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A Call to Action for Recycling and Waste Management Across the Alternative Energy Supply Chain

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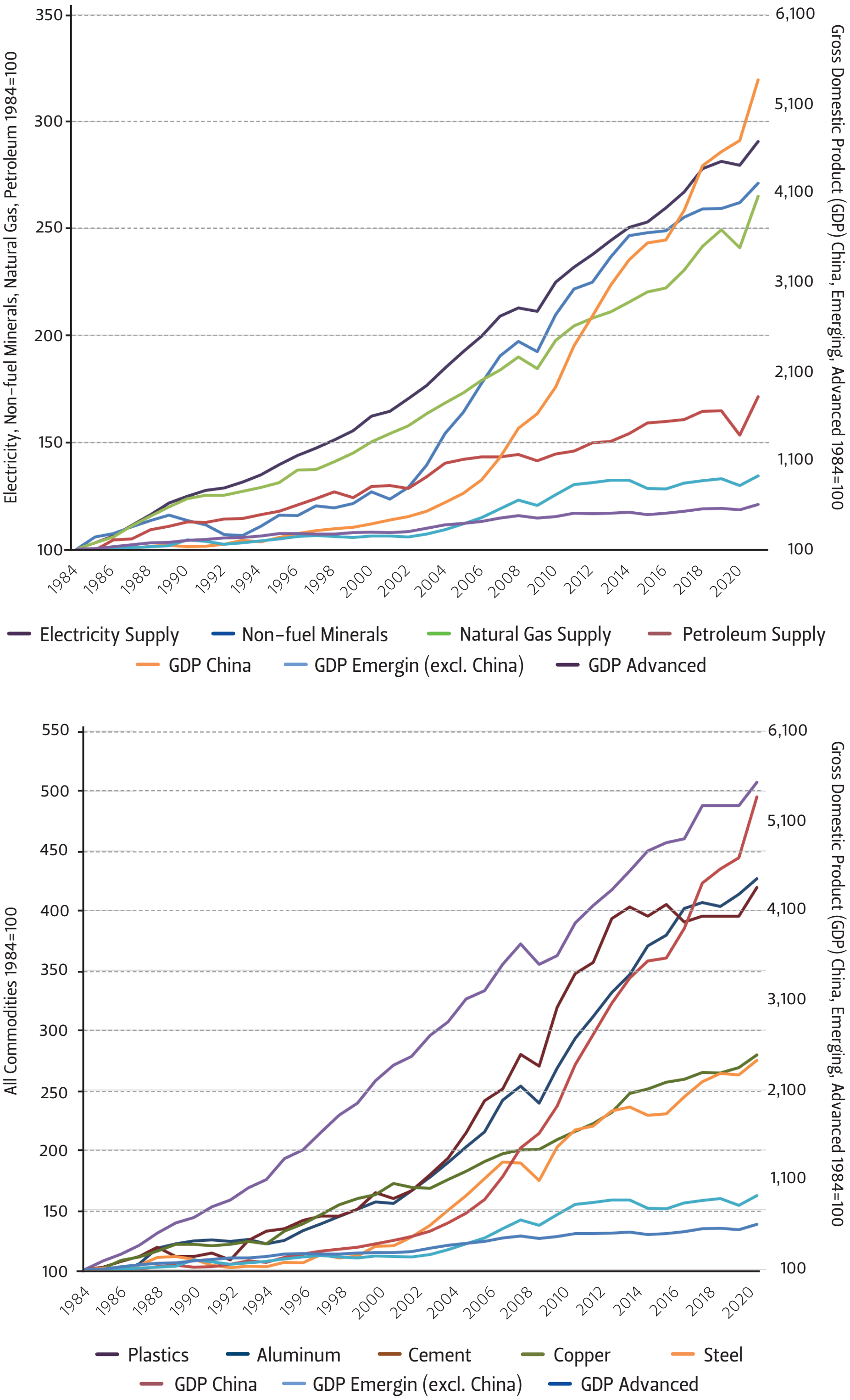
Investments in alternative energy technologies have surged worldwide. Public support has been prompted not only by energy and environmental concerns, but also by the promise of economic development and job creation. In fact, many countries have developed post-pandemic recovery strategies that include the installation of wind turbines, solar photovoltaic panels, and lithium-ion batteries (LIB) for electric vehicles (EV) and energy storage systems (ESS). However, the waste these technologies produce throughout their life cycles—particularly at the end of life—is largely unquantified.[1] The environmental and social impact of mining and waste disposal falls disproportionally on developing economies with already fragile ecologies and societies, while the manufacturing and processing of materials and devices is geographically concentrated in East Asia, particularly China. This results in a global supply chain that is neither equitable nor resilient. The lack of transparency regarding manufacturing and recycling within developed countries, in addition to the glut of information and misinformation surrounding alternative energy supply chains, create a dangerous mix of idealism and inaction. Without prioritizing material demands,[2] preparing for large projected waste quantities, designing a circular system for new materials and technologies, and planning for the safe and responsible disposal or recycling of alternative energy innovations, we risk altering the true sustainability profile of these technologies and being overburdened by novel waste streams in the near future.

Already, economic growth and existing needs around the world have accelerated the demand for energy and materials with commensurate implications for supply chains and geopolitical risks, along with unintended—and even unexpected—environmental and social impacts.[3] As we show in Figure 1, growth in non-fuel minerals production has exceeded that of crude oil and natural gas, and growth in plastics has exceeded that of major metals (for which plastics can be a substitute). Much of this growth can be explained by China's rapid entry into the mix of industrialized countries. The growth in China's manufacturing sector, which far exceeds both advanced and other emerging market nations, has had an outsized effect across the board.

The lack of transparency regarding manufacturing and recycling within developed countries, in addition to the glut of information and misinformation surrounding alternative energy supply chains, create a dangerous mix of idealism and inaction.

FIGURE 1 — GROWTH IN ENERGY AND MATERIALS WITH MEASURES OF GDP



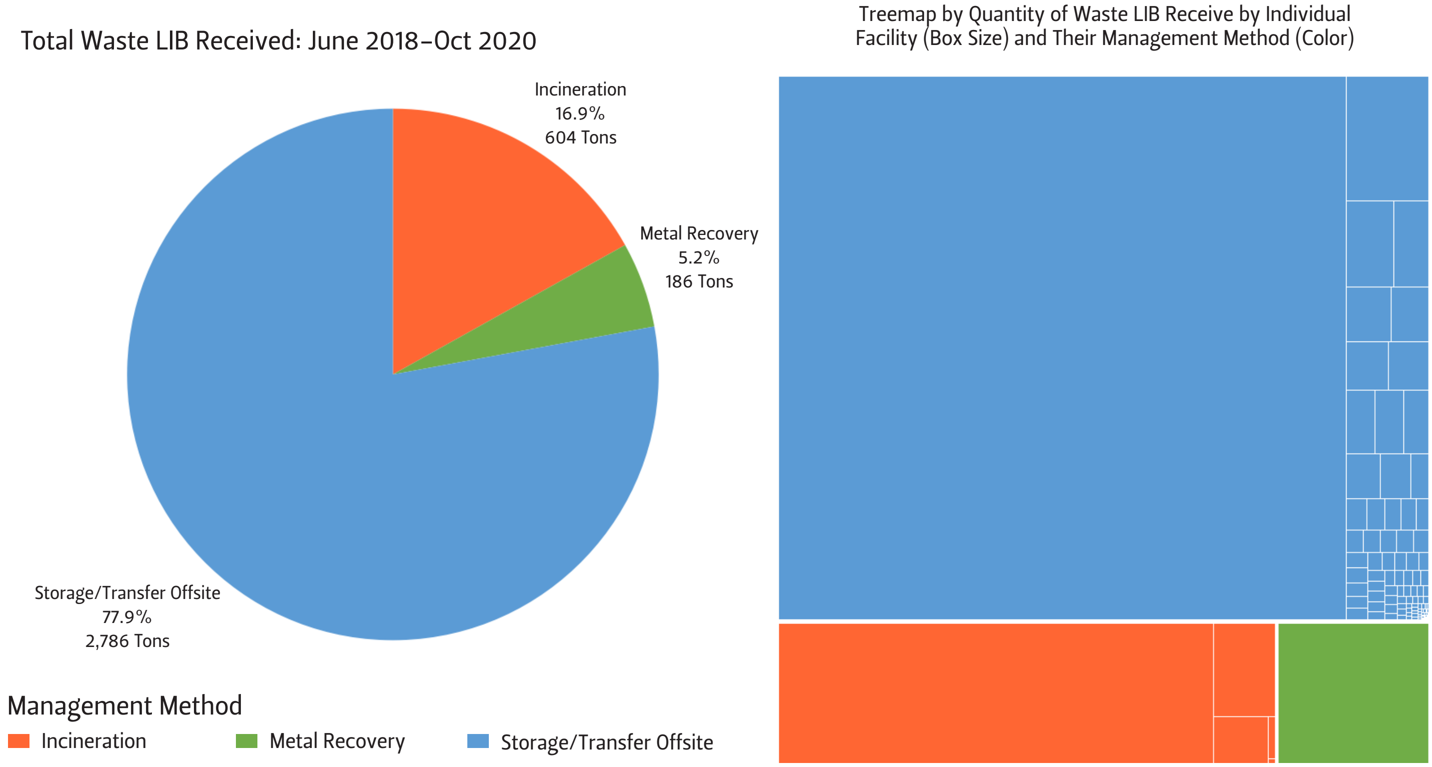
SOURCE Prepared by the authors using data from the International Monetary Fund, BP's Annual Statistical Review of Energy, the International Energy Agency, the American Chemistry Council, International Aluminum, the U.S. Geological Survey, the International Copper Study Group, and the World Steel Association.

Many opinions are that the goal of the Intergovernmental Panel on Climate Change to halve global CO_2 emissions[4] by 2040–2050 will require about 10 terawatts of power from wind, solar, and nuclear and many terawatt-hours of energy storage from LIBs.[5] Such an effort would constitute a civilization-scale endeavor that must be done with a great level of foresight and cooperative planning. In its recent report, *Minerals for Climate Action*, the World Bank indicates that a low-carbon future will be *more* minerals-intensive because "clean" energy technologies require more materials than fossil fuel-based electricity generation technologies.[6] The World Bank's viewpoint is largely confirmed in an International Energy Agency report on critical minerals.[7] In principle, depending upon scenarios and assumptions, there is enough lithium, copper, and other non-alternative mineral resources on Earth to scale up the LIB industry by a factor of 30 by 2040. This effort would require a 30% annual growth rate in mining and manufacturing year over year for two decades (excluding replacement), in addition to huge associated ecological and societal disruptions. Importantly, these results ignore fast growing demand for the same minerals for other applications.[8,9] Moreover, the lack of extraction and processing capacity in the United States relative to required inputs increases our reliance on foreign suppliers and ushers in geopolitical, national security, sustainability, and trade risks.[10] The data about overseas mining, refining, production, waste storage, and processing are complex and obscure, making it extremely difficult to quantify waste generation and management at present.

THE BALANCE OF WASTE GENERATION AND RECYCLING CAPABILITIES OF ALTERNATIVE ENERGY TECHNOLOGIES

Critically, the wastes from end-of-life solar panels,[11] wind turbines,[12] electronic wastes (e-wastes),[13] and LIBs from ESS and EVs[14] need to be collected, treated, and appropriately managed. For example, LIB

FIGURE 2 — EXAMPLE OF LIB WASTE SHIPPING AND MANAGEMENT METHODS IN THE UNITED STATES (JUNE 2018–OCTOBER 2020)



SOURCE Prepared by the authors with Elsie Hung and Mathilde Saada using data from the EPA's RCRAInfo database.

waste and e-wastes (which often include LIBs) contain persistent toxic organics and heavy metals that, if not responsibly managed, could leach into and contaminate the soil and groundwater. LIBs also contain valuable metals and minerals that could be reintegrated into the supply chain for a second life if remanufactured or recycled. Although precise figures are difficult to obtain due to lack of data transparency, estimates suggest that currently only about 5% of LIBs are recycled globally.[15] Without investments in state-of-the-art recycling technologies, economic incentives, and appropriate regulations/deregulations, scaling up alternative energies or ESS could come at a cost to society and the environment, crippling the trajectory of global sustainability goals and world climate targets. The lack of attention and investment will also increase our reliance on foreign entities for both the recycling and waste management of alternative energy waste, especially as technologies are scaled, internal markets evolve, and regulations are developed in the United States and elsewhere. Tremendous efforts in advanced and alternative materials and chemical engineering, policy development, and systems-level, life-cycle, and supply chain management are needed in order to fully "close the loop" with alternative energy waste.

In the case of LIBs in the United States, data taken from the Environmental Protection Agency's (EPA) RCRAInfo database from June 2018 to October 2020 show that 5.2% of waste classified as LIBs was managed through metals recovery, 16.9% was incinerated, and the majority was sent for off-site storage and bulking, awaiting transfer to another treatment, storage, or disposal facility. Although the 77.9% residing in storage and transfer will eventually be transported for final end-of-life management, tracking the actual numbers and final treatment methods is difficult due to the number of times the waste is transferred, the myriad transporters, the remanifesting of shipping documents, the consolidation of truckloads,

TABLE 1 — ALTERNATIVE ENERGY WASTES AND ASSOCIATED TECHNOLOGIES AND MATERIALS

Earth (population 7.6 B)	Tons/year (Global)
CO2 emissions (2019)	36,000,000,000[16]
Concrete production (2019)	4.4 billion metric tons[17]
Scrap metal recycling (2020)	895,800,000[18]
Steel recycling rate in U.S.	~70%[19]
Plastics recycled (2014)	7,700,000[20]
Plastic recycling rate	9–19.5%[21]
E-waste generation (2019)	53.6 million tons[22]
E-waste recycling (2019)	~9,300,000[23]
E-waste recycling rate (2019)	17.4%[24]
Solar PV waste (2050)	~78 million tons[25]
Wind turbine blade waste (2050)	~ 43 million tons[26]
Li-ion battery waste (2025)	~705,000 tons[27]
Li-ion battery production (2025)	509,000 tons[28]
Civilian nuclear energy waste (2020)	~8,000[29]

and waste reclassification. As the treemap in Figure 2 indicates, there are a limited number of facilities for metals recovery for LIBs in the United States. This makes the logistics of recovering LIBs challenging and can offset the economic and environmental gains (via transport emissions).

Historically, humanity has dealt with primary energy challenges through innovative and adaptive solutions as different technologies were scaled. This frequently resulted in phaseouts of some forms of energy (e.g., wood) through much of the world. Public acceptance and associated health and safety concerns often limit mitigation solutions even as they impact primary energy technologies. For example, although nuclear energy is a low-cost, zero-emission and highly efficient energy source, it produces high-level radioactive wastes that are small in volume, especially with reprocessing. Both reprocessing to capture the remaining useful fuel and reducing volumes of high-level waste for end-of-life management are constrained by societal factors. We have yet to see how far public acceptance of alternative energy technologies will go. With rapid expansion, such technologies will require the mining and extraction of enormous inputs of raw materials, necessitate commitments of huge natural endowments (water, coastal zones, and land competition that could intensify ecosystem resilience, biodiversity loss, and emissions from indirect land-use change) and generate large and often new volumes of waste and more emissions. Every energy technology and its associated infrastructure poses life-cycle management hurdles as technologies are pushed to larger scales. A sustainable transition requires ample data, planning, coordination, and an intimate understanding of the intricacies of the waste management and recycling systems. Clearer estimates of projected waste volumes are needed for strategic planning and for building the capacity and technologies to be able to manage the influx of alternative energy technology waste streams in the coming years, especially as such technologies reach the end of life and are decommissioned.

Table 1 contrasts the estimated annual tonnage of various end-of-life alternative energy wastes and associated technologies and materials with fossil energy waste and nuclear waste generated per year globally.[30] In terms of general-purpose recycling technologies today, bulk metals recycling of all materials in appliances, including ferrous metals, is quite mature and successful (~60% recycled[31]), but plastics recycling has consistently underperformed (9% in the U.S.;[32] 14–18% globally[33]). This is likely due to underdeveloped markets in the United States and elsewhere (primarily Asia and Europe) that create business models centered on exporting plastic waste to countries that lack the capability and capacity to responsibly manage all the chemistries of polymers. This has resulted in alarming environmental impacts—many of which are still being identified and quantified—on both land and ocean ecosystems.[34,35] Low plastic recycling rates can be attributed to technical challenges and contamination of recyclable polymers; the customization of particular applications that inhibit collection, separation, and reuse; the quality and complexity of plastics that are made of multiple polymers and additives; insufficient investment in collection infrastructure; and low municipal solid waste management budgets that fail to cover operating costs.[36]

Although data is scarce, and definitions, classifications, and regulations vary across states and nations, the e-waste recycling rate is estimated to be 17.4%.[37] Given the global lack of consensus on the legal definition of e-waste and an absence of national waste management policies for various types of alternative energy wastes in the United States, solar panels, components of EVs and wind turbines, and LIBs technically could be classified as e-waste or even hazardous waste, universal waste,[38] or non-hazardous, depending on state laws. This conglomeration of waste categories obfuscates tracking, treatment, and final disposal. E-wastes and LIBs are also notorious for their rapid technology development, deployment, and obsolescence; high consumption rate and short life cycles; complex transportation networks and logistics; and multiplex chemistries and composite materials—all of which contribute to underdeveloped regulations, recycling, and treatment markets that cannot keep pace with technology development and deployment. LIB research has predominately focused on lowering price, improving energy density and charging rates, and bolstering battery longevity as opposed to designing for reuse or recycling. Depending on the LIB chemistry and the recycling process employed, most LIB recycling is incomplete, generally non-profitable, accompanied by other toxic effluents, and centered on the recovery of higher value cobalt and nickel. Lithium is not always recovered.

While the steel structures, gearboxes, and generator magnets of wind turbines have more logical pathways to reuse and recycling, the glass/carbon fibers and thermoset polymer (plastics) blades are difficult to recycle due to their composite material and size, as well as complicated logistics. Recent attempts at recycling wind turbine blades and reengineering or replacing thermoset with thermoplastic polymers (which makes the composite more recyclable) are currently being field tested. Meanwhile, turbine blades now reaching their end of life (after about a 25-year lifespan) are routed to landfills.

As with many other alternative energy innovations, there is currently no scaled, efficient technology to recycle solar panels in the United States. Solar panels contain valuable materials such as silver, tin, lead, copper, aluminum, glass, and polymers (i.e., anti-reflective coating of ethylene vinyl acetate) that could be recycled and reintroduced into the market for a circular economy. However, the integrated nature of the panels and the cost-prohibitive process to collect and dismantle them results in direct landfill or, in some cases, incineration or export as waste or commodities to secondary markets where tracing and accountability are lost. Without changes in consumer attitudes and behavior around consumption, an understanding of systems-level thinking in upfront sourcing, design, manufacturing, and disposal, and accompanying investments and policy support for alternative energy waste management, it will be impossible to achieve the United Nations' Sustainable Development Goals or to meet any global climate targets. Further, technology diffusion takes time, and with "hard-tech" involving chemicals, materials, and processes that average 10+ years to be widely adopted, time is of the essence—we are just 18 years away from 2040.

Plastics are critical components to daily living and will be essential for the transition to alternative energy, as all alternative technologies rely on polymers.[39] Improvements and investments in automation, robotics, artificial intelligence, and advanced optical sorters can improve the recovery of polymers recycled through traditional mechanical recycling. However, mechanical recycling, the primary technology to manage PET, HDPE, and PE plastic (some of the most common types of plastic in use now), has fundamental limitations and cannot recycle the vast majority of mixed chemistry, low-quality, and low-density plastics. Advanced or chemical recycling can complement traditional methodologies to substantially increase recycling and recovery rates, but permitting and commercializing this industry will take years.

A sustainable transition requires ample data, planning, coordination, and an intimate understanding of the intricacies of the waste management and recycling systems.

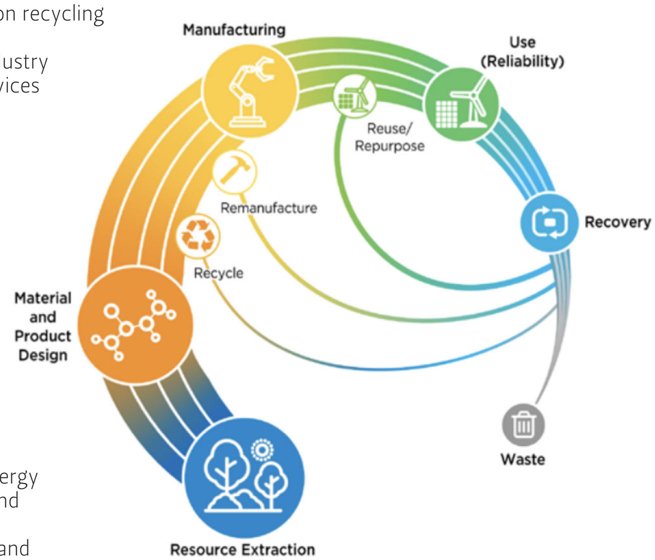
FIGURE 3 — CONSIDERATIONS FOR RECYCLING, REUSE, AND REPURPOSE (TOP) AND TYPICAL TIMELINE FOR PERMITTING NEW HAZARDOUS WASTE/RECYCLING FACILITIES (BOTTOM)

RECYCLING

- How will changes in consumer behavior, public perception of recycling, rapid technology development, and regulation impact the effectiveness and scaling of recycling?
- What regulations apply for each specific waste stream (e.g. LIBs are classified as hazardous waste in California but unregulated in other states; lack of national regulation for e-waste)?
- No harmonized regulatory definitions for recycling, especially for lithium and cobalt
- "Post-first-life" has a number of meanings: secondary use, reused, remanufactured, recycled, recover, etc.
- Complex transportation/logistics networks—wastes and materials have to be moved multiple times to reach material recovery/recycling facilities
- What are the supply chain logistics?
- How do damaged, defective, and recalled devices affect recycling, performance and safety?
- What are the permitting requirements and the associated timelines across jurisdictions (federal, state, local)?
- What personnel safety and industrial hygiene requirements?
- What is the value proposition for recovered materials?
- What is quality of products from recycled materials?
- Are there alternative business models for waste and recovered materials?
- What recycling technologies can be employed (i.e. most states do not recognize advanced recycling of plastics as a valid form of recycling)?
- Are the anticipated "waste" volumes sufficient to support and scale a recycling industry?
- Impact of extended producer responsibility laws on recycling industry
- M&As, bankruptcies are prevalent in recycling industry and leave stockpiles of cost-neutral/negative devices
- Transparency and access to information and data
- What is the role of export?

REUSE

- What are the costs of reuse to store end-of-life materials and to implement, comply with and enforce standards?
- What are the regulatory requirements: fire and building, electrical, industry certification standards, worker safety, industrial hygiene, hazardous materials storage, transportation, emergency response, hazardous waste export, etc.?
- What is the allocation of responsibility for the cost of repurposing, liability, and ownership?
- How are warranties affected by reuse?
- What are the anticipated volumes of end-of-life energy "waste"?
- Are the volumes sufficient to support and scale a reuse industry?
- What are the safety and integrity standards for reuse?
- How does reuse effect performance and safety?
- Transparency and access to information and data
- Old/obsolete equipment—lack of domestic markets for refurbished devices
- What is the role of export?



MATERIAL AND PRODUCT DESIGN

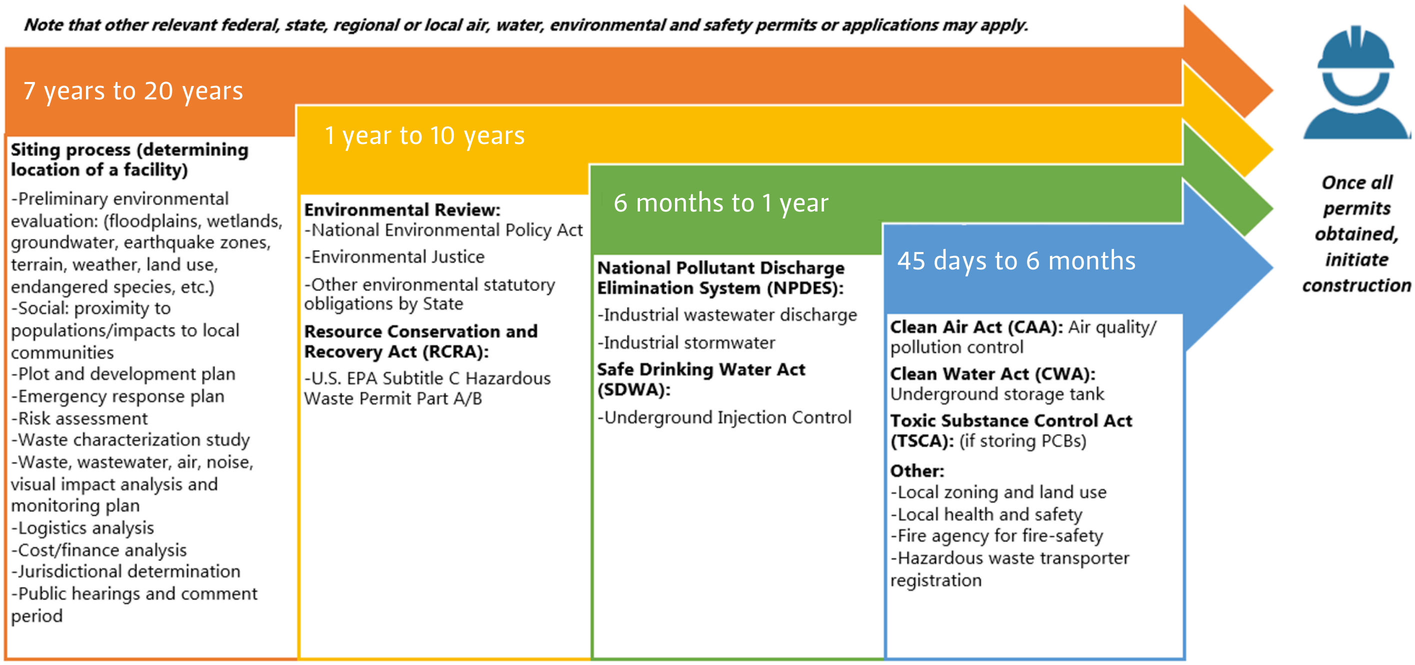
- Designing for recycling, reuse, repurpose or end-of-life disposal into various life cycle processes for a circular economy
- Lack of supply chain transparency, coordination and communication; dearth of data
- Disconnect in supply chain between upstream energy technology industries with waste management and recycling/recovery industries
- Current lack of incentive to reengineer materials and products for circularity

REPURPOSE

- What are the supply chain logistics and associated costs?
- How do extended producer responsibility policies impact repurposing?
- What are the personnel and industrial hygiene requirements?
- What is the allocation of responsibility for the cost of repurposing, liability, and ownership?
- How are warranties affected by reuse?
- How do repurposed materials effect performance and safety?
- What are the requirements for mitigating "hazmat" risks?
- What are the regulatory barriers, including how the definition of hazardous waste affects repurposing?
- How can the high costs and difficulties of compliance be improved, especially for new entrants and smaller companies?
- Old/obsolete equipment—lack of domestic markets for refurbished devices
- What is the role of export?

WASTE

- Regulatory and public acceptance challenges for certifying end-of-life waste facilities
- Promulgating waste management laws while advocating for circular economy frameworks
- Resolving conflicts between new policies that focus on end-of-life but are disconnected from supply chain realities (e.g. zero waste laws and lack of end-of-life technologies for wind, solar, ESS, LIBs)
- How does waste classification affect how materials are managed at end-of-life?
- What is the role of export?



SOURCES Rachel Meidl and Mathilde Saada using various federal and state agency sources.
NOTE In the U.S., depending upon state and location, it can take seven to 20 years before initiating construction (and up to 20+ years for completion) of a hazardous waste/recycling facility that is certified to treat, store, and dispose lithium batteries, solar, and other energy transition waste.

Advanced recycling, such as pyrolysis or depolymerization, occurs at the molecular level, where plastic polymers are broken down into their constituent monomers that can then be used as feedstock or raw materials for manufacturing new products of equal or greater quality.[40] Without investing in and scaling up advanced recycling and maintaining plastics at an economic value, the millions of metric tons of low-quality, mixed plastics currently on the market and entering the end of life will be managed either by landfill or incineration—if they are even collected in the first place. China's 2018 national ban on the import of many classes of foreign waste exposed the recycling industry's vulnerability and reliance on foreign nations, including many underdeveloped economies, for waste disposal. This further strained the recycling industry in the United States and other developed nations, and has acted as a catalyst to create and grow domestic markets.

AMOUNT OF EFFORT AND TIME TO FORGE TRULY "CLEAN" ENERGY SUPPLY CHAINS

The low-carbon, "zero-emission" technology and scientific advancements required to facilitate the energy transition—such as wind turbines, solar PVs, and LIBs for EVs and ESS—are pivotal. However, "zero-emission" often only applies to one stage of the value chain. For example, the generation of solar power does not include the global emissions from mineral extraction, refining, and processing in China; the long-distant transportation of materials and panels; the energy used to manufacture the panels; and the end-of-life environmental impact of panels being incinerated or landfilled.[40]

A true, "clean" energy transition will represent a massive transformation of our economy and society, but in the meantime, the key pillars of traditional energy systems will become even more important. Concrete/cement, steel, and plastics will be critical to the development of wind, solar, and other alternative energy infrastructure at scale, and the demands on

Clearer estimates of projected waste volumes are needed for strategic planning and for building the capacity and technologies to be able to manage the influx of alternative energy technology waste streams in the coming years, especially as such technologies reach the end of life and are decommissioned.

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these resources, as well as waste and supply chain impacts, need to be factored into any sustainability undertaking. Actions to ban or restrict the mining, extraction, production, and use of non-fuel minerals and fossil fuels will further constrain supply chains and introduce a range of potentially dangerous insecurities.[41]

The underlying issue that requires further analysis is the economic benefits of using particular fuels and technologies and whether they outweigh the costs (i.e., costs associated with waste management, recycling, life-cycle emissions, national security, geopolitical risk, social impacts, and so on). There is a learning curve associated with new energy sources and technologies and, coupled with a lack of awareness around the economics of hydrocarbons and other nonfuel minerals, this makes it easy to disregard the realities underpinning their supply and the huge variety of products derived from them—including those required to meet global climate goals, emissions reductions, and electrification.

Even if recycling operations were scaled for metals and polymer recovery, the materials recovered may not be able to sustain the quantities needed to meet the growing demand for many years,[42,43] due to a variety of factors including purity, safety considerations, performance, economics, and technology limitations. Scaling a robust recycling industry that captures the many types and varieties of materials, polymers, and technologies is a complex, extensive, and protracted process that can span many years and involve multiple agencies and jurisdictions. As an example, Figure 3 captures a portion of the policy, technical, and other challenges associated with recycling, reuse, and repurposing, as well as the vast array of permits and timelines for instituting a LIB recycling facility. Since LIBs are classified as regulated hazardous waste, recycling LIBs is considered "hazardous waste treatment" and is subject to the full Resource Conservation and Recovery Act (RCRA) Part A/B operating permits issued through the EPA.

Additionally, recycling is costly and can be an energy- and resource-intensive process that yields higher overall impacts across its life cycle compared to alternative methods. From a sustainability perspective, in regions of the world that lack the capability, capacity, technology, and resources for recycling, the preferred sustainable option (and perhaps the lowest-carbon option) may be energy recovery or managing waste in permitted and secure landfills. Again, because we are just 18 years away from 2040, perfectly "clean," ideal solutions may not be possible. Planning within this timeframe is essential, and painful trade-offs are sometimes necessary.

A CALL TO ACTION FOR DATA AND TRANSPARENCY

The world is moving ahead with the energy transition, and alternative energy and the technologies supporting them will continue to evolve and generate complex waste throughout their life cycles along the entire global supply chain. In the United States, state and federal hazardous and solid waste laws are not adapted to handle alternative and new energy systems. This is true across political jurisdictions in other countries. Additionally, there is a glaring blind spot in quantifying and understanding the true cost of the energy transition on sustainability. The dearth of data and lack of transparency make it difficult to capture the full extent of the evolving waste crisis, detract from the vision of sustainability, and leave societies, governments, and industries vulnerable and unprepared for the demands of burgeoning circular economy initiatives.[44]

There is a dire need to standardize data collection, data quality, reporting, and tracking across the global supply chain to provide clearer estimates of future alternative energy technologies nearing their end of life over the coming decades. This can help identify and quantify the variety of waste streams, along with their associated environmental and social impacts, to support the establishment of suitable regulatory and investment conditions for managing waste at the end of life. Data and transparency are necessary in order to strengthen domestic and global policies and to plan for future demand and appropriate management methods. An opportunity exists to enhance the economic, social, and environmental outcomes by developing transparent policies that utilize properly scoped life-cycle-based methodologies to capture and quantify the risks, uncertainties, and vulnerabilities of new technologies and to understand the trade-offs that exist, not just domestically but globally. This will allow various stakeholders to reprioritize resources, redirect investments, stimulate innovation in enterprises and value chain actors, assist decision-makers in promoting a sustainable circular economy, and understand how risks and costs can be lowered to drive investments. Integrating life-cycle dimensions into waste management and recycling policies can objectively inform decisions and accelerate the transition of innovations to higher levels of technology readiness, while securing long-term socioeconomic benefits such as materials recovery through recycling.

Policies that lack a life-cycle dimension, are not adapted to alternative energy systems, and fail to account for all factors within the three pillars of sustainability (social, environmental, and economic), will make the present situation challenging. On the technical front, substantial investments and progress in materials engineering, chemical engineering, mechatronics, software/data engineering, and advanced recycling technologies are needed within the next five years to better prepare for the incoming novel waste streams from alternative energy and EV industries.

Indeed, a focus on research and development (R&D) and the accelerated commercialization of advanced materials and processes could create disruptive technology "leapfrogs" with workable alternatives for materials sourcing and life-cycle management. For instance, the flash Joule heating process is being tested and applied for the conversion of plastic wastes to graphene, an important material for advanced applications.[45] Flash Joule heating is also being used to recover metals from waste.[46] These and other concepts and testbeds bolster the case for "urban mining" to reduce waste and recover valuable materials. This could be extended to the recovery of materials from "energy transition waste"—the huge influx of new waste anticipated from batteries, wind, solar, and many other sources. Certainly, accelerating commercialization and stepping up the capacity of materials recovery from waste will entail numerous complications ranging from investment funding to certifying new facilities (as mentioned previously). Thoughtful attention to emerging R&D and how best to facilitate commercialization within a "materials first" and circular economy/life-cycle framework could go a long way toward adding creative solutions into the mix sooner than later.

The alternatives to waste recovery entail a continued reliance on primary raw materials to meet demand. And even with waste recovery, demand for primary raw materials will remain a dominant feature of any long-term view and outlook. Much is being said about reinvigorating mining and minerals processing in the United States and other OECD countries.[47] Rebuilding domestic raw materials supply chains would have the advantage of greater transparency in oversight and stronger governance than exists in fragile states that are the main suppliers of strategic minerals. A distinct consideration, however, is whether existing policy and regulatory requirements, without being streamlined, will encumber new projects and expansions to such a degree that feasibility evaporates. Public opposition is notoriously negative, and many other weaknesses, especially workforce-related, make the proposition for mining and minerals processing in the United States and other countries, including in greater Europe, difficult, at best.

Even more is being said and written about "reshoring" manufacturing in the United States, Europe, and other OECD countries that have, by and large, steadily outsourced manufacturing to emerging markets.[48] These strategies are politically popular given that job creation is a distinct benefit central to political debates surrounding energy technology shifts. Efforts to reshore manufacturing face the

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same burdens of achieving public support, attaining workforce readiness, mobilizing investment, and facilitating policy and regulatory frameworks, along with the task of solidifying robust supply chains. As we emphasize in Figure 3, links between materials and product design are vital to achieve robust life-cycle management. At present, these are only nascent, at best. Industry and the R&D community are faced with redesigns of existing legacy products, as well as how best to achieve these links in new product designs.

Finally, any and all approaches will likely entail pressure for carbon tracking and accounting, which add additional costs and can complicate timelines, practices, and policy and regulatory frameworks. A number of creative approaches are emerging for collecting, assembling, vetting, and reporting the carbon emissions associated with various processes. These include the utilization of remote sensing and observation for monitoring, and blockchain and digital ledger innovations for data management to enhance transparency.

Clearly, we face a tall order in how best to manage our energy and materials future. Encouraging open dialogue about realities, developing transparent and effective markets, and promoting competitive R&D and commercialization could go a long way toward deploying state-of-the-art approaches and solutions—and building a common understanding of the challenges ahead.

ENDNOTES

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