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Energy Transition's Technical Pathways, Risks, and Equity—Review

Critical Review of Climate and Resource Costs and Benefits of Machinery and Equipment

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ABSTRACT

Environmental input–output analysis suggests that we use one-third of all metals to produce machinery and equipment (ME) and that their production causes 5% of greenhouse gas emissions globally. Yet, our empirical understanding of material use and emissions associated with ME remains limited, making it the least researched major aspect of material consumption. Machines are not represented explicitly in climate change mitigation models and there is little research considering mitigation opportunities related to ME. Meanwhile the practice and potential for circular material flows, which have dynamic interactions with machinery, have yet to be explored. ME is a very diverse category and so economic statistics and input–output models are essential for a holistic understanding. Mitigation, however, can only be understood through bottom-up engineering research. We identify data sources for future empirical research and suggest how to combine these. Future demand for ME can in part be foreseen by assuming that lower-income countries will use machines to increase their productivity to levels seen in high-income countries. Additional demand will arise from the introduction of autonomous machines, service robots, and artificial intelligence in workplaces and homes. We describe knowledge gaps and outline research questions important for anticipating the future requirements for machines and their potential contributions as both causes of and solutions to climate change and resource overconsumption.

1. Introduction

Machinery and equipment (ME) are tools humans use either for productive purposes or to provide services directly to consumers, alongside buildings and infrastructure and vehicles [1–3]. The Paris Agreement [4] poses the dual challenge of moving towards net-zero greenhouse gas emissions (GHGE) for both the operation and the production of ME. The operation of ME is responsible for most GHGE but, in 2020, the manufacturing of ME required one-third of the global metal supply and caused 5% of global GHGE [5,6]. These issues may be compounded as more and new machinery are required for other sectors to move to net-zero.

Two-thirds of the world's population live in countries with insufficient ME, and hence, meagre livelihoods, given ME's role in labor productivity and incomes [7]. To become productive and fulfil their populations' aspirations, developing countries require more ME [8,9] (Fig. 1). Producing the ME required for the decarbonization of the economy and to raise productivity in middle- and low-income countries while also maintaining the productive capacity of high-income countries will be a major challenge. In 2024, the Chinese government introduced the Plan for Promoting Equipment Renewal in the Industrial Sector [10], which includes replacing outdated equipment, upgrading key sectors such as solar energy and battery manufacturing, integrating digitalization with industrial equipment, and adopting green technologies. To produce all this ME within the remaining carbon budget and the planetary boundaries may be even more demanding. Yet, the challenge is poorly understood and inadequately described. As a result, an adequate response by policy makers and companies is lacking.

ME is at the core of a modern economy. Without knowing how to reform ME, our understanding of the required economic transformation to sustainability is incomplete. This critical review focuses on the resource requirements and GHGEs of producing, maintaining, and operating ME and the materials that can be recovered at the end-of-life. It addresses quantifications of the material flows, investigations of improvement opportunities

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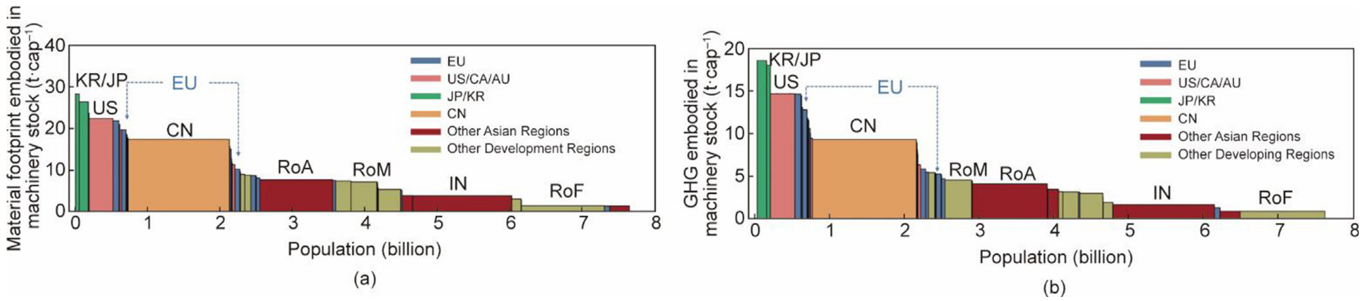

Fig. 1. (a) Materials footprint and (b) greenhouse gas (GHG) emitted to produce the stock of ME in different world regions, status 2019. Equipping everybody with the same per-capita (cap) stock of ME as the US would require 15 Gt of metals and cause more than 100 Gt CO_2 equivalent ($GtCO_2e$). The data and figures were updated based on our previous study [5], with transport equipment and unspecified manufactured products excluded. KR/JP: Korea and Japan; EU: European countries; US/CA/AU: the United States, Canada, and Australia; CN: China; RoA: rest of Asian countries; RoM: rest of Middle Eastern countries; IN: India; RoF: rest of African countries.

through GHGE mitigation and efficiency strategies, and the modelling of scenarios of future ME use. It identifies research questions related to ME for sustainable development and net-zero GHGE. It provides an overview of our current state of knowledge and indicates a potential direction for further work.

2. Methods

The literature search in Google Scholar, Scopus, and Web of Science used search terms such as "climate change mitigation" AND ("machine*" OR "equipment"), life cycle assessment (LCA) AND tractor, and so forth. We reviewed the mitigation modelling literature, the industry sector chapters of the last two climate change assessments of the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency's Energy Technology Perspectives reports and underlying activities, as well as supporting documents of European Union climate policies. We used a snowballing method to identify relevant citations or cited articles.

Research questions about specific ME: Relevant research questions can be asked of specific products and across product categories. The following questions concern individual machines or narrow categories of ME:

(1) What is the material composition of a product? How much energy was used to produce it, and how much waste and emissions were produced?
(2) How does this depend on design choices, product features, and scale of production?
(3) What is the energy use to run the ME as a function of the output produced? What are other operating inputs, including data requirements, maintenance and repair? How does this depend on factors of design, quality of production, or operations?
(4) What is the lifetime of the ME and what does it depend on?
(5) What are improvements and changes in this type of ME over time, historically in the past and expected for the future?
(6) What are the options to produce and operate ME in a more environmentally friendly manner? Can we improve energy and material efficiency, use low-carbon energy and materials, or avoid production altogether? Can we reuse and remanufacture ME or their parts? Can we improve the recycling of ME by taking better care of the specific functions of alloys used in different components?

Further, we also would like to understand the spread across ME.

(1) How different are different ME products of a specific type (e.g., conveyor belt)?
(2) What is the variation across different types of ME within a category (conveyor belts compared to cranes)?
(3) What is the variation across categories (conveyor belts compared to furnaces or server farms)?
(4) Are there any factors that predict the observed variations, such as weight/value ratios?

3. Machines in theories of sustainable development

ME belong to the category of capital goods, like buildings, infrastructure, and vehicles. In sustainability science, these are called manufactured capital, as distinct from human, social, or natural capital [11]. In economics, one refers to "real" as opposed to financial capital. Capital comprises goods that are used for productive purposes for more than one year. In national economic accounting, durable goods, such as dishwashers or lawn mowers, are not counted as capital if they are used by households, even if they are used for a long time because they do not produce economic output. If the same goods are used by a service company, however, they are counted as capital. This distinction around "productive purposes" does not necessarily apply in other fields, such as social ecology, but studies may be constrained by economic data. According to social ecology, ME form part of the material stock of society in the stock–flow–service nexus [2,12]. The stock enables and facilitates the flow of resource utilization for the purpose of service provision (Fig. 2). Capital stocks are part of provisioning systems [2,13], which also include human practices and skills, institutions such as firms and markets, and natural environments used for resource provision, providing distinct services such as nutrition and shelter. The structure and characteristics of these systems, alongside the quantity, quality, and design of the capital, influence the amount of resources required both to deliver services and to grow and maintain the capital stock.

The key insight of previous economic and sustainability thinking about ME is that ME is needed for economic production and delivery of services desired by humans (Fig. 2). ME is needed as a stock: it fulfils its function through its presence and is not consumed (i.e. it does not become part of the product and is not exhausted by service provision, at least within the course of a year). However, the stock delivers its service only over a limited time, due to degradation or technological change. Increasing the flow of goods and services to consumers requires an increase in the stock of capital, as well as the flow of raw materials and energy to feed and operate the capital stock. Increasing the productive capacity of the economy requires that part of today's productive capacity is utilized to produce capital rather than provide services. That is, investment implies deferred consumption.

A key aspect of capital goods is that they prescribe a production recipe [14]. A mechanical stamping press in a car factory prescribes both the type of vehicle that is produced and the material it is

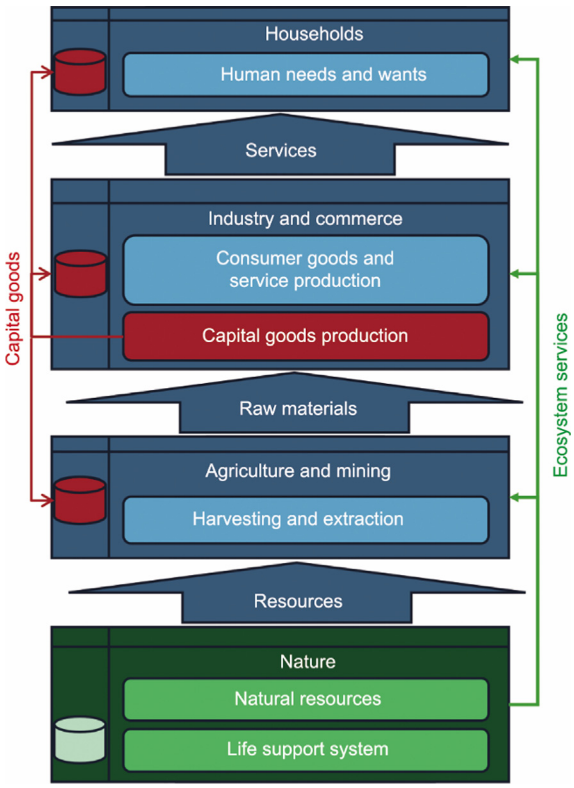

Fig. 2. The stock–flow service nexus shows the role of natural capital (green store) and manufactured capital (light blue store) in connecting resources to services. Machinery, equipment, and other capital goods facilitate the production of consumer goods and services, consumer durables, and capital goods. A consumption-driven model needs to capture these relationships.

made from. It requires a fixed ratio of inputs per unit output. Other ME may be more flexible in its use. A tractor can be used in various types of agriculture, as well as snow cleaning and road maintenance, and if need be, as a means of transportation. Independent of use, however, it requires a specific fuel.

The industry chapter of the IPCC sixth climate assessment report presented a decomposition analysis following the stock–flow–service nexus [3]. It addressed the stock of materials [15] and the flow of energy required to generate economic product [3]. The decomposition analysis showed that while the capital stock per unit gross domestic product (GDP) had changed little over the period of 1900–2019, the amount of primary material per unit stock formation had decreased since 2010 and the use of secondary materials (reused from other applications) had increased.

ME is an important category of stock in the stock–flow service nexus, both in terms of quantity, and in terms of quality which shapes the utilization of resources and the production of waste in the delivery of services. The socioeconomic development goals require meeting unmet service needs and improving labor productivity in developing countries through increasing the ME stock in those regions. The environmental and resource development goals suggest changing the quality of the ME stock by increasing efficiency, reducing waste, and shifting to technologies that require no fossil fuel. At the same time, ME production requires resources and causes pollution, so minimizing the amount of new ME may also reduce pollution, at least in the short run. An important question concerns the optimal timing for producing new, net-zero equipment given the raw materials and manufacturing required. Replacing existing equipment leads to GHGE now but may reduce energy use and emissions in the future. Delaying replacement postpones resource consumption for the capital stock but leads to higher operational emissions. There is hence an intertemporal trade-off between emissions today and reduced future emissions that needs to be considered. Given the constrained availability of resources and the limit to the cumulative CO_2 emissions before the world warms to a 1.5 or 2 °C threshold (the carbon budget), there is a limited set of feasible transition pathways to a sustainable, net-zero economy [16,17]. We call the set of feasible pathways the sustainable industry transition corridor. The lower boundary of the corridor is defined by the minimum number of ME that needs to be produced to replace existing, unsustainable equipment quickly enough to remove operational emissions in time. The upper bound is defined by the maximum number of ME that can be produced with existing resources and given the emissions associated with their production. What this corridor might look like, for ME, is yet unknown. Scenario modelling, with integrated assessment or dynamic optimization models, could serve to identify such a corridor once such models are able to represent the impacts of the production and use of ME.

4. ME in the global economy

Production of and investment in ME in national economic accounts. In economic accounting, investment is measured by gross fixed capital formation (GFCF), which comprises between 15% and 45% of GDP, typically around 20% [18]. In 2019, ME constituted 20% of global investment [19]. General ME accounted for half of this, electrical ME one-sixth, and the remaining two-sixths distributed evenly across three categories: office machinery and computers; electrical machinery and apparatus, radio, television, and communication equipment and apparatus; medical, precision and optical instruments, and watches and clocks [19]. ME, such as washing machines, kitchen machinery, computers, radios, televisions, communications equipment, and watches purchased by public institutions and households are recorded as final consumption, not as investment. This ME constitutes collectively 2% of household and government consumption.

ME in economics research. Despite the interest of classical economics in machinery [20,21], ME has received little attention in economics literature over the past two decades, except for historical analyses. Classical economists used the term machinery for capital in general, until the profession realized the importance of infrastructure and buildings [22], and as information and communications technology (ICT), software, research and development (R&D), and intangible assets [23,24] increased in importance. Around 1990, econometric analyses established that investment in ME made a significant contribution to economic growth, larger than investment in structures [8,25]. Economic growth, however, also requires investment in human capital through education and training to raise labor productivity. A substantial literature shows the complementarity of investments in human capital and ME [26]. Broader analyses of economic history have not provided conclusive evidence of what causes economic growth [27]; culture, freedom, property rights, market institutions, technology, investments, and resource endowments may each play a role but their relative importance and modes of interaction are debated.

This century witnessed the increasing globalization of value chains and the separation of different corporate functions across regions. These complex value chains make it difficult to disentangle the role of ME investment as regions that specialized in high value-added activity such as product and brand development could capture more of the value-added than those countries that specialized in manufacturing [24]. Across the value chain, however, manufactured capital is still needed to provide physical products and most services, its contribution has just become harder to measure.

Economic research has focused on capital and output measured in economic terms. Increasing total factor productivity [28,29] appears to suggest that, over time, more economic product can be produced with less and less capital. If one considers total material flows, however, there is no decoupling of economic output from material flows [30–32]. Such a productivity increase may instead reflect reduced prices of machinery, which require large volumes of material [6,33]. Historically, increased economic product (i.e., GDP) went hand-in-hand with an increased stock of capital assets measured in physical terms. The historical development of service efficiency of physical assets and its potential future development is poorly understood. The accumulation of ME with economic development remains to be explored.

5. GHGE from ME

In this section we review quantifications of the carbon footprint of producing ME, how its use influences the carbon footprint of products and services produced, and the assessment of GHGE reduction opportunities. We also consider what is known about who uses the ME. We first look at comprehensive but aggregate studies of production and use relying on economic statistics, and then at detailed, engineering-based studies.

There are various ways of looking at the GHGE from ME. One could investigate the emissions associated with the manufacturing of ME, the cradle-to-gate emissions of producing ME, the emissions associated with the use of ME, and the emissions associated with the total output produced with the help of ME. The first perspective would be very narrow, the last expansive. We will focus here on the emissions of both producing ME, and how ME influences the footprint of products it produces. We will assess the research progress on accounting for these emissions. Emissions have been assessed either using input–output models based on economic and environmental statistics, or by LCA, using bottom-up data for individual ME [34].

5.1. Carbon footprint of producing ME

Carbon footprint modeling using the multiregional input–output (MRIO) database EXIOBASE [19] has been used to investigate the carbon footprint of ME production [5] (Fig. 3). Over the past decade, the production of ME caused on the order of 2.5 Gt CO_2 equivalent ($GtCO_2e$) (5% of global GHGE) and required the extraction of 400 Mt of metal ores per year, or about one-quarter of metal produced (Figs. 3(a) and (b)). ME contributed about one-fifth to the carbon footprint of investments (Fig. 3(a)). Among ME, general ME (i.e., mechanical) is the largest emissions contributor, followed by electrical ME, communications and information technology, medical, precision and optical instruments, and other ME (Fig. 3(b)). ME consists primarily of metals, which can be produced with substantially lower emissions from scrap than from ore [35–37]. Hence, recycling provides opportunities for emission savings.

The use of materials was the most important contributor to GHGE in the production of ME, 57% in 2015 [6]. For most other economic activities, in contrast, emissions from energy use are more significant. Other important exceptions are construction, where materials also dominate [6], and food, where process- and land-related emissions dominate [38]. ME production is the most important use of materials after construction [6]. ME production requires 30% of metals and 18% of all materials, when material use is traced in terms of carbon footprint [6]. While it is the stock of ME that determines economic output and industrial energy use, it is the rate of new investment that drives material use. Emerging economies are still building up their capital stock, so have higher investments compared to the pre-existing stock of ME. As a result, several studies have found that they also have higher material use and associated GHGE [6,33,39].

5.2. The use of ME

Of a total material stock of 1100 Gt in 2016, ME constituted only a small part (Fig. 4). It amounted to five gigatons [40]. However, ME contain a significant fraction of the total stock of metals in society, and more precious and specialty metals than buildings and infrastructure, the largest share of the metal stock [5,40,41].

While the use of ME is ubiquitous in the modern economy, the contribution of ME is not always considered when calculating the life cycle impacts of produced goods and services. Including capital goods as a required input to the production of goods and services can add between 20% (food products) and 200% (post and telecom services) to their assessed carbon footprints [42]. Most ME are used in manufacturing and service industries (Fig. 3(c) and Refs. [5,41]), but ME adds most to the carbon multiplier of utilities [41]. Such assessments of the contribution of capital assets to the footprint of other products are limited by the availability and resolution of relevant statistical information [43]. In the national economic accounts, most purchase of ME is recorded as gross fixed capital formation, a column of final demand which does not specify who purchases the ME. The use of capital earns returns, which are recorded as gross operating profits in the value-added portion of input–output tables. Sometimes, gross operating profits are broken down into consumption of fixed capital (i.e. depreciation of investments) and net operating profits. Some national statistical offices have collected information on industries' investment in and utilization of types of capital, often grouped into only four to five categories: structures, ME other than ICT, ICT equipment, software, and research. These "KLEMS" statistics (for capital, labor, energy, materials, and services) have been used in previous efforts to assess the use of ME and its contribution to footprints [5,41,42,44,45]. Recently, there has also been a focus on intangible assets, such as brand reputation or supply chain management, which is increasingly important to explain economic success [24]. In the United States, detailed statistics are available on who invests in what type of capital, but these are not well organized and data from a wide range of statistical sources has to be interpreted, transformed, and collated [45] to provide an estimate of the capital used by each industry [46,47]. The advantage of the US data is the high level of detail on production of capital assets; such detail is, however, only available every five years and with delays of five or more years, so that the most recent table is for 2017 and estimates of capital use have not yet been assembled.

5.3. Assessment of specific products

So far, we have addressed the aggregate picture as it presents itself using economic statistics and approaches of economic analysis such as input–output modelling and econometrics. Here, we address specific ME products, because these are what ME manufacturers produce, and users purchase. We would like to understand the material use for producing ME and the GHGE associated with ME production and use. We would like to understand how future resource use and GHGE might develop given which ME will be demanded in the future and what options exist to reduce emissions and resource use. In the following, we review descriptive studies (mostly LCAs) and studies of improvement options addressing specific categories or individual examples of ME.

Construction machinery. For the carbon footprint of specific products, like excavators [48,49] or cranes [50], engineering-specific LCAs have been conducted [51]. For construction machinery, remanufacturing of components is well-established in some countries and reduces both material demand and GHGE [52].

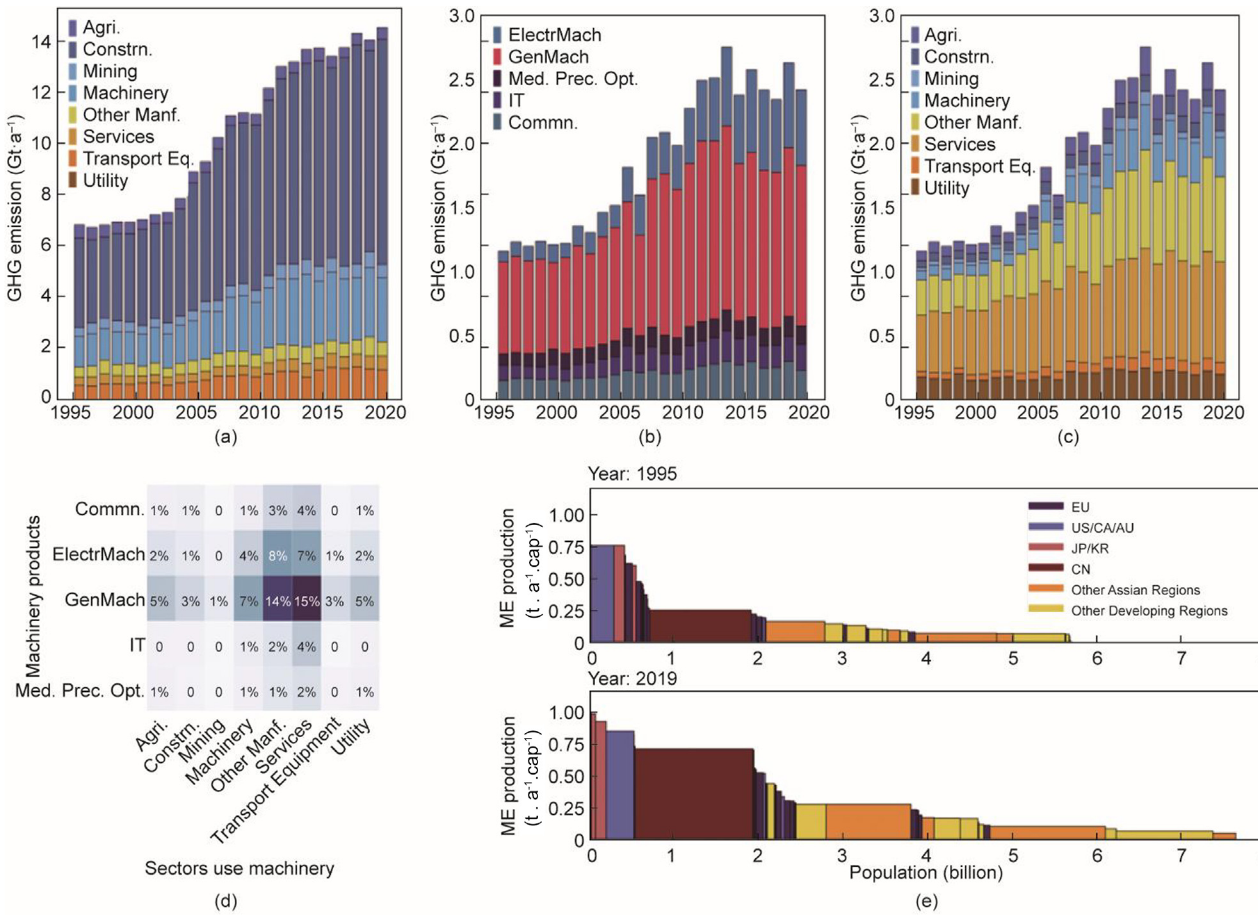

Fig. 3. Carbon footprints of machinery production. (a) Carbon footprint driven by GFCF: breakdown by product. Machinery depicted in light blue. (b) Carbon footprint of machinery production: breakdown of the machinery in (a) by detailed machinery category. (c) Carbon footprint of machinery production: breakdown of the machinery part in (a) by using sector. (d) Use structure of detailed machinery products in 2019 (normalized by the total amount). (e) Carbon footprint of ME production in 1995 and 2019. The machinery sector in (d) means the sector (using machinery) to produce machinery products. Source: updated from our previous study [5] with transport equipment and unspecified manufactured products no longer included in (b), (d), and (e). Agri.: agriculture; Constrn.: construction; Manf.: manufacture; Eq.: equipment; ElectrMach: electrical machinery and apparatus; GenMach: machinery and equipment; Med. Prec. Opt.: medical, precision, and optical instruments, watches, and clocks; IT: office machinery and computers; Commn.: radio, television, and communication equipment and apparatus.

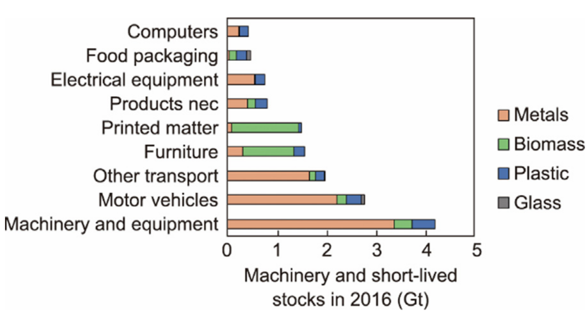

Fig. 4. Material stock estimate for machinery and short-lived stocks in 2016. Source: MISO2 database [40]. nec: not elsewhere classified.

Another important technology shift already ongoing in some European countries is from diesel-fueled internal combustion engines to electric motors [51,53,54]. This shift affects the material composition of the machine, durability, and energy supply. To model and understand the consequent changing resource requirements, studies can be based on alternative engineering designs (some based on first principle and others on existing engineering models) or by empirical observations (e.g. through existing LCAs and environmental product declarations (EPDs)).

Electrical ME. Research on electric motors often incorporates parameters such as technology, rated power, and efficiency classes [55], as well as the environmental impacts of different material usage during production [56,57]. The research on material usage in motors does not suggest clear directions for improvement. Instead, it highlights the need to consider the trade-offs between various environmental impacts and motor efficiency throughout the entire life cycle, rather than solely on reducing or replacing materials. Batteries, as part of the broader electrical machinery category, have received significantly more attention, with reviews summarizing model assumptions and inventory data sources across a broad range of studies [58–61]. In ecoinvent 3.8 [62], a widely-used LCA database, a substantial proportion of the production processes for the electrical ME category relate to batteries. Although battery recycling is not yet widely implemented, research confirms its potential for material efficiency [60] and GHGE reduction [63], highlighting its importance for improving sustainability in battery life cycles.

Waste electrical and electronic equipment (WEEE) has received a fair amount of attention given the high value of materials, with studies exploring the environmental impact, technical properties, and costs of recycled materials [64] and reused components [65]. However, the definition of WEEE often combines electrical machinery and electronics under one umbrella, which poses challenges for data organization and categorization. The effectiveness of repurposing or recycling depends on the equipment's characteristics. Pérez-Martínez et al. [65] highlighted that reusing devices with high energy consumption or short lifespans, such as programmable logic controllers (PLCs), could result in higher emissions compared to producing new equipment, with emissions increasing by up to 65%. In contrast, low-power equipment with less demanding technical requirements, such as perimeter security systems (PSAs), saw emissions reductions of 25% when repurposed, demonstrating the importance of tailored strategies for different types of equipment [65].

Electricity generation and distribution equipment have been widely investigated and will be treated below in the discussion of analysis approaches.

Material handling. Material handling machinery includes a wide range of ME designed for handling, storing, controlling, and transporting materials. Existing studies on material handling machinery primarily focus on the use phase, adopting comparative perspectives to evaluate factors such as the performance of different forklift types [66], design variations in belt conveyors [67,68], and modes of material transportation [69]. Research on the production phase is comparatively limited, with a few assessments about quayside cranes manufactured in China [70,71]. Data on this category of machinery in ecoinvent [62] is also limited. A hydraulic elevator is described as consisting of three metals, a cable, and some electronic components, produced involving a metal working machine and some electricity and lubricants. There is data on one conveyor belt, consisting of concrete, steel, rubber, and wire, yet without any manufacturing involved.

General machinery. General mechanical machinery, with its broad functionality across industries, has been widely studied. The research includes assessments of compressors, both large [72] and small [73], and comparisons of sustainable production technologies using detailed measurement [74]. Repairing and remanufacturing of compressors have also been explored, focusing on climate change but not addressing the effects of material use [75]. In the thermal sector, evaluations focus on boilers and heat pumps, including technical details [76–80] and decarbonization potential across countries and regions [81]. The multi-country study offers insights into scaling up technical data [81].

Agricultural machinery. The material flows [82,83] and inventory data [84] of conventional agricultural machinery like tractors, harvesters, sprayers, and planters have been documented, while innovative machinery models [85,86] are increasingly explored. Similar to construction machinery, electrification and hybrid electrification of agricultural machinery, particularly for tractors, follow the trend of transitioning vehicles from internal combustion engines to electric motors [87–89]. Another innovation in the agricultural sector is the development of digital agriculture [90], such as the introduction of robots for tasks such as harvesting and weeding [91]. However, there are limited available data on commercial agricultural robots so modelling relies on the material composition provided by specific manufacturers [92]. We have not found explicit consideration of material efficiency.

Robots. LCA has been used to investigate agricultural [92–94], industrial [95–98], and service [99] robots. These LCAs mostly serve to document environmental impacts and compare the performance of a task by a robot with the conventional execution of the same task. Robots in some LCAs were represented as a collection of metals [95] or as generic equipment [94], others consider various components and life-cycle stages [98]. Manufacturing, programming, and use of IT were often not considered. One study addressed the role of telematics and thus the ICT of a robot [100]. Some studies considered characteristics of task performance, such as reduced scrap through additive manufacturing. Other studies compared different operations, such as different methods of welding [101]. One paper considered the material choice for a component of an industrial robot [97]. Overall, little information could be found on the environmental impacts of robot manufacturing, electronics, software, and networks. While improvements are frequently the subject of LCA-based comparisons, these were often focused on simple binary choices, such as between materials or production methods of robots, or of robots versus conventional task fulfilment. Environmental assessments or improvement analyses of the "Internet of Things" consisting of sensors, actuators, and communication systems, could not be found.

Home appliances. The GHGE of home appliances can be reduced through remanufacturing, extending their lifecycle, increasing recycling and enhancing material efficiency. For example, Alejandre et al. [102] analyzed a strategy to reduce material usage by 10% during appliance production, which resulted in measurable reductions in GHGE—namely, a decrease of 0.93% for microwave ovens, 0.48% for dishwashers, and 1.69% for washing machines. Although material efficiency is considered a key pathway for lowering emissions, they indicate that the overall emission reduction potential in the home appliance sector remains limited given that the substantial operational energy consumption is not affected by reduced material use. In addition, when half of the materials used in production are sourced from recycled resources, environmental benefits become more pronounced; under this condition (combining a 10% reduction in material use with 50% recycled materials) increases savings to 3.09% in CO_2 equivalent for microwaves, 2.11% for dishwashers, and 4.05% for washing machines. Moreover, with a low-carbon electricity supply, extending the service life of existing appliances—such as through repairs—is the preferred option from an environmental standpoint. Rosenthal et al. [103] investigated refurbishing scenarios for refrigerators, washing machines, and air conditioners, and found that, from a waste reduction perspective, remanufacturing is more favorable than recycling, despite the challenges of achieving higher remanufacturing rates for refrigerators in today's market. Additionally, Fatimah and Biswas [104] demonstrate that remanufacturing key components—specifically, the motherboard and hard disk, which account for 62% of a computer's weight—can reduce energy use and GHGEs by approximately 40%.

Summary of findings for specific ME. It should be noted that few detailed LCAs for ME have been established (e.g. Refs. [84,105]), in which different components are addressed and production methods are included. Many equipment unit-process descriptions, for example in the prominent ecoinvent database [62], were developed to describe a specific production process and the ME is simply described as an assemblage of a few materials and generic electronics. We have not found systematic reviews or meta-analyses of LCAs of ME. A good overview would be needed to understand which factors contribute to the carbon cost of ME and the relative importance between production and operational emissions. Operational emissions are commonly assumed to be much more important, but production is significant enough to warrant its inclusion in assessments.

5.4. Climate change mitigation for ME

Analysis of industrial emissions and emissions mitigation has focused on technology improvements for energy-intensive bulk material production, including steel, aluminum, and cement, as well as ammonia and other chemicals [3,106,107]. Such mitigations mostly focus on reducing process emissions, improving the process energy efficiency or capturing emissions but these are not the only way to address industrial emissions. Alternative approaches can consider opportunities to reduce the demand for industrial products through measures such as lightweight design, product lifetime extension, increased utilization, service demand reduction, and reuse/remanufacturing/recycling [108–111]. Scientists have collectively grouped these strategies under the label material efficiency (Fig. 5), sometimes separating out service or product demand reduction as sufficiency [112].

The research reviewed in Section 4.1 indicated that three fifths of emissions from the production of ME are due to the use of materials. The review of studies on individual ME in Section 4.3 shows that there is limited work addressing emission reductions from material efficiency. We found studies addressing remanufacturing for compressors [75], construction machinery [52], and personal computers (PCs) [104], as well as recycling of batteries [60] and electric and electronic equipment [64]. The energy costs, material savings, and potential performance implications of such material efficiency strategies are not yet well understood. Few studies exist on the material efficiency opportunity at the component level. Addressing a catalogue of components [113], Allwood and Music [114] found savings of up to 80% of liquid steel and 90% of aluminum possible through different manufacturing processes, avoidance of overspecification, and more exact design. The shortage of studies on material efficiency for ME contrasts with the quickly growing body of literature on material efficiency for the construction sector and vehicles. Without an understanding of how and where emissions could be reduced, it is unlikely that measures and policies to realize these potential reductions will be implemented.

Integrated assessment models (IAMs), which capture the entire economy and its emissions over multiple decades are the workhorse of global climate assessments such as those of the IPCC. Historically IAMs have not explicitly represented material cycles and were unable to model material efficiency strategies; ongoing work aims to address this limitation for buildings and transport. A few types of ME, such as electricity generation equipment, have been included in some IAM analyses. For example, in one study industrial ecologists generated production and composition data at the level of individual power plant technologies and quantified the material needs, GHGE mitigation, and environmental co-benefits of moving from a baseline to a mitigation scenario [115]. A simplified representation of LCA data [116] was then used by an IAM to consider the influence of these ME and fuel cycle emissions on the technology choice by the IAM [117] and to quantify co-benefits and material requirements [118]. This bottom-up data has now become part of the datasets that can be used by IAMs for various types of analysis [119] and data from IAMs is now used in scenario-based LCAs [120]. A similar approach is needed to consider other types of ME.

6. Discussion

Much of the research reviewed above is descriptive, which is necessary to form the empirical understanding for identifying desirable courses of action. However, as manufactured capital used to manufacture capital, ME have a complex dynamic that has been little explored. How much is necessary to meet unmet needs? To decarbonize the economy? What are desirable investment and development strategies? What is the sustainability corridor for an industry transition to net-zero GHGE? ME is likely to require most of the rare minerals that advanced technology increasingly depends on Ref. [121], and which are of significant strategic concern. What are the steps needed to secure access to these materials at the rates required for the transition?

Daehn et al. [16] was not the first paper to investigate the energy required to produce the materials for clean energy technologies [115,117], but they nicely presented the challenge of doing so within a limited carbon budget. Like other research, they found that keeping within the carbon budget was challenging. However, they also identified material production technologies which enable the use of clean electricity where dirtier forms of energy or reductants are used today, allowing us to stay within the limits set by the Paris Agreement. We see this type of analysis as archetypical of the research that is required.

The transition will be made easier by incorporating a broader range of mitigation options, from shifting material production technologies, to reducing the material demand to produce equipment, remanufacturing, extending product lifetimes and recycling. The required stock of ME may need to change to meet these options, given machines are needed for remanufacturing and recycling and production processes will need to change to reduce primary material requirements, potentially requiring new equipment to do so. This new stock of ME, meanwhile, also needs to be produced. ME provision therefore becomes a dynamic optimization problem, which interacts with other demands for energy and materials and other mitigation actions by competing for resources but enabling the decarbonization of (e.g., services and construction). Such mitigation modelling must be based on good empirical evidence but requires substantial model development. It needs to capture material and capital dynamics, production technologies, demand, development trends, and options to change. IAMs used in climate change mitigation analysis represent these aspects for energy and transport, and they are on their way to include materials, at least those needed for vehicles and buildings [122]. No comparable modelling effort exists for the rest of industry sector, including ME.

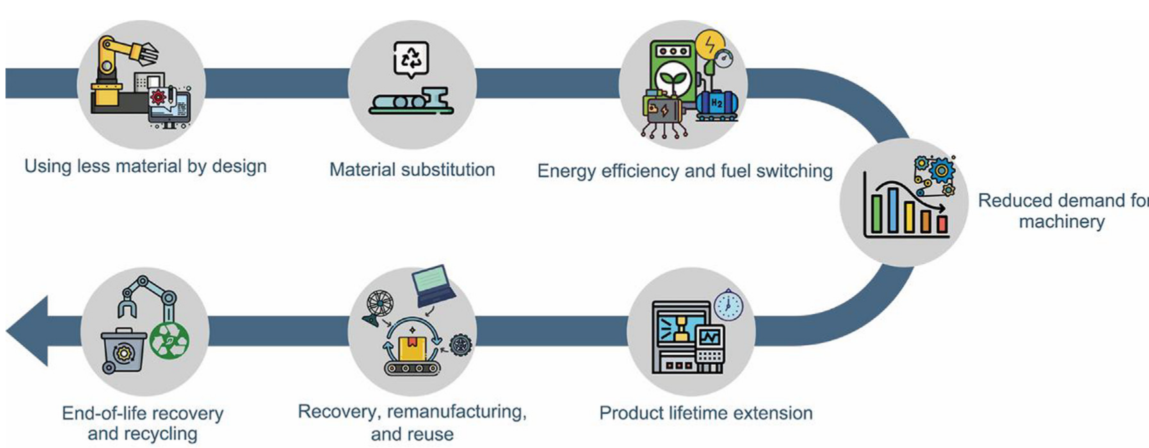

Fig. 5. Material efficiency strategies for reducing GHGE from machinery and equipment along the life-cycle.

To create such a model, we need to develop model representations for ME production, for demand, and for the end-of-life treatment. To explore different routes in a sustainability corridor, the model representation needs to include decision options that can potentially reduce emissions.

Our review indicated that an overview over the GHGE and aggregate material use of ME is emerging in top-down studies based on input–output analysis, but at a coarse level. There is a very uneven representation of individual machines through bottom-up studies, with many machines not represented. Many LCAs focus on the use of ME (i.e. are about the products produced or services rendered by ME). The production is often only described as an assemblage of materials, maybe supplemented by some energy use and machining process. The descriptions are as single unit processes. Life cycle inventory data is frequently withheld, making studies unusable. Some studies give some notion of what ME-specific improvement potentials could be, especially for alternative designs (e.g., electric construction machinery) or new technical innovations (e.g., additive manufacturing) and emerging literature addresses improvements in component manufacturing, which can be relevant for many types of ME. However, it will be difficult to integrate such research with LCAs that do not consider component manufacturing. There is an urgent need for a more systematic approach to assess potential improvements in the design, production, use, and end-of-life resource recovery, and in documentation.

Beyond empirical analysis and case studies with improvements, climate change mitigation research needs a sector model to explore the sustainability transformation of ME. Mitigation reports of the IPCC divide the economy into five sectors energy, buildings, transport, industry, and agriculture, forestry, and other land use, each treated in a chapter. It is only the industry sector for which a dedicated sector model is lacking. It would be logical for this industry-sector model to explicitly represent ME, just as transportation models represent vehicles and energy models represent coal mines, refineries, and power stations. Such a model will require data both from top-down studies to ensure that all ME are covered, and bottom-up studies for material content and improvement potentials. It will also need to consider the likely demand for ME considering both historical patterns of economic development and the emergence of new uses of ME.

The per-capita stock of ME [5] and of other capital assets [41] vary widely across countries (Fig. 1). More industrialized countries have higher ME stocks per-capita, and sectoral value added depends strongly on ME assets for transportation, manufacturing, and service industries [5]. For the large population of developing countries to catch up economically with rich countries in East Asia, Europe, and North America, they will need ME to increase the productivity of their labor. In rich countries, meanwhile, the share of the working-age population is shrinking, putting a premium on automation and associated ME. The development of ME for service industries, including elderly care, and home chores may open a much larger market. The introduction of sensors and "smart" products implies new sets of capabilities, functions, and areas of demand for established products but also requires new types of inputs and operational requirements. While the catch-up development of less developed countries could be modelled, based on statistical analysis, the role of new types of ME and new applications is better anticipated through expert dialogues and future studies.

CRediT authorship contribution statement

Edgar G. Hertwich: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Yiwen Liu:** Writing – original draft, Investigation. **Meng Jiang:** Writing – review & editing, Writing – original draft, Visualization, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Edgar G Hertwich reports financial support was provided by Horizon Europe. Edgar G. Hertwich reports a relationship with XIO Sustainability Analytics that includes: board membership and equity or stocks. Edgar G. Hertwich is a member of the International Resource Panel and the European Scientific Advisory Board on Climate Change. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data in Figs. 1, 3, and 4 are available in zenodo repository No. 14770524, https://doi.org/10.5281/zenodo.17665120.

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