Energy Policy 119 (2018) 226–241

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development

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ARTICLE INFO

Keywords:
Climate change mitigation
Critical material
Transition
Resource
Scarcity
Substitutes

ABSTRACT

This study analysed demand for 12 metals in global climate mitigation scenarios up to 2060 and quantified the impacts on demand of different assumptions on improvements and technological mix. Annual and cumulative demands were compared with reserves and current mining rates. The study results showed that reserves are sufficient to support the total level of solar power, wind power and electric motors. Insufficient reserves may very well constrain certain sub-technologies, but substitutes that take the role of 'back-stop' technologies can be used instead. The exception is batteries, since lithium battery chemistries and reserves were incompatible with the scenarios analysed. Batteries of moderate size, lithium-free chemistry or reserve expansion would make the transition feasible.

Choice of sub-technology (e.g. type of solar PV) had a decisive impact on demand for certain metals. Perceptions that many metals are critical and scarce for renewable energy transitions appear exaggerated if a dynamic view on technological development is adopted. Policy-relevant conclusions can be drawn from this, regarding e.g. the benefits of technological diversity, increasing metal intensity, recycling and integrating infrastructure and energy policies (e.g. fast chargers).

1. Introduction

In 2016, fossil energy represented approximately 80% of the global energy mix (IEA, 2017b). Fossil resources are finite and the combustion process produces emissions that are harmful to the environment. One option is to replace fossil energy with renewable energy.[1] The flows that renewable energy technologies utilise are abundant and often not as geographically concentrated as fossil fuels. However, renewable energy technologies can require the use of metals with geographically concentrated deposits. These metals are sometimes perceived as critical when a high possibility of disruption is combined with high importance, see e.g. (DoE, 2011).

Interest in assessing the criticality of metals has increased among academia and policymakers in recent years, for a review of the literature see (Graedel and Reck, 2016; Jin et al., 2016). Criticality is dynamic over time, but Erdmann and Graedel (2011) and Jin et al. (2016) found that criticality assessments frequently overlook the role of recycling, innovation, substitution and time horizons.

A handful of previous studies have quantified the amount of embedded metals in batteries, various types of renewable production and end-use technologies, and the amounts of metals that would be required to meet certain climate mitigation targets, see e.g. (Candelise et al., 2011; Elshkaki and Graedel, 2013; Moss et al., 2013). Metal supply bottlenecks that can restrain adoption have been identified for some current technologies, such as solar photovoltaics (PV)(Elshkaki and Graedel, 2013; Grandell and Thorenz, 2014) and energy systems that meet climate mitigation targets (Grandell et al., 2016). For example, some metals are produced as by-products, making the supply dependent on the extraction rate of the host metal.

However, previous studies have estimated the aggregated metal requirement from either one technology or one set of technologies while adopting a static assumption on metal intensity over a certain period, e.g. up until 2050. This is not consistent with historical experience of improved material intensity over time. Two exceptions are Davidsson and Höök (2017), who examine currently adopted technologies of solar PV alone, and Viebahn et al. (2015), who focus on Germany. No previous study has adopted a global perspective on several technologies or provided justifications for the expected annual improvements. Deetman et al. (2018) analysed demand for five metals in global scenarios with various levels of climate mitigation, gross

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[1] Other techno-economic options include improved efficiency, carbon sequestration and storage and nuclear power.

https://doi.org/10.1016/j.enpol.2018.04.056
Received 22 January 2018; Received in revised form 23 April 2018; Accepted 25 April 2018

Table 1
Summary of stocks in society in the 'beyond 2 degree' (B2D) scenario, 2015–2060.

	Stock in society (2015)	Stock in society (2060)	Stock increase
Personal vehicles: Battery electricity (million)	1.5	1300	87000%
Personal vehicles: Hybrid, plug-in hybrid and fuel cells (million)	14	710	5000%
Electric bikes (million)	460	1600	300%
Buses: Battery electric, hybrid, plug-in hybrid and fuel cell (million)	0	31	N/A
MFT and HFT: Battery electric, hybrid, plug in hybrid and fuel cell (million)	0	130	N/A
Wind power (GW)	430	4200	1000%
Solar photovoltaic (GW)	220	6700	3000%
Solar thermal (GW)	21	1300	6000%

Note: For simplicity, the data in this table is compounded from the 45 sub-categories used in the study model into eight different categories (see supplementary material for disaggregated data). MFT = medium freight transport, HFT = heavy freight transport.

domestic product and population growth rate. Tokimatsu et al. (2017) analysed global metal demand up to 2100 for business-as-usual and a 2-degree climate mitigation target met by centralised coal and nuclear or decentralised gas and renewable energy technologies. Future research needs identified by Tokimatsu et al. (2017) included: metal demand for global renewable energy systems and coverage of more metals and technologies, such as fuel cells. Moreover, some metals can be substituted, with trade-offs such as higher cost, increased weight and lower efficiency, but no previous study has addressed how this might affect metal demand and criticality.

This study aims to fill the research gaps described above by analysing how different technological development trajectories affect the demand for different metals over time and how it is affected by using technological substitutes. This study also addresses the role of recycling to meet supply which connects this study to the emerging field of the circular economy. This provides a dynamic perspective on theories and assessments of what makes resources critical and how this can be mitigated.

Twelve metals were included in this study, namely cobalt, copper, dysprosium, gallium, indium, lithium, neodymium, nickel, platinum, selenium, silver and tellurium. The criteria for inclusion were that the metal is critical for some renewable energy production, storage or end-use technology or can be used as a substitute for critical metals.

Data on metal embedded in various renewable energy technologies were obtained from the published literature and was used to develop four scenarios with different assumptions on sub-technologies market share, recycling rate, size of batteries and future metal intensity improvements. All four scenarios are compatible with a climate mitigation scenario developed by IEA (2017a) and would provide a global energy system that is in line with the Paris agreement.

Estimated demand for virgin metals was compared against current mining rates and reserves. The study shows that reserves are sufficient to support the total level of solar power, wind power and electric motors. Insufficient reserves and mining bottlenecks could constrain certain sub-technologies, their growth rates or make the metal more expensive, but substitutes that take the role as'back-stop' technologies can be used instead. Increased lithium demand is identified as the main long-term obstacle and policy options to manage this are proposed.

2. Method

This study adopted the 'beyond 2 degree' (B2D) scenario from the energy technology perspective study by IEA (2017a). This is a normative scenario generated by a cost optimisation model that shows how the global energy system can transition to become consistent with the Paris climate mitigation agreement. The scenario extends to 2060 and provides annual data on installed capacity of different renewable power technologies (offshore wind, onshore wind, solar PV and solar thermal) and the mix of end-use transportation technologies (personal vehicles, light trucks, heavy trucks, mini- and hybrid-busses, plug-in hybrids, battery electricity and fuel cells, and whether they are used in urban or rural areas). Table 1 provides a summary of societal stocks of various technologies at the beginning and end of the scenario timeframe. Annual flow to society was calculated based on stock change and assumptions on the life expectancy of each technology (see supplementary material for assumptions on life expectancy). Thus, cumulative flow to society was higher than the difference in stock between 2015 and 2060, since assumed technology life expectancy was lower than 45 years.

Previous literature was reviewed and data were obtained on material embedded in the technologies used in the B2D scenario. Material intensity was calculated as weight of material times the amount embedded in one unit (GW installed production, kW motor or fuel cell power, kWh energy storage) of technology y, e.g. weight of lithium embedded in 1kWh battery storage. Data on trends in metal intensities over time and possibilities to replace metals directly or using a technological substitute were also taken from the literature. These data were then used to construct four scenarios that were all consistent with the B2D scenario, but with different assumptions on the mix of sub-technologies, recycling rates, metals used in different technologies and trajectories of metal intensities. Assumptions on current recycling rates were taken from previous studies (Sverdrup et al., 2017; UNEP, 2011).

Finally, cumulative demand and peak annual demand for each metal were compared against current known reserves and mining rates, using data from USGS (2018) complemented with data from (Habib and Wenzel, 2014); Sverdrup et al. (2017). Reserve is defined as the part that can be economically extracted or produced at the time of determination (USGS, 1980). Improved extraction technology and higher market price increase the size of the reserve. Resources are (much) larger, but have lower economic feasibility of being produced and lower reliability. The degree of geological scarcity (i.e. exhaustion time of extractable global resources) does not provide a price mechanism of early warning of mineral exhaustion (Henckens et al., 2016).[2] Cumulative metal demand was therefore primarily compared with reserves, since this provides a comparison with the amount that can be mined at today's market prices. It also illustrates how much reserves needs to grow. In the discussion we highlight cases were cumulative demands are comparable to resources.

3. Electricity production

3.1. Solar PV

Two main designs of solar PV are currently used: crystalline silicon and thin film (see Fig. 1). These are sometimes referred to as first- and second-generation solar PV technologies, respectively. Crystalline silicon has a market share of approximately 90%. Cadmium-telluride (CdTe) has the second largest market share, but copper-indium-gallium-

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[2] Geological factors are one aspect of scarcity. The concept of scarcity is dynamic and can be understood as a result of "actors' perceived difficulties to access a resource" (Vikström, 2016).