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Global Transportation Decarbonization

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Abstract

A number of policy proposals call for replacing fossil fuels in the name of decarbonization, but these fuels will be difficult to replace due to their as-yet unrivaled bundle of attributes: abundance, ubiquity, energy density, transportability and cost. There is a growing commitment to electrification as the dominant decarbonization pathway for transportation. While deep electrification is promising for road vehicles in wealthy countries, it will face steep obstacles. In other sectors and in the developing world, it's not even in pole position. Global transportation decarbonization will require decoupling emissions from economic growth, and decoupling emissions from growth will require not only new technologies, but cooperation in governance. The menu of policy options is replete with tradeoffs, particularly as the primacy of energy security and reliability (over emissions abatement) has once again been demonstrated in Europe and elsewhere.

Keywords: climate policy, energy transition, transportation

JEL Classifications: P18, Q42, Q48

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The benefits of the transportation sector outweigh its environmental costs by orders of magnitude. For instance, transportation is a prerequisite to international trade, and despite generating roughly 2.4 gigatons of CO_2 emissions annually – just under 7 percent of total global emissions from fossil fuels and industry – through the geographic redistribution of goods, Shapiro (2016) estimates that gains from international trade outweigh emissions-related climate damages by a factor of 161-to-1. In addition, transportation facilitates the movement of people within and across urban areas, creating benefits for workers and firms, and generating distributional benefits for low-income and disadvantaged households by alleviating spatial mismatches between supply and demand in labor markets.

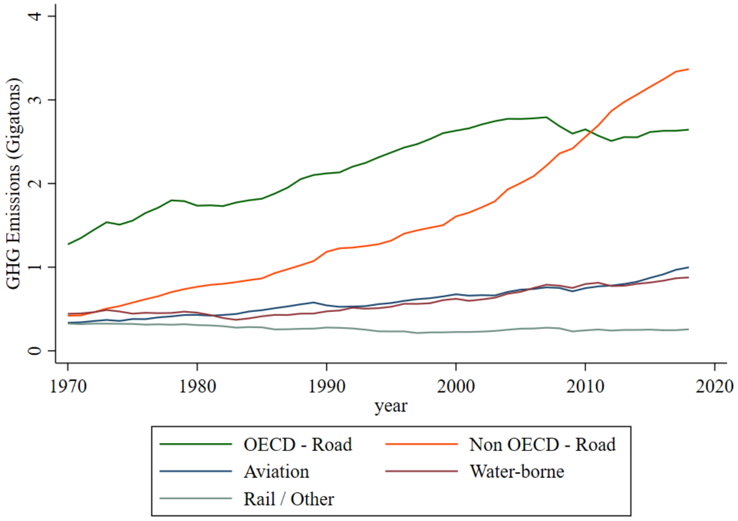
Such dramatic differentials in costs and benefits highlight the profound tradeoffs confronted by emissions abatement efforts in the transportation sector. Decarbonization must be implemented in a manner that supports the continued provision of low-cost transportation services, or risk eroding the foundation of the local and global economies.

At present, the vast majority of transportation services rely on fossil fuels as the primary source of propulsion energy. Nearly 100 million barrels per day of crude oil are processed primarily into gasoline, diesel and jet fuel for transportation. Emissions from transportation have increased at roughly 2 percent per annum for the past five decades and are closely linked to economic growth. Over a similar time-frame, transportation's share of total greenhouse gas emissions has risen from roughly 18 to 21 percent (based on author's calculations from European Commission (2023).) As noted by the Fifth Assessment of the Intergovernmental Panel on Climate Change, transportation emissions are likely to continue to increase by roughly 50 percent over the next 30 years in the absence of substantial carbon mitigation (Sims R. and Tiwari (2014)).

Four sectors account for over 97 percent of global greenhouse gas emissions from transportation: (1) on-road transportation in developed (OECD) countries (32.4 percent), (2) on-road transportation in developing (non-OECD) countries (41.4 percent), (3) maritime shipping (10.8 percent), and (4) air transportation (12.2 percent). Rail and other forms of transportation are comparatively negligible contributors to global emissions.

In figure 1, we plot the evolution of global greenhouse gas emission estimates from these subsectors from 1970 to 2018, based on European Commission (2023). For comparison, worldwide greenhouse gas emissions, across all sectors of the economy, were roughly 36 gigatons in 2018 (IEA (2022b)). Figure 1 suggests two themes that will recur throughout the essay: the centrality of road vehicles in the task of decarbonizing transportation and the ongoing rise in transportation emissions in developing countries. In 2018, on-road transportation accounted for roughly three-quarters of transportation emissions. The patterns of road emissions in the higher-income countries in the OECD peaked in 2008 and have maintained a slightly lower level and flat trajectory in recent years. For the first time in 50 years, road emissions in these higher-income countries appear to have become unlinked from economic growth. Total road emissions in other non-OECD countries, on the other hand, have overtaken OECD emissions and continue to grow. Likewise, emission from maritime shipping and air transport have risen consistently over the past five decades. Emissions from the maritime shipping and air trans-

Figure 1: Transportation Emissions by Sector



Source: Emissions Database for Global Atmospheric Research (European Commission (2023))

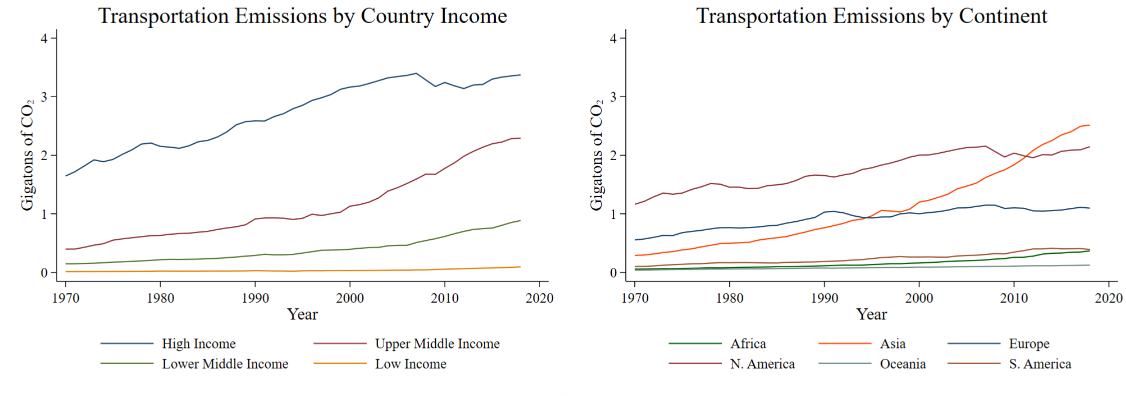
Note: This figure plots annual emissions greenhouse gas emissions (in gigatons) for five transportation sectors from 1970 to 2018.

port grew by 1.5 percent and 2.3 percent per annum between 1970 and 2018 and now account for roughly 23 percent of transportation greenhouse gas emissions.

The trajectories of emissions in OECD and non-OECD countries are consistent with the predictions of the environmental Kuznets Curve, a concept introduced by Grossman and Krueger (1991) and discussed in this journal by Dasgupta et al. (2002), which suggests that countries in the process of economic development see a sharp rise in environmental costs for a time, later followed by a leveling off and decline. The left panel of Figure 2 disaggregates emissions by GDP quartile. High-income country emissions mirror the OECD plateau described above. Upper- and lower-middle income countries are in high- and low-growth phases, respectively, while low-income countries exhibit low demand for transportation services. As economic development proceeds, demand for transportation services grows. This is particularly clear in upper-middle and lower-middle income countries in Asia, where emissions have risen ninefold since 1970 (a rate of roughly 4.7 percent per annum over half a century).

Asia, the most populous continent, has experienced rapid economic growth in recent decades and is now the largest contributor to transportation emissions (as seen in the right panel of Figure 2, that disaggregates emissions by geography). In coming decades, Africa will almost surely emerge as important contributor to transportation emissions growth. Since the 1980s, sub-Saharan Africa has experienced the fastest population growth of any region in the world. It is expected to add nearly one billion people by 2050, nearly doubling its population (United Nations Department of Economic and Social Affairs (2022)). While predictions of per-capita income growth in the decades ahead are inevitably uncertain (World Bank (2022)), aggregate demand for transportation services will nonetheless increase dramatically in coming decades

Figure 2: Transportation Emissions



(a) By Income

(b) By Continent

Source: Emissions Database for Global Atmospheric Research (European Commission (2023))

Note: This figure plots annual emissions greenhouse gas emissions (in gigatons) for five transportation sectors from 1970 to 2018.

due to population growth alone.

Per-capita income growth will contribute to the growth in emissions, as the demand for transportation is strongly correlated with per capita income. This can be seen most readily in historical patterns of vehicle ownership. The left panel of Figure 3 traces the path of vehicle ownership and per-capita GDP over time in the United States, Germany, Japan, and the United Kingdom. The trajectories for India and China over the same time appear in the bottom left of the figure. The expansion of vehicles is a substantial driver of the strongly positive relationship between per capita GDP and per capita carbon emissions from transportation, shown in the right-hand panel of Figure 3. If China and India (and other developing countries) follow the pattern of today's developed economies, they are on the early stages of a prolonged period of rapidly accelerating demand for transportation services. As the Intergovernmental Panel on Climate Change (2014) wrote:

> *"Without aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from the other energy end-use sectors and reach around 12 Gt CO2eq/yr by 2050. Transport demand per capita in developing and emerging economies is far lower than in Organisation for Economic Co-operation and Development (OECD) countries but is expected to increase at a much faster rate in the next decades due to rising incomes and development of infrastructure."* – Intergovernmental Panel on Climate Change, 5th Assessment Report, Chapter 8 (Transportation)[1]

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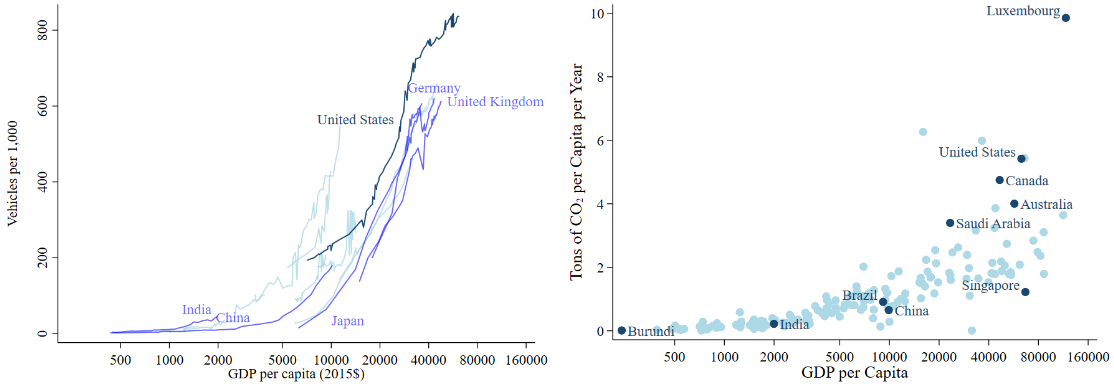
[1] Sims R. and Tiwari (2014)

Figure 3: Transportation Demand and Income



(a) Vehicle Ownership

(b) Transportation Emissions

Source: Vehicles per capita (Davis and Boundy (2022)); Transportation Emissions (European Commission (2023)); GDP per capita (World Bank (2023)).
Note: The left panel plots vehicles per capita against real GDP per capita for major economies over time. Country series begin in 1900 for the United States, 1960 for Canada, France, Germany, Japan and the United Kingdom, 1980 for China, and 1985 for Argentina, Brazil, India, Indonesia, Korea, Malaysia and Pakistan. The right hand panel plots emissions per capita against real GDP per capita in 2018, with major economies and outliers highlighted.

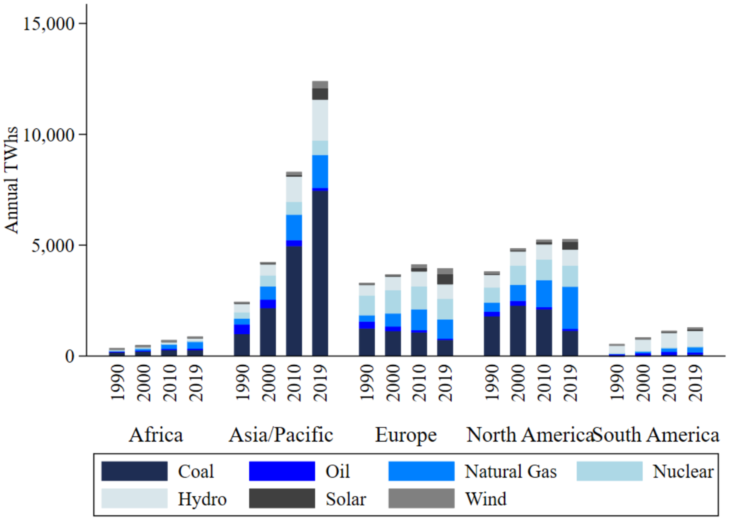
1 Electrification: Advantages and Limitations

Replacing fossil fuels is a fundamental step to reducing emissions in the transportation sector, but will be difficult due to fossil fuels' as-yet unrivaled bundle of attributes: abundance, ubiquity, energy density, transportability and cost. In the developed world, there is a growing commitment to electrification as the dominant pathway to a meaningful reductions in road transportation emissions. One of the appeals of the electrification vision is that much of the technology already exists at commercial scale, and costs have been declining steeply in recent years. The approach favored by policymakers in developed countries is to simultaneously shift towards greener sources of electricity generation while promoting adoption of electric vehicles in an attempt to reduce their cost. Although obstacles exist, there are reasons for optimism about this path.

Electric vehicles are getting cheaper. This is driven mainly by reductions in battery costs, which fell by 14 percent per annum from 2007 - 2014 (Nykvist and Nilsson (2015)) and have continued to decline since. Over the past decade, the speed at which battery costs declined exceeded even the most optimistic of earlier projections (as discussed in Knittel (2012)). Many expect electric vehicles to achieve price parity with gasoline powered vehicles within the next decade (National Academies of Sciences and Medicine (2021)). An expanding slate of electric light-duty vehicle models is being sold, targeting different price points and a broader set of consumer preferences.

The grid is getting cleaner. In Europe and North America over the past 20 years, the electric grid has shifted towards less carbon-intensive sources of power in both cases (Figure 4). In North America, natural gas has displaced coal as the dominant source of electricity and the grid has absorbed substantial growth of wind and solar power. On the margin, electric vehicles now generate unambiguously lower greenhouse gas externalities than gasoline-powered vehicles (Holland et al. (2020)) wherever coal is not the marginal source of electricity (so in most of the country). Renewable energy comprised over 20 percent of electricity generation in 2021, double its contribution from a decade earlier. In Europe, over the past two decades solar and wind generation has grown rapidly, replacing coal on a one-for-one basis.

Figure 4: Electricity Generation Mix over time, by region



Source: IEA (2022a)

Note: The bars reflect Terawatt hours of electricity generation by region and fuel source for 1990, 2000, 2010 and 2019. As a rough point of reference, one terawatt-hour of electricity is enough power to light over a million homes for one year or cool half a million homes for a year.

Governments are directing the full strength of their conviction behind electrification. The electric vehicle market share (of new sales) has grown to over 14 percent globally in 2022, driven by enthusiastic early-adopters, large government incentive programs and the aforementioned 90 percent decline in battery costs (IEA (2023)). Policymakers extrapolating early successes into the future appear to conclude that electric vehicles will render gasoline cars obsolete within two decades. As of this writing, the European Union, China, Japan, South Korea, several US states and many others have declared the intention to ban gasoline and diesel cars. The force and magnitude of these efforts are, in effect, choosing electrification as *the* winner of the decarbonization sweepstakes in rich countries.

However, it would be risky to extrapolate from recent trends what the world may look like in the future. There is no guarantee that the electric grid will remain reliable as we replace the most flexible sources of supply with intermittent renewables. There is no guarantee that batteries, which require enormous quantities of increasingly-scarce metals, will continue to enjoy steady cost declines. And there is no guarantee that the political will to support electrification will continue if cost and reliability concerns become reality.

At present, electrification is the most likely technology pathway for deep transportation decarbonization. Yet there are reason to be skeptical of the aspirations for a fully electric transportation future. This skepticism applies to both the rich and developing worlds. Rapson and Bushnell (Forthcoming) offers a discussion of the limitations of electric vehicles even in the rich world, where the electric grid is advanced and resources are relatively abundant. In what follows here, we take a global perspective to describe several obstacles for electrification to become the default transportation energy source for light-duty road transportation.

1.1 Electricity reliability in the developing world

The electrification vision faces particular challenges in the developing world, where fossil fuels dominate electricity generation. China is a revealing case study. It is on track to put more electric vehicles on the road this year than the rest of the world combined (Wakabayashi and Fu (2022)). However, the environmental benefits of this shift are more modest because China's investments in electricity generation capacity and grid infrastructure over the past several decades are dominated by coal (Qiao et al. (2019)). In Asia overall, new coal generation outstripped new "renewable" generation by a factor of *five* over 2000 - 2019 (Figure 4).[2]

Many developing countries also face the hurdle of improving electricity distribution infrastructure and grid reliability. Figure 5 plots country-level generation per capita (on the x-axis) and a proxy for the reliability of electricity (on the y-axis), the average response by country business leaders to the World Economic Forum Global Competitiveness Report survey question "In your country, how reliable is the electricity supply (lack of interruptions and lack of voltage fluctuations)? [1 = extremely unreliable; 7 = extremely reliable]." Electrification of transportation requires both sufficient generation capacity and a reliable grid. Wealthy nations score highly on electricity availability and reliability. But most developing countries have less reliable electricity as well as substantially lower levels of generation per capita. Distributed solar microgrids are unlikely to perfectly substitute for a centralized grid (Lee et al. (2016)). Moreover, the scale of incremental fixed investment required for widespread electrification might prove prohibitive for many developing countries and may first require addressing other market failures impeding electricity infrastructure investment, such as imperfect contract enforcement (Ryan (2020)), and insufficient regulated tariffs (Blimpo et al. (2018)). For a back-of-the-envelope estimate, 4000 miles per capita of annual travel requires roughly 1 megawatt-hour of electricity per capita, each year. Even with rapid development, Chinese generation per capita only rose 4.5 megawatt-hours per capita per annum over the past three decades. Moreover, while vehicle electrification is one possible electricity end use, transport would compete directly with other uses of additional electricity with high marginal value to households (for example, Dinkelman (2011)) and firms (for example, Allcott et al. (2016)), including lighting,

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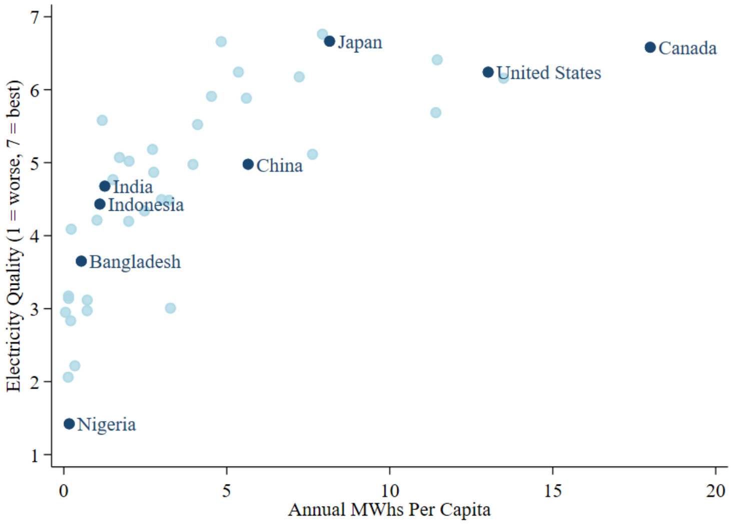
[2] Admittedly, much of this increase is the result of the expansion of China's electricity industry, roughly 60 percent of generation and 67 percent of coal generation in Asia occurred in China in 2020. But, coal generation also grew substantially in Asia outside of China, more than quadrupling from 1990 to 2020.

cooling, and powering industrial equipment.

Figure 5: Per Capita Generation and Electricity Reliability



Source: Electricity Reliability (World Bank (n.d.)); Electricity Generation (IEA (2022a)).

Note: This figure plots electricity quality and annual electricity generation capita by country in 2018. Electricity quality is measured a scale of 1 to 7 and reflects the average response by business leaders to the survey question to the World Economic Forum, Global Competitiveness Report "In your country, how reliable is the electricity supply (lack of interruptions and lack of voltage fluctuations)? [1 = extremely unreliable; 7 = extremely reliable]" Generation is measured in megawatt-hours per capita. Select countries are highlighted.

1.2 High costs of electrification

Even in rich countries, there are reasons to expect the marginal costs of electrification to rise, not fall, as the share of electric vehicles increases (Rapson and Bushnell (Forthcoming)). To date, demand for electric vehicles in the US has been concentrated among wealthy, highly-educated buyers who express concern about climate changes (Davis (2018), Archsmith et al. (2021)). These buyers tend to own multiple cars and live in single family homes in coastal states or the suburbs of large cities. To achieve full (or even deep) electrification, adoption of electric vehicles will need to extend into new consumer segments. Two of these include low- and middle-income households who are interested in adopting an electric vehicle, and rural Americans who tend to prefer light trucks to sedans and are less compelled to make decisions based on concerns about climate change.

A multitude of practical obstacles to electric vehicle adoption arise for these customer segments. Lower-income households tend to have smaller vehicle portfolios, and thus cannot easily hedge their transportation needs across different vehicle types. For these buyers, electric vehicles are a more expensive and potentially less reliable alternative to gasoline cars. Many of these potential buyers live in multi-unit buildings that tend not to offer on-site charging options. Rural consumers tend to prefer larger vehicles, which are currently not widely available in an electric drivetrain. While new models are already being introduced to meet some of these needs, it remains to be seen how popular they will be among this subpopulation. Finally, physical obstacles exist even beyond the well-known multi-unit dwelling issue. Rapson and Bushnell (Forthcoming) estimate that roughly 20 percent of US single family homes would require an electric system upgrade in order to accommodate a dedicated (level 2) charger.

Public costs of electric vehicle adoption are already high and are likely to increase. Despite progress, the carbon intensity of the electric grid remains a challenge, even in developed countries. Almost 60 percent of US electricity generated from coal (21 percent) and natural gas (36 percent) in 2022 (EIA (2023)). Substituting towards more solar and wind energy is inexpensive from an energy production perspective, but must be supported by transmission (long-haul) and distribution system ("last mile") infrastructure to transport energy to consumers. Such upgrades range from costly to potentially impossible. Brockway et al. (2022) estimate that distribution system upgrades in California will cost between $200 and $2,000 per household, depending on the ability of electric utilities to shift the timing and location of demand on the grid. Davis et al. (2023) paint an even more discouraging picture about the prospects for transmission investments, the amount of which needs to triple in order to integrate sufficient clean electricity to achieve net-zero goals by 2050 (Pascale et al. (2021)). Such investments encounter obstacles relating to permitting, the current process for which is distributed in a manner that gives property owners on the right-of-way a string of potential vetoes.

1.3 The battery supply chain

Demand for electric vehicle batteries doubled in 2021, and prices for key battery inputs rose by as much or more. The price of lithium (an ingredient to all electric vehicle battery chemistries in use today) was recently seven times greater than at its 2020 trough, though it has since fallen. Prices of both nickel and cobalt doubled over a similar timespan. A dramatic expansion of the battery supply chain will be necessary to meet demand under existing transportation electrification policies, with an even larger expansion required to meet stated future goals. IEA (2022c) estimates that global battery anode and cathode production will be required to expand by six to ten times present day volumes to meet 2030 demand under these scenarios.

Such a dramatic expansion of battery production requires unprecedented growth to occur at each link of a complicated battery supply chain. The supply chain has three main links, or levels. "Upstream", raw materials for production must be extracted. Precisely which battery minerals are needed depends on the battery chemistry, which is an endogenous choice made by automakers and battery manufacturers (we'll come back to this). In the "midstream" segment, raw minerals are processed and intermediate battery components (cathodes and anodes) are produced. Finally, battery cells are produced and linked in "packs" that can be used in electric vehicles, which is referred to as the "downstream" segment.

Expanding production in each of these links on the chain requires long lead times. According to IEA (2022c), developing new lithium and nickel extraction sites can take between 5-20 years; raw materials processing and cathode/anode production facilities requires 2-8 years; and battery production facilities between 1-5 years. In this section we assess the prospects for success, and describe a wide array of complexities and costs associated with the task ahead.

The Good. While the required supply chain expansion is enormous, there are reasons to be optimistic that we can make substantial progress in the next 10-20 years. Primary among these is evidence that governments and industry participants are already responding to economic incentives. When confronted with high nickel and cobalt prices, for example, China and Tesla have shifted towards alternate battery chemistries. Lithium-iron-phosphate batteries sacrifice some energy density relative to others, but eliminate the need for nickel, cobalt and magnesium entirely (though they do nothing to reduce demand for lithium). Half of Teslas produced in 2022 will use these batteries. China had already prioritized lithium-iron-phosphate batteries to take advantage of patent expirations, and because their focus on shorter-range cars in the domestic market makes these batteries more suitable. These decisions will relieve pressure on some of the upstream bottlenecks, at least in the short run. High mineral prices will also stimulate supply expansions. Policymakers and private firms alike are aware of the need to expand midstream and downstream capacity, and abundant capital is flowing towards these areas.

The Bad. Due to long lead times required to expand at any level of the supply chain, the status quo exhibits strong inertia. This is particularly concerning to Western countries who currently rely on China and Russia for key inputs. Russia dominates the market for battery grade nickel, and China dominates midstream and downstream activities across the board. IEA (2022c) reports that over half of global capacity for lithium ($\sim$ 60%), cobalt (65%) and graphite (70%) processing resides in China. China has an even larger share of cell component production (70-85%) and battery cell production (75%). Many have expressed concerns about relying on China for critical inputs in this time of geopolitical adversity.

How big a problem is this for the West? Our view is that it is less problematic than one might think. A strategic Chinese battery supply disruption would harm China economically and is unlikely to produce the jarring economic adjustments caused by a major OPEC supply disruption in global oil markets or the Russian suspension of natural gas exports to Europe. Still, the strategic, if not economic, benefits to diversifying and even onshoring some midstream and downstream capabilities are hard to predict and potentially substantial.

Relieving supply chain bottlenecks via reuse and recycling of batteries is, at present, unlikely to provide a solution. Few EV batteries are in circulation today relative to future demand, and the profit margins in recycling are typically not high. IEA (2022c) estimates that less than one percent of 2030 lithium and nickel demand will be met from recycling. Cobalt is only slightly better, at under two percent.

The Ugly. A shift to electric vehicles, at least to some degree, amounts to trading greenhouse gas reduction benefits for local environmental and social damages relating to the battery supply chain (Lee et al. (2020)). While the electric vehicle transition may nonetheless pass a global cost-benefit test in the long run, the (often) severe environmental and social costs to local communities supplying the minerals cannot be ignored. The most notorious instance is cobalt mining in the Democratic Republic of Congo. The Democratic Republic of Congo produces the majority of global cobalt supply, and has a reputation for using unsafe mining practices and child labor (Kara (2023)). In Chile, mining for lithium has disrupted local ecosystems due to the use of evaporation pools created by converting meadows and lagoons into salt flats, a process that has depleted groundwater across the Atacama Desert (Lee et al. (2020)). A promising source of abundant reserves of lithium, cobalt, magnesium and nickel exists at the bottom of the Pacific Ocean, and it is difficult to envision how it can be made accessible without destroying substantial (multiple square miles) of the ocean floor. Our ability to assign an accurate value to these non-market goods is poor, yet the moral, social and ecological stakes are high.

To summarize, producing enough electric vehicle batteries to meet demand through 2030 is possible, but will be costly and requires careful planning and patience. Supply chain constraints may directly influence the cost and desirability of electric vehicles. For example, earlier we lauded Tesla's decision to use lithium-iron-phosphate batteries as a way to relax contemporary upstream constraints; but it does so at the cost of electric vehicle range. Average battery size increased by 60 percent between 2015 and 2021 (IEA (2022c)). While many electric vehicle drivers likely don't need a 300-mile range battery, one of the main industry and policy goals in recent years has been to overcome range anxiety, which is seen as an obstacle to widespread adoption, particularly for high-use drivers or drivers living in cold areas where range declines.

Innovation may help, but likely only in the medium- and long-run. IEA (2022c) mentions two promising technologies in the upstream segment. Direct lithium extraction bypasses the need to evaporate unconcentrated brine. If successful, this will drive down costs and lead-times for capacity expansion, as well as dramatically reducing local environmental damages. It is being piloted today. Reliance on Russian battery grade (class 1) nickel could be reduced by producing class 1 nickel from class 2 nickel, for which Australia is the world's largest supplier. However, it this process is twice as capital intensive, takes longer, and is three times as carbon-intensive as present class 1 nickel mining methods. Early-stage deployments have encountered cost overruns and project delays.

It is quite possible that you, our reader, may read some of these "under-appreciated challenges" and wonder in what world these aren't obvious. But for each of those such readers, we suspect there is another kind who views emphasizing these challenges as unnecessary dithering about minor details that ought to be subservient to saving the planet. To this we can only emphasize that our view arises from acknowledging that tradeoffs exist. If renewable electricity and electric vehicles were superior to fossil fuels and the internal combustion engine in every dimension, there would be little need to write this paper. Our goal is to highlight costs of electrification that we view as non-trivial and worthy of consideration by climate and energy policymakers as they weigh the costs and benefits of various paths forward.

2 What alternatives exist to decarbonize other sectors?

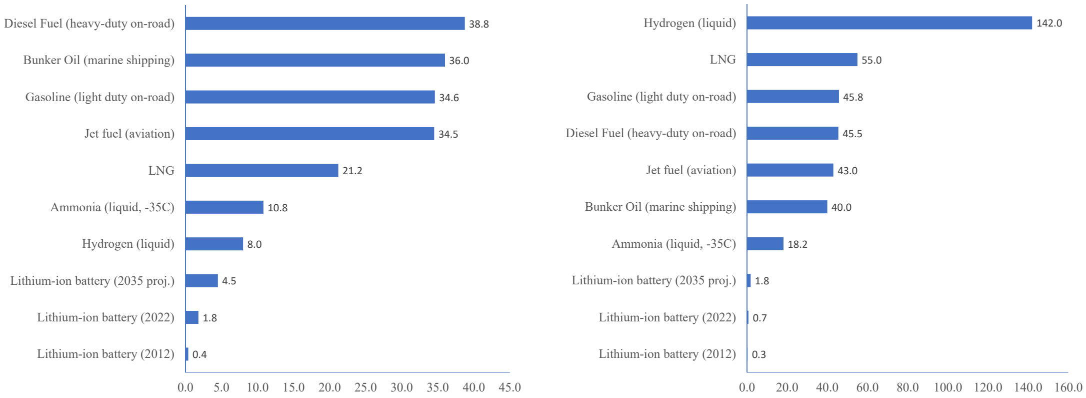
Electrification is unlikely to be a viable technology pathway for transportation segments that require very large amounts of energy and/or have extreme energy density requirements. The primary alternatives to electrification are "renewable" transportation fuels. These include: biofuels, chemically-similar substitutes for petroleum-based transportation fuels (gasoline and diesel) produced from biomass; hydrogen, that can be combined with oxygen in a fuel cell to produce energy and water vapor; and other alternatives, such as liquified natural gas or ammonia. Although these fuels take different forms, they share three potential advantages that would bypass the expansion that would otherwise be needed for the electric grid in developing countries, and offer a viable long-run alternative for maritime trade and air travel.

First, renewable transportation fuels can be (and are) transported over long distances. They potentially provide a trade-based decarbonization pathway for developing countries, rather than electrification that requires local generation and distribution infrastructure, and faced the hurdles and road-blocks already described.

Second, some (though not all) renewable transportation fuels can "drop into" existing fuel supply chains and engines, further reducing upfront investment or switching costs relative to electrification. Biofuels, which are refined to be interchangable with gasoline and diesel fuel, offer a particular advantage here. They are designed to be roughly equivalent, can be blended to different degrees with existing fuel depending on use, used in conventional engines, and transported, stored and distributed through similar infrastructure. US drivers are already familiar with ethanol, one of the most well-known biofuels, which in the United States is blended with gasoline and comprises between 10 and 15 percent of each gallon of "gasoline" purchased at the retail pump. Ethanol-blending, at these levels, offers similar performance to pure gasoline, but does lower the overall energy density, reducing fuel economy by about 3 percent per gallon of fuel. In the near term, sustainable aviation fuel offers a pathway for reducing carbon-intensity in aviation, as it is operationally-indistinguishable from jet fuel, offers similar energy density and does not require any additional investment or regulatory approval to be blended at a 1:1 ratio with jet fuel.

Finally, these fuels are more "energy dense" than electric batteries, storing more energy per unit of space (volumetric energy density) or in a given amount of weight (gravimetric energy density) and providing a pathway for sectors for which electrification is unlikely to offer a solution (at least over the timeframe of the next several decades). Whether evaluated on a volume basis or a weight basis (the left and right panels of Figure 6, respectively), petroleum based and alternative liquid fuels offer energy densities one and sometimes two orders of magnitude greater than current (and projected) lithium ion batteries. These constraints are particularly relevant for air transport where both space and weight for fuel are paramount considerations for any lower-carbon aviation fuel alternatives, but also relevant for ocean-borne freight that traverse long-distances without refueling. In both cases, electrification is unlikely to meet the industry needs in the near term. As one example, fully battery-reliant systems for commercial air travel are viewed as unlikely to develop beyond small private aircraft for the next few decades. Anticipated energy requirements for sustained, even short-distance commercial

Figure 6: Energy Density of Transportation Fuels



(a) Volumetric Density (MJ/liter)

(b) Gravimetric Density (MJ/kg)

Source: Allain et al. (2012); Schlachter (2012); National Academices of Sciences, Engineering, and Medicine (2016); Tran et al. (2018); Kargul et al. (2019); Holladay et al. (2020); Rodrigue (2020); Esau (2021); Statista (2021); US Department of Energy (2021, n.d.).

Notes: Values for volumetric and gravimetric density are collected from a range of sources and compiled by the authors.

flights would require battery with energy density greater than 6.5 megajoule per kilogram relative to projection of 1.8 megajoule per kilogram by 2035 (National Academies of Sciences and Medicine (2021)).

2.1 Drawbacks of alternative fuels

The potential for cost-effective carbon mitigation depends on the how the alternative fuel is produced. The carbon benefits and potential quantity of different biofuels depend largely on the biomass “feedstock” used and on the efficiency of the refining process (US Environmental Protection Agency (2023)). First-generation biofuels are produced from consumable “feedstock,” like corn, sugar cane, and oilseed crops. These feedstocks are the most straightforward to process and account for the majority of current biofuel production. Corn- and cane-based ethanol are both cost competitive with gasoline at roughly \$50-\$75 per barrel of oil; first-generation biodiesel is cost-competitive at \$80-\$120 per barrel (IEA (2022d)). Although cost have fallen over time, the cost of SAF remains two to three times more expensive than petroleum-based jet fuel (Congressional Research Service (2022)). The price premium associated with sustainable aviation fuel has limited its adoption amongst cost-conscious airlines – estimates place 2021 sustainable aviation fuel production at approximately 25 million gallons, relative to 13.7 *billion* gallons of jet fuel consumed by US airlines. The carbon benefits of biofuels and sustainable-avaiation fuel are undermined by the fuel and fertilizer used for cultivation of crops (Melillo et al. (2009)) and by indirect shifts in the use of land for cultivation (Keeney and Hertel (2009), Searchinger et al. (2008)). Although hydrogen is an alternative to electrification (and biofuels) and offers emission-free combustion, the carbon benefits and costs depend on the method by which hydrogen is produced. Presently, most hydrogen is produced by processing natural gas (Nikolaidis and Poullikkas (2017)), which is substantially lower cost than carbon-free "green" hydrogen, produced by separating water into hydrogen and oxygen using solar- or wind-based electrolysis. Similarly, ammonia as presently produced is both energy and carbon-intensive, accounting for roughly 2 percent of total worldwide energy consumption and generating roughly half a gigaton of carbon per year (IEA (2021)).

All of the alternative fuels have opportunity costs that are particularly salient to policymakers. Biofuel feedstocks are also part of the food supply chain, placing energy end uses in direct competition with food. At present, roughly 15 - 20 percent of cereal production is used for biofuels (IEA (2022f)). Roberts and Schlenker (2013) finds evidence that feedstock demand of commodities has a meaningful impact on commodity prices. Using roughly one-third of corn as ethanol feedstock (as in the United States) increases corn prices by roughly 20 percent. The estimated impact on crop prices are roughly comparable to those from Condon et al. (2015), which conducts a meta-analysis of estimates from the food-versus-fuel debate literature. The direct competition for consumable resources and the modest carbon reduction benefits of first-generation biofuels (Hill et al. (2006)) have motivate research into "second-generation" biofuels that rely on non-food feedstocks, which include used cooking oil, switchgrass, and plant cellulose, and even "third-generation" biofuels that rely on cultivated algae as feedstock. Second-generation biofuels offer potential for higher carbon savings when they are not directly cultivated or are waste by-products (Havlík et al. (2011)). Some of the these feedstocks offer the potential for development at scale on marginal cropland, avoiding direct competition with convention crops (Cai et al. (2011)). But with the exception of used cooking oil, these biofuels are not cost-competitive at current oil prices (Witcover and Williams (2020)). Similarly, "third-generation" biofuels are not cost competitive, impose substantial demands on water supplies, and have not yet reached commercial scale. Likewise, ammonia's use is as a fertilizer, and hydrogen (and natural gas) are key inputs into fertilizer production. In the future, demand for these products as transportation fuels may compete with traditional agricultural and industrial uses.

Finally, many technologies that cannot drop-in to existing supply chains or leverage existing combustion technology face a similar "chicken-and-egg" problem as vehicle electrification. As one example, widespread use of hydrogen would require a new transportation, storage and delivery network, development of which has been impeded by high costs on both sides of this two-sided market. At present, hydrogen cars and fueling infrastructure are not economically competitive. To date, 54 hydrogen stations are open nationwide, all but one of which are located in California where large subsidies are available (US Department of Energy (2023)).

2.2 Energy efficiency: Once more unto the breach

The absence of viable alternatives to liquid hydrocarbons for jet propulsion and maritime shipping highlights the value of getting more from less, where possible. So despite a checkered past when it comes to delivering energy savings[3], energy efficiency makes it once again onto a list of possible decarbonization pathways.

Emissions are a function of both the fuel used and the efficiency with which that fuel is transformed into usable power. Although less flashy than electrification or novel transportation fuels, efficiency gains in some sectors will likely be needed to reduce carbon intensity over the long-term. In sectors in which fuel costs are a significant component of overall costs, commercial firms have a strong incentive to seek efficiency gains. In the airline industry, the desire to lower fuel costs that average ~15 - 20% of total airline costs (US Department of Transportation (2019)) has contributed to steadily increasing efficiency over the past five decades. Airline fuel usage per seat mile has fallen by roughly 2% per annum since 1970, while engine efficiency alone rose at an average rate of roughly 7% per decade (National Academices of Sciences, Engineering, and Medicine (2016)). Fuel economy improvements through engine efficiency gains, airframe weight reductions, and aerodynamic improvements, are anticipated to continue at a rate similar to historical levels for the next several decades. In the significantly longer term, further operational efficiency gains might be realized through alternative engine technologies, such as engines powered by electricity generated from liquid fuels (National Academies of Sciences and Medicine (2021)). The question is how much of the efficiency gain leads to carbon reductions, as opposed to increases in demand for energy services (Knittel (2011), Gillingham et al. (2016)).

Similarly, short-run options for alternative fuels in maritime shipping are limited. According to the International Energy Agency, the most promising alternative (lower carbon) fuel options are ammonia, hydrogen, and biofuels, although liquified natural gas and electricity may also play a role (IEA (2022e)). The International Maritime Organization is in the process of initiating demonstration projects to allow the industry to gain experience with various technology alternatives and to, ideally, bring down costs. But these are seeds that will only bear fruit in the long run. In the near-term, maritime regulators have turned first to energy efficiency. The main regulatory body, the International Maritime Organization, recently mandated that ship operators meet Energy Efficiency Existing Index standards, with the goal of reducing carbon intensity from all ships by 40 percent by 2030 compared to 2008 (International Maritime Organization (2021)). While some technology investment can help, the most common compliance mechanism will be for older ships to simply slow down. A 10 percent drop in cruising speeds will cut fuel usage by almost 30 percent, according to marine sector lender Danish Ship Finance. However, this is not without cost. A first-order effect will be to reduce the available industry tonnage capacity as the time to transport a given cargo on a given route will, on average, increase. Since the ability to expand the size of the shipping fleet is constrained in the short run (shipyards worldwide are already pre-booked to operate at capacity until 2026), there is a direct tradeoff between decarbonization efforts and the cost of the shipping services that form the backbone of international trade.

This will not be the first time we have sought to rely on energy efficiency for emissions reductions. It appears as an important "wedge" in most abatement forecasts and, until recently,

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[3] For an incomplete list, see Fowlie et al. (2018), Allcott and Greenstone (2017), Jacobsen and Van Benthem (2015), Jacobsen (2013), Allcott and Greenstone (2012).

has been a pillar of US climate policy. Corporate Average Fuel Economy and Greenhouse Gas Emissions Standards have governed the rate of emissions from the light duty vehicle fleet for decades. Still, gasoline demand grew until its plateau in the mid-2000s, muddying the causal link between the policy and the intended outcome. The risk with rate-based standards is that compliance can be achieved without reducing aggregate energy use (e.g. Holland et al. (2009)). The Environmental Protection Agency is considering applying ever more stringent standards to the light duty car fleet. Whether decarbonization goals can be achieved through such policies is an open question. And in the case of both cars and maritime shipping, the compliance costs may be sufficiently large as to reduce the aggregate level of transportation services enjoyed in the economy. The economic costs could outweigh the environmental benefits, even when approximated by using the most aggressive estimates of the social cost of carbon.

3 Implications for Policy

Decarbonizing transportation is a challenge of immense scope. It entails a transformation of how we move people and goods throughout the economy. Many countries are proceeding with aggressive policies that seek to speed this transition. Four challenges are likely be important in determining the success of the transition path.

3.1 Decoupling of emissions and income

Successful decarbonization involves the decoupling of transportation emissions from income. For developed economies, this step means reducing emissions from current levels; for developing countries, it means a lower growth rate of emissions as these economies develop. As incomes rise in developing countries, their populations will increasingly demand transportation services that capture the immense societal benefits transportation brings. The majority of growth in transportation emissions over the past several decades has occurred in the light-duty sector in developing countries, and this will likely be the main source of future growth. Developing countries' emissions growth can swamp reductions in developed countries. As an illustration, a 50 percent reduction in on-road transportation emissions by developed countries relative to current emissions would be *completely offset* by just eight years of growth in on-road transportation emissions in the developing world (assuming the continuation of 4.4 percent per annum growth rate experienced since 1970).

Here, two areas of innovation are important. Conditional on growing demand for transportation, it will be necessary to reduce the carbon intensity. Although, to date, attention in this area has focused on solutions that leave the fundamental concept of personal transportation unchanged (e.g., electrification of traditional passenger vehicles), innovation in the developing world might move in novel directions. One such example are the electric rickshaws with swappable batteries that have grown quickly in India and allow for electrification while avoiding the challenges of household-level charging (Schmall and Ewing (2022)). Second, some quickly growing cities in the developing world may offer opportunities for novel approaches to urban planning, to purposefully direct urban development towards reducing transportation demand or strategically siting high-density development along public transport corridors (Nakamura and Hayashi (2013)). Admittedly, this problem is likely to be a challenging one to solve given the strong historical links between transportation demand and income. In the developed world, such opportunities are already constrained by existing (vehicle-based) infrastructure (Glaeser and Kahn (2010)). High transportation demand growth in the developing world thus presents not just a challenge, but an opportunity.

3.2 Maintaining flexibility

Deep decarbonization of the transportation sector depends on continued innovation and technological progress. As the direction, cost and pace of innovation is unpredictable, maintaining the viability of many technological pathways is valuable.

History is replete with examples of both overly pessimistic and overly optimistic assessments of environmental innovation. For instance, forecasted compliance costs of the Acid Rain Program exceeded ex-post estimate by a factor of five (Chan et al. (2012)), dramatically underestimating the ability of industry to adjust in response. On the other hand, despite substantial government subsidies and a federal mandate in the Energy Independence and Security Act of 2007 that advanced biofuels like cellulosic ethanol would constitute roughly half of biofuel production by 2022, progress in this area has been elusive and cellulosic ethanol remains uncompetitive on a cost-basis with other fuels (Chen et al. (2021)).

Technological progress sometimes proceeds smoothly with a series of incremental gains to an established technology; at other times, innovation can be lumpy and discontinuous. As one example, hydraulic fracturing led to a doubling of US natural gas production in the past fifteen years, whereas just before that time, the Annual Energy Outlook predicted stable domestic natural gas production and increasing US reliance on imports (EIA (2008)). This resulting rapid expansion of natural gas production has facilitated some decarbonization of the US electric grid, improving the emissions profiles of electric vehicles (Holland et al. (2020)). The unpredictable and lumpy nature of technological progress highlights the benefits of technology-neutral policies that do not foreclose potential decarbonization pathways. Although electrification is, based on current technology, the most direct pathway to reduce emissions from light-duty vehicles, innovation may offer lower-cost pathways in the future. Here, technologically-neutral policies (e.g., a carbon tax) offer a way to reward innovation based on a common yardstick of carbon emission reductions.

In a similar vein, decarbonization of transportation in developing world will rely on continued innovation, along potential novel directions. Solutions, such as widespread vehicle electrification, may work well for some sectors or regions, but may not be able to address unique challenges in other settings. Innovation along other pathways (like biofuels) might ultimately provide the most cost-effective prospects for decarbonizing on-road transportation in developing countries.

One challenge is that the majority of energy innovation occurs in a handful of countries – the United States, Japan, China, Korea and countries of the European Union – and roughly three-quarters of energy research and development spending is incurred by the private sector

(IEA (2020)). A long literature in environmental economics documents how policy can induce innovation along specific pathways (e.g., Newell et al. (1999), Grubb et al. (2021)). If policy in developed countries focuses innovation along domestic pathways (e.g., vehicle electrification), decarbonization in emerging economies might occur more slowly. Similar concerns have long been recognized for pharmaceutical innovation, where market and policy combine to slow innovation for therapeutics for less-affluent patients (Pecoul et al. (1999)). In such cases, subsidies for primary research have long been employed to encourage innovation, particularly for specific uses in developed countries and the future needs of developing countries.

3.3 Solving problems of collective action

Decarbonization is unlikely to succeed without addressing the collective action problems inherent in carbon markets. One (obvious) challenge to collective action is that the environmental costs and benefits associated with climate change, spillovers from research, and economies of scale in production all extend beyond the political and economic boundaries of nations (Das Gupta (2014)). The political economy of decarbonization has long posed challenges within and across countries. It is fraught with ethical arguments about the responsibilities of countries that developed through the use of carbon emissions and often pits winners and losers from abatement policy against each other.

Yet political motivation seems higher now than in the past. At the country level, policymakers have enacted policies to speed the energy transition: for examples from the United States, the Inflation Reduction Act of 2022 and the Infrastructure Investment and Jobs Act of 2021 both subsidize decarbonization efforts in different ways. Internationally, a growing number of nations have joined the Net-Zero Coalition, with countries that currently account for roughly three-quarters of global emissions pledging to reach carbon-neutrality. Business, educational institutions, and other organizations have joined the UN Race to Zero, with the goal of halving carbon emissions by 2030.

Despite the apparent progress, we note two sources of context for the momentum of the past few years. First, although many countries have pledged to reduce their carbon emissions, the 2018 report from the Intergovernmental Panel on Climate Change assesses that the aggregate pledges to date are either too small or insufficiently prompt to limit temperature increases to 1.5 deg C by the end of the 21st century. The Intergovernmental Panel on Climate Change notes emissions must fall by 45 percent by 2030, while current commitment plans allow for 10 percent growth in emissions over the period (United Nations Climate Change (2022)).

Second, financial support for developing countries has generally been insufficient relative to the anticipated costs. UN estimates adaptation costs for developing countries to exceed $300 billion per year by 2030 (United Nations (2021)), the cost of the United Nations Sustainable Development Goals at $5 - 7 trillion over 2015 - 2030, and the gap in infrastructure funding worldwide at $15 trillion through 2040 (Economics (2017)). Financial commitments from developed countries were the focus of the United Nations Climate Change Conference (COP27) held in November 2022 and strike at the heart of ethical arguments about the responsibility of the developed world to compensate developing countries for climate damages and subsidize decarbonization in lower-income countries. Although developed countries have increasingly made monetary commitments to assist developing countries, the aggregate commitments have fallen short on a \$100 billion per annum climate finance target, despite a high fraction of the funding being offered as loans rather than grants to developing countries (Timperley (2021)).

A technological solution to the collective action challenge is also being developed: direct air capture. These technologies extract carbon dioxide directly from the atmosphere. Unilateral deployment would yield benefits for the entire planet in the same way as the global inventory of emissions determines the level and rate of warming. If direct air capture were to become economically viable at scale, it would introduce the prospect of a climate change mitigation path that supports a higher level of long-run emissions and allows for some degree of decarbonization defection.

3.4 Mitigating the political costs of action

The public and political appetites for bold climate action are implicitly predicated on continued access to inexpensive energy and transportation services. The substantial increase in energy prices in general during 2022, and transportation fuels in particular, increased pressure on governments around the world to lower prices and increase supply – even at the expense of substantially increasing carbon emissions. For example, high US gasoline prices led a number of states to enact temporary moratoria for state gas taxes and for roughly one-third of the oil to be withdrawn from the Strategic Petroleum Reserve. European countries enacted electricity price caps. Concerns about the reliability of natural gas supplies led Germany and other European countries to restart previously decommissioned coal-fired power plants in the past few months (Morris (2022)). Actions by developed countries have cascaded down to developing countries. Voracious European demand for liquified natural gas as a substitute for Russian natural gas pushed many developing countries towards older, higher carbon sources of energy (Tani and Parkin (2022)). And sanctions on Russia have been repeatedly diluted to maintain the flow of Russian oil and refined products into the world market. India and China have snapped up imports of these discounted Russian products over the past twelve months (Menon (2022)).

Although future cost reductions in green technologies might soften the economic blow of climate-friendly policies, revealed preference suggests that climate concerns take a back seat to lower energy prices for citizens and policymakers alike. As we've seen time and time again, it is the politics of carbon abatement, not the policy of carbon abatement, that has most stymied progress towards a cleaner global transportation sector.

4 Hard Truths

Policymakers wishing to decarbonize the transportation sector face a menu of options. We remain in a phase of technology development characterized by significant uncertainty about the optimal path in all sectors. Governments worldwide, to the extent they are taking action at all, have overwhelmingly chosen the path of "carrots", not "sticks". In the absence of several favorable draws from innovation lotteries, this pathway will likely be expensive and characterized by only partial decarbonization success. Electrification, today's preferred technology in many countries still faces obstacles, each of which will have to be overcome to make this pathway environmentally transformative while remaining affordable. Electrification in developing economies faces particular challenges. One task in society is to figure out where and how hard to push forward with electrification. Fortunately, economists know how to set incentives that will help guide resource allocation in this environment.

Raising the price of pollution remains the an important approach to decoupling growth from emissions, the merits of which are surveyed by Knittel (2012). However, it is out of favor in many places. Governments have instead turned to subsidizing "green" alternatives. Even if the green alternatives were carbon free (which they typically are not), subsidies for green technology are not equivalent to taxes on pollution. In at least one important sense, the subsidy approach is counterproductive. Subsidy-favored technologies become artificially inexpensive to adopt, which expands overall demand while crowding out profitable innovation along currently unfavored or not-yet-imagined abatement pathways. Africa offers a concrete example of this concern. Its population will likely double in the next century, and transportation demand will increase in concert with a larger and richer population. It will be advantageous for urban planning to center around public transit and small vehicles in these economies. Increasing the cost of pollution creates incentives for cleaner urban growth, but cheap electric vehicles does not.

With these broader issues and options in mind, it is especially valuable to implement policies that set the right incentives. (Economists have an essential advisory role to play here.) Climate policymakers would be well-served by extending their time horizon to reflect the fact that decarbonizing transportation will be a multi-decade project. Framing decarbonization as necessary to occur by <insert your preferred net-zero date here> undermines credibility if we continue to miss "point-of-no-return" deadlines. It also risks locking us into the set of presently-feasible technology options. Similarly, all-or-nothing targets ("100 percent <insert preferred technology here>") and thresholds ("1.5 degrees...") may impose high costs of abatement, or achieve lower than expected levels of abatement, by failing to equate social costs and benefits on the margin. This is especially true with respect to abating the last units of pollution, or with converting the last users to green technology if green and brown technologies are imperfect substitutes (Holland et al. (2021)). In short, a return to basic economic principles would lower the cost for any level of decarbonization that is ultimately achieved.

The world is on a cusp of a transformational shift in how we move goods and people which will involve balancing environmental goals with the immense value of the underlying transportation services. A defining challenge will be to develop and select technologies that reduce carbon emissions from transportation sectors that have starkly different needs. How to decarbonize light-duty vehicles is particularly important, especially in light of the anticipated increase in transportation demand as incomes and populations rise in developing countries. We are in early days of a long transition, and humility about which technology pathways will ultimately satisfy the needs of each sector is appropriate.

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