanadium		Copper
	Indium	Tin		
		Chromium		

Figure 23. Criticality ratings of European supply of metals required for clean energy technologies. Source: Moss et al. [131]

Scattered metals such as gallium, tellurium and indium are not necessarily rare in terms of volume of materials available in the terrestrial crust, but they seldom form deposits of their own. These metals are recovered as by-products of other mineral commodities, such as zinc, copper and aluminium. The small market for these metals – produced in the scale of hundreds of tonnes, versus dozens of millions of tonnes for their 'parent' metals – provides limited incentive for zinc, copper and aluminium refiners to invest in capital and technology to recover those scattered metals. Thus, the future availability of these metals is uncertain and tied to the demand for the main metals [164].

Solar photovoltaics: demand for silicon and scattered metals

PV cells can be installed either as stand-alone power plants or installed in the rooftop of residential and commercial buildings. The most common solar PV technology is crystalline silicon (c-Si) PV cells, either monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si). In 2017, these two technologies corresponded to over 95% of the total PV installed capacity, the highest market share for c-Si in two decades: thin-film PV technologies accounted to 10-20% installed capacity until the early 2010s [150]. PV cells made of c-Si have posed little concerns over material availability because silicon is the second most abundant element in the earth's crust. However, silicon metal is considered a critical material for the EU economy, and it is important to quantify the needs for expansion of the silicon refining industry to meet the rapid forecasted expansion of solar PV.

The cumulative demand for silicon between 2019 and 2040 in the low-carbon scenario is of around 14.5 million tonnes, lower in case there is a higher uptake of thin-film PV. This increased demand is considerable: the average annualised cumulative demand of silicon in these scenarios are of around 10% of silicon metal production in 2019 [162]. This high growth will lead to the need for increasing material efficiency in PV production and recovery of secondary silicon from processes and from end-of-life products. Additionally, the high growth of demand for silicon by the PV industry will also compete with the growing demand of silicon from other uses, as even in scenarios with high low-carbon technology growth, the demand of silicon for PV represents only a low share of future demand projections [167].

Thin-film PV technologies offer advantages over c-Si panels. First, it provides a lower cost PV panel without significant efficiency losses. It also requires less materials and energy to be manufactured, and it can be produced in flexible modules that can be integrated into a variety of surfaces, such as buildings façades [4]. However, thin-film PV technologies rely on by-product metals, for which uncertain availability might restrict the growth of these technologies [133]. There are three main thin-film technologies used in large scale today: amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium (gallium) selenide (CIS or CIGS). Thin-film a-Si cells use un-crystallized silicon from silicon refining, but also new scrap from computer and semiconductor industries. They require considerably less silicon than c-Si PV systems, and it uses indium as conductor. CdTe technology uses cadmium and tellurium, and CI(G)S cells require copper, indium, gallium, and selenium for their production.

Indium is produced as a by-product from zinc refining, and there are substantial limitations to expanding global production capacity. Indium demand for PV cells is forecast to grow rapidly. It might create a conflict with its main application in the electronic industry, which is the production of flat display panels, responsible for around three quarters of indium demand, as well with the new rapid demand growth in the telecommunications industry for data transmission [162]. The demand of indium for solar PV between 2019 and 2040 is of over 4 million tonnes, resulting in an average annualised cumulative demand equivalent of one quarter of 2019 primary production. Recycling of indium is costly and inefficient [169], and circular economy measures will be needed to allow for the growth of thin-film technologies.

Like indium, tellurium is also a by-product metal and its availability can impose severe constraints to the growth of thin-film PV [133]. It is produced as a by-product from copper refining, and there are significant constraints to the expansion of primary production capacity. The main use of tellurium (around 40%) is on CdTe technology. Other uses are the production of bismuth telluride, used in thermoelectric devices for cooling and energy generation, and alloys for steel, copper, lead and iron [162]. The demand of tellurium until 2040 will be of around 400 tonnes – an average annualised cumulative demand of around 90% of 2019 primary production.

Cadmium is recovered as a by-product of zinc refining. It is not considered to present any supply chain risks due to low regional concentration of supply of raw material, as well as low limitations to expanding production capacity [153]. Most cadmium is used to produce NiCd batteries, which are increasingly being replaced by Li-ion and NiMH batteries. This, allied to increased recycling, will likely result in low pressure from rapid expansion of CdTe PV on primary cadmium production [162]. The increased demand for cadmium by 2040 – of about 12 thousand tonnes – represents an average annualised cumulative demand of around 2% of 2019 primary cadmium production.

Gallium is a by-product of the mining of other mineral commodities, mainly zinc, copper and aluminium, and most of the production of primary gallium is concentrated in China. About 75% of global demand for gallium is for the manufacture of integrated circuits, while most of the remaining use is in the optoelectronic industries, including PV cells, industrial and medical equipment, smartphones, LED screens, and telecommunications [162]. Cumulative demand for gallium will be of around 575 tonnes, and the average annualised cumulative demand will represent around 8% of current primary production. Finally, selenium is obtained as a by-product of copper production. Although the use of selenium for PV is estimated to grow, it is estimated to be offset by low growth in traditional applications, such as metallurgy, glass manufacturing and agriculture [162]. The total demand for selenium by 2040 will be of around 3,5 thousand tonnes, an average annualised cumulative demand of around 6% of current primary production.

Wind turbines and electric vehicles: demand for rare earth metals

There are two main markets for wind power, which rely on different technologies and materials. The traditional market, which today comprises over 95% of wind power capacity installed [138], comprises onshore wind power plants. Offshore wind power plants are becoming increasingly popular due to the better wind conditions and rapid cost reductions, and the offshore market is expected to grow significantly over the next decades. Offshore wind turbines are experiencing large technological innovations, with growth in the size of turbines, floating foundations, and development of drivetrain and control technologies.

The recent development and uptake of more efficient drivetrains constitute a potential bottleneck for the rapid growth of wind turbines in low-carbon energy scenarios. The new generation of direct-drive generators use permanent magnets, which result in more efficient and compact generators with fewer failures, lower maintenance and lower costs. However, these permanent magnets require rare earth metals to be produced. Typical permanent magnets comprise of a neodymium-iron-boron (NdFeB) alloy, combined with additives – usually dysprosium, but also praseodymium and terbium – to enhance their properties. On average, direct-drive generators contain around 600kg of magnets per MW capacity, of which around one third of the weight is neodymium, and about 4% dysprosium [4]. Rare earth metals are considered critical due to their unique properties, the rapid growth in demand and, additionally, due to the concentration of primary production nearly all dominated by China. There are many concerns regarding future availability of neodymium and dysprosium for wind energy expansion [168,170]. The growth in demand for neodymium and dysprosium is expected to be strong, and there will likely be competing pressures for rare earth magnets: besides their current use in computers, audio systems, household appliances and MRI machines [134], another rapid growing technology which is vital for a low-carbon energy system and requires permanent magnets is hybrid and electric vehicles. Direct-drive generators with permanent magnets account for 20% of all wind turbines installed in 2018 [138]. It is expected that this technology will increase moderately for new onshore turbines, but it should account for the majority of new offshore turbines installed in the next decades.

Current electric vehicle technologies rely on critical materials for two main applications: electric traction motors and batteries. Electric traction motors with NdFeB permanent magnets are the leading technology, and it accounted for 93% of all EVs sold in 2018 [171]. The increase in the demand for neodymium and dysprosium for electric vehicles are estimated to put even higher pressures on rare earth metals than wind turbines [170]. The amount of rare earth in electric vehicles depends on the technology used. For plug-in hybrid EVs, battery EVs and fuel cell EVs, the average amount of rare earth metals is of 565g per car, while for hybrid EVs, this amount is of 237g per car [130].

Rare earth metals are highly critical materials due to the high economic and technological importance, low availability, and the concentration of supply by China, which imposes export quotas on these metals. The cumulative demand for neodymium, praseodymium and dysprosium for wind turbines and electric vehicles is illustrated in Figure 23. Without circular economy measures and material substitution, the availability of rare earth metals will pose significant challenges for wind energy and electric vehicles. Neodymium is the most abundant element in rare earth oxides and is the main rare earth component of NdFeB permanent magnets. The demand of neodymium, praseodymium, and dysprosium from wind power and EVs are estimated to be, respectively, of around 300 thousand tonnes, 75 thousand tonnes, and 60 thousand tonnes by 2040, which represents an average annualised cumulative demand of 62%, 51% and over 200% of annual primary production [172], respectively[21]. The high demand compared to rates of primary rare earth production, especially of dysprosium, highlights the urgency for production expansion, material substitution, material efficiency and recycling for increasing the material availability for low-carbon technologies.

The main use of neodymium, dysprosium and praseodymium are on permanent magnets. Dysprosium presents virtually no competing uses, but the demand for neodymium and praseodymium also depends on the demand for other products, especially especial metal alloys, NiMH batteries, catalysts, glass, and ceramics [172]. However, it is estimated that most of the growth in the future demand for these metals come from low-carbon technologies [167].

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[21] For rare earth metals, the annual production is not based on 2019 as with the other materials in this report, but based on 2010 production rates. This might lead to an underestimation of the actual primary production.

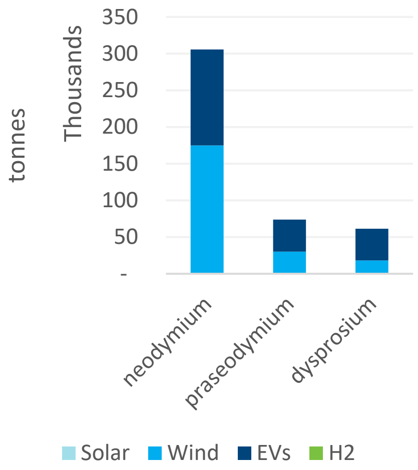

Figure 24. Cumulative demand of neodymium, praseodymium and dysprosium between 2019 and 2020 for the four technologies assessed. EVs = electric vehicles. H_2 = hydrogen. Source: Own calculation

Hydrogen and fuel cells: demand for platinum-group metals

Hydrogen today is almost exclusively produced from fossil fuels – 6% of global natural gas consumption and 2% of global coal consumption are used to produce hydrogen, most of which are used in oil refining and chemicals production. Low-carbon hydrogen can be produced from electrolysis using renewable energy and low-carbon electricity, as well from fossil fuels with CCUS and low emissions during extraction [127]. Electrolyser plants are capital intensive and require a high amount of concrete and steel. The high demand for stainless steel for producing, storing and transporting hydrogen will result in higher demand of chromium and nickel [135], two metals which are considered critical or might become critical for low-carbon technology growth.

Fuel cells, on the other hand, require highly critical materials for its production. The membrane electrode in most fuel cells use platinum-group metals (PGM), which are among the rarest metals on the earth's crust. PGM have high use in the chemical industry, metallurgy, electronics, health, consumer goods, and finance. Primary platinum production is highly concentrated, with over 90% of global production concentrated in South Africa, Russia and Zimbabwe [162], but recycled PGM provide a significant proportion of the world's supply. High-temperature fuel cells do not require platinum as a catalyst, but instead, it uses rare earth metals.

Considering current fuel cell technology, a high adoption of fuel cells will lead to a demand of around 1.9 thousand tonnes of platinum, around 1 thousand tonnes of lanthanum, around 600 tonnes of ruthenium and around 200 tonnes of iridium by 2040. These values are significant considering current primary production: annual primary production of platinum in 2019 was of 187 tonnes [162], and production for other PGM were around 44 tonnes in 2014 [172]. However, secondary PGM provide an important amount of materials globally. Due to their economic importance, PGM have high recycling rates. Around two thirds of total platinum supply come from secondary sources, mostly from end-of-life recycling. This rate is much lower for other PGM – around 10% - but it has been growing strongly in recent years [172]. The additional demand of PGMs will add to current use of these metals in catalytic converters for motor vehicles, jewellery, catalysts in chemical, electrochemical and petrochemical applications, electronics, glass production, and the health industry.

Batteries for hybrid and electric vehicles: demand for lithium, cobalt and graphite

Hybrid and electric vehicles can be classified according to different technologies. Hybrid electric vehicles (HEVs) use electric traction motors as a secondary source of propulsion, in parallel with the internal combustion engine. Plug-in hybrid electric vehicles (PHEVs) include rechargeable batteries that can be charged by an external power source and use an internal combustion engine to extend the range of the vehicle. Battery electric vehicles (BEVs) run exclusively on one or more electric motors and are powered by rechargeable batteries, charged exclusively by external power sources. Fuel cell electric vehicles (FCEVs) use a fuel cell instead of rechargeable batteries. The market for rechargeable batteries for EVs is dominated by Li-ion batteries. Li-ion batteries require three materials which are considered critical or potential supply bottlenecks: lithium, cobalt, and graphite.

Around two thirds of global lithium are used in the manufacture of Li-ion batteries, most of which are used in portable electronic devices, electric tools, EVs and grid storage applications [162]. The growth of electric vehicles in the stated policies scenario would lead to a demand of lithium to around 2 million tonnes by 2040, which corresponds to average annualised cumulative demand above the production capacity in 2019 [162]. Although the demand is expected to rise and put substantial pressure on primary lithium, the production has expanded rapidly in the last decades, and it is considered that there are low limitations to future expansion of lithium supply [141].

Cobalt is considered a critical material, and one of the main reasons is the concentration of supply, with the Democratic Republic of Congo being responsible for around 70% of global cobalt mining in 2019. Most of primary cobalt is mined as a by-product of copper or nickel production, and like lithium, the main use of cobalt is on Li-ion batteries [162]. Around 30% of in-use cobalt stocks is in batteries [169], and this share is likely to grow with the electrification of transport. Current battery recycling provides a yet low amount of secondary cobalt [173]. The demand from EVs will lead to a demand of around 1,3 million tonnes of cobalt by 2040, corresponding to an average annualised cumulative demand of around 45% of current cobalt production [162].

Graphite is a key material for Li-ion batteries. Natural graphite, a critical mineral, has been the dominant graphite source for Li-ion batteries in EVs [130]. Natural graphite production is mainly concentrated in China, which produces around two thirds of world's supply, while another 20% is produced in Mozambique and Brazil [162]. The demand of graphite from EVs will amount to average annualised cumulative demand of nearly 90% of current production rates, accumulating over 21 million tonnes by 2040.

5.5 Summary of the material demand for the transition to a low-carbon society

The transition to a low-carbon economy will demand a large amount of materials. Of special interest are critical raw materials. Critical materials have high importance in terms of end-use application and participation in value added of industries, and they may face risks of supply disruption due to limited availability and high concentration of primary supply. In this chapter we discussed the demand of critical materials by four low-carbon technologies: solar photovoltaics (PV), wind power, hydrogen and fuel cells, and electric vehicles.

Solar PV is one of the significant drivers for the future demand for critical materials. PV cells made of crystalline silicon have posed little concerns over material availability due to its abundance, but the cumulative demand of silicon to meet the rapid growth of solar PV would account to approximately 10% of primary silicon production if current production rates were constant. The highest risks for materials availability for solar PV concern thin-film PV technologies, which rely on so-called scattered metals, namely indium, tellurium, gallium, and selenium. These metals are recovered as by-products of other major metals, such as zinc and copper. At highest supply risks are indium and tellurium, for which annualised cumulative demand represents 25% and 90% of primary production based on 2019 production rate, respectively, and there are substantial challenges for their primary production expansion.

New generations of wind turbines are more efficient, but they rely on a technology which requires rare earth metals – in particular, neodymium, dysprosium, and praseodymium. These rare earth elements are also used in electric traction motors, the dominant technology in current electric vehicles. Future growth of wind power, especially offshore wind power plants, and the growth in electric passenger vehicles, will put pressure on the primary and secondary production of rare earth metals. Rare earth metals are highly critical materials due to the high economic and technological importance, low availability, and the concentration of supply by China, which imposes export quotas on these metals. The annualised cumulative demand of these rare earth metals for wind power and electric vehicles will correspond to 50% to over 200% of current primary production, highlighting the need for circular economy measures to alleviate the pressures on primary resources.

Besides the demand of rare earth metals, the growth of electric vehicles is also expected to put pressure on the supply of lithium, cobalt, and graphite for batteries. With current technology, the growth of electric vehicles could lead to an annualised cumulative demand of lithium above current production capacity, and cobalt and graphite to around 45% and 90% of the production capacity respectively, based on 2019 rates. Material efficiency and recycling measures will be needed to alleviate potential bottlenecks for the expansion of electrification of transport.

Hydrogen produced from low-carbon energy has the potential to provide energy storage, clean gaseous fuels, and clean feedstocks for the chemical industry. The production of hydrogen by electrolyser plants is capital and material intensive, requiring a high amount of concrete and steel for producing, storing and transporting hydrogen. The use of fuel cells to convert hydrogen to electricity is not as material intensive, but it requires platinum-group metals, which have important applications in other industries. Platinum-group metals have high recycling rates, and secondary metals constitute an important source of total supply.

6 Circular economy measures for critical materials

As discussed through the first part of this report, a more efficient use of material stocks in the society is possible through extending the lifetime of in-use stocks, improving material efficiency, and by increasing the re-use and recycling rates of materials – whenever technically and economically feasible. Recycling is a key activity to contribute to security of supply of raw materials, improvement of sustainability of raw material production, and is a risk-reducing factor in the assessment of criticality for raw materials [174].

6.1 Recycling and use of secondary materials

The recycling rates and the use of secondary materials are two indicators that are complimentary to each other. While there might be high recovery rates for pre- and post-consumer scrap for a number of metals, the composition and lifetime of in-use stocks and the demand growth for critical materials can result in low rates for the use of secondary materials in total material demand. The long lifetime of new infrastructure that rely on critical materials, such as power plants and vehicles, mean that these materials will not be available for recovery before the upcoming decade [170]. Thus, even with increased end-of-life recycling rates, a large share of the material demand for low-carbon technology will come from primary extraction.

Urban mining

These critical materials, however, are also available in a variety of other products currently in use. Both traditional internal combustion engine (ICE) vehicles and EVs contain critical materials. Systems for the control of tail-pipe emissions from ICE require platinum-group metals and rare earth elements, and electric and electronic systems contain critical metals such as gallium, tantalum and rare earth elements [175]. In-use stocks of rare earth metals used in permanent magnets in 2007 were equivalent to four times the primary production rate for these metal, being used in computers, audio systems, household appliances and MRI machines, besides their use in wind turbines and vehicles [134]. Likewise, scattered metals for thin-film PV are found in a range of electronic, communication and optic equipment [176].

Urban mining is the process of recovering materials from end-of-life stocks of products, buildings and waste. Batteries, electric and electronic equipment and components, vehicles and mining waste contain critical materials needed for building a low-carbon society. Electrical and electronic equipment (EEE) constitute important uses of critical materials, used for example in circuit boards, LCD displays, and rechargeable batteries. The lifetime of critical materials in EEE largely depends on the products, and they can last from a few months or years in lamps and mobile phones, up to decades in high efficiency motors [15]. Other in-use stocks for critical materials include vehicles, batteries, energy technology infrastructure, and industrial processes.

Scattered metals for thin-film photovoltaics: Some of the most critical materials for thin-film PVs have low recycling rates. The use of indium, gallium and tellurium in other industries is highly dissipative, and low recycling rates come mainly as recovery from process scrap [169]. The amount of gallium, indium and tellurium recovered from end-of-life products is currently virtually null [15]. Most of the cadmium recovered outside alloying content in metallurgy is from consumer and industrial NiCd batteries [162]. As thin-film technologies reach the end of their lifetime, a higher amount of secondary materials will be available for recovery.

Rare earth metals: There is currently no large-scale commercially available recycling of end-of-life permanent magnets, although there are many ongoing technological developments [177,178]. As permanent magnets in wind turbines and EVs reach the end of their lifetime, the availability of secondary rare earth metals will likely increase. Today, there is no secondary dysprosium production, very low recycling rates of neodymium, and around 6% recycling of praseodymium from other products. The main challenge for recycling of rare earth metals is their use – they are usually incorporated as small components in complex items. The processes required for recycling of these components are usually complex, energy intensive, and costly [15].

Platinum-group metals: The high value of PGM, allied to its important applications, result in high recycling rates for these metals. The main contributor for secondary PGM is the recycling of automotive catalysts, for which recycling can recover up to 95% of the PGM content. Recycling of process catalysts from the chemical industry and of PGM used in the glass industry are also highly efficient, with recycling rates above 80%. Other sources of secondary PGM from consumer products are jewellery and electronic waste. However, Losses from lack of proper collection and treatment of end-of-life products reduce actual recycling rates from automotive catalysts of around 50-60%. Industrial by-products of non-ferrous mining, processing, and manufacturing industries can be processed for recovery of secondary PGM. These include complex mining concentrates, slags, flue dust, ash, and production waste from the electronics, glass, jewellery, and chemical industries [172].

Lithium, graphite and cobalt: Lithium and cobalt can be recovered from Li-ion batteries. As a growing number of EVs and electronics reach the end of their lifetime, these materials become available to be recovered and recirculated in new batteries, reducing the pressures on primary demand of lithium and cobalt. By 2030, it is estimated that approximately 1,2 million EVs will reach the end of their lifetime. Lithium has a very low recycling rate, and virtually all new demand is supplied by primary production. Cobalt has a higher end-of-life recycling rate, of around 30% [15,179]. Current recycling rates for end-of-life Li-ion batteries are of less than 5% due to its complex and costly processes of recycling, to the abundance and costs of primary materials, and to the lack of proper disposal and treatment of portable electric and electronic devices [173]. Lithium and cobalt can be recovered from Li-ion batteries using new techniques, but graphite is not recovered in the process[22]. Recovery rates of natural graphite are low, and the rate of use of secondary graphite on total material use is below 5%. Major challenges for increasing recycling rates of graphite are not technological, but economic, as current primary natural graphite prices are too low [15].

Extractive waste and landfills

Extractive wastes are generated during the prospecting, extraction, treatment, and storage or mineral resources from quarries. It includes mineral excavation wastes, such as overburden and waste-rocks; wastes from mineral processing and treatment, such as tailings and waste gravel, sand, and clays; and drilling wastes. These wastes can contain critical metals, such as indium or germanium in residues of treated zinc ores, but their exploration might also present risks to the environment and human health. The recovery of critical materials from extractive wastes depends on the waste volume and concentration, the market demand for recovered metals, and whether the recovery is economically feasible. The recovery of critical materials from extractive waste can reduce the need for active or passive treatment and storage of extractive waste, also reducing its environmental impacts, and reduce the demand for primary extraction. In order to fulfil this potential, there is a need for collection and reporting of data on extractive wastes, including relevant data about the volume or concentration of critical raw materials. According to this principle, advancements in technology for the recovery of by-products, as well as demand and commodity prices for these by-products, might result in deactivated mining sites to be reopened for new extraction. In Northern Spain, a mine deactivated in 1985 was reopened in 2011, and currently produces concentrates of tin and tantalum, niobium, and other minerals. The recovery of metals can also be done in the waste of operating mining facilities, such as the BRAVO (Bauxite Residue and Aluminium Valorisation Operations) in Ireland, which recovers critical materials from bauxite residues (red mud) [15]. However, the recovery of metals in extractive waste still faces many technical challenges, as energy consumption for material separation raises exponentially as concentration of the target metal falls below 1%. Elements which are present in significantly low concentration or in complex form are difficult and expensive to recover [180].

Landfills, on the other hand, concentrate a variety of waste. Non-active landfills can represent a source of secondary materials and energy, including critical raw materials. However, there is often no systematic collection and reporting of data specific to composition and amount of critical materials in landfills, especially in countries in which it constitutes the main waste disposal treatment. Due to a

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[22] See also: https://fullycharged.show/episodes/can-electric-vehicle-batteries-be-recycled/

range of waste being disposed in landfills instead of properly sent to recovered, such as electronic waste, the concentration of critical materials in landfills can be higher than in mined ores [15]. However, there are high challenges to provide a substantial amount of critical materials from landfills at a profitable value [181].

6.2 Material efficiency and lifetime extension of in-use stocks

Material efficiency is one of the key strategies for reducing the demand for primary materials. It includes the production of similar products with less materials through lightweight design, improvement in utilization rate of materials in industry by decreasing losses, and increased production yield [167]. Material efficiency can be achieved by reducing the amount of materials that are contained in the end product, for example, by designing products with lower weight or thickness, such as decreasing the layer thickness of thin-film PVs; by increasing the efficiency of the service, such as the energy conversion efficiency of energy technologies; and by increasing the efficiency of production of the material, reducing losses in industrial processes. For some materials such as indium, the losses in the material processing, allied to a large share of dissipative losses, emphasized that improving the recovery rate of new process scrap is as important – or even more important – than focusing on end-of-life recycling processes [167].

Energy technologies have experienced important advances in material efficiency during the past decades. For example, the use of silicon in crystalline solar PV has declined in 75% in two decades, from 16 g/W to around 4 g/W [182]; Li-ion battery packs for EVs have had a significant reduction in the amount of cobalt, and this reduction is expected to continue in the future [175]; and due to concerns on the availability of rare earth metals, wind turbine manufacturers have reduced the dysprosium content of NdFeB magnets [172]. Material efficiency gains in will reduce the pressure on primary resources and potential bottlenecks on the future material availability for the shift to a low-carbon energy system.

There has been little attention so far on circular economy potential and strategies for critical materials focused on re-use, remanufacturing and lifetime extension [167]. A number of products that contain critical metals, such as electronics, can be re-used as final products, as discussed in section 3.1.2. Lifetime extension of products such as consumer electronics depends on products being easily repaired, with parts possible to be replaced. The lifetime of in-use stocks can also be extended by reuse of the product or components and remanufacturing. This means that the materials stay in society for longer, being able to be upgraded to add new functionalities or more efficient technologies. One solution for Li-ion batteries is the remanufacture and repurpose of "end-of-first-life" batteries from EVs into storage units for power grids, commercial use and households [15,183]. At the end of that first lifetime, these repurposed batteries are estimated to still retain 70-80% of their initial energy storage capacity [173], and extending the lifetime of these batteries can lead to significant reduction in total demand for primary lithium [184].

6.3 Barriers for the circular economy for critical materials

Despite encouragement from governments to move towards a more circular economy, products containing rare earth elements have been insufficiently recycled so far. One of the reasons is that prices of many metals have been too low to run an economical recycling process, considering the costs of collection, dismantling and treatment, as well as recycling processes [144,185]. However, even in the case the recovery processes are economically beneficial, there are still barriers such as real and perceived risks, financial costs and time constraints, limited awareness and training, fragmented supply chains, and restrictive designs standards that may hamper the uptake of new materials or design methods [127].

There are major challenges for recycling of consumer goods, such as electric and electronic equipment (EEE) and vehicles, as well as infrastructure such as energy technology. Some of the main challenges are summarized below [15,144,169,186]:

- Current product designs often do not make disassembly and material separation technically feasible. This is the case, for example, with electronic products such as laptops and mobile phones that, usually, prioritize compact and lightweight design instead of end-of-life recovery of critical materials.
- There is a high mobility of products, with uncertain material flows. This is caused, for example, by international trade of finished and unfinished products, multiple changes in ownership, and widespread use. Thus, properly collecting, sorting and sending these products to material recovery poses a logistical and economic challenge, and target policy measures to alleviate this barrier are often lacking.
- There is a lack of appropriate recycling infrastructure for end-of-life management of complex products, such as EEE, in many locations, especially in developing and emerging economies.
- Despite new policy interest on the circular economy, especially in developed economies, there are overall missing economic recycling incentives due to the low cost of primary resources, and there a somewhat low global awareness about the social, economic and environmental impacts of resources loss.
- There is a significant amount of so-called hibernating goods, which are products not in use stored in households and not yet discarded, and small electric and electronic devices that are discarded in the trash bin, reducing the potential for recovery of secondary materials.
- A large amount of critical materials is stored in infrastructure with long lifetime, creating a lag between demand for materials and availability of scrap for secondary material recovery. For these materials, even though recycling rates (i.e. amount of materials recovered from end-of-life products) can be high, a growing demand results in low rates of use of secondary materials as input.
- Recycling technologies have sometimes not kept pace with complex modern products with a large variety of elements to be recovered, leading to losses of different materials in the recycling process.
- Some critical materials which are required for low-carbon technology cannot be recovered due to dissipative losses (see below).

A potential conflict that might arise from circular economy strategies is the availability of by-product metals. "Closing the loop" for major metals such as zinc, aluminium, and copper aims to reduce the amount of primary material extracted and refined and improve the environmental and social sustainability of material use. In fact, recycling metals reduce considerably the amount of material extracted from mining, leading to lower ecosystem and health effects in local communities, and require considerably lower amount of energy – for example, copper recycling uses up to 85% less energy than primary copper production [187] – leading to lower greenhouse gas emissions. However, reducing the primary demand for these major metals will impact the supply of by-product metals required for low-carbon technologies. Although these impacts have not been widely studied, it is estimated that the reduction in primary aluminium production might reduce the availability of by-products such as gallium [188]. On the other hand, if the supply of by-product metals such as tellurium will increase to meet future low-carbon technology demands, it can lead to oversupply of major metals like copper, reducing prices and thus, reducing economic incentives for recycling [189]. There is a need for further studies on the future dynamics of material availability under different scenarios of material demand and circular economy [167].

Losses by design: unrecyclable critical materials

Some materials cannot be recovered. There are two main reasons that classifies materials as unrecyclable: the dissipative material losses during the use phase of a product, such as selenium use in fertilizers, and "losses by design", where the use of the materials is currently considered unrecyclable due to technological and/or economic barriers [169]. Some of the critical materials for low-carbon technology have a high percentage of dissipative losses, such as zinc (around 20% of total use is lost during use phase) and selenium (above 25%). Furthermore, some rare earth metals and material for thin-film photovoltaics are currently present in in-use stocks which are considered unrecyclable.

Indium: Most of the indium able to be recycled today is in solders and alloys and in electrical components and semiconductors, but the recovery of indium from electronic products which contain very low concentrations is currently considered challenging. Around 80% of indium in end-of-life products is considered unrecyclable, most of it used in thin-film coatings. There have been recent advancements in recycling techniques for indium recovery, but these are considered costly [176], but the high demand of indium for new technologies and advancements in recycling techniques could improve the rates of recyclable content from EEE waste.

Gallium: Gallium can be recovered from solar cells, alloys and magnets. However, around 75% of current gallium uses is considered unrecyclable, mostly due to its high geographical dispersion in products such as integrated circuits, which make investments in recycling higher than the cost of primary raw material [169]. The growing use of gallium in CIGS solar PV is likely to increase the rate of recyclable material in the upcoming decades, when a significant number of solar PV cells reach the end of their lifetime.

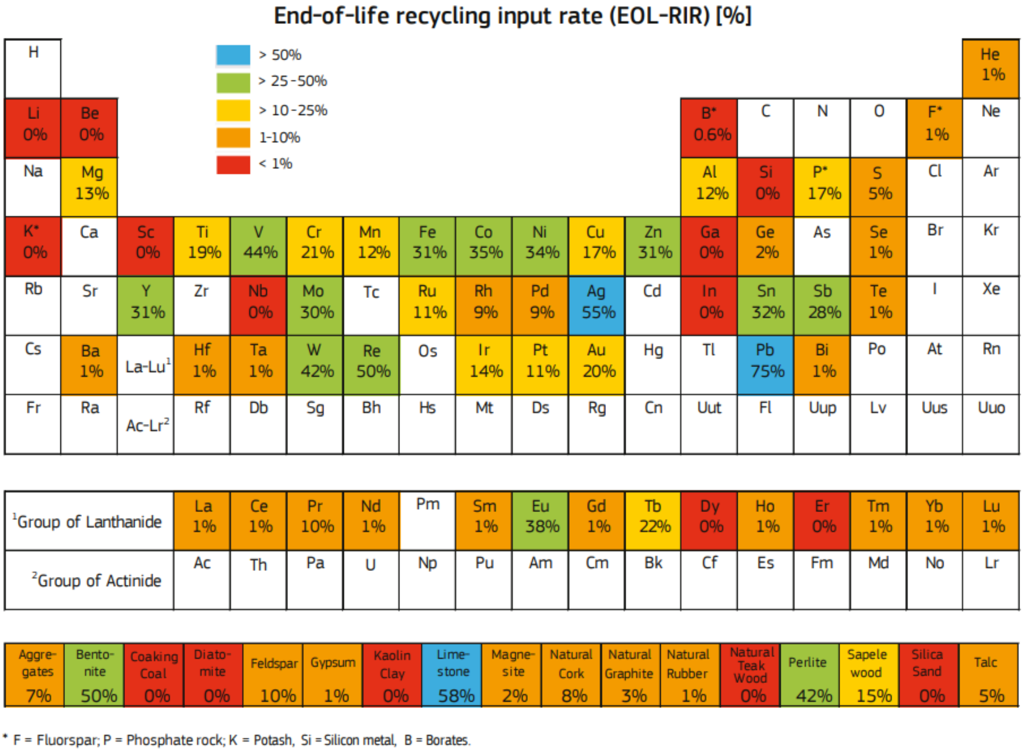
Rare earth metals: Some rare earth metals present a significant rate of dissipative uses that cannot be recovered or are not technically of economically feasible. Around 16% of praseodymium and 13% of neodymium in use cannot be recycled due to its dissipative use in glass polishing, metallurgy, ceramics, and autocatalytic converters. Although technically not a dissipative use on its own, rare earth metals gets lost in autocatalytic recycling for recovery of PGM.

6.4 Opportunities for the circular economy in Norway and in Europe

Europe, and Norway, is highly dependent on imports of several metal ores, and on materials embodied in finished and unfinished products. In particular, Europe has a high dependency on most of critical materials, and thus concerns exist regarding security of supply, especially when accounting for the high growth of low-carbon technologies in the next decades. To reduce the import dependency and contribute to the transition towards sustainable production and consumption patterns, whilst maintaining the competitiveness of the European industry, the European Commission launched the Raw Material Initiative (RMI). The RMI builds on three pillars: 1) fair and sustainable supply of raw materials from global markets; 2) sustainable supply of raw materials within the EU; and 3) resource efficiency and supply of secondary raw materials through recycling [190]. The promotion of the reduction of consumption of primary raw materials and increased production and consumption of secondary materials is tightly linked to the European Circular Economy Action Plan. The Circular Economy Action Plan is one the main blocks of the European Green Deal, and it has the aim to promote circular economy processes in the European industry, foster sustainable consumption, and ensure that resources used are kept in the European economy for as long as possible [191]. In addition, the Circular Economy Action Plan is expected to boost innovation and jobs in related with the re-use and recycling sectors [174]. To translate these policies into actions, the European Commission established the European Innovation Partnership (EIP) on raw materials, a platform that brings together stakeholders in industry, academia, governments and non-governmental organizations to promote innovations in the raw material industry [192].

There are substantial rates for recovery of metals in Europe from waste streams. For example, recycling rates for iron (and steel) are above 60%; for nickel, aluminium and platinum, above 50%; and above 40% for chromium and cobalt. However, these recycling rates can be much higher than the rate of use of secondary materials. Figure 25 shows the end-of-life recycling input rate for different elements in the European Union. This indicator quantifies the total material input to the production systems that comes from recycling of post-consumer scrap, that is, the rate of use of secondary material. The use of secondary materials in the European industry is significant: around 75% of all lead (Pb) used in Europe comes from recycled products, as well as 58% of limestone, 55% of silver (Ag), as well as over 30% for materials used in low-carbon technologies such as iron (Fe), cobalt (Co), nickel (Ni), zinc (Zn), molybdenum (Mo) and tin (Sn). These materials have high recycling rates due to being used in easily collected applications (for example, machinery), high economic importance and mature recycling technology (for example, steel recycling), or specific waste legislation that requires the extraction and recovery of specific components, such as for batteries. Platinum-group metals have high recovery rates from end-of-life products from industrial and automotive catalysts, but they present a relatively low (9%-20%) rate of secondary material use due to the rapid growth of demand for these materials by new technologies. Therefore, even though recycling rates are substantial (up to 95% from industrial catalysts and 50-60% from vehicles), recycling alone is not enough to meet the high demand. For rare earth metals (located in the figure in the Group of Lanthanide, third row from the bottom) and other specialty metals like lithium (Li), silicon metal (Si), gallium (Ga), selenium (Se), indium (In) and tellurium (Te), secondary raw material from post-consumer scrap correspond to virtually no share of material use. One of the main reasons for that is that primary extraction is often cheaper than recycling, since the concentration of these materials in products is low. Furthermore, as the demand for these materials grow rapidly for new applications in sectors such as low-carbon technology and communication and the in-use stock for these materials grow in society, there will likely be incentives to improve the technology for recovery of these materials at the end of their lifetime.

Figure 25. End-of-life recycling input rates (EOL-RIR) in the EU-28. EOL-RIR quantifies the total material input to the production system that comes from recycling of post-consumer scrap. Source: Vidal-Legaz et al. [174]



End-of-life recycling input rate (EOL-RIR) [%]

🟦 > 50%
🟩 > 25-50%
🟨 > 10-25%
🟧 1-10%
🟥 < 1%

H																	He 1%
Li 0%	Be 0%											B* 0.6%	C	N	O	F* 1%	Ne
Na	Mg 13%											Al 12%	Si 0%	P* 17%	S 5%	Cl	Ar
K* 0%	Ca	Sc 0%	Ti 19%	V 44%	Cr 21%	Mn 12%	Fe 31%	Co 35%	Ni 34%	Cu 17%	Zn 31%	Ga 0%	Ge 2%	As	Se 1%	Br	Kr
Rb	Sr	Y 31%	Zr	Nb 0%	Mo 30%	Tc	Ru 11%	Rh 9%	Pd 9%	Ag 55%	Cd	In 0%	Sn 32%	Sb 28%	Te 1%	I	Xe
Cs	Ba 1%	La-Lu[1]	Hf 1%	Ta 1%	W 42%	Re 50%	Os	Ir 14%	Pt 11%	Au 20%	Hg	Tl	Pb 75%	Bi 1%	Po	At	Rn
Fr	Ra	Ac-Lr[2]	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

[1]Group of Lanthanide	La 1%	Ce 1%	Pr 10%	Nd 1%	Pm	Sm 1%	Eu 38%	Gd 1%	Tb 22%	Dy 0%	Ho 1%	Er 0%	Tm 1%	Yb 1%	Lu 1%
[2]Group of Actinide	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

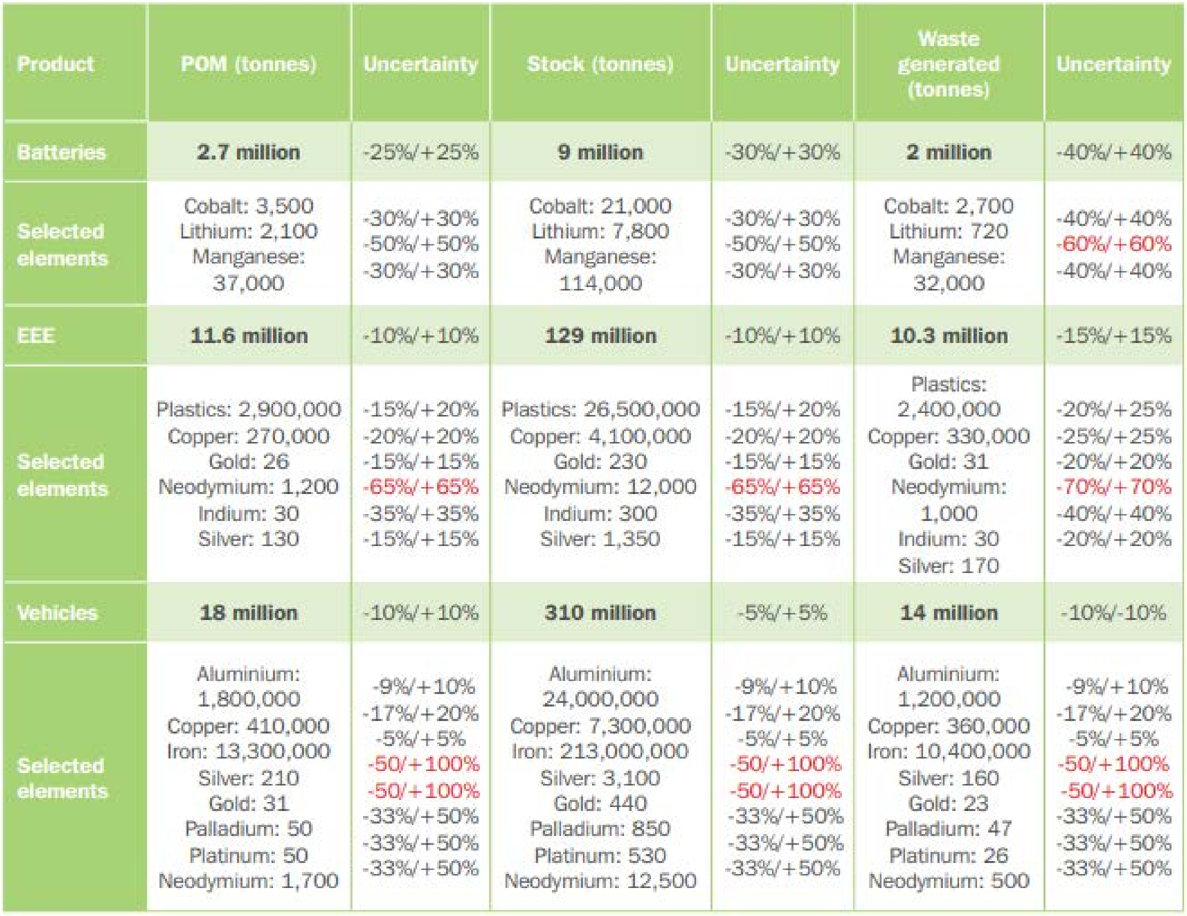
Aggregates	Bentonite	Coaking Coal	Diatomite	Feldspar	Gypsum	Kaolin Clay	Limestone	Magnesite	Natural Cork	Natural Graphite	Natural Rubber	Natural Teak Wood	Perlite	Sapele wood	Silica Sand	Talc
7%	50%	0%	0%	10%	1%	0%	58%	2%	8%	3%	1%	0%	42%	15%	0%	5%

* F = Fluorspar; P = Phosphate rock; K = Potash, Si = Silicon metal, B = Borates.

Improving recycling rates and the use of secondary materials relies on technology development, market value, but also on logistics and material availability. Many end-of-life products do not make their way into the proper secondary processing industries in Europe, resulting in the loss of recovery of critical and precious materials and creating barriers for the internal market for scrap [190]. The Circular Economy Action Plan identifies key product value chains for circularity. Among the key value chains is electrical and electronic equipment (EEE), which corresponds to one of the fastest growing waste streams in Europe, but only less than 40% of these are recycled in Europe. Increased recovery rates can be implemented through take back schemes to return or sell back old mobile phones, tablets, chargers, and other electronic equipment. Another key value chain is batteries and vehicles, which becomes paramount with the growing electrification of the European passenger vehicle fleet and the need to enhance the sustainability of batteries. The proper collection and recycling of batteries – from electric or internal combustion engine (ICE) vehicles, industrial, or consumer batteries – can provide valuable materials to European production processes. In addition, there is a need to revise the rules of end-of-life vehicles to link design issues to end-of-life treatment, such as recycled content for materials and components and improving recycling efficiency [191].

Urban mining and in-use stocks

The efficient recovery of materials from end-of-life products, buildings and waste in-use stock depends not only on proper sorting of materials, but also on reliable data on quantities, concentrations, trends and location of waste flows of secondary materials. The mapping of market inputs, stocks, raw material content and waste flows of electrical and electronic equipment, vehicles and batteries for the European Union Member States plus Norway and Switzerland has been gathered and publish in an Urban Mine Platform [175]. Figure 26 shows a selection of materials placed on the market (POM), in-use stocks, and waste generated by end-of-life products for batteries (2015), EEE (2015) and vehicles (2014) in the entire region. There are high uncertainties regarding the content of critical materials due to the high variation of those materials in different products (for example, the content of lithium, cobalt and graphite can vary widely depending on vehicle models [130]).



Product	POM (tonnes)	Uncertainty	Stock (tonnes)	Uncertainty	Waste generated (tonnes)	Uncertainty
Batteries	**2.7 million**	-25%/+25%	**9 million**	-30%/+30%	**2 million**	-40%/+40%
Selected elements	Cobalt: 3,500 Lithium: 2,100 Manganese: 37,000	-30%/+30% -50%/+50% -30%/+30%	Cobalt: 21,000 Lithium: 7,800 Manganese: 114,000	-30%/+30% -50%/+50% -30%/+30%	Cobalt: 2,700 Lithium: 720 Manganese: 32,000	-40%/+40% -60%/+60% -40%/+40%
EEE	**11.6 million**	-10%/+10%	**129 million**	-10%/+10%	**10.3 million**	-15%/+15%
Selected elements	Plastics: 2,900,000 Copper: 270,000 Gold: 26 Neodymium: 1,200 Indium: 30 Silver: 130	-15%/+20% -20%/+20% -15%/+15% -65%/+65% -35%/+35% -15%/+15%	Plastics: 26,500,000 Copper: 4,100,000 Gold: 230 Neodymium: 12,000 Indium: 300 Silver: 1,350	-15%/+20% -20%/+20% -15%/+15% -65%/+65% -35%/+35% -15%/+15%	Plastics: 2,400,000 Copper: 330,000 Gold: 31 Neodymium: 1,000 Indium: 30 Silver: 170	-20%/+25% -25%/+25% -20%/+20% -70%/+70% -40%/+40% -20%/+20%
Vehicles	**18 million**	-10%/+10%	**310 million**	-5%/+5%	**14 million**	-10%/-10%
Selected elements	Aluminium: 1,800,000 Copper: 410,000 Iron: 13,300,000 Silver: 210 Gold: 31 Palladium: 50 Platinum: 50 Neodymium: 1,700	-9%/+10% -17%/+20% -5%/+5% -50/+100% -50/+100% -33%/+50% -33%/+50% -33%/+50%	Aluminium: 24,000,000 Copper: 7,300,000 Iron: 213,000,000 Silver: 3,100 Gold: 440 Palladium: 850 Platinum: 530 Neodymium: 12,500	-9%/+10% -17%/+20% -5%/+5% -50/+100% -50/+100% -33%/+50% -33%/+50% -33%/+50%	Aluminium: 1,200,000 Copper: 360,000 Iron: 10,400,000 Silver: 160 Gold: 23 Palladium: 47 Platinum: 26 Neodymium: 500	-9%/+10% -17%/+20% -5%/+5% -50/+100% -50/+100% -33%/+50% -33%/+50% -33%/+50%

Figure 26. Selected materials placed on the market (POM), in stock and waste generated in the EU plus Norway and Switzerland, embodied in batteries, electrical and electronic equipment (EEE) and vehicles. Data for batteries and EEE for 2015, and for vehicles for 2014. Source: Huisman et al. [175]

Batteries and vehicles

Europe accounts for around one third of global market of electric vehicles, against around 20% for traditional internal combustion passenger cars. The European policies for electrification of transport will further increase the proportion of electric vehicles – hybrid, plug-in hybrid, or battery electric vehicles – in total sales and in total vehicles stock in the next decades. In 2017, around 2.7 million tonnes of batteries entered the marked in the EU plus Norway and Switzerland, mostly industrial and automotive lead-based batteries. The share of rechargeable Li-ion batteries is estimated to increase due to its use in portable electrical and electronic equipment, but mainly in plug-in hybrid electric vehicles and battery electric vehicles [175].

Europe's ambition to become competitive in the global battery sector and establishing a full value chain in Europe [193] involves securing the access of the European industry to the critical raw materials. Due to the sizeable market, the recycling industry has the potential to become a relevant supplier of secondary raw materials for the battery value chain [174]. There have been important European initiatives to strengthen the competitiveness on the battery industry. The European Battery Alliance

(EBA) is a network which comprises the European Commission, interested EU countries, the European Investment Bank, key industrial stakeholders, and innovation actors. It was launched in 2017, and it builds on the EU Strategic Action Plan on Batteries, which aims to make Europe a global leader in sustainable battery production and use, having the circular economy at its core [194]. Among the goals, it highlights the need to develop a recycling industry for secondary raw materials for batteries.

In 2020, the Urban Mining Platform estimates that end-of-life vehicles leaving the stock in Europe will provide thousands of tonnes of critical materials that could be recovered: around 450 thousand tonnes of copper; over 160 thousand tonnes of silicon; 5 thousand tonnes of molybdenum; around 1,6 thousand tonnes of chromium, neodymium, and indium; almost 400 tonnes of cobalt (excluding Li-ion batteries); around 250 tonnes of praseodymium; around 210 tonnes dysprosium; around 200 tons of gallium and silver; and almost 45 tonnes of platinum. The recycling of batteries (not only in vehicles, but also in EEE) can also recover substantial amounts of critical materials: around 14,5 thousand tonnes of graphite, almost 4,5 thousand tonnes of cobalt, and over 3,5 thousand tonnes of lithium [175].

However, over 40% of the materials in all end-of-life vehicles in Europe are not reported as recovered materials. This can be due to export of vehicles for disposal or recycling abroad, disposal without recovery of materials (for example, landfills) or complimentary recycling (for example, as mixed metal scrap together with other waste streams) in Europe. A higher recovery rate of these materials in end-of-life vehicles can contribute to increase the supply of secondary raw materials needed for the growth of low-carbon technologies.

Norway is one of the countries with a higher share of EVs in new passenger car sales, and the highest in Europe. In Norway, petrol and diesel cars corresponded to almost 75% of all new cars entering the market in 2015, and this share is estimated to decrease to around one third of new vehicles by 2020. However, the share of electric vehicles in the total vehicle fleet is still low. As these vehicles are more intensive in the use of critical materials, the amount of rare earth metals, lithium, cobalt, and graphite available for recovery will increase when the new vehicles reach the end of their lifetime.

Electric and electronic equipment

The composition of the products put in the market and in-use stock for EEE products is rapidly changing as new products enter the market. At the same time, products tend to become lighter and more compact, and thus while the number of equipment owned might have a steep increase, it does not lead necessarily to an increase in the weight of materials in waste flows. It also means that the composition of waste flows for EEE can change significantly over the next decades. For example, the share of neodymium in display screens put in the market has decreased over time, as well as the amount of copper in various EEEs due to the reduction in the use of cables and coils [175]. Similarly, there are changes in secondary materials in waste flows, as the preference towards new technologies will lead to the disposal of older EEE, often before the end of their lifetime.

The flows of recycling of EEE waste are small compared to other waste flows in the European economy, but they are important because they comprise an important source of precious and critical materials [174]. The Urban Mining Platform estimates that, in 2020, the end-of-life EEE in Europe could provide almost 350 thousand tonnes of copper, around 850 tonnes of cobalt, 80 tonnes of dysprosium, 40 tons of praseodymium, around 28 tonnes of indium, and 8 tons of tellurium. However, there is a large gap in Europe for the recovery of critical and precious metals in EEE products. Only around one third of all critical and precious metals present in EEE waste is reported as recovered. Consumer EEE waste is often found in non-sorted municipal solid waste, exported for reuse or recycling, recycled in complimentary processes (which might lead to sub-optimal recovery of critical materials), or unaccounted. For example, the amount of indium in reported collection in Europe is of around 25% of the total waste generated, and this figure is about 50% for copper. Electrical and electronic equipment are also source of materials for batteries. There are over 9 million batteries in use or stored in EEE in Europe, mostly rechargeable Li-ion and zinc-based batteries. The recovery and reuse rates of these batteries are likely underreported, leading to around 50% loss of recovery of cobalt and lithium [175]. The Directive on waste electrical and electronic equipment (WEEE Directive) aims to improve the environmental management of EEE waste, including improving the collection, treatment and recycling of end-of-life EEE [195]. The Directive foresees minimum targets for recovery and recycling of materials, but it does not require the recycling of critical materials.

Like with battery materials, there is a big potential for the development of a recycling industry for thin-film PV metals and for rare earth metals from permanent magnets. Ongoing research has shown the potential for using new techniques for efficient and cost effective of recycling of critical materials, for example, of indium and gallium from PV panels and EEE in Europe [196] and of rare earth metals from NdFeB permanent magnets [178].

The collection of EEE waste is not enough for an efficient recovery of critical material. Recycling rates depend on whether key components can be easily separated and extracted at the end-of-life. The circularity of critical materials depends on design for easy disassembly and on availability of technical information relevant for disassembly, recycling and disposal at end-of-life of the products [15]. The Ecodesign Directive [197] highlights the need for information from manufacturers to improve recycling rates of end-of-life products.

6.5 Summary of circular economy measures for critical materials

The large amount of critical materials needed for the growth of low-carbon technology in the next decades – representing a significant share of current primary production capacity – highlights the need for circular economy measures for critical materials. These include increasing recycling rates and the use of secondary materials, improving material efficiency, and extending the lifetime of in-use stocks.

Increasing recycling rates is key to minimize the pressure on primary extraction and production of raw critical materials and to improve the sustainability of material consumption. The large growth rates of low-carbon technologies, and their relatively low participation in the global electricity production and mobility, mean that the critical materials used to produce these technologies will not be largely available for recovery for at least a decade. These critical materials, however, are also available in a variety of other products currently in use. Batteries, electric and electronic equipment and components, vehicles and mining waste contain critical materials needed for building a low-carbon society. Platinum-group and rare-earth metals are available in automotive catalysts for the control of tail-pipe emissions. Electric and electronic components, communication and optic equipment contain metals required by thin-film photovoltaics, such as indium, gallium and tellurium. Rare earth metals required for permanent magnets are available in computers, audio systems, household appliances and MRI machines. Urban mining – recovering materials from end-of-life stocks of products, buildings and waste – can provide substantial stocks of critical materials that could be recovered through recycling processes. However, the recovery of critical materials from end-of-life products is still low due to complex and inefficient recycling technologies and to sub-optimal collection and treatment destination of end-of-life products. Extractive wastes and landfills can also constitute a potential source for secondary critical materials, but there are substantial technical challenges to recover these materials at a low energy cost. The successful recovery of critical materials from urban mining depends on having good information on the volume, composition, and location of the stocks of materials, both for the products entering the market, and the products reaching their end-of-life and able to be recovered. In

Europe, the ProSUM project has collected and made publicly available estimates on the material stock of batteries, electric and electronic waste, and vehicles in Europe, available at www.urbanmineplatform.eu. This database can help stakeholders in industry and policy to improve recycling rates of critical materials in all European countries.

Increasing material efficiency and increasing the lifetime of in-use stocks are also key strategy for reducing pressure on critical materials. Energy technologies have experienced important advances in material efficiency during the past decades in the form of reduced critical materials per equipment and of increased energy efficiency of energy technologies, allowing for a much higher energy generation or storage at a similar or lower material demand. The lifetime of in-use material stocks can be extended not only by extending the lifetime of individual products, but also by reuse of the product or components and remanufacturing. Instead of end-of-life, products can enter a "second-life" by being repurposed. Li-ion batteries from electric vehicles can be repurposed after the "end-of-first-life" into storage units for power grids, commercial use and households, leading to an overall reduced demand for total (primary or secondary) lithium, cobalt and graphite.

7 Discussion

Circular economy strategies are important for the transition to a low-carbon society for two reasons:

On the one hand, given the material requirements for low-carbon technologies including the extensive utilization of critical raw materials, circularity is necessary to ensure the best possible utilization and useful life-time of these materials through all circular strategies, ranging from the development of technologies that require none to very little of these materials, via design for repair and recycle and a more effective use and reuse to collection and recycling. Here, it is necessary to take a global picture of material availability and bottlenecks, as low carbon technologies around the world are competing for a limited material base. International collaboration for reducing material use and increasing material recycling is essential to avoid shortages that would lead to slowing down or even halting the deployment of individual low-carbon technologies, such as solar, wind or battery technologies. Recycling procedures for these materials are not yet mature and the technologies need to be designed for repair, reuse and recycling, an area where Norwegian researchers today are already very active[23][24][25].

On the other hand, circular strategies can support the reduction of GHG emissions through a large variety of channels, that in the end all result in a better utilization of the material base, reducing emission intense production activities, and keeping both materials and its value in the economy as long as possible. Norway's material production is already very emission efficient (the Norwegian process industry has the lowest emissions in the world per kg of aluminium, silicon and other ferroalloys produced), thus, the usual CO_2 emission reduction potentials from circular strategies for reducing material use are less effective for decreasing associated emissions in Norway. But, measured using SDG indicator 12.2.1 Norway has one of the largest material footprints per capita in the world (37 tonnes per capita), more than three times the global average (11 tonnes per capita) and still more than twice the European average (17 tonnes per capita) [198]. Thus, circular strategies for reducing material consumption and related GHG emissions will need to be addressed from the consumer, rather than the producer side in the Norwegian context.

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[23] http://ecosolar.eu.com/

[24] https://www.eydecluster.com/en/eyde-innovation-centre/batman/

[25] http://www.ree4eu.eu/

7.1 GHG emission reduction potential estimations

Total GHG emissions in Norway in 2018 were approximately 54 Mt CO_2e (excl. international shipping), see Box 2. For 2015, we estimate consumption-based CO_2 emissions, i.e. those emissions that occur along global value chains of final goods and services consumed in Norway, to be approximately 53Mt CO_2. Using a large variety of different methods in the different case studies, we estimate that about 6 – 10 Mt CO_2e of emissions can be saved through the selected circular strategies analysed here. Some of the emission savings will occur outside Norway, but it is not easy to differentiate those across some of the strategies.

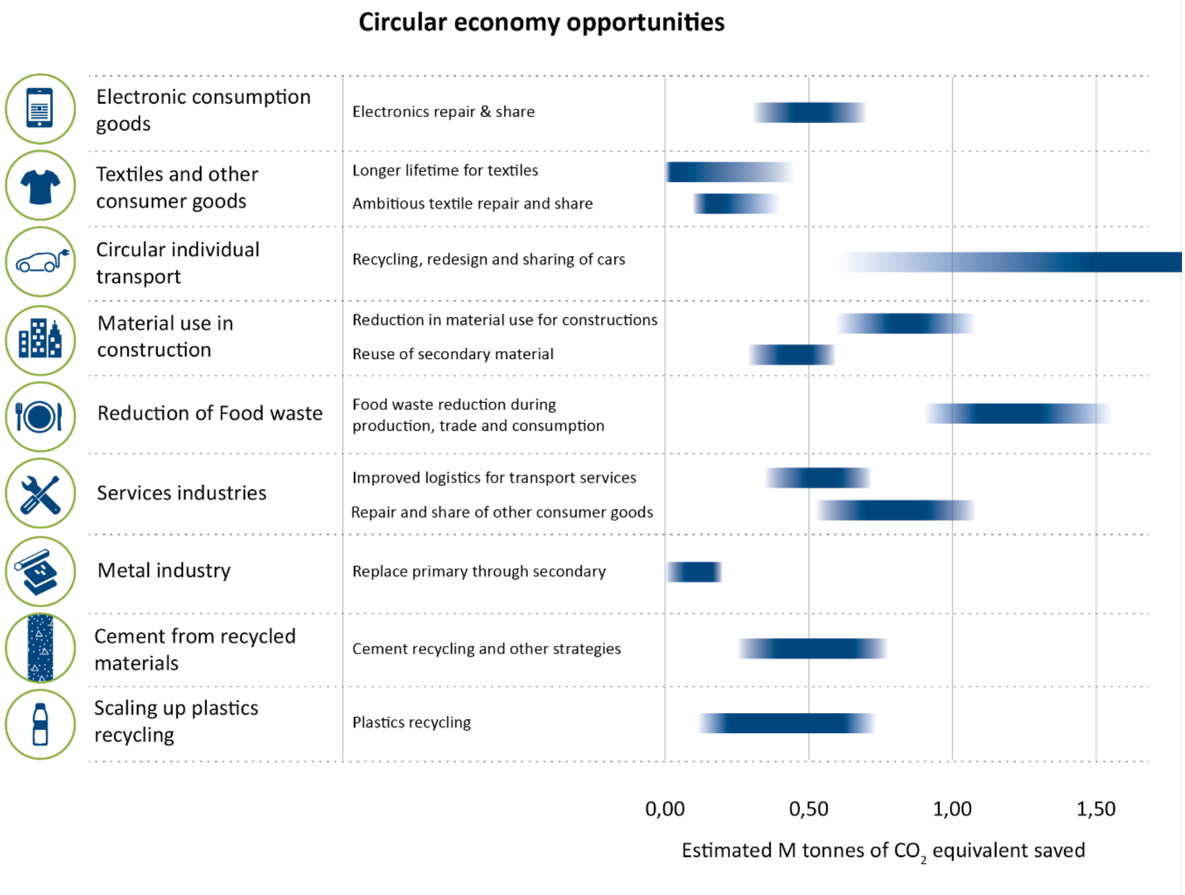

Figure 27: GHG emission reduction potentials through selected circular strategies. Note, these numbers are rough estimations and depend on assumptions. Source: Own estimations.

On the one hand, the potential is very much an upper bound in some of the cases, e.g. for sharing consumer goods. This assumes that everything that can be shared, will be shared. However, more realistically, only a fraction of these goods will be shared. The size of the fraction will largely depend on policy and changes in consumer behaviour. But, share and repair services for capital goods, such as machinery and equipment, can provide significant opportunities that have not considered here.

On the other hand, the potential can be significantly larger when including other products, materials and value chains. We have only included 12 Strategies across 9 broad sectors/value chains. We selected those based on their emission intensity and their economic size. However, for the cases, we looked at individual aspects within these broad sectors/value chains and focused on those circular strategies that were mentioned in the literature to have a reducing effect on GHG emissions. For the process industry, for example, we only focussed on the largest materials, and only on recycling strategies, but not on upstream and downstream potentials. A lot of circular strategies aim at increasing material efficiency and decreasing material use. Using less materials goes hand in hand with the production of stronger and more durable materials, which needs to be done by the process industry. These processes may have a higher energy requirement, but since less material need to be produced the overall effect can still be positive. Other circular strategies, especially from the user side, may also affect emissions, maybe not directly, but even more indirectly than through the holistic value chain perspective we have taken here. One of these possibly induced effects is the "rebound effect" in consumption, that occurs through savings (due to e.g. sharing), spent on more GHG intensive goods or activities. Another effect of a more circular strategies could be an awareness raising among consumers and producers, resulting in changes in behaviour outside the value chains directly targeted by the circular strategies, thus further decreasing material use and emissions.

Examples of cases or value chains that we have not covered, but that may have substantial potential for reducing greenhouse gasses are a better utilization of the existing building stock, reuse of buildings, renting and sharing options for manufacturing and service industries, renting and sharing of other consumer goods. Through a better utilization of the building stock, e.g. more people per household or smaller dwellings per household emissions related to construction and use could be reduced by 10-20% over the life cycle [199]. A recent study of 120 projects in Norway including building new buildings and rehabilitation of old building showed that on average rehabilitation projects resulted 22% fewer emissions [200].

7.2 Circular economy strategies for low carbon technologies

The transition to a low-carbon society will demand a large amount of materials. As in large infrastructure projects, there will be a need for basic materials for construction and energy projects, such as concrete, steel, and aluminium. With the exception of rooftop solar power, the installation of renewable energy is often decentralised, located in various power plants located far from energy consumption, which will demand large investments on grid expansion and materials for electricity transmission, such as copper and aluminium. Furthermore, the production of low-carbon technologies depends on critical materials for which future prices and availability are uncertain. In this report we focused on critical materials because of their importance for the growth of low-carbon technologies, as well because these low-carbon technologies are estimated to be significant drivers for the future demand for these materials [[167]].

Whether materials will be a bottleneck for the deployment of different technologies will depend on a number of factors, such as:

- The technology mix of future low-carbon energy system, not only between different technologies per se – such as solar versus wind power – but the actual technology mix within them, such as future market share of direct-drive generators and generators without permanent magnets for wind power, or different thin-film photovoltaics.
- Technological development on reducing critical material requirements or substituting critical materials. This is the case for ongoing research on high-efficiency wind turbine generators without rare earth metals, reduction of platinum-group metal contents in fuel cells, and cobalt-free or lower cobalt content on batteries for electric vehicles, for example.
- The growth of competing resource use by other emerging applications, such as medical devices, robotics, and data and communication technology.
- The adoption of circular economy measures, such as the development of regional markets for recycling of batteries, solar cells, permanent magnets, and other electrical and electronic waste for the recovery of critical materials.

The circular economy is important to reduce material intensity and emissions in the main bulk material use, such as concrete and steel. This has been discussed in the first part of the report through the demand-side (section 3.2) and production-side (sections 4.1and 4.2). However, circular economy strategies are essential to secure the high growth rates of low-carbon technologies. As discussed in section 5, the average annual demand for some of these materials – distributed in equal annual shares between 2019 and 2040 – correspond to a significant share of current primary production.

Figure 28 illustrates the global demand for strategic (aluminium, steel, and copper) and critical materials demanded by the different low-carbon technologies assessed in this report. The colour of the bubbles represents different technologies (solar photovoltaics, wind, electric vehicles, and hydrogen and fuel cells), and the size of the bubbles represent the percentage of the average annualised cumulative demand compared to the current primary production. The average annualised cumulative demand corresponds to the cumulative estimated material demand between 2019 and 2040, distributed equally throughout the period. While it is an approximation, it reflects what would be the highest bottlenecks if technology and material production rates were to remain like the current ones. This is likely to overestimate risks of supply, after all, highest growth in technology use will likely happen throughout the second half of the period, when production expansion should increase following increased material demand, and there will likely be gains in material and energy efficiency, resulting in lower material requirements per MW installed. However, this analysis allows us to look into the current supply chains and see where those risks can be decreased by new investments in primary production and by circular economy measures such as material efficiency, higher recycling rates, and new recycling techniques.

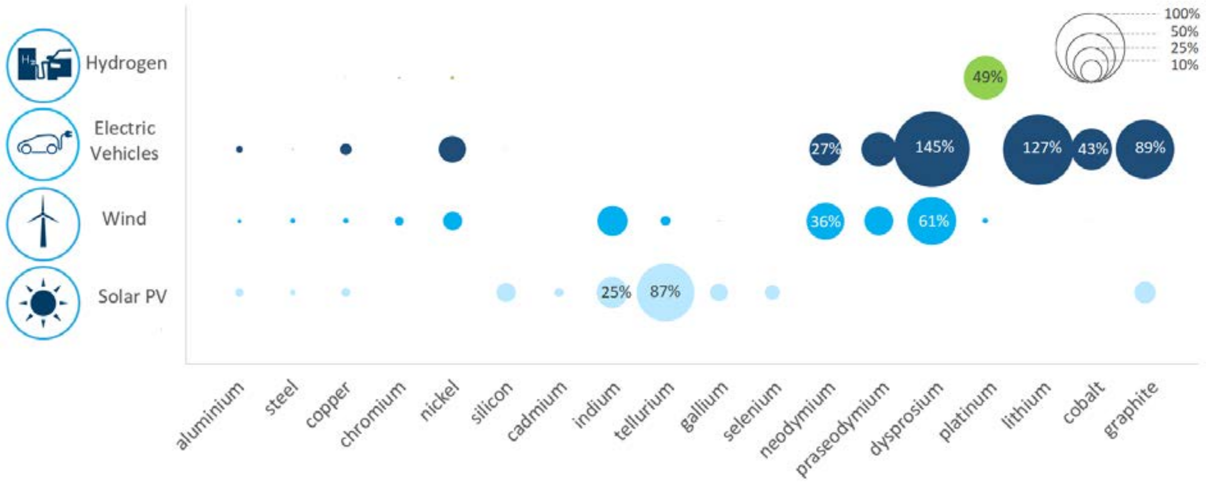

Figure 28. Average annualised cumulative global demand of strategic and critical materials needed by 2040 for the growth of low-carbon technologies, compared to current primary material production rates. Values above 25% are detailed.

Circular economy can reduce the risks associated with the supply of these critical materials. Material efficiency measures in the industry can reduce the demand for primary raw materials in the processing industry and in the manufacture of low-carbon technologies and components. Increasing the rates of secondary material use is achieved by collection and recovery of critical materials available in in-use stocks using commercially available techniques, and to setting up more efficient and cost-effective recycling schemes for critical materials in low-carbon technologies such as Li-ion batteries and permanent magnets, as well as in end-of-life products such as electric and electronic waste, batteries, automotive catalysts, and medical equipment.

Recycling is a key activity to reduce the pressure on the extraction of primary raw materials, improving resources availability, reducing the risks of future supply, and improving the sustainability of the materials. The production of secondary materials demands a much lower energy and material demand than extraction and refining of primary materials, and metals have an advantage that they can, in many cases, be recycled with low loss of materials and quality. The recycling of critical materials depends, ultimately, on the technology for material recovery and on the availability of pre- or post-consumer scrap.

While increasing recycling rates for critical materials is of high importance for the resource availability for low-carbon technologies, there are many factors that can hinder the recovery of these materials to a level much lower than what is technically feasible. Among the identified barriers are: product design which are not optimized for recovery of (critical) materials, low cost of primary materials compared to secondary and lack of recycling incentives, lack of appropriate recycling infrastructure, high costs and logistic barriers for proper collection and treatment of end-of-life consumer products such as electrical and electronic equipment, and technical barriers for recycling.

Another important barrier is the delay between building of stocks and the lifetime of products: the volume and composition of materials required today are not necessarily those available to be recycled.

One example is the composition of end-of-life electrical and electronic waste which compose the stock reaching the lifetime now, compared with the materials demanded for the production of electric and electronic components today. Rapid technological advancements have resulted in a significant change in the composition of materials in in-use stocks, as can be compared between old and new mobile phones and televisions, changes in size and composition of batteries for portable devices, or the rapid advancement of cordless electronics. Besides that, the lack of proper collection and destination of waste, especially from consumer goods, can decrease the rates of recycling: a large amount of portable electric and electronic goods is discarded in the municipal solid waste, destined for incineration or landfills, or stored in households without being used, the so-called "hibernating goods". Another example refers to the volume of materials demanded versus the materials available to be recovered. The long lifetime of technologies mean that the materials used in solar PV cells and wind power plants will not be available for recovery in two to three decades, and the materials in batteries for electric vehicles will not be able to be recovered in the next decade. While this gives time to improve recycling techniques for the recovery of these materials, the high growth rates expected for low-carbon technologies in the next decades will mean that most of the increase in material demand – including critical raw materials – will have to be satisfied by increased extraction and refining rates of primary material.

There are an increasing number of ongoing researches to advance recycling techniques for critical materials, including efficient and cost-effective ways to recover critical materials from electric and electronic waste, solar cells, permanent magnets, fuel cells, and Li-ion batteries. Those techniques, however, are not yet commercially available and thus it is hard to estimate what will be the material, energy and financial costs of large-scale recycling of low-carbon technologies when a large volume of these come to the end of their lifetime.

Although material efficiency and lifetime extension are of high relevance for critical materials, there is a large focus on recycling when it comes to circular economy measures for critical materials. This is likely because increasing recycling rates is able to reduce the risk of supply disruptions. Many of the critical materials are concentrated in countries with medium or high political risks, such as South Africa in the case of platinum-group metals, the Democratic Republic of Congo for Cobalt, and China for rare earth metals and indium. Securing supply of critical materials to national industries reduce import reliance and result in gains in competitiveness and jobs.

7.3 Data and knowledge gaps, current limitations and future research

To analyse circularity, taking a systems perspective including complete value chains and covering the entire economy and international trade rather than individual products or processes is inevitable. It requires a combination of research methodologies from very different fields ranging from economics and statistics via environmental and material science to physics and chemistry, and combining data that are compiled by a different actors (researchers, statistical offices, industry), at different levels, using a large variety of methods and sources. Economic data usually comes in monetary values and aggregates to product groups or industries. For material recycling, data details material groups or even individual chemical elements that are to be taken out of discarded products. Emissions occur during processes that extract raw materials, transform materials into products, intermediate products into final goods, move goods and people around the world, and transforms goods back into materials (recycling). Data on CO_2 emissions from fossil fuel combustion is readily available at the macro-economic level and relatively reliable, while data on other GHG emissions is more difficult to estimate, due to a lack of mature methodologies for data collection and reporting. To follow materials through entire value chains, assessing related emissions, and putting this into the global context is challenging due to many reasons, the most important being

- The multitude of products and processes involved.
- The high degree of interdependency in globally fragmented production chains.
- The inoperability of existing data.
- The lack of data collection, especially regarding detailed emissions and material data related to economic activities, resulting in large data gaps.

More concretely, in this report, we have encountered the following challenges with respect to measuring "the impact of circularity on climate change mitigation and adaptation […] in a systematic way" [2,p.20]:

Data for (direct) emissions detailed for the most important greenhouse gasses (CH_2, N_2O, CH_4, HFC, PFC, SF_6) was readily available from SSB at the industry level (44 industries + households) for Norway. CO_2 emissions related to international trade could be estimated from OECD data, while other emissions are not covered in this data set. Based on this, we were able to estimate emissions in value chains (at the aggregate industry level) and analyse these from a consumer and producer perspective to identify emission hotspots. For assessing emission reduction potentials for individual case studies from these data, we encountered two main problems: the classification of material data (limiting own calculations) and the level of aggregation of the emissions data (e.g. aggregating motor vehicles, trailers and semi-trailers) while specific case studies are looking at passenger cars. Material data is not available at the same level of industry classification. In fact, while material extraction data is available by material group, there is no information on the economic sectors using and further processing the materials at a detailed level. Thus, combining the assessment of material circularity and related emissions is difficult, without consulting a large body of different literature. The literature, however, is based on a large variety of research fields and different methodologies, making it difficult to relate the findings back to the industry level emission data, that is used for reporting to UNFCCC. One example is the assessment of life cycle emissions for private car usage [21], which reports total emission reduction potentials, combining emission reduction potentials from using lighter materials with resulting lower in-use emissions, and car sharing options for G7 countries. On the one hand, this analysis is very detailed for the specific case, but then it is averaged across all users in G7 countries, making it difficult to relate to Norwegian data. Another interesting research question is the amount of CO_2 emissions that occurred during the production of goods that are discarded (without being fully used) or sitting in homes and are never used. While the composition of mixed waste is known from sampling waste [63], there is no information about the condition of discarded products, so that we cannot distinguish between waste of products that were used up and waste of products that were almost new. Further, while it is possible to estimate the amount of emissions that occurred during the production of the materials underlying waste (by using waste material quantities[26] and average emission factors for the production of the materials), it is not known in which types of products the materials were used, so that large parts of the value chain would not be accounted for.

Estimating future material demand also involves uncertainties. Here, we combined bottom-up life cycle inventories with energy scenarios to estimate the volume of critical materials needed for the transition to a low-carbon energy system. Life cycle inventories are based on specific models for the product assessed – in this case, solar photovoltaic panels, wind turbines, electrolysers, fuel cells, and

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[26] Norway produces annually about 2.5 million tonnes mixed waste for combustion [63] 15% food waste/biowaste (375000 t), 6% paper and paper products (150000 t), 55% plastics (1.25Mt), 3% glass (75000 t), 15% metals (375000 t), 10 % textiles (250000 t), and 4% EE-waste (100000 t).

battery packs for electric vehicles. These inventories reflect the mass of materials included in each technology, and they constitute a good approximation of reality when assessing the material demand of energy scenarios. There are, however, uncertainties when using specific products' inventories to scale up to future material demands. First, different manufacturers and even different models from a same manufacturer can have different material composition. For example, the amount of lithium per battery electric vehicles sold in Europe in 2015 ranged from 4,58kg to over 20kg per vehicle, depending on the size of the battery [130]. Second, these inventories have a cut-off criteria for reporting, which refer to omitting non-relevant material or processes for the goal of the inventory. Although ideally a life cycle inventory would include 100% of all materials used, it would lead to high complexity. Thus, some inventories do not include specific materials or information for critical materials, such as alloying elements for steel in wind power turbines, or elements which are contained in relatively low amounts, such as rare earth and precious metals in wind turbine generators. Third, the inventories reflect the material intensity and composition of a technology in a certain point in time. It does not capture advancements in material efficiency or substitution of critical materials in key technologies. With the expected increases in material efficiency, the demand for materials is likely to be lower than the reported here. And fourth, the technology mix chosen will influence the demand for critical materials – for example, a higher uptake of thin-film photovoltaics will lead to higher demand of metals such as indium and tellurium, and lower demand of silicon. In addition, the choice of energy scenario will affect the demand for materials. The choice of the sustainable development scenario over the stated policies leads to higher growth of solar photovoltaics and wind. Likewise, the IRENA scenarios would forecast an even higher increase of these technologies. For example, previous studies [130,168] have estimated lower demand of a range of critical materials due to not the material intensity of technologies, but because low-carbon technologies had lower growth rates.

The increase in the production of secondary critical materials depends on the advancement of recycling techniques and on the availability of end-of-life products to be recycled. The extent to which the critical materials discussed in this report will be able to be recovered to support the low-carbon technology growth is still a knowledge gap. The material, energy, and costs associated to the large-scale recycling of these materials is still unknown due to the recent developments of new recycling technology. Furthermore, information regarding the location and volume of these materials will help to identify market opportunities for recycling industries. Stock-cohort models provide an overview of the volumes of materials entering the in-use stocks, but also provide an estimate of when current stock will be retired and able to be recycled. Databases such as The Urban Mine Platform, presented in section 6.4, are of great importance to identify the potential for proper waste and scrap collection and material recovery in different countries, and efforts to update and extend these platforms might contribute to the transition towards a circular economy for critical materials.

Modelling tools that can be used "*to capture the benefits of the circular economy on greenhouse gas emission reduction at EU and national levels*" [2,p.20] span several very specific research fields from economic value chain modelling via material flow analysis to life-cycle impact assessment, that in turn all rely on a multitude of data and methods from economics, statistics, chemistry, physics, material and environmental science. Interdisciplinary research is a must, however, there still are lacks in data availability, data consistency and model interoperability.

Further Circular Economic research and innovation needs

Transitioning to a circular economy should require value chains to operate in a different mode than today. To establish new circular industry and businesses we will need a number of innovations.

Innovation in business models, socio-economic innovations, and not least technological innovations including new materials, new process, new products. Technical innovation needs identified in this study are:

- Upscaling and improved economic efficiency of collection, sorting and recycling technologies and value chains. Particularly for consumer electronics, plastics, construction waste, waste and valorisation of bi products from the metallurgical industry.
- Digital tools and platforms for production planning and decision support across the supply chains, logistics and exchange of embedded information about materials, and platforms for sharing and better utilization of side-streams and by-products

Also non-technical research on:

- Consumer education and changing public attitudes towards waste minimisation
- Reform of tax system and regulations to support prolonging economic lifetime of goods, stimulate the repair and leasing service industry and stimulation of the markets for secondary materials and products

Investment in new technology has an associated risk that that can be mitigated by cooperation and consensus along the value chain to ensure the technology that will be relevant for 10- 30 years from now. Short term circular economy research requires insight and system understanding to enable the industry and business to manoeuvre to a functioning and environmental and economically sustainable circular economic model. Each of these strategies also have associated social impact, creating value and jobs particularly distributed in districts and regions. The environmental impact of greenhouse gas emission is a is critical driver of the green economy as outlined here but it is also critical to further measure the other environmental impact of the strategies on resource use, ecological impact and waste generation. Additionally, studies on the social and economic impact of the circular economic strategies should be carried out for example economic gain or job creation at a value chain, national or global level [201].

Outside of Norway the EU Green Deal (see box 4 below) launch in March 2020 sets forward a number of action plans to drive the European level transition to a circular economy. The findings of this study reflect that the same Circular Economy strategies that could be beneficially applied in Norway are paralleled in the European Union Strategy. The policy framework that EU will roll out will have a large influence on Norwegian industry and activities and public policy. Research and development in the highlighted areas above will be necessary to facilitate the transition.

Box 4: The EU Circular Economy Strategy and the European Green Deal.

Many of the key circular strategies proposed to reduce emission are reflected by the EU Circular Economy Action Plan that was published in March 2020 as part of the European Green Deal. The main measures identified in the green deal are listed below:

- **Make sustainable products the norm in the EU**. The Commission will propose legislation on Sustainable Product Policy, to ensure that products placed on the EU market are designed to last longer, are easier to reuse, repair and recycle, and incorporate as much as possible recycled material instead of primary raw material. Single-use will be restricted, premature obsolescence tackled and the destruction of unsold durable goods banned.
- **Empower consumers.** Consumers will have access to reliable information on issues such as the reparability and durability of products to help them make environmentally sustainable choices. Consumers will benefit from a true 'Right to Repair'.
- **Focus on the sectors that use the most resources and where the potential for circularity is high.** The Commission will launch concrete actions on:
    - **electronics and ICT** – a 'Circular Electronics Initiative' to have longer product lifetimes, and improve the collection and treatment of waste
    - **batteries and vehicles –** new regulatory framework for batteries for enhancing the sustainability and boosting the circular potential of batteries
    - **packaging –** new mandatory requirements on what is allowed on the EU market, including the reduction of (over)packaging
    - **plastics** – new mandatory requirements for recycled content and special attention on microplastics as well as biobased and biodegradable plastics
    - **textiles** – a new EU Strategy for Textiles to strengthen competitiveness and innovation in the sector and boost the EU market for textile reuse
    - **construction and buildings** – a comprehensive Strategy for a Sustainably Built Environment promoting circularity principles for buildings
    - **food** – new legislative initiative on reuse to substitute single-use packaging, tableware and cutlery by reusable products in food services
- **Ensure less waste.** The focus will be on avoiding waste altogether and transforming it into high-quality secondary resources that benefit from a well-functioning market for secondary raw materials. The Commission will explore setting an EU-wide, harmonised model for the separate collection of waste and labelling. The Action Plan also puts forward a series of actions to minimise EU exports of waste and tackle illegal shipments

8 Conclusion

Norway is a small, open, highly developed economy with a large per capita resource and emission footprint. While consumers and producers are increasingly becoming aware of the environmental problems they create, not only in Norway but also abroad, there is still some changes necessary.

Consumption must be reduced and channelled towards more sustainable, higher quality and longer lasting products. Producers and wholesale/retail trade services must offer and promote the more sustainable options. This includes not only goods that are designed for repair and reuse and to reduce material use and emissions, but also new business models offering leasing, repair and share services. Material reuse and recycling strategies must become the norm rather than the exception, this is especially important in the context of new low-carbon technologies.

Across sectors and value chains this study identified several recurring and essential enablers for achieving a Norwegian Circular Economy, there are;

- Strengthened requirements for sorting of waste and increased collaboration across the value chain to improve on product recyclability
- Improved production planning and decision support across the supply chains
- Long-term public and private RD&D investments in new circular economy enabling innovations
- Reform of tax system, prolonging economic lifetime of capital goods and penalising the use of materials and non-renewable energy instead of labour
- Focusing on consumer education and changing public attitudes towards waste minimisation
- Stimulation of the markets for secondary materials and products
- Digitalization for improved logistics, embedded information about materials, and platforms for sharing, and better utilization of side-streams and by-products

This green change needs to be supported by public authorities through e.g. investigating increasing environmental taxes, or supporting regulations such as the "right to repair", so that circular options become more attractive. A potential benefit of making leasing, repair and share services more attractive are job creation opportunities in Norway. Norway has a highly educated workforce and is leading in different technological research fields; efforts and investment should support the development of environmentally friendly design of products and processes and design for repair, such as the solar cell developed by the project ECO solar [[202]]. This also shows the potential of circular strategies for supporting the transition to a low carbon economy. Regulations need to ensure that circularity potentials can be fully exploited.

One of the most important things supporting the transition to a green economy is policy coherence and consistency in the long run to create certainty and guarantees for long-term planning by small and large private and public investors [[203]]. The transition to a circular economy entails a system change, everyone along global supply chains is affected and needs to participate and collaborative inter-disciplinary actions across various levels need to be fostered and supported. The communication by world leaders from policy and industry around the 2020 Petersberg Climate Dialogue is clear: "It's time for emergency packages. Green emergency packages. A new green start" [[204]].

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