



Full length article

Mobilizing materials to enable a fast energy transition: A conceptual framework

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ARTICLE INFO

Keywords:

Climate crisis

Defossilization

Energy transition

Materials

Circular economy

ABSTRACT

Limiting climate heating while meeting basic needs for all necessitates large-scale deployment of renewable energy. Understanding the dynamics of mobilizing materials for the transition requires considering: 1) availability of resources in the environment and technosphere; 2) accessibility depending on resource quality and available technologies; 3) processability depending on energy availability, processing capacity, and impacts on planetary boundaries; and 4) operability depending on social acceptance and geopolitical agreements. Materials can be mobilized through four routes: 1) increasing primary production; 2) diverting existing primary production; 3) repurposing in-use stocks; and 4) re-mining wastes and emissions. The interplay of these enabling factors, material efficiency in design, and substitution with materials that are easier to mobilize determines the maximum possible rate of material mobilization and consequently the energy transition itself. This paper presents and discusses a framework to explore joint energy-material transformations, enabling to consider material aspects in transition modelling and guide technological developments.

1. Introduction

Decades of delays in climate action reduced safe carbon budgets for the energy transitions. With every delay, increasingly fast energy transition pathways are required to stand a chance of limiting overshoot over 1.5°C or even staying below 2°C (IRENA, 2022; United Nations Environment Programme, 2022; IPCC, 2023), preventing a climate catastrophe while avoiding energy and food scarcities (IPCC, 2021, 2022; Mooney et al., 2022). Achieving such a transformation requires investing energy and materials for building renewable energy (RE) infrastructure, which will have to succeed the current fossil-based energy system at a much faster rate than is commonly projected (Desing and Widmer, 2021).

Traditionally, transition pathways are designed by using integrated assessment models (IAMs), which are based on economic transactions and the assumption of (partial) economic equilibrium in each time interval (typically 5a or 10a). As there are less than six years left before crossing 1.5°C with 50% probability¹, transition models that allow modelling a fast dynamic change (i.e., a system not in equilibrium) become necessary. Minimizing climate risks—necessary for both staying below or limiting overshoot above 1.5°C—requires to prioritize minimizing cumulative CO₂ emissions (Desing and Widmer, 2021). Furthermore, IAMs are usually “energy blind” because they disregard the energy investments needed to build the new RE infrastructure (Capellán-Pérez et al., 2020; Desing and Widmer, 2021; Hagens, 2020; Sgouridis et al., 2016; Hache et al., 2019; Andrieu et al., 2022). When modelling slow and gradual transitions over the time scale of decades,

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¹ <https://www.mcc-berlin.net/en/research/co2-budget.html>.

energy investments are insignificant. However, given the urgency of climate action, energy investments need to be much larger (Slamersak et al., 2022; Desing and Widmer, 2021) and this feedback loop needs to be taken into account. For example, a transition within a decade may be physically feasible, if fossil energy output is increased at the beginning of the decade to provide extra energy for kick-starting RE growth (and doing so minimizes cumulative GHG emissions) (Desing et al., 2022). After the initial fast transition is complete, the infrastructure has to be replaced repeatedly, necessitating additional capacity in the RE system (Desing et al., 2022). Besides that, the economic foundation of IAMs is increasingly challenged, as they tend to underestimate or even neglect future risks, damages and uncertainty (Stern et al., 2022; Anderson, 2019).

Moreover, transition models (including IAMs and others) usually disregard the physical requirements of materials (Pauliuk et al., 2017; Wang et al., 2022; Le Boulzec et al., 2023), the dynamics of mobilization, as well as social implications. Studies on raw material demand induced by the energy transition take pathways as exogenous inputs, and usually analyse the cumulative demand for selected time periods only, e.g., up to 2050 or 2100 (Kullmann et al., 2021; UBA, 2019; Visser, 2019; Zepf et al., 2014; IRENA, 2022; World Bank, 2020; de Koninck et al., 2018; Moreau et al., 2019; Zhang et al., 2023; Rinaldi et al., 2023; Xu et al., 2022; Kalt et al., 2022; Wang et al., 2023; IEA, 2023; Energy Transitions Commission, 2023). As with energy, material investments for building RE infrastructure can have a critical influence on the dynamics of the transition. If materials cannot be mobilized, the transition will slow down or even come to a halt. Reciprocally, the speed and extent of material mobilization has an influence on the energy demand for building RE infrastructure. Changing energy investments, measured in Energy Return on Energy Invested (EROI) or Energy Pay Back Time (EPBT) (Murphy et al., 2022), influence the dynamics of the transition. These interrelations are neither well understood nor explored in current models. This is also true for the United Nations Framework Classification for Resources (UNFC), a tool to communicate the availability of resources and the maturity level of resource development projects (UNECE, 2020, 2022). UNFC considers controlling factors for the viability of mining and recovery projects, but does not consider the complex dynamic relationships between energy and materials. The dynamics of primary mineral resource markets and their physical/geological limits are commonly neglected, while inflow of recycled resources based on previous product sales and global recycling rates are sometimes included (Vidal, 2018; IEA, 2021; Carrara et al., 2023). Additionally, fossil infrastructure will become obsolete during the transition, however, the extent to which this can contribute to the transition has been relatively little explored (Le Boulzec et al., 2022).

Consequently, there is a need for new modelling approaches that are rooted in the laws of physics, including essential feedback loops in the dynamic system, and integrating knowledge from geology, mineralogy, and materials processing. Building new RE infrastructure requires materials, and the mobilization of materials requires energy. This paper outlines a conceptual framework for exploring the physical dynamics of joint energy-material transformations. The purpose of the framework is to analyse from where, at which energetic costs, and when materials can be mobilized, ultimately enabling or limiting a rapid energy transition. Materials can originate from the lithosphere, biosphere, atmosphere, and hydrosphere. They can be either directly extracted as primary materials from the environment or retrieved as secondary materials from the technosphere. Here, the focus is on physical, chemical, biological, and geological factors determining quantities, timeliness and energy needed for material mobilization, which can be regarded as the “size of the valve” representing the mobilization potential: e.g., concentration, chemical bonds, mineralogy, or planetary boundaries (Richardson et al., 2023). Societal factors—such as economics, policies, acceptance—determine the fraction of this potential that may be realized, the “hand on the valve”. But they cannot increase the potential itself. Derived from the presented framework, this paper outlines research directions

to quantify and explore material mobilization dynamics and the interconnections between materials and energy.

2. Material mobilization framework

Building the required RE infrastructure implies building up a significant stock of materials during the transformation (Fig. 1), which necessitates to transform and expand the current socio-economic metabolism. Society currently extracts primary materials from the environment, accumulates them in societal stocks (e.g., buildings, IT equipment, or car fleets), and recycles some of its waste. Most of the outflow accumulates as losses in the technosphere (e.g., landfills, mining wastes) and the environment (e.g., emissions, pollution) (Circle Economy, 2021; Ciacci et al., 2015). For most materials, global stocks in society are still growing, as their inflows are larger than their outflows (Krausmann et al., 2018). Only a small fraction of outflows is currently circulated in a way that retains functions (e.g., through reuse, remanufacture, recycling (Desing et al., 2020b; Circle Economy, 2020)). Even when circular economy and recycling strategies are implemented, these often lead to losses in material quality (downcycling) (Cullen, 2017) and accumulation of impurities (Lovik et al., 2014). Besides, recycling tends to focus on increasing recycled content and recycling rates, especially of pre-consumer scrap (i.e., manufacturing losses). This type of material is generally easier to recycle but ultimately addresses an inefficiency of the system that should be minimized, not encouraged. Recycling of post-consumer scrap is important to maintain existing stocks without using more primary resources, but is only available with a delay and cannot contribute to the initial build-up of the stocks. Moreover, the complexity of materials used in technologies has increased significantly—requiring most of the elements of the periodic table (Zepf et al., 2014)—, which results in growing challenges not only to recycle all elements, but also to retain their functions (Graedel and Miatto, 2022; Desing and Blum, 2023).

The speed of the transition will depend on the flows of materials that can be mobilized, which in turn require energy from the current fossil and future RE systems (Fig. 2). Enabling factors for material mobilization can be categorized on multiple levels, which will be explained in the following subsections: availability of source stocks, technical accessibility of these stocks for extraction, processability of material flows during production, as well as operability for making materials flow. The latter refers to factors in distribution and operation, which includes aspects commonly referred to as criticality (Schrijvers et al., 2020; Frenzel et al., 2017)—i.e., supply chain vulnerability and geo-political risks—and additionally business models, markets, trade, as well as social acceptance. Here we focus on the bio-physically enabling factors of material mobilization, i.e., availability, (technical) accessibility and processability.

2.1. Availability and accessibility of source stocks

The first question is: are there enough materials available and accessible to build the needed RE stocks? Materials can be mobilized from anthropogenic and environmental source stocks. Availability describes the knowledge of location—Where are materials?—and quantity—How much is there?—of material stocks and is the prerequisite for making them accessible. Determining the accessibility requires to analyse the quality of these available stocks. A stock is only accessible, if suitable extraction technologies exist and when it is not vital to maintain Earth system functions. For example, technologies to extract scandium from wastes are still under development (Chernoburova and Chagnes, 2021; Shoppert et al., 2022), leaving it inaccessible for the moment. Or, current biomass stocks in natural ecosystems will have to be maintained or even increased for stabilizing vital ecosystem functions (IPBES, 2019; Steffen et al., 2015) and are thus accessible only to the extent of what can grow beyond ecosystem needs. Additionally, stocks are more or less accessible depending on factors determining the efforts for extraction.

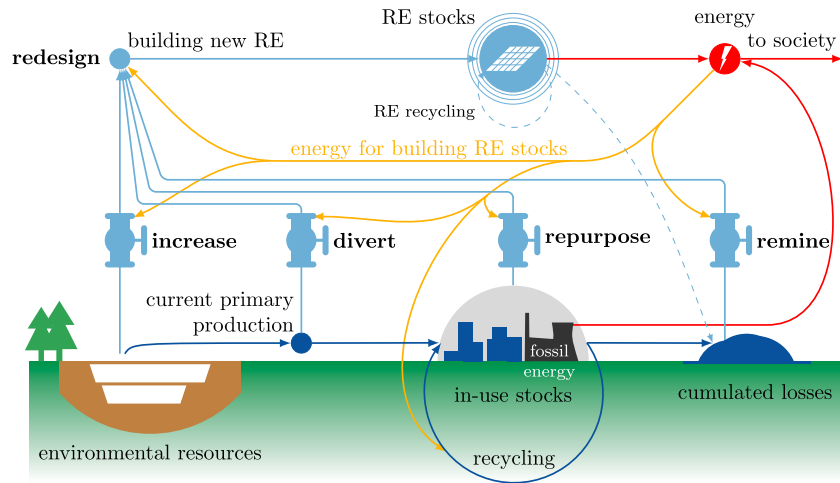


Fig. 1. Schematic representation of energy and material flows in the Material Mobilization Framework: dark blue flows in bottom part of figure depict current material flows from primary production out of environmental resources, through in-use stocks, which are to a small degree maintained by recycling, to cumulated losses. This metabolism is currently predominantly powered by fossil energy, itself consisting of in-use stocks (fossil infrastructure) and primary extraction (i. e., coal, oil and gas) leading to losses (i. e., emissions). To replace fossil energy with renewable energy (RE), new RE stocks have to be built. Four strategies can be applied for building RE (light blue): **increase** primary production, **divert** currently existing primary production by reducing material demand by society (e. g., by increased recycling), **repurpose** existing in-use stocks (e. g., obsolete fossil infrastructure), and **remine** cumulated losses (e. g., from landfills, tailings, emissions). Additionally, the **redesign** of RE components can help to reduce the demand for materials (material efficiency) and substitute with materials that are easier to mobilize. Recycling and losses of RE stocks will only come into effect once the first RE stocks reach their end-of-life (dashed blue arrows). Building RE stocks requires energy for mobilizing materials (yellow arrows), which has to be supplied by both fossil energy and RE, in addition to the demand from society (red arrows).

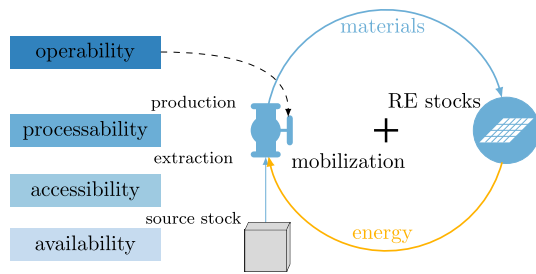


Fig. 2. Overview of enabling factors for mobilization (left) and their relation to the energy-material feedback loop (right): Building renewable energy (RE) infrastructure requires materials (blue), and mobilizing materials requires energy (yellow). The availability of source stocks in the environment and technosphere is limited, and the accessibility of these stocks depends on its quality and available technologies. Processability describes where from and how fast materials can be mobilized, which depends on the availability of energy, processing capacities, and environmental impacts on planetary boundaries. The operability, describing societal factors for actually making materials flow (geo-political relations, economics, organisational capacities, social acceptance), further limit material mobilization.

The energy costs for extraction depend mainly on the concentration (i. e., ore grade of minerals, atmospheric CO₂ concentration), but also on factors such as location (e. g., under water or land, depth below surface, remoteness), geometry (e. g., grain size and distribution in host rock), or binding energy of chemical compounds.

Anthropogenic stocks—such as currently in use, “hibernating”, or accumulating as wastes and emissions (Dewulf et al., 2021)—already contain large quantities of materials (Elhacham et al., 2020; UNEP and International Resource Panel, 2010; Wang et al., 2018; Wiedenhofer et al., 2021). Using secondary materials will need to take into account the quality of recycled materials obtained (Tonini et al., 2022), as well as the quantity and timing of released material flows (Streeck et al., 2021). Repurposing in-use stocks—such as materials contained in fossil infrastructure and related to luxury consumption—can, at most, provide as much material as is contained in society today. How much of it can be mobilized in practice depends on societal decisions discerning essential from superfluous consumption, which is a question of operability.

Even if the availability (location, quantity) and composition of these stocks are known with sufficient detail, they will only become accessible when released from previous use—for example, when fossil equipment becomes obsolete or consumption is reduced. Losses can be dissipative (i. e., unrecoverable, not accessible) or recoverable with current technologies. New technologies can make some of today’s dissipated losses accessible (Beylot et al., 2020; Ciacchi et al., 2015). For example in Europe, the location of mining wastes is more or less well known but knowledge on stored volumes and the characteristics of wastes—composition, mineralogy and total quantities—is partial and often does not cover the presence of critical metals (Šajn et al., 2022; Žibret et al., 2020). Furthermore, valuable elements in mining wastes have so far not been extracted due to inferior quality, lack of markets (e. g., Nd or Co were hardly in demand in the past) or suitable technologies. Making them accessible may thus require developing new technologies.

Additionally, materials are contained in environmental stocks in lithosphere, biosphere, hydrosphere, and atmosphere. Most of these stocks are dispersed at extremely low concentrations, a characteristic that makes extraction unfeasible, such as for Au or Li dissolved in seawater. The only minerals extracted from seawater today are the few highly concentrated ones (Na, Mg, K, Ca, and Cl). The extraction of uranium from seawater has been much discussed, but so far, there are no commercial applications able to produce it at reasonable prices (Bardi, 2010). Exploration can increase availability of known resources for minerals in the lithosphere, while changing economics and improved technologies determine how much of these known resources are mineable reserves, which is an aspect of operability. Exploration is not only an increasingly energy- and cost-intensive endeavour, it also involves high uncertainties. It is estimated that only one out of 1000 exploration sites will be able to be developed as an economically profitable mine (Gandhi and Sarkar, 2016). It is also a question of time, as it takes currently around 17 years from resource discovery to exploitation (Garside, 2022). For instance, it has been argued that Li is likely to remain a limiting factor in the transition, mainly because of the time delay for opening new mines (McNeil, 2022).

Even though there are likely enough materials for the energy transition in the anthroposphere and the environment as a whole (Kesler and Wilkinson, 2008; Henckens et al., 2014), knowledge regarding location, quantity and quality is limited or scattered. Availability and accessibil-

ity are dynamic and change with the state of knowledge, technological developments and state of depletion of source stocks. Gathering the necessary data and developing new technologies for making these stocks accessible represents a time delay for mobilizing materials.

Comparing yet-to-be-built stocks with potential source stocks may reveal needs to re-design RE infrastructure if materials are not available and accessible in sufficient quantities. To illustrate: if every person out of the expected ten billion people in 2100 (UN, 2022) should have access to 2000 W (2000 W Society, 2019)—roughly twice the annual average power demand per person today—it would require a RE capacity of 20 TW. Using a simplistic back-of-the-envelope calculation (see Supplementary Materials (SM)) and keeping current RE (about 1 TW) constant, it can be estimated that the additional RE capacity could theoretically be provided by solar PV on the already built environment alone, not needing any further land conversion and associated biodiversity impacts (Desing et al., 2019). Leaving the material requirements for energy storage, distribution, and other RE technologies aside, building additional 19 TW of PV output capacity (corresponding to roughly 155 TW peak capacity, which is in between the estimates for 80 TW by 2050 (Haegel et al., 2023) and up to 200 TW by 2100 (Keiner et al., 2023; Goldschmidt et al., 2021)) with currently available technologies (Frischknecht et al., 2020; Müller et al., 2021) without continuous improvements would require at least 8.8 Gt of materials (see SM). For some of these materials, the new stocks would be equal or higher than currently existing in-use stocks. One example is Ag used as current collector in Si solar PV cells (Zhang et al., 2021; Piano et al., 2019; Victoria et al., 2021). It has been widely recognised that, if current utilization rates remained unchanged, Ag availability would be critical for upscaling PV to multi-TW scale. In fact, efforts are under way to reduce the demand of Ag by design (Zhang et al., 2021; Victoria et al., 2021) or avoid it through substitution, e.g., with graphene (Zang et al., 2018), Al, or Cu (Grübel et al., 2021; Haegel et al., 2023). Promising are also perovskite and Si-perovskite tandem cells (Tockhorn et al., 2022; Tian et al., 2020), as they allow for higher efficiencies, but they still have to overcome significant development challenges (Fu and Jen, 2023; Shalan, 2020). Furthermore, they currently use significant amounts of In, Cs and Br, which are critical for upscaling perovskite PV technologies (Wagner et al., *under review*). Similarly, thin film PV technologies—such as CdTe—are advantageous in terms of embodied energy (Wikoff et al., 2022), however, they require specialty metals—e.g., Cd, Te—and scaling them to multi-TW scale could potentially exceed current availability by orders of magnitude. Consequently, these technologies may only play a minor role in the transition unless the demand for these elements can be cut substantially and/or availability and accessibility increased rapidly. A careful assessment of the required material stocks will be key in revealing the needs for reducing the material intensity of RE technologies; and, if such reduction were found to be not feasible, the assessment could possibly indicate that the maximum size of the overall RE system would be smaller. Furthermore, if material demand exceeds available source stocks, there is need for increasing availability for example through exploration. Ultimately, based on such assessments, the portfolio of RE technologies can be optimized according to the availability and accessibility of materials.

2.2. Processability: mobilizing flows

The second question regards the material flows needed to build RE infrastructure, which are to be extracted and processed from accessible source stocks. The processability describes where from and how fast materials can be mobilized. It is determined by available energy to build and operate processing facilities (Fig. 2) and constrained by environmental impacts caused on planetary boundaries (Desing et al., 2020a).

For filling RE stocks for the first time, materials can be mobilized through four distinct routes (Fig. 1), which are listed and briefly discussed below:

- **Increase** primary production: e.g., by upscaling output from existing extraction facilities as well as developing new extraction routes from the environment;
- **Divert** current primary production: by reducing demand from the rest of the economy during the transition, i.e., maintaining existing in-use stocks with less primary input by increasing residence time (Charpentier Poncelet et al., 2022) and reducing final losses through circular strategies (Desing et al., 2020b, 2021);
- **Repurpose** existing stocks: reducing in-use stocks and using its materials to build RE stocks, in particular from obsolete fossil infrastructure, reduced consumption, and “hibernating” stocks;
- **Remine**: extraction from losses, such as mine tailings (Adrianto and Pfister, 2022), landfills (Lucas et al., 2019), desalination brines (Lundaev et al., 2022), or past emissions (Desing, 2022).

There is no predefined hierarchy of these different routes, which necessitates optimizing material mobilization according to multiple criteria: each of these routes has implication on the energy demand for the transformation as well as the scale and dynamics of mobilized material flows. They also cause impacts on planetary boundaries and generate social benefits or adverse social impacts. Building new mining, processing, recycling and production capacities takes time and energy, which ultimately limits the rate of change (i.e., slow rate limits: restriction of how fast flows can change). Energy demand for material mobilization depends on the size and routes of mobilized flows, which in turn determine the maximum possible speed of the transition (Desing et al., 2022). In addition, energy intensity can be reduced with technological developments for extraction and processing. For example, non-biological extraction of CO₂ from the atmosphere requires direct air capture (DAC) technologies (Desing, 2022; Climeworks, 2022), which were only developed recently (outside niche applications in space crafts and submarines), and are still energy intensive. Technological improvements have the potential to reduce energy demand for DAC significantly, though. In more general terms, the availability of surplus net energy (i.e., energy not simply required to maintain the status quo) is critical to the achievable speed of mobilizing materials and building new RE infrastructure (Desing and Widmer, 2021).

Furthermore, environmental impacts on Earth system boundaries restrict the mobilization of materials (Desing et al., 2020a; Lebre et al., 2020). A fast increase in production may result in higher environmental impacts, as in the example of Ni (Young, 2021; Schenker et al., 2022a). Biodiversity conservation targets or boundaries for water consumption, for example, may limit the processable material flow (Desing et al., 2020a). Another example is biomass: the global potential of appropriable bio-based material flows (Haberl et al., 2007; Krausmann et al., 2013; Creutzig et al., 2015) for sustainable agriculture (Willett et al., 2019; Gerten et al., 2020) and forest management (O'Brien, 2015) is limited by land, nutrients, and water boundaries. Because feeding the still growing world population (UN, 2022) within planetary boundaries is a challenge (Gerten et al., 2020), bio-based material flows are limited, but may—whenever not in conflict with planetary boundaries—utilize unavoidable food waste, agricultural residues not needed for regenerating soils, and sustainable forest management. Such materials may, for example, be used for thermal insulation contributing to the transition by reducing heating and cooling demand (Wernery, 2023).

Increasing circularity in society can help to maintain current in-use stocks with less primary input, allowing to **divert** existing primary production for building RE stocks. While reducing final consumption and reuse can make more energy available for mobilizing materials, upscaling recycling may increase energy demand through the increased efforts for collection, sorting and purification (Schäfer, 2021; Schmidt, 2021; Baum, 2018). During the transition, parts of the current fossil infrastructure—primarily composed of steel, Al, Cu, and concrete (Le Boulzec et al., 2022)—gets replaced and becomes obsolete. Similarly, materials can become liberated when reducing consumption and mobilizing “hibernating” materials, such as unused pipings or mobile phones.

These materials can be **repurposed** for RE infrastructure when they become accessible. Energy demand for repurposing depends on the efforts for purification and processing.

Increasing the output of existing mines and processing facilities could be relatively quick, but it is limited by the capacity of existing infrastructure. Expanding extraction and processing infrastructure and thus further increasing primary production requires more time. The mean time between discovery and production of a new mine is found to be 17 years (International Energy Agency, 2021), and 20 years for minerals necessary for electrifying mobility (Petavratzi and Gunn, 2022). Moreover, it will also require more energy, affect local communities (Owen et al., 2022; Lebre et al., 2020), and cause additional environmental impacts—e.g., on biodiversity (IRP, 2019), or water resources (Schomberg et al., 2021). Increasing the primary activity is not only an onshore question, deep-sea mineral resources have been known for a long time but have been the subject of renewed interest in recent years. Presently, efforts are done to explore deep-sea resources such as polymetallic nodules with some related works assessing associated environmental risks (Amon et al., 2022; Levin et al., 2020; Alvarenga et al., 2022). Exploiting mineral reserves from the ocean floor carries with it a lot of unknown impacts, as the regions in discussion are vast and the ecosystems in place are poorly understood (Levin et al., 2020; Hein et al., 2020). Yet, increasing primary production will be inevitable for some materials, because of the different material composition of RE infrastructure in comparison to the current socio-economic metabolism (Petavratzi and Gunn, 2022). The energy demand for mobilizing materials will change non-linearly with material flows. Declining ore grades tend to increase energy demand in an inversely proportional way (Koppelaar and Koppelaar, 2016; Calvo et al., 2016; Magdalena et al., 2021; Northey et al., 2014), while learning effects from scaling production and improved technologies may reduce it (Schmidt, 2021). Given the need to accelerate the energy transition, it remains an open question how quickly learning can be realised (Desing and Widmer, 2022; Grafström and Poudineh, 2021). Additionally, energy demand of mining depends on accessibility factors, such as mineralogy, geometry of the ore body, depth of the deposit, or remoteness of the mine site (Frenzel et al., 2017). Differences in extraction technologies strongly influence energy and water demand, as shown for example for lithium mining (Schenker et al., 2022b). Many metals necessary for the RE infrastructure are currently mined and processed as co-products in bulk material production (e.g., Co with Cu, In with Zn or Pb) (Reuter et al., 2018). Increasing the output of the target mineral may, in these cases, require either upscaling the production of the host metal, or developing new extraction routes.

The energy demand for **remining** accumulated losses—e.g., mining wastes (Adrianto and Pfister, 2022; European Commission Joint Research Centre, 2019), landfills (Lucas et al., 2019; European Commission Joint Research Centre, 2019), or past CO₂ emissions (Desing, 2022)—will depend on historical evolution of waste composition and concentration. In the best case it may be lower than for current primary production, as some legacy tailings are expected to have higher concentrations than currently mined deposits, but generally it can be expected to be higher. Proper management of landfills and mining wastes is inevitable for reducing ecological risks (Nicholls et al., 2021), and regain land area (Winterstetter et al., 2018). Compared to “increase”, access, such as through roads or to permits, may be easier. Remining landfills and mining wastes can have environmental benefits (as opposed to impacts from new primary mining), such as reducing methane emissions, landfill volumes and risks of leaching hazardous substances (Yi, 2019; Lopez et al., 2018; Beylot et al., 2022), yet it may also cause significant environmental impacts and the quality of recovered metals may be lower (Lucas et al., 2019). Similarly, CO₂ concentration in the atmosphere must be reduced to stabilize the climate and avoid triggering tipping cascades (Steffen et al., 2015; Wunderling et al., 2022; Armstrong McKay et al., 2022). Spending extra energy for transforming CO₂ into useful materials substituting traditional materials may be

beneficial overall (Desing, 2022; Mertens et al., 2023; Galimova et al., 2022). Remining can also be performed on current waste streams, such as extracting materials—e.g., Mg or Li—from desalination brines (Lundaev et al., 2022).

Because of the efforts for and consequences of resource extraction and processing—i.e., energy demand and impacts on planetary boundaries—, it may be most sensible to prioritize the **redesign** of RE components with materials for which production is easier to scale up. For example, building 19 TW of PV panels with current technology, societal stocks of Al—used in PV for module frames—would need to more than double (just for module frames, mounting systems and grid integration not included; see SM). Even though Al resources would be available and accessible (USGS, 2021), mobilizing them would be a tremendous effort (Lennon et al., 2022). It would require as much energy humanity needed over eight months in 2019 just to mobilise enough Al (see SM) and cause environmental impacts correspondingly. This could be avoided by re-designing PV systems to avoid the use of Al: for example by designing frame-less modules (Müller et al., 2021), semi-flexible cells using existing structures for support (Holzhey et al., 2023), replacing Al with steel, or perhaps carbon-fibre reinforced plastics synthesised from atmospheric CO₂ (Lopez et al., 2023; Huo et al., 2023). Redesign can encompass the strategies of material efficiency (Allwood et al., 2010)—such as simply using less material (thinner wafers and sawing wires for PV cell production (Haegel et al., 2023; Goldschmidt et al., 2021)), or component reuse (applying solar layers on existing structures (Holzhey et al., 2023))—and substitution with materials that are easier to mobilize. For example, Lithium-Iron-Phosphate (LFP) batteries are gaining momentum and starting to replace current Nickel-Manganese-Cobalt (NMC) chemistries in less demanding applications (IEA, 2023), which substitute Co and Ni with the more abundant and easier to mine Fe and P. Yet such a substitution can lead to problem-shifting, as for example P is essential in food production (Lunde, 2022). Or even Na-ion batteries, which avoid the use of Li (Peters et al., 2021; Vaalma et al., 2018). New technological developments can help material mobilization by constantly improving material efficiency and providing substitution options. However, scaling such new technologies remains uncertain. Transition modelling may thus not rely entirely on yet-to-be-proven technologies.

Recycling of RE infrastructure can help maintain stocks but cannot contribute materials during the transformation. Yet once RE infrastructure is built, increasing lifetime and recyclability will be essential for preserving it throughout subsequent replacement cycles. Frequent substitutions, however, may reduce the recycling potential, as materials contained in older stocks may no longer be in demand in new generation technologies. Design considerations therefore have to focus on both minimizing the efforts for material mobilization during the transformation as well as losses during replacement cycles (e.g., for PV panels (IRENA and IEA, 2016), wind turbines (Mishnaevsky, 2021) or batteries (Neumann et al., 2022)).

3. Research directions

To plan fast energy transition pathways, it is important to better understand the effects of mobilizing materials on the overall dynamics of the transition. The scale and type of material mobilization can affect the dynamics in multiple ways that are poorly understood. Consequently, research will have to be conducted in the following directions.

Improving modelling of transition pathways based on biophysical principles

Due to the fundamental role of materials for the transition and the efforts associated to mobilize them, transition modelling will have to be based on the feedback loop between energy and materials. Time delays for building critical infrastructures—mines, processing facilities, production plants—, gathering knowledge, and building up skills, as well as the efforts for mobilizing materials will shape transition pathways. This will require to rethink current modelling approaches: energy demand

will not be an exogenous parameter, but a dynamic variable consisting of the energy required for material mobilization and the desired demand from the remaining societal metabolism (Desing et al., 2022). As energy supply is constrained by the installed capacity, which is dynamically constrained by mobilized materials and absolutely constrained by the maximum accessible materials as well as biophysical limits, it can then happen that supply does not meet demand. The energy available for mobilization changes over the course of the transition, making energy and materials inherently interlinked. And there are unavoidable time delays for gathering knowledge, and building extraction and processing facilities. It is important to investigate the dependence of energy demand on material flows and the feedback into energy-constrained transition pathways. It will be necessary to develop suitable modelling approaches out of a multitude of possibilities combining insights from technological models—such as process simulations—, supply chain models—such as (prospective) life cycle assessment or (dynamic) material flow analysis—, energy system models, and transition models—e. g., based on system dynamics or IAMs. Any such approach will need to ensure that materials and energy balances are fulfilled, requiring a new type of integrated models by dynamically integrating sub-models based on material and energy exchanges instead of monetary flows. Economic and agent-based models may inform on societal decisions related to operability and final material and energy demand. Future research will show which combination and concrete integration of models is best suitable to address the material-energy feedback loop in transition modelling. Scenarios on technological developments are crucial to understand what may become possible and where research efforts should concentrate on. However, transition planning should not rely entirely on prospective technologies, as they may come too late or fail. Therefore, baseline scenarios should use proven technologies with and without (most precautionary) continuous improvements. This is because technological learning (Goldschmidt et al., 2021), although observed in the past, may not materialize in the future, especially when ramping production extremely fast (Desing and Widmer, 2022; Grafström and Poudineh, 2021). Price developments will be a result of such modelling, as both supply and demand for raw materials and RE system components may change widely during the transition.

Understanding material mobilization dynamics and identifying bio-physically critical materials Materials represent potential bottlenecks to the transition not only due to their limited availability and accessibility, but also due to energy demand and environmental impacts during extraction and processing (processability). As knowledge about quantities and quality of source stocks is scattered and incomplete, efforts need to be taken to map the available and accessible material stocks. The energy needed for mobilizing one unit of material changes as a function of flow and the state of depletion and quality in the source stock, yet these relationships have to be still better understood. Models have to be developed that estimate time delays and correlate the efforts for extraction and processing to few key parameters, such as concentration, chemical state, and remoteness. Different mobilization routes may show synergistic effects or be in competition with each other and the rest of the economy. For example, early retirement and repurposing of fossil infrastructure may decrease the production of transition metals as by-products of fossil fuels. One example is synthetic graphite used e. g., in Li-ion batteries, which is today made from needle coke, a by-product of petroleum refining. Additionally, dynamic environmental impacts on planetary boundaries will constrain the maximum level of material mobilization. When designing rapid transition pathways, it will be important to investigate effects on biodiversity, nutrient cycles, water demand, etc. Knowledge regarding the bio-physical potential for mobilizing materials and their effect on the energy transition as well as planetary boundaries can inform about which parts of the future RE infrastructure should be redesigned, where technological developments and societal decisions need priority.

Material substitution and dematerialization Once bio-physically critical materials are identified, the question arises: how well can they be substituted by other materials and where are limits imposed by material physics? One example is substituting Ag in PV (Zhang et al., 2021; Pivano et al., 2019), another one is replacing Li in batteries (McNeil, 2022). It may be beneficial to research the possibilities to substitute with more abundant elements, such as H, C, N, O, Fe, Si, or Al (“elements of hope” (Diederer, 2010; Desing and Blum, 2023)), while improving the understanding of impacts on energy demand and planetary boundaries. Another research line could be to incorporate and immobilize (mandatory) abandoned elements—e. g., Hg (United Nations Environment Programme, 2019), Pb, Cd, atmospheric C—in long lasting infrastructure. E. g., Pb could be immobilized in perovskite PV (Lee et al., 2023), or excess atmospheric carbon (Desing, 2022) in plastics used in PV or graphite for battery electrodes. The effects of substituting, diverting and increasing material flows on the socio-economic metabolism are complex and need to be better understood (van der Voet et al., 2017), especially in the light of a rapid “emergency” transformation. Additionally, dematerialising RE technologies by design and in line with availability, accessibility and processability of materials can help speeding up the transition by minimizing energy and material demand, as well as easing subsequent replacement cycles.

New extraction and processing technologies Accessing, extracting and processing source stocks may require, or be eased by, new or improved technologies. For example, the majority of known mineral resources related to transition metals is located below the land of indigenous and pastoral peoples (Owen et al., 2022). Extracting them in the traditional way will cause environmental and social impacts, even if they have a societal licence to operate. Perhaps it might be possible to invent “minimally-invasive” mining technologies (in analogy to minimally invasive surgery) (Lopes et al., 2020); however, so far the only possibility to reduce the problem is to limit the amounts extracted, and focusing on areas where damage to the ecosystem is lower. Also, remining tailings, landfills and past emissions may benefit greatly by new extraction and processing technologies. As many transition metals are currently mined and processed as by-products, novel extraction routes may need to be developed. Additionally, mining and processing is today heavily reliant on fossil fuels, making it necessary to develop new de-fossilized extraction and production routes. All new extraction technologies will need to be assessed for their environmental and social impacts, e. g., by using life cycle assessments.

Enabling legislation, business models, governance and social acceptance All mobilization strategies will require changes in legislation, business models and social acceptance—be it for opening new mines, repurposing in-use stocks, or prolonging materials’ residence time in the economy. Acceptance can be influenced by the design of these strategies, which opens a new field of research: How can the design foster social acceptance and maximise social benefits, thus enabling implementation? Are there socially preferable strategies at different stages of the transformation? Mobilizing materials shall not come at the cost of local communities, which will require to envision national and transnational governance strategies for avoiding negative side effects and for learning from the disadvantages of the green revolution (Gloaguen et al., 2022). Furthermore, it is essential to devise political and economic strategies for implementation able to transcend social resistance and concerns of “societal security” aiming at maintaining the status quo (McLaren and Corry, 2023).

Monitoring and steering the socio-economic metabolism transformation The RE infrastructure lies at the interface between climate mitigation and resource criticality. The knowledge base of the energy-material nexus is still insufficient to adequately address this challenge. Existing models of the socio-economic metabolism are highly fragmented by countries, sectors, and materials and they lack the necessary spatial and

temporal granularity to capture the complex feedback loops between energy, materials, and environmental impacts. Improving our understanding of the energy-material nexus and the role of RE infrastructure is fundamental for informing, planning, governing, and monitoring energy transition strategies and ultimately for stabilizing the climate.

4. Conclusions

Trends and technologies can change faster (or more slowly) than expected. For instance: future batteries could be made out of abundant materials (such as Na and S), Ag in solar panels could be replaced by Cu, Al, or graphene, circularity could become “trendy” and effective recycling could boost companies’ reputation. Prospectively, materials and their applications can vary a lot, and simplistic views and conclusions should be avoided. Be that as it may, the general principles expressed in this paper reflect the natural laws of our physical environment and, as such, they are robust. The growth of RE stocks is physically limited by the available, accessible, and processable materials in natural (lithosphere, atmosphere, biosphere and hydrosphere) and anthropogenic resources (urban mines), as well as limited by the energy required and environmental impacts caused for their processing into RE devices. The speed of the transformation is then also limited by the willingness of society to invest in harvesting and processing infrastructure and operationalize the flows (i.e., the “hand on the valves”). The presented framework can help taking the dynamic interconnections between energy and materials into account in energy transition modelling and guide technological developments towards fast material mobilization.

CRedit authorship contribution statement

Conceptualization, H.D.; validation, all; visualization, H.D.; writing—original draft preparation, all; writing—review and editing, all.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

Financial contributions: H.D. and H.S. were supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 22.00166 in the frame of Horizon Europe “CircEULAR: Developing circular pathways for a EU low-carbon transition” co-funded by the European Union (project 101056810). D.M. was supported by French research project Scarcyclet (ANR-21-CE03-0012).

Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.resconrec.2023.107314>.

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