Tackling material constraints on the exponential growth of the energy transition

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Commentary

Tackling material constraints on the exponential growth of the energy transition

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Renewable energy technologies are experiencing exponential growth rates. However, these technologies rely on materials, and it is not a given that these supply chains can keep up with exponential growth. We discuss how the scientific community can support responsible sourcing and responsible stewardship of materials.

The human mind generally has a hard time with grasping the implications of exponential growth. We overestimate the impact of a new technology when it is in the early stages of growth but subsequently underestimate the full force of the new technology when it is fully realized. The economist Richard Baldwin coined the phrase "holy-cow moment" to describe this (see Figure 1).[1] A technology with an exponential growth curve slowly grows beyond early adopters and newspaper articles and eventually scales to the point that it becomes noticeable in daily life. The holy-cow moment is the point when one realizes the true meaning of exponential growth: that from that point onward, change will keep accelerating rather than slow down.

We argue that the global energy transition, driven by the need to move away from fossil fuels toward low-carbon energy systems, is approaching its holy-cow moment. The switch from fossil to renewable energy can be fast and unexpected and, if unmanaged, will be viciously destabilizing to the people whose livelihoods depend on fossil-fuel jobs and can critically strain the supply chains of critical materials that, by definition, have their own limits to supply-chain resilience.[2]

The rise of renewables

The energy transition has been gathering pace, as evidenced by the Global Energy Monitor's analysis showing that 2020 was the first year on record in which the global fleet of coal-fired powerplants shrank. The global economy has reached the tipping point where real-world events are catching up with, and in some cases even exceeding, the upper band of scenario projections. For example, compare real-world trends with the extreme growth scenarios of Alonso et al.,[3] who in 2012 assumed a 15% compound annual growth rate (CAGR) for renewable technologies. Installed global photovoltaic (PV) capacity grew from 5 GW in 2005 to almost 700 GW in 2020—a whopping 140× increase in the stock of materials related to this technology and an almost 40% CAGR, which is projected to continue for the foreseeable future.[4] Figure 2A illustrates that for electric vehicles (EVs), a similar exponential growth exceeding scenario projections has occurred (Figure 2B). In 2010, around 20,000 EVs were on the road. There were over 7 million vehicles in 2020, and 250 million are projected to exist in 2030 (a 43% CAGR is projected for the coming decade).[5] Wind energy is growing with a global average CAGR of around 10%.[6] Stationary residential battery storage has achieved a 60% CAGR in the past couple of years, albeit from a much smaller install base.[7]

Although this rapid buildup of renewables has until now been largely dependent on strong government policies, the technologies of the energy transition (PV, wind, EVs, and storage) are now in many places cheaper than their fossil-fuel-based counterparts.[8] The economic competitiveness of renewables is further enhanced by progressive carbon pricing in many parts of the world.

Societal support for the energy transition is rapidly growing as well because more people, companies, and whole industries are realizing the benefit to themselves. Homeowners can earn money by investing in solar panels. Tesla is now worth more than the next top six car companies combined, and car producers are tumbling over each other to announce dates that the last internal combustion engine will roll off the conveyer belt. The market capitalization of "supermajor" renewable energy companies has rivalled and, in some cases, even exceeded the market capitalization of oil majors.[9] The share price of British Petroleum jumped by 7% when its CEO announced in August 2020 that it would shift to renewables while reducing oil and gas production by 40% in the coming decade.

This long-overdue growth of renewable technologies certainly deserves to be celebrated. However, the concept of unconstrained exponential growth needs to be examined more closely. It is most often observed in the digital domain because scaling up is relatively easy. Consumer electronics can similarly expand market share rapidly (e.g., from the introduction of the smartphone in 2007 to over 1 billion users 5 years later). However, Kramer and Haigh[10] argue that "unlike with consumer goods (…) there are robust empirical 'laws' that limit the build rate of new and existing energy technologies" and that exponential growth will be constrained once "material levels" are reached. Kramer and Haigh define material levels as the point when a new technology, such as PV, starts supplying ~1% of the world's energy demand.

Constraints on the exponential expansion of renewable energy technologies stem from the basic fact that the technologies that make up the energy transition are based on physical stuff: raw materials and intermediate products, associated

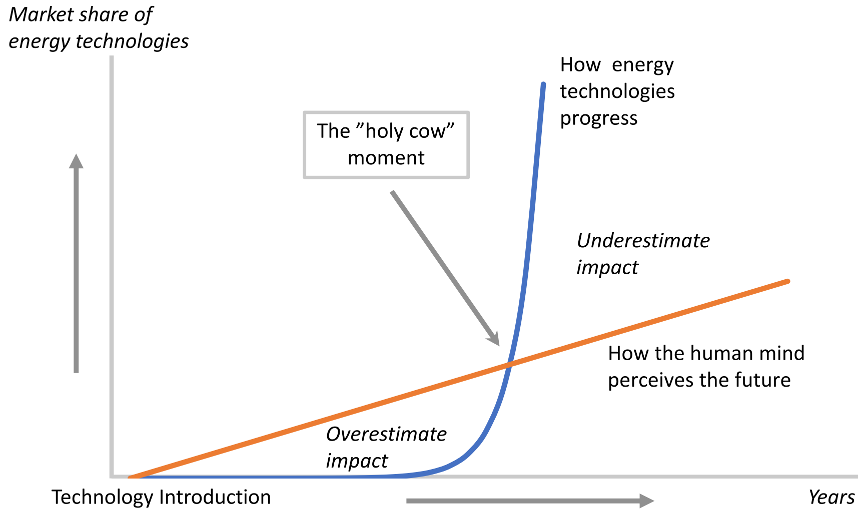

Figure 1. The holy-cow moment
Adapted with permission from Baldwin.[1]

process chemicals, the entire associated supply chains, and last but not least, infrastructure such as the (smart) power grid and hydrogen pipelines. All of these have their own dynamics. Building a new mine will take anywhere between 5 and 15 years. The time frame for upgrading an existing national electricity grid to the capacity, international connectivity, and "smartness" required for accommodating high levels of renewable energy is measured in decades.[10]

These differences in speed with which systems can change will lead to their own holy-cow moments: those of unexpected constraints and disruptions. Broadly speaking, disruptions can be classified as being on either the supply or demand side of the supply chain and can be fast or slow acting.[2] A fast supply disruption could be a natural disaster or a suddenly erupting civil war. Travel restrictions imposed by the coronavirus disease 2019 (COVID-19) pandemic caused a fast disruption to the demand for oil of such a magnitude that for a brief moment, the price of West Texas crude oil plummeted to −\$40. Examples of slow disruptions are gradually reducing ore grades (supply) or increasing urbanization (associated with much higher per capita material demands).

The National Research Council defines critical materials as materials for which the supply is prone to relatively fast disruptions *and* materials that are of high importance such that a disruption would have a debilitating ripple effect on the wider economy.[11] These critical materials have long been a topic of scientific study,[12] leading to hundreds of publications in scientific journals, as well as dozens of consultancy and policy-related reports, detailing potentially disruptive effects for countries across the globe. Beyond the economic effects of supply-chain disruptions, the environmental and social impacts of producing these materials should be considered. Although the production of critical materials is not necessarily more damaging than other activities of the extractive industry, the mining footprint of renewables has received significant attention in the media because of the inherent tension between protecting the environment through sustainable technologies and the damage done to the environment through the mining of critical metals needed for those technologies. Fossil-fuel-powered technologies rely on the extractive industry for their fuel and are vastly more damaging than renewables in the long run. But renewables do generally have a higher metal intensity than fossil fuels, increasing their exposure to issues of criticality.

The holy-cow moment for renewables

Crises tend to amplify existing trends. The COVID-19 crisis is no exception, and for example, the EU stimulus funds have allocated significant budgets to stimulate the energy transition. Reuters reports that 30% of the recovery fund is earmarked for climate protection, as well as the stipulation that "all spending must contribute to EU emissions-cutting goals. This could see nearly 550 billion euros spent on climate over 2021–27."[13] Individual member states have gone even further; for example, Finland has allocated two-thirds of its stimulus funds to supporting climate initiatives.[14] But these plans to stimulate the energy transition beyond the already rapid pace of expansion don't account for material constraints.

The scientific literature up until now has mostly explored the metal demands of the energy transition. Minor metals such as rare-earth metals, used in wind turbines and EVs, have long been a fixture of these discussions. More recently, the scale of the energy transition has started to put a strain on the supply of base metals, such as nickel (used in batteries) and copper (more generally used in everything electric). However, this laser focus on a limited group of elements might have left some significant blind spots in our understanding of material constraints on the growth of renewable energy. As an example of how unexpected these material constraints can be, recent news reports indicate that automobile factories worldwide have temporarily shuttered because of a lack of computer chips and integrated circuits (although fossil-driven vehicles are affected, EVs by their nature contain many more electronics and thus are more susceptible to constraints of these types). Wind-turbine supply chains are constrained by the supply of balsa wood (used by some manufacturers as the core material of turbine blades), the unmanaged increased production of which reportedly led to massive destruction of fragile ecosystems.[15] In 2018, the very industry that is supposed to supply the economy with raw materials, the mining industry, was constrained by a shortage of specialized large tires, the production of which was unable to expand as a result of shortages of a raw material, rubber.[16]

The specter of raw-material shortages has not gone unnoticed by politics, nor has the fact that some steps in the supply chains of critical raw materials are concentrated in very few countries. On September 29, 2020, the European Commission launched the European Raw Materials Alliance with the stated goal to

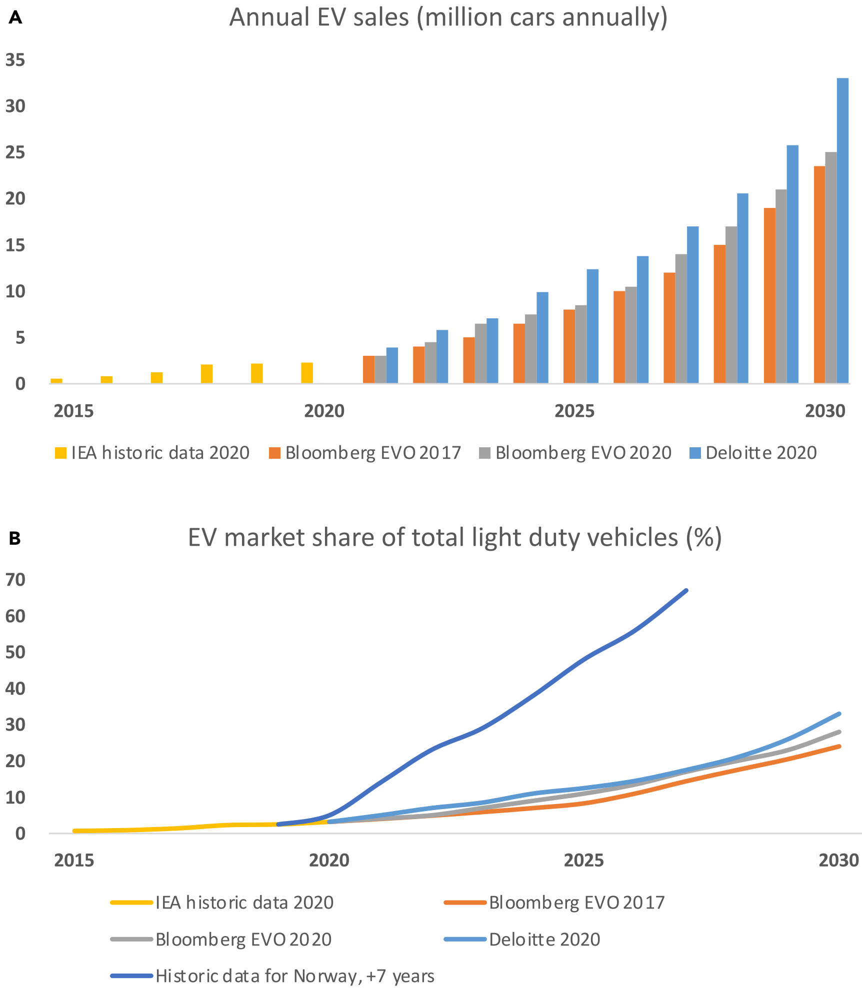

Figure 2. The exponentially growing demand for EVs
(A) Exponential growth curve of EV sales.
(B) Market share of EVs; the historical data of Norway are transposed on global EV market share to illustrate that countries can switch very rapidly to EVs if the circumstances are right.

"build resilience and strategic autonomy for Europe," starting with rare-earth metals and battery materials.[17] Just 1 day later, on September 30, 2020, former US President Donald Trump signed an executive order that declared a national emergency because the "nation's undue reliance on critical minerals, in processed or unprocessed form, from foreign adversaries constitutes an unusual and extraordinary threat, which has its source in substantial part outside the United States, to the national security, foreign policy, and economy of the United States."[18]

This grim future of cascading constraints and disruptions, combined with escalating rhetoric in the name of national security, need not be inevitable. We have identified three ways in which the scientific community can contribute to avoiding such outcomes.

First, more research should focus on how to grow the installed capacity of renewable energy technologies with a much lower material intensity than has historically been the case. Examples are eliminating the use of the cobalt in lithium-ion batteries or moving to completely different battery chemistries, such as graphene; reducing the use of platinum-group metals in polymer electrolyte membrane fuel cells to levels equivalent to those in catalysts currently used in cars with internal combustion engines; or replacing Balsa wood with alternatives with reduced ecosystem impacts.

Second, even with reduced material intensity, we must accept that during the energy transition, society will need to invest new materials into the system. A circular economy is key to ensuring that after the exponential growth phase, the demands for primary materials will go down to sustainable levels. In order to achieve high levels of recycling, the design of solar cells, wind turbines, batteries, fuel cells, and electromotors should facilitate reuse and recycling. The necessary recycling technologies should be developed in parallel with the design for recycling of products.

Third, during the time of buildup of material stocks in the new energy infrastructure, we will have to accept that mining will increase. The scientific community should not limit itself to projecting future material demands but get into the nitty gritty of helping the extractive industry to become more sustainable. Mining can have devastating social and environmental impacts, but as is shown in many new mining projects in developed countries, this is not a given. High-tech mining, including robotization, can significantly reduce the risks for miners but at the same time limit job opportunities. Certification, due-diligence schemes, and regulations promise to prevent the most damaging types of mineral extraction. But implementing these measures could also destroy the livelihoods of tens of millions of artisanal and small-scale miners. Proponents of deep-sea mining claim to be able to significantly reduce the impacts per kilogram of mined material, although it might also destroy ocean ecosystems. All these developments in the mining industry need to be assessed with scientific scrutiny if we are to determine potential social and environmental trade-offs.

Exponential growth of the renewable energy sector is necessary to stave off the worst impacts from climate change. But let us not lose track of the materials underpinning the energy transition. Responsible sourcing of new materials and responsible stewardship of materials once they enter the economy are a necessity if we are to manage the environmental and social side effects of the energy transition.

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