Environmental Science & Technology

Article

pubs.acs.org/est

Managing Critical Materials with a Technology-Specific Stocks and Flows Model

Jonathan Busch,*[,†] Julia K. Steinberger,[†,§] David A. Dawson,[‡] Phil Purnell,[‡] and Katy Roelich[†,‡]

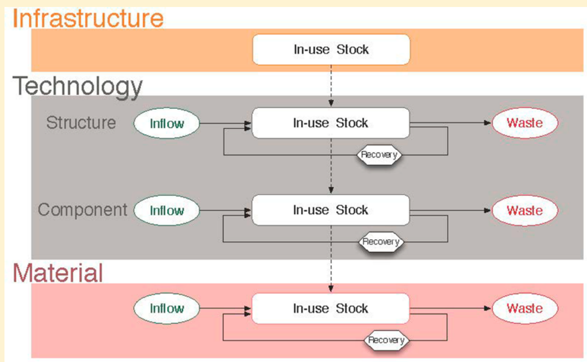
[†]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom

[‡]Institute for Resilient Infrastructure, School of Civil Engineering, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom

[§]Institute of Social Ecology, Vienna, Alpen-Adria University, Klagenfurt, 1070, Austria

Supporting Information

ABSTRACT: The transition to low carbon infrastructure systems required to meet climate change mitigation targets will involve an unprecedented roll-out of technologies reliant upon materials not previously widespread in infrastructure. Many of these materials (including lithium and rare earth metals) are at risk of supply disruption. To ensure the future sustainability and resilience of infrastructure, circular economy policies must be crafted to manage these critical materials effectively. These policies can only be effective if supported by an understanding of the material demands of infrastructure transition and what reuse and recycling options are possible given the future availability of end-of-life stocks. This Article presents a novel, enhanced stocks and flows model for the dynamic assessment of material demands resulting from infrastructure transitions. By including a hierarchical, nested description of infrastructure technologies, their components, and the materials they contain, this model can be used to quantify the effectiveness of recovery at both a technology remanufacturing and reuse level and a material recycling level. The model's potential is demonstrated on a case study on the roll-out of electric vehicles in the UK forecast by UK Department of Energy and Climate Change scenarios. The results suggest policy action should be taken to ensure Li-ion battery recycling infrastructure is in place by 2025 and NdFeB motor magnets should be designed for reuse. This could result in a reduction in primary demand for lithium of 40% and neodymium of 70%.



■ INTRODUCTION

The need to decarbonize the global economy is widely recognized and, in the UK, it is enshrined in legislation in the form of the 2008 Climate Change Act, which mandates an 80% reduction in carbon emissions by 2050 relative to 1990. To achieve this, a rapid transformation of infrastructure is required, a process which, as described by the National Infrastructure Plan published by the UK Treasury in 2012, is aligned with the needs to overhaul and retrofit the national infrastructure to support economic growth. The infrastructure transition envisioned by the UK government[1,2] includes the adoption of new, low-carbon technologies (e.g., electric vehicles for transport and wind turbines for electricity generation) at unprecedented levels. These new technologies contain a material mix that is very different to that of the current infrastructure stock, potentially introducing a reliance on "critical" materials at risk of supply disruption (e.g., rare earth elements, cobalt, and lithium).[3−6] Owing to the huge scale of infrastructure, changes thereto are likely to cause a step change in the demand for such materials. Currently, policies planning the deployment of low carbon technologies are based primarily on carbon abatement potential and economic cost.[1,2] The impacts in terms of new material demands, along with changing infrastructure stocks and future waste treatment, are not considered although these will significantly impact both the sustainability and resilience of future infrastructure systems.

Introducing technologies into infrastructure that rely on critical materials should prompt a greater effort into understanding and quantifying the changed material. The materials included in current technologies will remain embedded in infrastructure for many years, since infrastructure remains in use for lengths of time ranging from a few years to several decades or even centuries. The resulting delay between materials being introduced into infrastructure and becoming waste complicates the potential for a circular (or closed-loop) economy, a concept that has been gaining traction in policy internationally.[7−10] When the materials embedded in infrastructure are critical materials[3,5,6] that may suffer from supply shortfalls, understanding where, when, and how these materials and technologies within which they are embedded may be

Received: June 10, 2013
Accepted: December 11, 2013
Published: December 11, 2013

recovered (or better, reused) becomes important, first for enabling a closed-loop system of material use, and second to ensure the continuing functioning of basic infrastructure. To this purpose, infrastructure planning should include estimates of material demands: these estimates should be dynamic, including deployment and end-of-life, and take into account a variety of different technologies and components and their recovery and recycling potentials. By integrating such an analysis into infrastructure transition planning, scenarios can be developed that make optimal use of material resources, minimizing the risk of supply disruptions and making the best use of future end-of-life material. This Article presents such a planning tool: a dynamic stocks and flows model for technologies embedded in infrastructure.

Previous work on dynamic material flow forecasting has established stocks and flows modeling (SFM) as a robust and useful tool for predicting future demand, in-use stocks, and waste of material resources.[11−20] The approach of deriving future material demand from a service demand scenario has found wide use,[11,19,21,22] with the calculation of future waste based on the lifetime characteristics of stocks in-use.[23,24] Past implementations of this approach, however, have limited the lifetime dynamics calculations to a single layer in the model. This is typified by the model of Modaresi and Müller[22] which includes a nesting of three classes of stocks: the total vehicle stock, three different drive technologies, and three different materials. Within this model, the technology stocks and flows alone are dynamically calculated with a lifetime function. This approach may be appropriate where the materials have a one-to-one correspondence with the relevant infrastructure, e.g., concrete used in building stock[11] but falls short when we want to study materials in technologies embedded within infrastructure, where one technology relies on subcomponents, each with their own in-use dynamics and lifetime characteristics. This complex technological structure results in material flow dynamics that are difficult to predict, yet must be understood in order for supply bottle-necks to be averted, and to take advantage of recovery possibilities.

In this paper, we present a novel SFM that projects the stocks and flows of technologies and materials based on low-carbon technology deployment scenarios. Technology components and materials are explicitly incorporated in the model, each with their own stock and flow dynamics. This allows the projection of material dynamics to include technology components with diverse lifetimes, the recovery and reuse of technology components, and the recycling of materials, an analysis that is often discussed qualitatively in the "circular economy" literature[7] but has not previously been studied quantitatively. The model provides a methodology to assist planning of technology roll-out, define the materials demand profile and potential bottlenecks, and avoid or diminish supply risks through the planning of recovery and recycling: in short, to manage critical materials in infrastructure. Quantifying the potential for recycling and reuse can also act as a driver for the adoption of better material stewardship practices in a circular economy.

We demonstrate the approach on the transition in personal transportation vehicles in the UK from internal combustion engine to electric vehicles. This transition involves the potential introduction of large quantities of lithium and cobalt (in electric vehicle batteries) and the rare-earth metal neodymium (in electric vehicle motors), while releasing the platinum in catalytic converters, unnecessary in electric vehicles. All four of these materials have been included in previous assessment of material criticality at national and EU scale[3−5] and found to be of interest. With our model, we show how the demand for these materials and their anthropogenic stocks and waste flows change over time and how different recovery scenarios affect these stocks and flows.

■ METHODOLOGY

The model we present has been designed to study the relationships between the attributes of technologies that make up infrastructure and the stock and flow dynamics of the material contained in these technologies. To enable this, the model has three key features: first, a dynamic representation of stocks and flows; second, a focus on infrastructure transitions with the adoption of new technologies; third, the potential for recovery and substitution to occur at the level of technology as well as materials. The first feature is already included by the methodology for dynamic material flow modeling developed by Müller,[11] and it is this approach that we build on. To incorporate the second and third feature, we develop a hierarchical, nested representation of stocks and flows. Technologies and their components are explicitly included with their own dynamic stocks and flows. As the purpose of this model is to study the relation between infrastructure and technology dynamics and material flows, the focus is on the in-use phase of the material life-cycle, including the recovery of end-of-life stock for reuse or recycling. The system boundary excludes extraction and manufacturing activities. Furthermore, the purpose of this model is not to produce a perfect representation of every processing step involved in the waste management phases of the infrastructure lifecycle. Rather, we design the model to allow us to identify the availability of end-of-life stocks for reuse or recycling. Figure 1 shows a graphical representation of the hierarchical model structure.

Model Structure. The model separates an infrastructure system into three distinct classes of stocks:

1. Infrastructure stocks represent the service level an infrastructure provides, e.g., vehicles providing transportation. This stock does not refer directly to physical objects, and hence, no physical flows are necessary.
2. Technology stocks represent the technologies that provide the infrastructure service and are further disaggregated into technology structures, which directly provide the service (e.g., vehicles that provide transportation services), and their components (e.g., batteries, motors, magnets), which can be nested to any depth.
3. Material stocks that are contained in the technology stocks described above, e.g., lithium contained in an electric vehicle Li-ion battery.

In any implementation of the model, there can be multiple instances of each class of stock. An infrastructure service could be provided by any number of different technology structures, each of which could be made up of multiple components. A single component stock can also be shared by more than one structure, as would be the case in two types of electric vehicle that share a common motor design. The same is true for materials, where one material stock can represent material contained in several technology components and structures. The result is a complex hierarchical network of different stocks.

Each of the stocks in the model has its own properties and associated inflows and outflows (see Supporting Information 2 for a full stocks and flows diagram). This means each structure

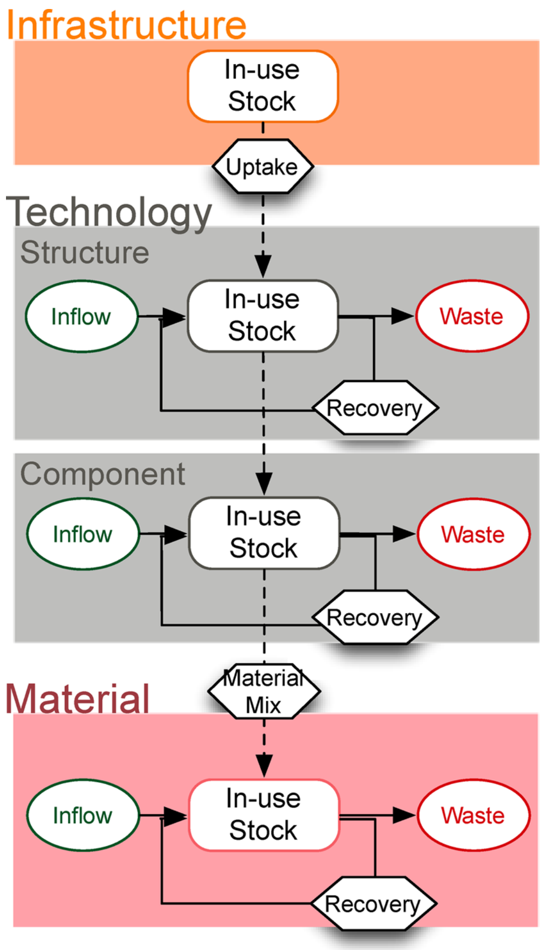


Figure 1. Elements of the hierarchical Stocks and Flows Model, from infrastructure stocks to technological structures and components and their material requirements, each resulting in in- and outflows.

and component can have different lifetimes, and the outflows from each stock will depend on its own lifetime as well as the dynamics of the stocks in which it is contained. This interaction can result in significant differences to stocks and flows dynamics compared to a simpler model that only considers the lifetime of either vehicle or battery (see the Supporting Information for an illustration of the difference). The separate representation of each stock requires a separate treatment of these stocks at end-of-life. Any of the structures, components, or materials can potentially be recovered at end-of-life and reused or recycled to displace virgin inflow.

Model Calculations. The calculation of the stocks and flows is done for each class of stocks from the top of the hierarchy down. Infrastructure stocks are determined from historical data and a deployment scenario for future dates. The technology structure stocks follow from a combination of the infrastructure stocks and a technology mix that describes what split of technologies is used to provide the infrastructure service. Technology component stocks must then match the stock levels of the structures (or other components) of which they are constituent parts. Finally, the material stocks are determined by the material intensities of the technology stocks which they make up.

Central to the calculation of every stock and flow in the model is the balance equation

$$\frac{\mathrm{d}}{\mathrm{d}t}K_m(t) = I_m(t) - O_m(t) \tag{1}$$

where $K_m(t)$ is the stock amount (Kapital) of structure, component, or material m at time t and $I_m(t)$ and $O_m(t)$ are the corresponding inflows and outflows of m, respectively. From this balance equation, the determination of stock and flow time-series can proceed through either a flow driven or a stock driven approach. A flow driven approach is appropriate where the inflow and outflow are known or straightforward to model. This would be the case particularly with consumable objects that do not have a complex or long-lived in-use phase, such as aluminum cans or plastic cups. A stock driven approach determines the inflow and outflow from known stock levels and the dynamics of in-use stocks. This is more appropriate where the in-use dynamics are more complicated, for example, in the case of infrastructure where technologies and materials remain in use for long periods and there is a long delay between the inflow of material and it becoming available for recycling.[13,15,19,20]

Following the stock driven approach, the outflow of any stock is determined by a lifetime function that determines the fraction of the stock added at any previous time that reaches end-of-life at the current time, i.e.,

$$O_m(t) = \int_{t_0}^{t} \mathrm{d}\kappa L_m(\kappa, t) I_m(\kappa) \tag{2}$$

where $L_m(\kappa,t)$ is the lifetime function that gives the fraction of stock added in year κ that reaches end-of-life in year t and the integral goes over all historical inputs to the current time. The lifetime function is assumed to take the form of a Gaussian; for further details, see the Supporting Information. Given this and the required stock level, $K_m(t)$, the inflow required is calculated using eq 1. For structure stocks, this is a simple procedure. For components and materials, the calculations are complicated by the additional outflow due to a parent stock reaching end-of-life. The detailed calculations are given in the Supporting Information.

The potential for future reuse or recycling is handled in the model by a recovery process that is described in technical detail in the Supporting Information. Technology structures and components that reach end-of-life have the potential to be reused at the same system level or lost as a waste stream. Reuse of technology will usually involve a remanufacturing process that, like primary production, is not included in our model. Lithium-ion batteries for example would require remanufacturing before reuse in vehicles is practical, whereas NdFeB magnets could be reused directly without a remanufacturing step. For consistency, we use the term "reuse" to refer to both possibilities. What was termed "reuse" for technology structures and component, we call "recycling" for materials; recycling is thus defined as a process that occurs strictly at the same system level and is distinct from down-cycling (without a measure of the function or quality of materials and components, it is difficult to define down-cycling anyway). Both components and materials can also be contained in parent structures or components that are reused at end-of-life. The model tracks these as "embedded" stocks. For both technology structures and components, and materials, the term "waste" is used in the sense of no longer being of use for its previous purpose. This does not preclude the stock being down-cycled and its constituent components or materials being reused or recycled. These definitions of reuse, recycling, and waste are intended to

dx.doi.org/10.1021/es404877u | Environ. Sci. Technol. 2014, 48, 1298−1305

be compatible with the definitions commonly used in circular economy literature and EU waste framework and end-of-life vehicle directives.

In the model, the split of end-of-life stock into waste and reuse flows is supplied to the model as a recovery scenario. The purpose of this approach to reuse and recycling is not to give an accurate representation of the end-of-life treatment of technology but to account for the availability of end-of-life stock for recovery and highlight the potential impact of adopting different recycling policies.

Case Study System. The transition to low carbon personal transportation is vital to the UK meeting its carbon emission reduction targets, as the transport sector accounts for almost a quarter of GHG emissions in the UK.[2] The Department of Energy and Climate Change (DECC) publishes a series of scenarios for decarbonization[25] that would achieve emissions reduction targets and has an online "Pathways" analysis tool[26] detailing the impacts of different decarbonization measures. The scenarios are published by DECC on five year increments; to get a realistic timeline, we apply a cubic interpolation algorithm to calculate consistent yearly increments. We use one of the core scenarios from this work as the driver for infrastructure service and technology roll-out in our model. The scenarios detail the fleets of internal combustion engine vehicles (ICEVs), plug-in hybrid electric vehicles (PHEVs), and fully electric vehicles (EVs). We use the "Renewables" scenario, which is biased toward the adoption of renewable energy production. This scenario forecasts a decline of ICEVs starting in 2020 with PHEVs becoming the most common technology around 2030 and EVs taking over in about 2040, as illustrated in Figure 2.

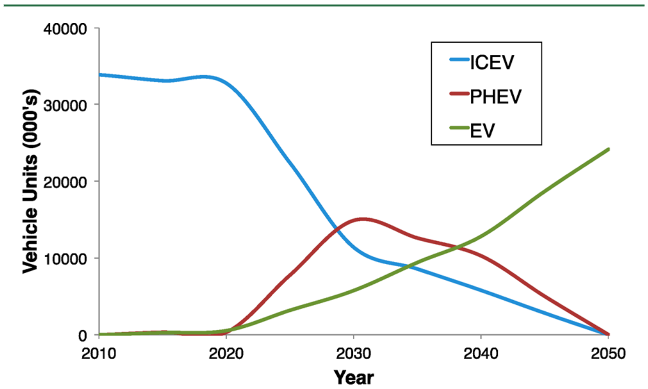


Figure 2. Total in-use stocks of vehicles for the UK deployment of electric vehicles under the DECC pathway analysis Renewables scenario used in the model.

The materials we are interested in tracking in this study, lithium, neodymium, cobalt, and platinum, are contained in the batteries, motors, and catalytic converters of vehicles. We take most of the material intensities of these components from the US Department of Energy[4] as shown in Table 1, and they are consistent with a number of similar studies.[27−33] The range of material intensities for Li-ion batteries is due to uncertainty in the battery chemistry that will be used. A number of candidates exist, each of which has their own advantages and drawbacks, well described by Gaines et al.[28] In the model, these ranges are accounted for by sensitivity analyses presented in the Supporting Information.

The lifetime of all three vehicle types is assumed to remain at 13 years with a standard deviation of 3 years (c.f. Supporting Information). Catalytic converters and electric motors in modern cars are designed to last for the full lifetime of the vehicle and will not usually be replaced, so there is no lifetime for these separate from the vehicle lifetime. The Li-ion batteries found in both PHEVs and EVs today are sold with a warranty of 8 years. Due to the relatively recent introduction of these batteries, there is no reliable statistical data for their lifetimes. We hence use a lifetime of 8 years with a variance of 2 years for these batteries in the model. We note that the model has the capability for both material intensities of technology and technology lifetimes to change over time; however, due to a lack of reliable forecasts for what technological changes may bring, we make the conservative estimate that they will remain constant. The Supporting Information includes a sensitivity analysis for both the vehicle and battery lifetimes.

Table 1. Material Intensities of Components and Their Sources

component	material	intensity (kg/unit)	source
NdFeB motor	neodymium	0.31−0.60	USDOE[4]
Li-ion battery EV	lithium	3.38−12.68	USDOE[4]
	cobalt	0−9.41	
Li-ion battery PHEV	lithium	1.35−5.07	USDOE[4]
	cobalt	0−3.77	
catalytic converter	platinum	0.0015−0.0025	Ravindra[26]

Recycling of materials from end-of-life vehicle stock are limited by both the efficiency of recycling processes and collection efficiency. A combination of these two factors leads to realistic recycling rates of 70% for lithium, 90% for cobalt, 70% for platinum, and 80% for neodymium (for detailed sources, see the Supporting Information). The limits to lithium recycling lie mostly in the difficulty of chemical separation of battery material whereas cobalt and neodymium recycling are limited mostly by collection efficiencies (which we assume to be very high due to the EU end-of-life vehicle directive).

The reuse of remanufactured Li-ion batteries we analyze in this paper is highly speculative. There is currently no commercial activity in this direction, although research projects are beginning to investigate the possibility.[34] The reuse of NdFeB permanent magnets in motors is also failing to see commercial application, although the process is much simpler as magnets degrade only negligibly over the lifetime of a vehicle. In the absence of more detailed information, we assume an optimistic rate of 95% for both of these, to demonstrate the model's potential. More detailed justifications of recycling and reuse rates are given in the Supporting Information.

RESULTS AND DISCUSSION

Stocks and Flows without Recovery. Figure 3 shows the stocks and flows of cobalt, lithium, neodymium, and platinum under the Renewables scenario assuming no recycling or reuse of any material or technology. For the three materials found in low carbon transport technologies (cobalt, lithium, and neodymium), we see the expected steep increase in in-use stock from 2020. For cobalt and lithium, there is a very steep increase between about 2020 and 2025, which then continues to increase at a slower rate. Neodymium use, in contrast, shows a very rapid increase between 2020 and 2025 and then stabilizes after 2025. This difference can be explained by the lower material intensity of cobalt and lithium in PHEV batteries compared to EV batteries. The stock level hence continues to rise after 2025 as EVs replace PHEVs. Neodymium, however,

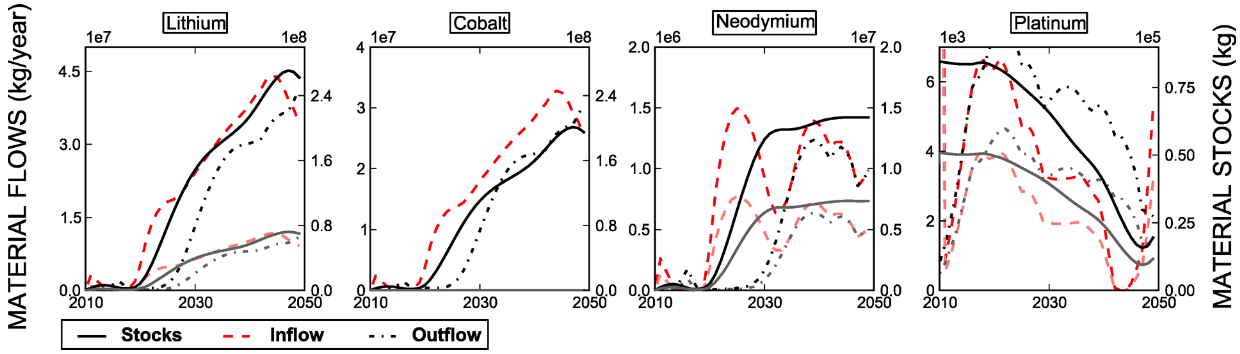


Figure 3. Material stocks and flows without recovery under the Renewables scenario. Solid lines indicate the high estimate for material intensity with the low estimate shown as fainter lines (the low estimate for Cobalt being zero).

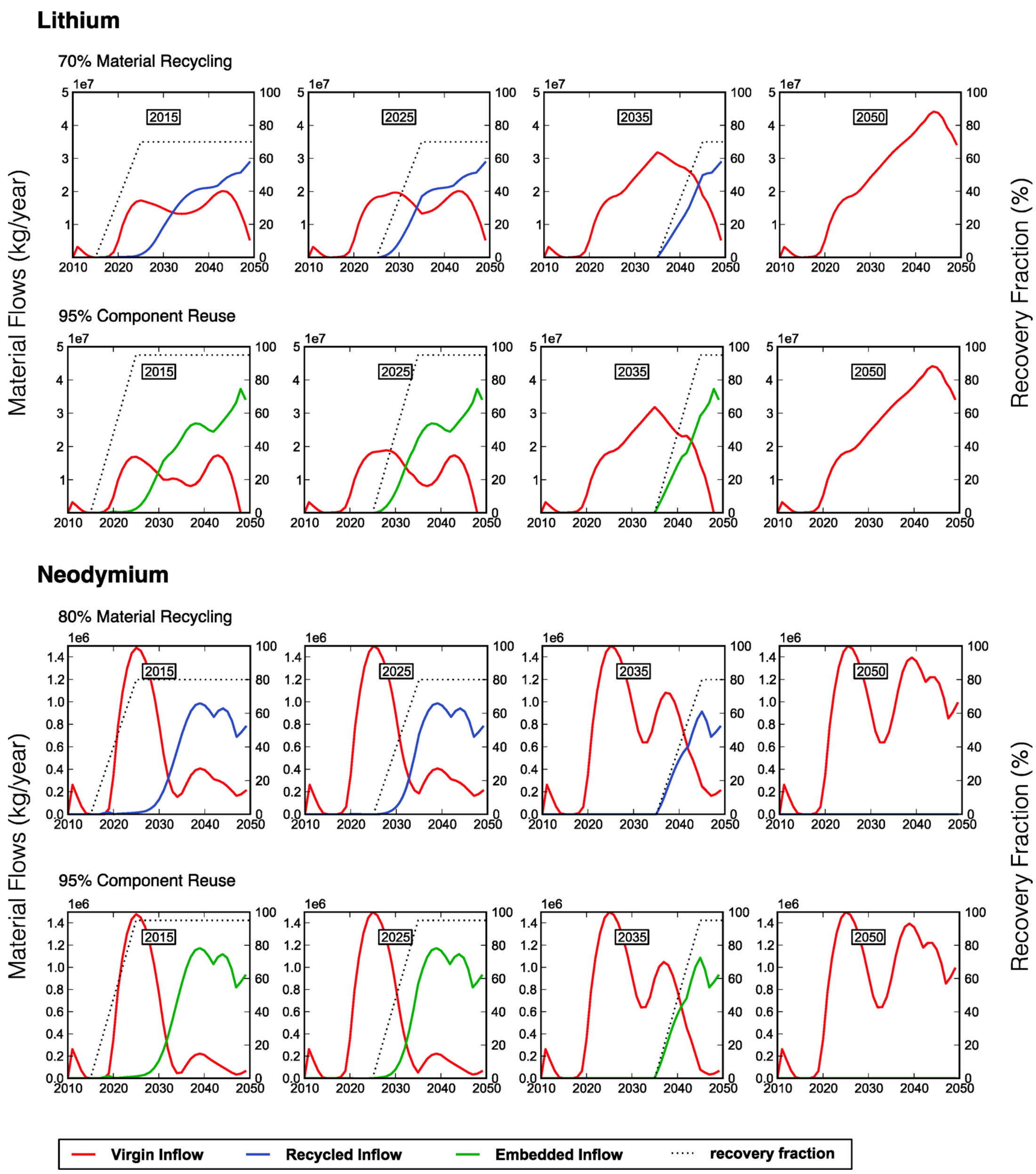


Figure 4. Recovery scenarios for material recycling and component recovery applied to lithium and neodymium in the Renewables scenario with a high estimate for material intensity. Graphs show the virgin inflow, reuse inflow (recycled material), and embedded inflow (in reused components) along with the recovery fraction which is also indicated on the graph by the year recovery begins.

has equal material intensity in both types of vehicles; hence, a switch from PHEVs to EVs results in no further increase in material inflow.

The pattern for platinum stocks and flows is very different. In use stocks are initially high and drop from 2020 onward, mirroring the decline in ICEV stock. What is clear for all three of the "low-carbon" materials (cobalt, lithium, and neodymium) is that the UK demand for these materials for the transport sector will increase rapidly from 2020. By 2030, the UK would require over 30 kilotons of cobalt, between 10 and 45 kilotons of lithium, and between 0.7 and 1.5 kilotons of neodymium per year (depending on the technologies used). To provide a sense of scale, in 2010 world production was 88 megatons of cobalt, 28.1 kilotons of lithium, and 22 kilotons of neodymium. This puts the high estimate scenario results in 2030 at 0.03%, 160%, and 7% of 2010 world production for cobalt, lithium, and neodymium, respectively. While it is important to note that we make no forecast for future world mine production, which would be required for fair comparison, or any assessment of any other factors that would lead to potential material criticality, these results are still significant. The relatively short time horizon of the step-change in demand for lithium from 2020 and the scale of this step-change being on the order of 2010 world production is enough to suggest that concern for the supply of lithium is warranted. The scale of the step-change for neodymium is also of concern, especially in context of the wider uses for neodymium which include other low-carbon technologies such as permanent magnet wind turbines.[16] Cobalt, however, from a purely supply vs demand perspective does not appear to be particularly critical. There is a step change in demand due to UK electric vehicle estimates, but it is not significant compared to global production. The results from this model are clearly a good starting point for highlighting the potential risks to infrastructure from critical materials.

Material Recycling and Technology Reuse. The outflows for all materials (shown in Figure 3) and technology components are split in the model into waste flow, recycling/reuse flow, and embedded flow (material or components that are embedded in reused technology). To illustrate the potential for recycling or reuse to displace virgin material or component inflow, we model a set of possible recovery scenarios. Three scenarios are modeled with an initial recycling/reuse rate of zero that increases, beginning in 2015, 2025, and 2035, to a set maximum linearly over a period of ten years. The scenario beginning in 2015 represents a highly optimistic roll-out of recycling infrastructure and almost immediate adoption of design standards for reuse. The 2025 scenario represents a more realistic estimate assuming still ambitious targets for policy action and subsequent changes in practice. The 2035 scenario represents late action, with a time scale that will miss most of the alarming demand projections identified above. For lithium, cobalt, and neodymium, the maximum recycling rates are 70%, 90%, and 80%, respectively. For Li-ion batteries and NdFeB, the maximum reuse rate is 95%. The results of applying these scenarios for lithium and neodymium are shown in Figure 4. The result for cobalt is not shown because the shape is identical to the lithium result; only the scale is different.

The material recycling results for lithium show that a large reduction in virgin inflow is possible with the use of recovered material. It is not possible to completely displace virgin inflow as there will not be enough secondary stock, but the volume of recycled material can be greater than virgin material by 2030 if recycling facilities are in place before then. The peak requirement of about 15 kilotons by 2024 is unavoidable, as there is no vehicle end-of-life stock available for recycling at that time but the no-recovery level of 25 kilotons in 2030 can be reduced to around 15 kilotons. The reductions grow progressively more significant toward 2050 where the requirement for virgin material disappears completely.

The effect of reuse of Li-ion batteries on the demand for virgin lithium is very similar to the material recycling option, despite the much higher recovery fraction (70% to 95%). The reason for this is that batteries from PHEVs are not the same as those needed for EVs. This highlights the higher flexibility in recycling materials than trying to reuse more specific technology components.

The results for neodymium recycling are similar to those of lithium, i.e., an unavoidable peak in demand in 2024. The timing of the impacts of recovery are different because of the longer lifetime of the NdFeB motor compared to Li-ion batteries, so there is little difference between the 2025 and the 2035 recovery scenarios. The second peak in demand of 1400 tons seen around 2039 (Figure 3) can be reduced to a peak of just 400 tons by material recycling. The effect of NdFeB motor reuse has the potential to reduce this peak even further to 220 tons, a reduction of over 80%.

The application of material recycling on platinum is obvious already from the results in Figure 3. This shows that outflows of platinum are significantly greater than inflows in almost every year. Recovery and recycling of platinum with a modest recycling rate would thus clearly reduce virgin platinum requirements to almost zero as soon as it is applied (for details, see the Supporting Information). The remaining recycled platinum surplus would likely also find use in other technologies, given the high value and demand for platinum.

The comparison of material recycling and technology reuse allowed by this model enables two important results. First, the explicit inclusion of components with distinct lifetimes in the model is needed for an accurate prediction of the availability of end-of-life resources for recovery. This accounts for the earlier impact of lithium recycling compared to neodymium recycling because the battery lifespan is only 8 years as compared to a 13 year vehicle lifespan. Second, the incompatibility of Li-ion batteries between PHEVs and EVs is representative of a general feature of remanufacturing and reuse of components: there is a loss of flexibility which must be balanced against the potentially lower efficiency and higher cost of disassembly and material recycling. This type of trade-off is evident only through using technology-specific dynamic modeling, such as the model presented here.

Implications for Low-Carbon Transitions. The transition from internal combustion engine to electric vehicles, as shown in the DECC scenarios, has the potential to make a significant contribution to the planned UK transition to low carbon personal transport. We have now seen that this technology change will be accompanied by the introduction of lithium and neodymium into infrastructure in amounts that will significantly increase UK demand for these materials. The possibility of shortages in supply of these materials constraining a successful transition to low carbon transport should prompt policy actions to mitigate against this. By including the possibilities for material and technology recovery, we have shown how the potential for reuse can be used to mitigate potential supply bottlenecks and support a circular economy, as well as when this option is not viable, due to a lack of available secondary resources.

In the case of lithium (and less critically cobalt) for Li-ion batteries, our results indicate that there exists a trade-off between a battery remanufacturing approach and a lithium recycling approach. The difficulty in component reuse is likely to be compounded by the variety of different Li-ion battery chemistries that exist. The implication is that a policy of encouraging the development of material recycling from Li-ion batteries is likely to be more fruitful in the medium term, with benefits most significantly felt if recycling infrastructure is in place by 2025.

The conclusions are different for neodymium and NdFeB motors. Although material recycling is effective in this case, the higher rate component reuse leads to greater demand reductions. Furthermore, the properties of permanent magnets are such that reuse could require only minimal remanufacturing, given appropriate design for reuse. Material recycling provides no significant flexibility advantage as magnet technology is relatively mature and uniform (reflected by the smaller range in material intensity). The appropriate policy intervention in this case would be to enable efficient reuse of magnets in NdFeB motors through high collection efficiency and design standards that allow reuse without remanufacturing.

In the example of a transition to electric vehicles for personal transportation, these results highlight the need for an evidence based material stewardship policy. Understanding where materials go into infrastructure, when they will reach end-of-life, the potential for either material recycling or technology remanufacturing and reuse, and when to prioritize one over the other is crucial to achieving a circular economy.

Beyond personal transportation, the model could also be applied to wider infrastructure transitions involving many more technologies and materials. A nation-wide study involving interdependent infrastructure systems which share common material bases would have the potential to highlight the full scale of nationally relevant supply bottlenecks and identify significant reuse opportunities for technologies and materials. The trade-off between higher efficiency component remanufacturing and reuse and the lower efficiency, more flexible material recycling, that allows materials to be recycled between different technologies and infrastructures, could be extended in such a study to the reuse of components between different infrastructures, such as EV batteries reused for grid-attached storage. Quantifying this trade-off for specific infrastructure systems and technologies where the recovery efficiencies are known could thus inform policies that foster industrial strategies toward optimizing material efficiency.

In a broader context, the results from this model bring into focus challenges in the transitions to a low carbon economy. These transitions are often discussed with reference to two separate ideas: the use of low carbon technologies and the move to a circular economy. There is a fundamental short-to-medium term conflict between these two ideals: low carbon technologies have a radically different material mix compared to existing infrastructure stock. For these critical materials, a truly circular economy is therefore not possible until the infrastructure has reached a low-carbon equilibrium state where end-of-life stock is available to substitute for virgin material demand.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

A full description of the model with detailed calculations, the case study system with parameters, and more detailed results of model simulations. This material is available free of charge via the Internet at http://pubs.acs.org

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: j.busch@leeds.ac.uk; telephone: +44-113-3432663; fax: +44 113 343 5259.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The support of the UK Engineering and Physical Sciences Research Council (grant number EP/J005576/1) is gratefully acknowledged.

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