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ADVANCED REVIEW

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Policy for material efficiency in homes and cars: Enabling new climate change mitigation strategies

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Abstract

Material efficiency (ME), making products with less material or substituting with less carbon-intensive material without a loss of functionality, can reduce greenhouse gas (GHG) emissions and complement other strategies to mitigate climate change. Seven ME strategies for cars and homes in the G7 countries were recently modeled in a study by the International Resource Panel. Modeling indicates that ME strategies focusing on construction and use of homes could lower the overall cumulative emissions in the G7 between 2016 and 2060 by 8.5 Gt CO_2e (20%), while ME strategies for the production and use of cars could reduce up to 12 Gt (24%). For both homes and cars, the strategy of more intensive use—where fewer or smaller products are required to provide the same basic service—showed the greatest potential. A review of existing ME policies reveals that attention to ME in climate policy has been limited. Policy toward ME has historically focused on waste management rather than GHG reduction. Ex post evaluation of policies that do exist, especially for recycling and related waste strategies, is infrequent. Framing efficient use of materials as a measure *primarily* intended for climate mitigation is relatively recent and uncommon. Production-related policy opportunities have been neglected because using ME to reduce GHGs is novel in some sectors and because increased ME faces economic and social barriers. Rebound effects where reduction of the cost of housing or transportation can increase material consumption offsetting potential gains, a problem for all efficiency-based approaches, is understudied and not currently addressed through policy.

This article is categorized under:

The Carbon Economy and Climate Mitigation > Policies, Instruments, Lifestyles, Behavior

The Carbon Economy and Climate Mitigation > Decarbonizing Energy and/or Reducing Demand

KEYWORDS

automobiles, building and construction, climate policy, circular economy, material efficiency, resource efficiency

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1 | INTRODUCTION

Reducing greenhouse gas (GHG) emissions sufficiently to meet the Paris Accord target of 1.5°C is a daunting challenge. Most research, discourse, and policy have focused on shifting to renewable energy, increasing energy efficiency, and sequestering carbon. Given the challenges those approaches face and the scale of the mitigation task, additional approaches are needed. Material efficiency can add an important strategy to that portfolio.

Material efficiency (ME) is "the pursuit of technical strategies, business models, consumer preferences, and policy instruments that would lead to a substantial reduction in the production of high-volume, energy intensive materials required to deliver human well-being" (Allwood et al., 2011).[1] In practical terms, ME can be thought of as reducing the amount of materials required per unit of functionality delivered.

In the context of reduction of GHG emissions, material efficiency takes on a specific meaning: using less material and thereby reducing materials production or substituting emissions-intensive primary (virgin) materials with less emissions-intensive materials.

Following the definition above, ME targets the emissions-intensive materials needed to provide a given function. It encompasses measures targeting the product, such as production of smaller cars that use less material; measures targeting the product system, such as reusing components; and measures at a higher system level, such as designing communities where most mobility needs are met by walking and biking. Behavioral changes contributing to ME, such as buying a smaller car or reduced car usage, may also be seen as "sufficiency" measures. Sufficiency, however, is not a synonym in this context as it suggests that there should be a cap on the total amount of functionality provided, whereas material efficiency addresses inputs required per unit of functionality provided. In other words, material efficiency has no component of restraint and can simply mean that the total amount of mobility provided remains constant (or even grows) but is delivered in a manner that has less environmental impact (Jungell-Michelsson & Heikkurinen, 2022; Princen, 2005).

Underlying the call for material efficiency for mitigation of climate change are several key premises:

1. A significant proportion of global GHG emissions occur in the extraction and processing of materials. In many product life cycles, it is the production of materials rather than product manufacturing that accounts for the majority of production-related (cradle-to-gate) emissions (Hertwich, 2021).
2. In the short to intermediate term, the carbon intensity of technologies for material production is unlikely to improve significantly (International Energy Agency, 2020).
3. Reduction of the quantity of materials produced can reduce GHG emissions (Allwood et al., 2011; Worrell et al., 2016).
4. Reduction of materials production occurs through reduction in the demand for materials—material efficiency (Allwood et al., 2011).

A variety of related frameworks and concepts have emerged in recent decades that overlap with material efficiency including resource efficiency, eco-efficiency, sustainable materials management, a sound materials-cycling society, the 3Rs (reduce, reuse, recycle), dematerialization, and most recently, the circular economy.[2] To varying degrees, these frameworks share an emphasis on the importance of waste reduction and reuse throughout the life cycle of products. All of the frameworks include strategies, claims, and policy prescriptions regarding the climate mitigation benefits of improved management of material resources but vary in scope, emphasis, and detail regarding potential GHG reductions. Critically, despite significant potential for GHG emissions reductions, none of these frameworks advocate for the efficient use of materials as a measure *primarily* intended for climate mitigation.

Given the growing quantitative understanding of the potential GHG emissions reductions from material efficiency (e.g., International Energy Agency, 2020; Scott et al., 2019), policy makers have sought to identify policies that encourage or mandate such strategies (Aoki-Suzuki et al., 2019; G7 Alliance on Resource Efficiency (ARE), 2022; G7 Environment Ministers, 2017). At the same time, the Organisation for Economic Cooperation & Development (OECD, 2016, p. 42) argues that "a striking feature of the literature on resource efficiency is the lack of studies evaluating the impact of policy instruments … and ultimately [on] material consumption and extraction."

In this article, we discuss the results of an extensive review of peer-reviewed and gray literature on current material efficiency policies or those that might be developed as a complement to the findings of recent modeling. This review is based on the framework of material efficiency, rather than the related approaches, because of the strong focus of ME on GHG reductions and because a quantitatively-grounded ME research literature is emerging. Where understanding of the nature or efficacy of ME policy requires background on the ME strategy, research on the strategy is described as well.

The analysis presented here builds on recent research including a report, *Resource Efficiency for Climate Change Mitigation* (RECC): *Material Efficiency for a Low Carbon Economy* (Hertwich et al., 2020). The report was prepared for the Group of Seven (G7) countries by the International Resource Panel (IRP), an international scientific panel operating under the auspices of the UN Environment Programme.[3] The report provides both quantitative estimates of the potential reductions of GHG emissions arising from increases in material efficiency and an extensive inventory and discussion of policy related to material efficiency.

Our goal is to characterize opportunities, challenges, and limitations of government efforts to reduce GHG emissions through material efficiency policies. This analysis presents current understanding of the policy opportunities and challenges in two sectors of the economy: residential buildings (homes) and light duty passenger vehicles (cars).[4]

Rather than replicating the detail in the RECC report, we focus on findings with implications across the sectors, individual policies, and life cycle stages. We present several policies that are illustrative of larger patterns in the sectors. Readers interested in greater depth and breadth of detail on material efficiency policies are referred to the RECC report (Hertwich et al., 2020).

2 | MATERIAL EFFICIENCY STRATEGIES

Material efficiency research as discussed here had its origins in the engineering and industrial ecology communities. This research explores specific strategies and approaches that can help reduce material consumption in particular applications (Allwood et al., 2012; Masanet et al., 2021; Worrell et al., 2016). It quantifies potential savings of materials, energy, and emissions through strategies such as closed-loop recycling (e.g., Nakamura et al., 2012; Niero et al., 2017), extension of product lifespans (e.g., Glöser-Chahoud et al., 2021; Nakamoto & Kagawa, 2021), and sharing (e.g., Bonilla-Alicea et al., 2020; Meshulam, Font-Vivanco, et al., 2023). It includes details of applicable technologies and empirical aspects such as the excess amount of structural steel in buildings beyond engineering standards (Moynihan & Allwood, 2014). Some recent work is beginning to include material efficiency in the analysis of economy-wide GHG reduction opportunities (International Energy Agency, 2019; Lu & Schandl, 2021; Scott et al., 2019), and the potential for consumption-based measures (Ivanova et al., 2020; Scott et al., 2019).

A variety of characterizations of material efficiency strategies have been suggested (Allwood et al., 2011; Barrett & Scott, 2012; Hertwich et al., 2019, 2020) and for related frameworks such as the circular economy (e.g., Ellen MacArthur Foundation, 2023; McKinsey Center for Business and Environment, 2016; Potting et al., 2017). The review presented here is based on seven material efficiency strategies characterized by Allwood et al. (2011, 2012, 2013), used in the RECC modeling and scenario development work, and summarized in Table 1.

Material efficiency strategies can be applied at various stages of the product life cycle (see Figure 1): material selection or processing, manufacture of products and construction of buildings, use and maintenance, and end-of-life management. A life cycle framework is necessary because ME strategies which target one stage of the product life cycle can also affect other stages leading to counterproductive outcomes.

The motivation for ME with respect to transport and construction is not the diversion of waste from landfill, as landfilled waste from those sectors is generally not a significant source of GHG emissions. Rather, the focus is on reducing the use of materials in order to lower GHG emissions—mainly arising from the extraction and processing of primary materials (Worrell et al., 2016).

3 | WHY HOMES AND CARS?

The RECC report focused on two product groups, homes, and cars, each of which illustrate the impacts of material efficiency in a broader product category—construction and manufacturing—while constituting important product groups in themselves. The analysis of homes and cars also illustrates the type of details that must be addressed in policy for material efficiency and the sort of issues that may be relevant to other sectors of the economy.

In 2015, construction and use of homes caused about 10 gigatons[5] (Gt) of CO_2-equivalent (CO_2e) emissions, approximately 20% of global GHG emissions (Hertwich et al., 2020). Of these 10 Gt CO_2e, 6 Gt were associated with the supply and use of electricity and fuels in homes worldwide, and 4 Gt were emitted in the construction of homes cradle-to-gate,

TABLE 1 Material efficiency strategies for homes and cars assessed in the Resource Efficiency for Climate Change Mitigation (RECC) report.

Strategy	Homes	Cars
Using less material by design	Lighter buildings: using less material through optimized design and engineering without loss in functionality.	Smaller vehicles: shifting from large vehicles (light trucks, sport utility vehicles) to smaller ones (passenger cars).
Material substitution	Using construction materials with lower life cycle emissions, for example, wood buildings which can have fewer life cycle emissions than concrete or brick buildings.	Substituting materials to achieve less operational energy demand. Replacing steel with lighter materials reduces life cycle emissions because lower vehicle weight reduces fuel use.
Improvement of fabrication yield	Improving fabrication yield to reduce the amount of scrap created in the production processes, lessening the demand for material input.	
Enhanced end-of-life (EoL) recovery and recycling of materials	Improving the EoL recovery rate to increase the share of materials salvaged from discarded products leading to a displacement of primary materials by recycled materials.	
Diversion of scrap	Diverting manufacturing scrap, such as trimmings or cuttings, into other manufacturing units to make other components. This avoids re-melting for recycling and may reduce costs.	
More intensive use (fewer or smaller products used to provide the same amount of service)	Increasing household size/cohabitation and shifting from single to multi-family houses lowering material use per person.	Car-sharing (shifting from personal cars to a shared fleet) and ride-sharing (people with same or similar driving destinations sharing a ride) can reduce the fleet size or the overall amount of vehicle miles traveled across the entire fleet.
Product lifetime extension	Extending product lifetimes through better design, increased maintenance, and enhanced second-hand markets.	
Recovery, remanufacturing, and reuse of components	Using value-retaining processes[a] to reduce the production of spare parts or even primary products.	

[a] Value-retaining processes (VRPs) refer to end-of-life processes that enable the continued use of a product and include remanufacturing, refurbishment, repair, and arranging direct reuse (Nasr et al., 2018). Because recycling maintains only the value of the material, but not of the product, it is not considered a VRP.

Source: Adapted from Hertwich et al. (2020).

that is, from raw materials to the finished building (Hertwich et al., 2020). Globally, 40%–50% of the carbon footprint[6] of materials arose from the construction of buildings and infrastructure in the period 1995–2015 (Hertwich, 2021).

The life cycle emissions of the global light-duty vehicle fleet in 2015 were 7.5 Gt CO_2e. Of those, about 19% were associated with the production of fuels, 62% were tail-pipe emissions occurring during driving, and the remaining 19% were emissions associated with the production of vehicles (Hertwich et al., 2020). Vehicle production was the single largest contributor to the carbon footprint of all manufactured goods in the period 1995–2015. Manufactured goods accounted for 35%–40% of the carbon footprint of materials, motor vehicles accounted for about 7% (Hertwich, 2021).

Results of the RECC report show that, in wealthy countries, emissions associated with energy in the use (operational) phase dominate the full lifecycle emissions of homes and cars. For buildings, climate, technological, and behavioral factors all contribute to lower heating, ventilation, and air conditioning energy use in hotter developing countries compared to those in colder industrialized regions. Together, cars and homes constituted one third of global material use and generated one third of the 50 billion tons CO_2e of total GHG emissions in 2015 (Hertwich et al., 2020).

4 | THE POTENTIAL FOR GHG REDUCTION THROUGH MATERIAL EFFICIENCY

As noted above, the RECC report investigated the reduction of GHG emissions attainable through a selected set of material efficiency strategies for homes and cars in the G7 countries (Canada, France, Germany, Italy, Japan, United Kingdom, United States), China, and India. The modeling was extended to the global level by Pauliuk et al. (2021). Varied assumptions regarding the future economy, population, and politics are reflected in three storylines—those of the shared socioeconomic pathways SSP1 and SSP2 and those of the low energy demand scenario.[7] Savings

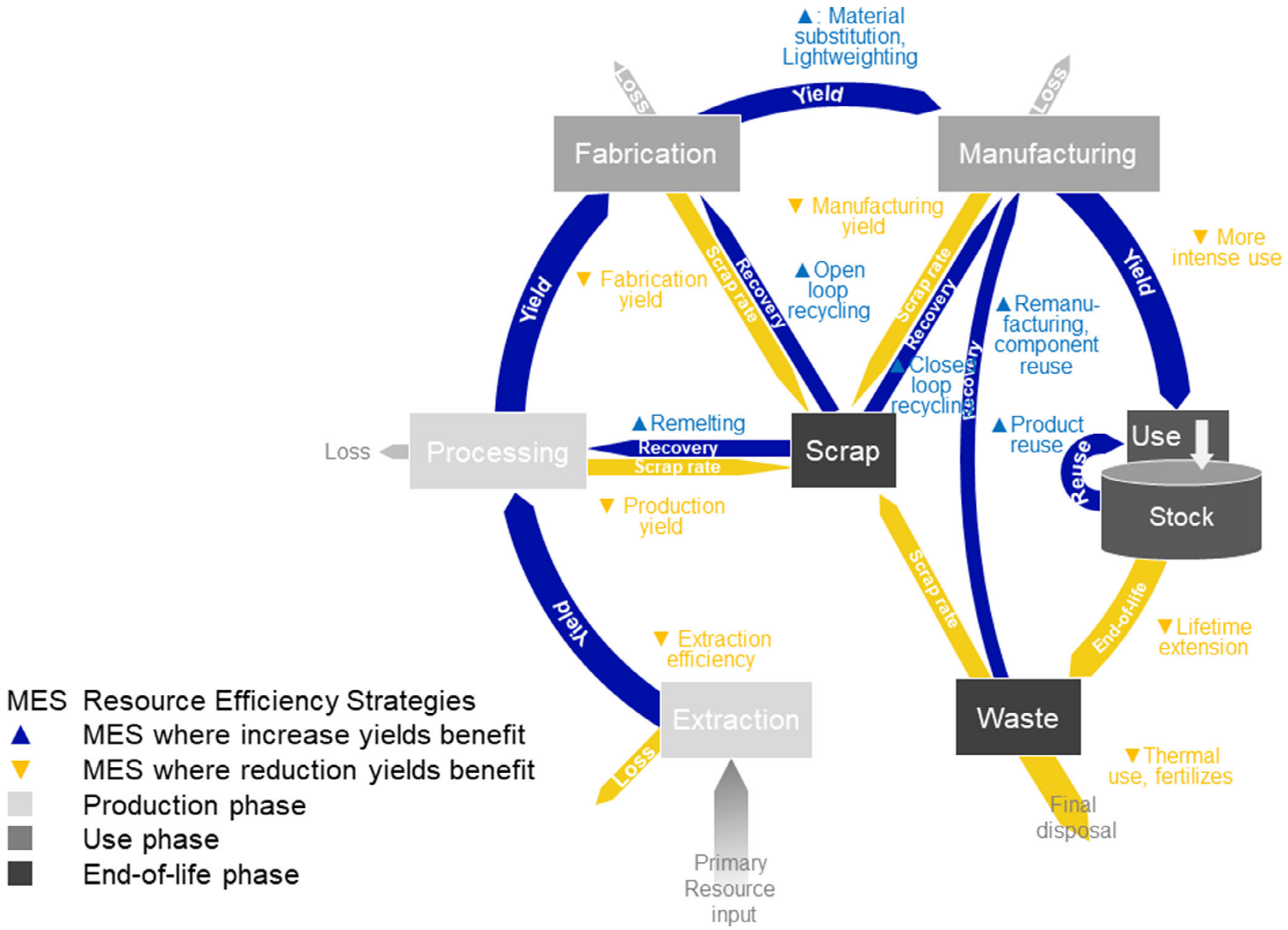

FIGURE 1 The product life cycle and material efficiency strategies. The blue arrows indicate an increase in outflow for the same inflows improves material efficiency. The yellow arrows indicate a reduction in outflow improves material efficiency. *Source*: Hertwich et al. (2020) inspired by Reck et al. (2008) and Allwood et al. (2011).

resulting from the adoption of material efficiency strategies in G7 countries were quantified by comparing scenarios with ME measures to scenarios without those measures (Figure 2). The comparisons consider both the situation where current climate policies are continued and the situation where climate policies are strengthened to achieve a stabilization of the climate at two degrees above preindustrial levels.

For residential buildings in G7 countries, up to 8.5 Gt CO_2e, or 20% of overall cumulative emissions expected for the years 2016–2060 under the SSP1 2° pathway, can be saved through adoption of the ME strategies listed in Table 1. Assuming gradual implementation of the ME measures, by 2050 emissions would be 35% lower than without these measures. The largest savings (6.8 Gt) are attained through more intensive use, specifically up to a 20% reduction in floor space per capita. Other important strategies include more extensive use of wood as a construction material (0.5 Gt), the design of lighter building structures (0.3 Gt), lifetime extension and improved recycling of construction and demolition waste (0.1 Gt), and improved construction yield (resulting in reduced construction waste – 0.8 Gt).

The relative importance of the various strategies is similar across different scenarios. In the modeling, lifetime extension is implemented only when it leads to emissions reductions, which is the case only when buildings have high energy efficiency. As a result, the importance of lifetime extension grows over time as the building stock becomes more energy efficient. For the strategy of more intensive use, part of the savings results from a lower energy demand needed to heat and cool smaller spaces.

For light-duty vehicles, the SSP1 2° scenario assumes a gradual introduction of electric vehicles (EVs) in addition to the decarbonization of the energy supply. Material efficiency would reduce cumulative emissions in G7 countries by 12 Gt or 24% over the period 2016–2060. The annual emissions in 2050 would be 40% lower than without the implementation of the measures. The largest reductions are from ride-sharing (when people share a ride) and car-sharing (a form

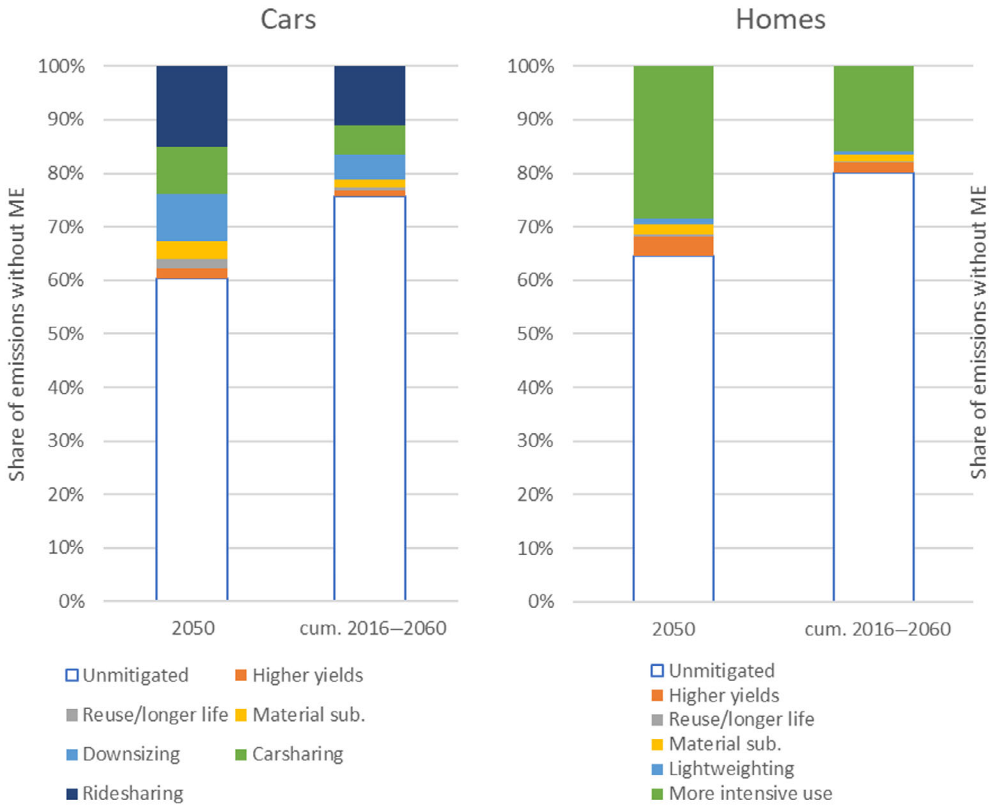

FIGURE 2 Greenhouse gas (GHG) emission reductions attained by material efficiency strategies as a fraction of total emissions without these strategies in G7 countries. The white portion shows the remaining emissions after the implementation of the strategies. The left bars represent the situation in 2050, while the right bars indicate the cumulative emissions from 2016 to 2060. A smaller fraction of cumulative emissions could be saved than of emissions in 2050, because strategies are introduced gradually, and the emissions rate is higher in the earlier years.

of car rental), 5.3 and 2.7 Gt, respectively. By 2050, lifetime extensions and the use of smaller cars can also contribute to several percent of emissions savings given that they lower material requirements. Lifetime extension is assumed to be beneficial only once EVs are introduced; it otherwise delays the introduction of this cleaner technology (Wolfram et al., 2020). People participating in car-sharing tend to use vehicles that are smaller than the ones they would buy, which may be sized for vacation or utility trips. Here, downsizing and car-sharing were modeled separately.

5 | MATERIAL EFFICIENCY POLICIES

The nature and scope of material efficiency policies are diverse and vast. Policy intervention can occur within or across economic sectors, at a specific point in the product life cycle, and at many jurisdictional levels—local, state/provincial, national, and supranational (e.g., the European Union). Policies can employ a wide variety of measures and can be mandatory, voluntary, or informational.

Ideally, then, an understanding of the current state of ME policy would encompass the status and outcomes for policies related to each strategy in the relevant sector across the product life cycle throughout the globe as well as policies that cut across sectors. The compilation and analysis of ME policies presented here focus on the G7 countries at the national level. Where pertinent, policies at the subnational level were examined. A summary of the findings of the RECC policy review is presented in Tables 2 and 3. A discussion of the patterns and themes that emerge from the review follows.

The policy review focuses on "hard policy," defined as regulatory and economic instruments that prioritize material efficiency, rather than "soft policy" approaches that rely on voluntary or informational measures. This choice stems, in

TABLE 2 Material efficiency strategies and policies for homes.

Material efficiency strategy	Policy instruments[a]	Description	Regional/country/local level example[b]
Using less material by design	No policy instruments directly focused on lightweighting identified		
	Mandated prefabrication and modular construction	Mandating prefabrication and modular construction can facilitate lightweighting.	Singapore Building Control Regulation (https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-and-assembly-dfma/prefabricated-prefinished-volumetric-construction-ppvc) Hong Kong Housing Authority (https://doi.org/10.1080/09613218.2021.2010030)
	Mandated use of building information modeling (BIM)	Use of BIM during design can help to locate areas of medium and low structural loads allowing lightweighting.	British Standards Institute and Department for Business (https://www.ukbimframework.org/)
Material substitution	Revision of building and fire codes with respect to mass timber wood framing	Compared to concrete and brick, wood construction typically causes fewer life cycle greenhouse gas (GHG) emissions. Many building codes have limitations on timber construction for fire safety reasons. Provisions for construction of mass timber structures are being updated in some building and fire codes.	2021 International Building Code (https://codes.iccsafe.org/content/MTBIBC2021P2)
	Standards allowing cement with clinker substitutes	Production of Portland cement causes significant GHG emissions. Alternative binders are currently being researched.	EU Cement Standardization (https://shop.bsigroup.com/ProductDetail/?pid=000000000030391002)
	Revision of building codes to address embodied impact of materials	Performance rather than prescription-based standards facilitate use of alternative materials (e.g., concrete with lower Portland cement content).	Marin County, California Building Code) (https://www.bruce-king.com/building-codes)
Improvement of fabrication yield and diversion of scrap	Mandated prefabrication	Prefabrication allows for better planning of components and more automation thus avoiding waste. Prefabrication is sometimes mandated in public and subsidized buildings.	Singapore Building Control Regulation (https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-and-assembly-dfma/prefabricated-prefinished-volumetric-construction-ppvc) Hong Kong Housing Authority (https://doi.org/10.1080/09613218.2021.2010030)
	Mandated use of building information modeling (BIM)	BIM allows for better collaboration of building planners and a higher degree of digitalization and automation. Both help to identify potential waste early in the planning process and minimize scrap generation through prefabrication and other techniques.	British Standards Institute and Department for Business (https://www.ukbimframework.org/)

(Continues)

TABLE 2 (Continued)

Material efficiency strategy	Policy instruments[a]	Description	Regional/country/local level example[b]
		BIM mostly used for large buildings. No evaluation of material efficiency impacts of mandates found.	
More intensive use	Reduction of transaction costs and removal of taxes on home sales	Levies on home sales or a taxation of the income from the appreciation of property can limit downsizing after changes in households.	UK Stamp Duty Land Tax (https://www.legislation.gov.uk/ukpga/2003/14/contents)
	Relaxation of single-family zoning	Land-use restrictions with minimum site and structure requirements increase house sizes and limit construction of multi-family homes.	Minneapolis 2040 plan (USA) (https://minneapolis2040.com/media/1488/pdf_minneapolis2040.pdf) Oregon House Bill 2001 (USA) (https://www.oregon.gov/lcd/UP/Documents/HB2001OverviewPublic.pdf)
	Revision of laws restricting accessory dwelling units (ADUs) and infill development and increase in building height	ADUs and infill development allow for use of land within existing built-up areas leading to increased urban density and typically smaller dwellings.	State of California, US, Department of Housing and Community Development (https://www.hcd.ca.gov/community-development/housing-element/docs/adu_ta_memo_final_01-10-20.pdf) San Antonio, TX, Inner-City Reinvestment/Infill Policy (https://www.sanantonio.gov/Portals/0/files/ccdo/Inner%20City%20Reinvestment%20Infill%20Policy.pdf) Court ruling on infill and top-up development, North Rhine-Westphalia, Germany (https://www.ltmk.de/ovg-nrw-baurecht-nachbarn-bauherren/)
Enhanced end-of-life recovery and recycling of materials	Mandated sorting and processing of construction and demolition waste	Mandated sorting helps maintain value of materials and increases likelihood of recycling.	Norway Planning and Building Act rules (https://www.regjeringen.no/en/dokumenter/planning-building-act/id570450/) Japan Construction Material Recycling Law (https://www.env.go.jp/en/laws/recycle/09.pdf)
	Landfill levies and bans	Landfill bans often target recyclable materials and coupled with supporting policies. Landfill taxes create an incentive to find alternative uses of the waste.	Vermont Agency of Natural Resources Acts 148 and 175 (https://dec.vermont.gov/sites/dec/files/wmp/SolidWaste/Documents/Act175-FactSheet.pdf) Massachusetts Waste Disposal Bans (https://www.mass.gov/doc/310-cmr-19000-solid-waste-management-facility-regulations) UK landfill ban on selected products and tax (https://www.gov.uk/guidance/dispose-of-waste-to-landfill)

TABLE 2 (Continued)

Material efficiency strategy	Policy instruments[a]	Description	Regional/country/local level example[b]
Recovery, remanufacturing, and reuse of components	Mandated prefabrication and modular construction	Prefabricated elements and modular construction facilitate design for disassembly and component reuse.	China, 30% of new builds being prefab, 14th 5-year plan (http://english.scio.gov.cn/pressroom/2022-01/26/content_78011624.htm) Hong Kong Housing Authority (https://doi.org/10.1080/09613218.2021.2010030)
	Building codes allowing use of salvaged components	Allowing the use of salvaged wood without regrading facilitates reuse.	State of Washington Building Code (https://sbcc.wa.gov/state-codes-regulations-guidelines/state-building-code)
	Mandated reuse	Obligating contractors not only to recycle but also reuse materials and components from building demolition increases component supply and stimulates salvage businesses.	Cook County, Illinois, US Demolition Debris Ordinance (https://library.municode.com/il/cook_county/codes/code_of_ordinances?nodeId=PTIGEOR_CH30EN_ARTVASRESU_DIV3DEDEDI_S30-773DEDEDIRE)
Product lifetime extension	No policies for durable construction identified		
	Heritage listings	Policies to preserve historic buildings that restrict demolition or alteration can limit building energy efficiency.	US National Historic Preservation Act (https://www.gsa.gov/real-estate/historic-preservation/historic-preservation-policy-tools/legislation-policy-and-reports/section-106-national-historic-preservation-act-of-1966) New York City Local Law 97 (https://www1.nyc.gov/assets/buildings/local_laws/ll97of2019.pdf)

[a] Policy instruments for or related to material efficiency. Some policies which are not intended to encourage ME are included because they have important impacts on ME. The list of policy instruments and examples in this table are meant indicate the relevance of the instrument to the given material efficiency strategy, but not to imply that the instruments are sufficient to achieve the quantitative outcomes obtained in the modeling results in the Resource Efficiency for Climate Change Mitigation (RECC) report.

[b] Laws, regulations, and other forms of policy in this column are provided as examples, but not necessarily as instances of effective policy. Some are examples of policies that constitute barriers.

Source: Adapted from (Hertwich et al., 2020).

part, from the difficulty in comprehensively evaluating the extensive range of soft policy programs. Furthermore, despite their limitations, mandatory instruments are more likely to produce outcomes and evaluations than voluntary measures.

6 | PATTERNS IN MATERIAL EFFICIENCY POLICY

To contribute to climate change mitigation, material efficiency policies must reduce both material use and GHG emissions. Thus, the analysis of ME policies should encompass the causal chain from ME *policies* through ME *strategies*, to changes in material *use* and then *impacts* on GHG emissions (Figure 3).

Ideally, research on ME policy would encompass all four stages in the causal chain. Such research is rare, however, so this review describes patterns in material efficiency policy related to the seven strategies described above. The examples of ME policy discussed in the text and shown in Tables 2 and 3 were identified by (1) surveying government members of the IRP,[8] and (2) searching peer-reviewed and gray literature specific to the policy interventions relevant to a

TABLE 3 Material efficiency strategies and policies for cars.

Material efficiency strategy	Policy instruments[a]	Description	Regional/country/local level example[b]
Using less material by design	By-product of fuel economy measures	Fuel economy is widely regulated throughout the G7 resulting in reduced material weight to meet targets	US Corporate Average Fuel Economy Standards (https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards)
	Vehicle registration tax	Taxes based on vehicle weight encourages the choice of lighter vehicles.	EU regulations on emission performance standards for light-duty vehicles (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007R0715&from=en) Norwegian vehicle registration tax (https://www.skatteetaten.no/en/person/duties/cars-and-other-vehicles/importing/which-duties-do-you-have-to-pay/one-off-registration-tax/what-is-the-one-off-registration-tax/)
Material substitution	By-product of fuel economy policy	Fuel economy is widely regulated throughout the G7 resulting in increased use of aluminum, plastics, and novel materials. No policies directly focused on material composition identified.	US Corporate Average Fuel Economy Standards (https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards) EU regulations on emission performance standards for light-duty vehicles https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007R0715&qid=1707359311765
More intensive use[c]: Ride-sharing[d]	High occupancy vehicle (HOV) lanes	Ride-sharing is a practice long encouraged by governments to reduce congestion, energy use, and pollution. As with other forms of shared mobility, digital platforms have enhanced its use.	Bay Area Toll Authority, San Francisco region, US (https://mtc.ca.gov/operations/traveler-services/bay-area-express-lanes) City of Portland, Oregon Car-sharing Parking Policy (https://www.portland.gov/policies/transportation/special-parking-permits/trn-3309-carsharing-parking-administrative-rules)
More intensive use: car-sharing[e]	Favorable treatment in parking, zoning, and building codes. No policy identified that focuses on material efficiency	Policies generally encourage car-sharing through relaxation of regulations relating to parking, real estate development, and urban planning.	San Francisco On-Street Shared Vehicle Permit Program (https://www.sfmta.com/projects/street-shared-vehicle-parking-permit-program) Vancouver On-Street Car-Sharing Parking Policy (https://vancouver.ca/streets-transportation/car-sharing-carpooling-and-ride-sharing.aspx) German Car-sharing Privileges Law (https://recht-energisch.de/2022/03/03/carsharing-gesetz-autoteilen-leicht-gemacht/)

TABLE 3 (Continued)

Material efficiency strategy	Policy instruments[a]	Description	Regional/country/local level example[b]
Enhanced end-of-life recovery and recycling of materials	Extended producer responsibility with recycling and recovery targets	Policy toward end-of-life vehicles (ELVs) focuses on auto shredder residue (non-metallic materials remaining after shredding of car hulks). Material efficiency could be enhanced if a life cycle approach were employed with greater attention to the end use of recycled metals.	EU End-of-Life Vehicle Directive (https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en)
	Regulation of pollution arising from auto recycling	ELV policy in the US and Canada focuses on reduction of risk/pollution arising from ELV management practices without explicit attention to material efficiency.	US Clean Air Act, for refrigerants (https://www.epa.gov/mvac/section-609-clean-air-act-mvac) US Clean Water Act, for stormwater management (https://www.epa.gov/compliance/clean-water-act-cwa-compliance-monitoring)
Recovery, remanufacturing, and reuse of components	Mandating reuse and recycling fees and targets	Prevention and management of pollution from dismantling and recycling processes. Remanufacturing of engines and tires extends the life of vehicles and components but is largely limited to heavy-duty vehicles.	Japanese Automotive Recycling Law (https://www.env.go.jp/en/laws/recycle/11.pdf)
	Standards and definitions for reuse and remanufacturing	Standards and definitions of used and remanufactured goods differ across industries and countries inhibiting trade.	Basel Convention (https://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW.13-4-Add.2.English.pdf) EU Waste Framework Directive (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098) US Federal Trade Commission (https://www.ftc.gov/legal-library/browse/rules/rebuilt-reconditioned-other-used-automobile-parts)
Product lifetime extension	Regulations mandating access to or quality of repair	Consumer protection, rather than product lifetime extension, is a common focus of policy on auto repair. Repair may extend product life increasing material efficiency but can keep less fuel-efficient vehicles in service.	EU regulation (EC) No 715/2007 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02007R0715-20121231&from=EN) US Federal Vehicle Repair Cost Savings Act of 2015 (https://www.congress.gov/bill/114th-congress/senate-bill/565)

[a] Policy instruments for or related to material efficiency. Some policies which are not intended to encourage ME are included because they have important impacts on ME. The list of policy instruments and examples in this table are meant indicate the relevance of the instrument to the given ME strategy, but not to imply that the instruments are sufficient to achieve the quantitative outcomes obtained in the modeling results in the Resource Efficiency for Climate Change Mitigation (RECC) report.

[b] Laws, regulations, and other forms of policy in this column are provided as examples, but not necessarily as instances of effective policy. Some are examples of policies that constitute barriers.

[c] Research suggests that ride-hailing does not currently improve material efficiency and was not modeled (i.e., Diao et al., 2021; Meshulam, Goldberg, & Makov, 2023; Schaller, 2021; Ward et al., 2021).

[d] Sometimes called car-pooling, ride-sharing refers to driving arrangements where people with same or similar driving destinations share a ride. This differs from ride-hailing (e.g., Uber and Lyft), which is a modified taxi service.

[e] Car-sharing includes both companies with centralized digital platforms which own vehicles that are rented to members (e.g., ZipCar and Share Now) and platforms for direct peer-to-peer rental of a vehicle owned by another person or entity.

Source: Adapted from Hertwich et al. (2020).

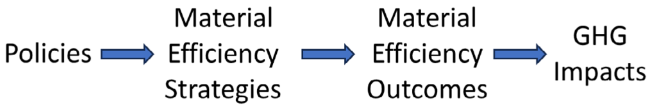

FIGURE 3 Simplified causal chain for material efficiency policy.

TABLE 4 Number of G20 countries that include energy or material efficiency commitments in the second round of National Determined Contributions, 2023.

	Buildings		Cars		Sector non-specific		Total
	Quantitative[a]	Qualitative	Quantitative	Qualitative	Quantitative	Qualitative	
Material efficiency	1	6	1	7	1	9	25
Energy efficiency	7	13	4	11	3	7	45

[a] Quantitative commitments include numerical targets or metrics for the reduction of use of energy or materials or of greenhouse gas (GHG) emissions; deadlines for reporting emissions; metrics or targets for deployment of programs, or uptake or implementation of standards. Because details of country policies were often contained in the National Plans associated with the Nationally Determined Contributions (NDCs), rather than in the text of the NDCs, the counts are based on both types of documents. More detail on the commitments summarized in the table can be found in Zenodo (Lifset, 2023).

given ME strategy, followed by (3) intensive searching of primary and secondary literature to verify the details of the policies and their fit with the relevant ME strategy. Research on ME strategies is also provided where understanding of the nature or efficacy of ME policy requires background on the ME strategy.

The review of existing ME policies revealed recurring patterns: limited use of ME policy as means of climate mitigation, a historical emphasis on waste management, weak alignment between policy attention and the ME strategies with the highest GHG reduction potential, and lack of rigorous ex post policy evaluation.

6.1 | Limited attention to material efficiency in climate policy

GHG emissions from production and end-of-life management of materials have been studied for many decades (e.g., Denison, 1996; Smith et al., 2001; US Environmental Protection Agency, 2006). However, regarding materials efficiency as a strategy *primarily* intended to mitigate climate change mitigation is new (International Energy Agency, 2020).[9] A variety of non-governmental and multilateral organizations have started to draw attention to the potential for GHG reduction through circular economy strategies but material efficiency is only starting to be included in climate policy (e.g., Bardout & Hoogzaad, 2017; K. Wang et al., 2022). One indication of the relative absence of material efficiency as a climate policy can be found in the Nationally Determined Contributions (NDCs), the non-binding national plans for climate actions by governments as a contribution to achieve the global targets set out in the Paris Agreement.

The first NDCs were submitted by 2015 and were updated at the 2021 Glasgow meeting (Climatewatch, 2021). The majority of mitigation approaches specified in the first round of NDCs from G20 countries referred to energy production and energy efficiency. In 13 of the 16 G20 NDC documents energy efficiency was mentioned (Hertwich et al., 2020). However, resource efficiency, resource management, material efficiency, circular economy, or material-related consumption-side instruments scarcely appeared in the first set of NDCs, present as explicit mitigation measures only in 4 of the Intended Nationally Determined Contributions.[10]

The 2021 update to the NDCs showed an increase in attention to material efficiency in homes and cars in the form of qualitative commitments. Table 4 shows the number of G20 countries that reference either energy and/or material efficiency in the newer NDCs. As might be expected, given the relative maturity of the strategies, more attention continues to be given to energy rather than material efficiency. While explicit statements of intention to utilize ME strategies increased, quantitative commitments to ME in the form of measurements of, or targets for, GHG emissions reductions, levels of adoption of efficiency programs or standards, or specific commitments of funding, were dwarfed by less specific, qualitative commitments. Detail on NDCs for ME homes and cars on a country-by-country basis can be found in an appendix in the Zenodo data repository (Lifset, 2023).

6.2 | Material efficiency policies focused on waste management

The RECC report found few policies aimed at increasing material efficiency "upstream," that is, in the production and use of homes and cars. In contrast, environmental policies related to the end-of-life management of homes and cars are very common (Bardout & Hoogzaad, 2017). This is important because the carbon benefits of recycling of construction and demolition (C&D) waste and end of life vehicles (ELVs) arise principally from the displacement of primary materials by recycled materials (Berrill et al., 2021a).

Historically, the focus of policy on C&D waste from buildings has been on air and water pollution from waste disposal (Laquatra & Pierce, 2011). That has evolved over the last three decades, with policies related to recycling enacted across governmental levels throughout much of the world (Bio Intelligence Service, 2011; Clark et al., 2006; Ecorys, 2016; Menegaki & Damigos, 2018; US Environmental Protection Agency, 2017).

Policy in the European Union toward C&D management has grown and evolved significantly as a result of the Waste Framework Directive (WFD) 2008/98/EC (Deloitte, 2017). Laws specifying the 70% C&D recovery targets in the WFD have been enacted by EU Member States with higher targets set by some countries. There are a range of policies for the management of C&D waste including mandatory audits of construction waste, requirements for separation of recyclable materials on-site, recycling rate targets, landfill taxes, and disposal bans. These policies are typically defined in terms of recycling rates, often consider the need to improve markets for recycled materials, and sometimes offer climate mitigation as a rationale in qualitative terms. However, these policies rarely if ever distinguish among materials based on their carbon intensity, nor do they prioritize management for carbon-intensive materials.

Much like policy toward housing, material efficiency policy for ELVs sometimes cites climate benefits, but quantitative goals for GHG emissions reduction are not defined. Regulation of ELVs is present in G7 countries but differs significantly between North America and Europe. In the United States and Canada, regulation focuses on minimizing environmental impacts of recycling processes (Sawyer-Beaulieu et al., 2014). In the United States, for example, the federal Clean Air Act regulates air emissions resulting from the processing of ELVs. Fluids from dismantling and recycling are regulated under the federal Clean Water Act. Regulatory authority is often delegated to state governments with variation in details across states. Recycling rates are not regulated by the federal government and no US state regulation of ELV recycling rates were identified (Junior et al., 2016; Saidani et al., 2019).

In contrast, in the European Union, Korea, and Japan, extended producer responsibility is employed (Saidani et al., 2019; Sakai et al., 2013). Manufacturers are assigned responsibility for achieving designated recycling targets. Here too, climate change mitigation is often cited as one of the motivations for the recycling requirements, but the targets are not defined in terms of the GHG emissions reductions. For example, the EU's End of Life Vehicles Directive makes no mention of climate change[11] and the 2021 European Commission evaluation of the Directive discusses the coherence of the Directive with EU climate change policy stating:

> Although it is currently difficult to appropriately quantify impacts/benefits of end-of-life phase due to lack of robust data, improvements in end-of-life management of vehicles and especially of low-tailpipe emissions vehicles has the potential to reduce greenhouse emissions beyond the transport sector and including from industry, where vehicles are produced, or from waste, where vehicles are recycled....
>
> (European Commission, 2021).

6.3 | Upstream opportunities neglected

Policies advancing material efficiency upstream in the product life cycle—in building design and construction and in automobile manufacturing—are uncommon, likely because material efficiency in production is thought to already be motivated by conventional market incentives. The need for higher levels of efficiency to address climate externalities beyond what market incentives already generate is a new concept. Policy has not caught up.

6.3.1 | Material efficiency policy in building design and construction

Most material efficiency strategies in housing require appropriate design, which building codes encourage or mandate. Building codes are requirements a building must meet to obtain permission for construction and operation from the relevant authority at the national, regional, or local levels. Although they primarily address new construction, building codes can also contain regulations for repair and renovation (Beardsley, 2022; Ching et al., 2012).

Building codes can be both a barrier and an aid to material efficiency. When codes mandate material-intensive designs or make material-efficient designs costly or cumbersome, as when requiring a minimum cement content in concrete (Wassermann et al., 2009), they serve as an impediment. Codes can facilitate material efficiency by mandating specific designs, materials, or performance criteria. Current efforts, however, are primarily directed towards aligning model green building codes, such as the International Green Construction Code (IgCC), with building certification programs, such as the Building Research Establishment Environmental Assessment Method (BREEAM) or Leadership in Energy and Environmental Design (LEED), and on the integration of the model codes with existing codes, which typically do not include material efficiency measures or carbon targets (IgCC, 2018) (See Box 1).

Building *construction* is somewhat different. Some construction practices, such as prefabrication and building information modeling (BIM), can facilitate the use of less material by design, lightweighting of materials, and improved fabrication yields. A few jurisdictions mandate the use of prefabrication or BIM, though not as a means to reduce material use and GHGs.

Prefabrication of buildings and modular building components can facilitate ME in several ways including standardization and efficiency of off-site production, use of ME-related materials and technologies, and prevention or increased recovery of construction scrap. Prefabrication can range from assembly of a few small-scale components such as window frames to complete modular structures (Kamali & Hewage, 2016). Research comparing the environmental impact of conventional and modular construction typically indicates that modular and prefabricated construction generate less waste and fewer GHG emissions (Mao et al., 2013; Quale et al., 2012; Tavares et al., 2018; Teng et al., 2018).

Because of the need to address labor shortages and increase productivity in construction, Singapore has been a leader in policy encouraging the use of prefabrication (Park et al., 2011). The United Kingdom, China, and Hong Kong also have policies that support, set targets, or establish standards for the use of prefabrication (KPMG, 2016; The Hong Kong Chief Executive's Policy Address, 2017; Y. Wang et al., 2021). BIM, the shared use of digital representations of a building project by architects, engineers, contractors, and suppliers, is mandated for public projects in some jurisdictions such as the United Kingdom, Denmark, and the State of Wisconsin (Danish Building and Property Agency, 2018; UK Department for Business, Energy, & Industrial Strategy, 2019; Wisconsin Department of Administration, 2009). Given the dearth of policy evaluations for either prefabrication or BIM, it is difficult to know if these policies reduce material use or GHG emissions.

6.3.2 | Material efficiency policy in car production

Although no regulations or policies were identified that target material consumption in automobile manufacturing, fuel economy and carbon emissions regulations can result in lighter vehicles, especially in passenger cars, when compared to designs that prioritize speed and safety performance.

Even though changes in the materials used can result in higher GHG emissions in car production—as with the substitution of iron and steel with wrought aluminum (Oliveux et al., 2015; Wolfram et al., 2012)—most studies suggest that the GHG emissions avoided via improved fuel economy outweigh the added GHGs incurred during production (Cheah et al., 2010; Kelly et al., 2015; Modaresi et al., 2014; Serrenho et al., 2017), though effects at the fleet level for EVs may be problematic (Billy & Müller, 2023).

Fuel economy standards have been uneven in their subsequent impact on material efficiency. For example, vehicle weight in the United States has increased even while meeting the relatively unchanging fuel economy standards (National Academies of Sciences, Engineering, and Medicine, 2021). A trade-off between vehicle lightweighting and the performance and features in vehicles led An and DeCicco (2007) and Knittel (2011) to conclude that nearly all the

BOX 1 Is green building certification a path to material efficiency?

Certification systems for green building offer a potential pathway for enhancing material efficiency in design and construction. Voluntary environmental certification systems for buildings and construction, such as LEED based in the US and BREEAM in the UK, develop standards and confirm performance which can function de facto as a component of building codes.

Adoption of building certification is increasing (World Green Building Council, 2021), as are policies, such as property tax abatements, to incentivize adoption of building certification (Beardsley, 2022). Public sector procurement policies that encourage green building certification can lead to greater adoption of certification systems (Simcoe & Toffel, 2014). Thus, the incorporation of material efficiency into certification ratings can be a path to policy for material efficiency, but the criteria and details of the systems determine the actual relevance. The chart in Figure 4 depicts the number of US jurisdictions that have incorporated LEED in their construction-related policies in some manner.

Building certification systems typically use a combination of required practices and attributes and optional points to determine certification. In LEED, for example, applicants for certification must meet the required prerequisites as well as accumulate the relevant total of optional credits to be awarded the desired level of certification.

The certification systems often include requirements and credits for practices related to material efficiency. The Residential Single Family Home rating system in LEED 4.1 includes prerequisites for the certification of the sourcing of tropical wood (sometimes related to a ME strategy) and water/moisture management measures. The requirement for water/moisture management measures relate to ME by minimizing water damage in the home thereby increasing durability and longevity.

Many of the LEED rating systems also include categories for the reduction of construction and demolition waste through waste prevention and the reuse, recovery, and recycling of materials. In the Building Design and Construction and Residential Multifamily Homes systems, ME is considered part of the strategy for “Building Life Cycle Impact Reduction” which awards credits for the reuse and salvage of materials and for the use of life cycle assessment (LCA) (US Green Building Council & LEED, 2021). LEED 4.1 also includes additional ME strategies, though not labeled as such, that can earn credits including the use of “environmentally preferable products,” which includes recycled and reclaimed materials (but can also be met through practices unrelated to material efficiency) and implementing advanced framing techniques to reduce material use.

Thus, certification systems can be a double-edged sword. The rating systems provide flexibility in the ways in which certification can be achieved—through the multiple ways in which credits can be earned. While it likely that this flexibility has helped such systems grow, it also means that certification can be obtained without meeting some specific requirements (Todd et al., 2013). It is entirely possible, for example, for a LEED Platinum home—the highest level of certification which requires 80 credits—to meet only the water/moisture management prerequisite without pursuing any other ME strategies.

improvements in automotive technology since the 1990s have aimed to increase power and weight without sacrificing fuel economy. Put another way, advances in fuel economy have been invested in increased performance and comfort rather than additional reductions in fuel consumption and weight. More stringent standards for cars versus light trucks and sport utility vehicles in fuel efficiency standards also provide incentives for manufacturers to increase vehicle size (Whitefoot & Skerlos, 2012). The EU's CO_2 performance standards lead to a similar outcome. They use the mass of vehicles instead of the vehicle footprint to set emission limits. Because standards for heavier vehicles are less stringent, incentives for lightweighting are reduced (Mock, 2017).

Policies other than fuel economy standards and CO_2 regulations can also encourage material efficiency. Norway had a vehicle registration tax based on engine power, weight, and engine size that indirectly encouraged smaller vehicles. However, in 2007, the basis of registration tax shifted to CO_2 intensity. The carbon-based tax may have indirectly continued to incentivize use of smaller vehicles (Yan & Eskeland, 2018). Starting in 2023, the registration tax is based on weight, CO_2 and NO_x emissions and applies to both internal combustion and EVs (Norwegian Tax Authority, 2024). The main purpose of the weight component of the tax is to limit road damage and cover the cost of road maintenance.

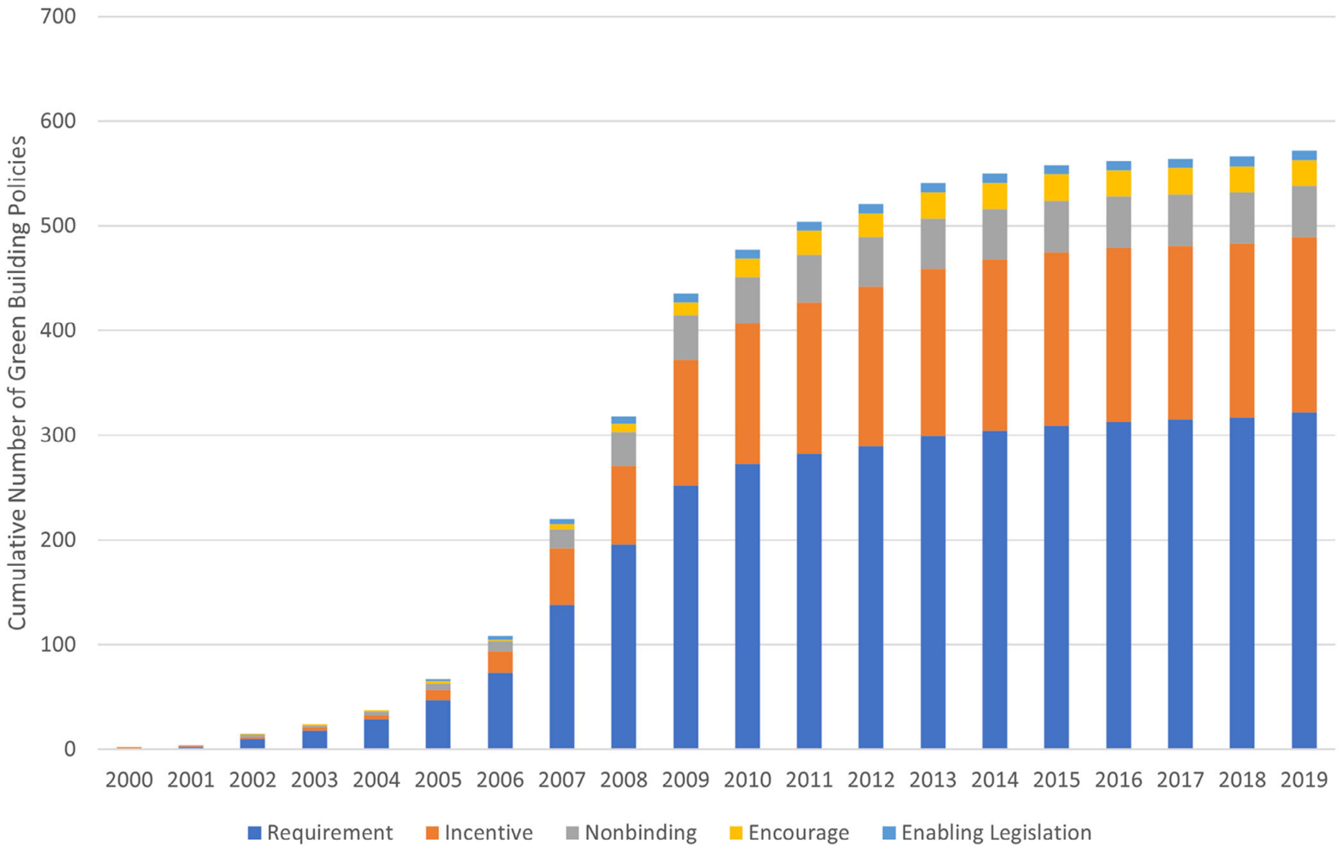

FIGURE 4 Cumulative number of green building policies based on LEED adopted by US jurisdictions by year and policy. *Source*: Adapted from Hertwich et al. (2020). Data from US Green Building Council Policy Library (US Green Building Council, 2021).

6.4 | Weak alignment of material efficiency policies with GHG reduction potential

The RECC report (Hertwich et al., 2020) and follow-on research (Berrill et al., 2021a; Pauliuk et al., 2021) indicate that increased intensity of use has the highest potential for reducing GHG emissions from the life cycle of materials in cars and homes. For homes, this translates into reduction in the square meters per capita. For cars, this means downsizing of vehicles and increased shared mobility through car-sharing and ride-sharing.[12] Material efficiency is rarely cited as a central motivation for policies related to intensity of use and many such policies are barriers to increases in intensity, as described below.

6.4.1 | Increasing use intensity in homes

The intensity of use of buildings can be increased through a variety of approaches including sharing of space, adaptable use of space (leading to more efficient use of built space over time), and reducing space without alteration in function (i.e., smaller homes). Shared housing can take the familiar form of apartments or houses shared by extended families or by unrelated co-inhabitants (e.g., roommates) as well as more novel arrangements such as co-housing and co-living where residents share common spaces such as kitchens (Shulevitz, 2021). All have the potential to decrease the space used per household or person, increasing the intensive use of the building stock and reducing emissions.

Numerous social, political, and economic factors run counter to efforts to reduce housing size. Homeownership is often seen as a form of investment particularly for financial security in old age. Real estate, construction, and financial industries often benefit from larger homes and local governments rely on higher property tax revenues.

Historically many countries have focused on setting standards for the minimum size of housing to ensure decent living conditions.[13] As a result, policies supporting smaller home size are rare (M. Cohen, 2019a). In addition, some policies can discourage shifts to smaller dwellings when home requirements change—as when children move out. For example, real estate transfer taxes (also known as stamp duties), which must be paid for properties or land sold above a specific amount, can deter homeowners from downsizing by reducing the seller's profits from the sale (Fritzsche & Vandrei, 2019; Kopczuk & Munroe, 2015; Ommeren & Leuvensteijn, 2005). According to Scanlon et al. (2017), the United Kingdom's Stamp Land Duty, while a significant source of revenue for the government, is the second most significant factor affecting households' decisions to downsize.

Zoning laws that favor single-family homes and impose minimum lot sizes have played a crucial part in encouraging larger dwellings in the United States. They, in combination with other housing and land-use policies, such as floor-to-area ratios, have heavily influenced the country's urban landscape in ways that intertwine material efficiency considerations with other policy issues including sprawl, housing costs, and racial segregation (Grabar, 2018). In addition, in countries where tax policies support capital gains or extend other tax advantages linked to the value of a home, bigger dwellings are incentivized (M. Cohen, 2016, 2019b).

6.4.2 | Increasing use intensity in cars

More intensive use of private vehicles can be achieved by reducing idle time (i.e., the time a car spends parked) or by increasing vehicle occupancy (i.e., the number of travelers in each ride).

Shared mobility provides access to a private vehicle without the obligations of ownership and can increase vehicles' use intensity through improved capacity utilization—more people per car or trip. There are several types of shared mobility models and their ME and climate change impacts may vary: car-sharing platforms (e.g., ZipCar and Share Now) own and manage fleets of vehicles that are rented to their members, often by the hour; ride-sharing (called carpooling in the United States and car-sharing in the United Kingdom) is a long-standing practice that has evolved to leverage app-based platforms, such as Waze and Scoop, to pair drivers and passengers with similar destinations; ride-hailing services, such as Uber and Lyft, use digital platforms to link drivers, who use their personal vehicles as a form of taxi service, with passengers.

From the perspective of material efficiency, what matters is whether shared mobility decreases overall demand for new cars, resulting in a decline in overall car production. Several studies indicate that some consumers are willing to give up private vehicle ownership once their needs for mobility are met via shared transportation (Becker et al., 2018; Klincevicius et al., 2014; Martin & Shaheen, 2016). For example, one study found that round trip car-sharing, where a car is picked up and returned to a set location, can remove 9–13 vehicles from the road for every shared car (NCSL, 2020). Another study found that 12%–68% of people participating in car-sharing delayed purchasing a new vehicle and 11%–26% sold a vehicle (A. Cohen & Shaheen, 2016). Car-sharing has the potential to lower the rate of ownership for specialized vehicles such as all-wheel drive, seven-seaters, vehicles with longer ranges, or those with larger trunks (Sprei & Ginnebaugh, 2018). In a sharing economy, however, where vehicles are owned and maintained by mobility companies, household vehicle ownership rates may not be a good indicator of the overall demand for new passenger vehicles (Keith et al., 2022).

In addition to fleet size reduction, shared mobility models have the potential to incentivize the use of more fuel-efficient vehicles because cost of the fuel in ride-hailing and car-sharing is often borne by the mobility provider (the Uber driver or Zipcar owner) rather than the consumer (Bellos et al., 2017). Through more intense utilization of vehicles and faster replacement cycles, shared mobility also has the potential to increase fuel efficiency by changing the composition of vehicle fleets, that is, the types and sizes of the cars used, providing the opportunity to take advantage of more efficient technologies available in newer models (Allwood et al., 2012). More intense utilization could also encourage faster adoption of electric and autonomous vehicles by shortening the investment payback period (Material Economics, 2018).

While shared mobility could potentially reduce fleet size and lead to fleet level innovations that can increase material efficiency, this is typically not reflected in policy discourse which often focuses on transport gaps, increasing use of public transit, and EV adoption. Reduction of vehicle ownership and the overall size of the passenger vehicle fleet is less frequently the focus of policy.

6.5 | Limited policy development for many material efficiency strategies

The notion that GHG emissions can be reduced through changes in material use is uncommon in many sectors of the economy. Where it exists, it is largely confined, as noted above, to end-of-life management. While the reduction of

GHG emissions is included as a motivation for end-of-life policies in some cases, no regulations were identified that are based on GHG reduction *targets* or otherwise designed specifically to minimize GHG emissions. Smaller homes and shared mobility illustrate the mixed and often limited nature of ME policy development.

6.5.1 | Policy to encourage smaller homes

A variety of policies have the potential to reduce dwelling size. Carbon taxes or other policies that increase energy prices may lead to smaller homes (Costa & Kahn, 2011). The use of graduated property taxes (GPTs) that have increasing rather than flat taxation rates or are based on dwelling floor space per capita rather than market value are a possible but politically difficult approach. A variety of jurisdictions have unsuccessfully attempted to enact GPTs including Cyprus and the US states of Minnesota and Massachusetts (M. Cohen, 2019a, 2019b). Because policy encouraging downsizing is uncommon, however, little can yet be said about the impact on material efficiency.

In the United States, zoning and land use policies have encouraged large and single-family housing over smaller and multi-family residences. The construction of highways made the development of suburbs feasible often with larger housing lots. Since 1970, there has been a moratorium on federal funding for public housing and a variety of financial policies that increased the cost of capital for multifamily homes and decreased those for single family homes (Berrill et al., 2021a; Morris, 1974). Research suggests that together, these policy changes shifted 14 million residences from multifamily to single-family between 1970 and 2015 (Berrill et al., 2021b).

To address these issues, several jurisdictions in the US, including the states of California and Oregon,[14] have enacted policies to limit zoning that requires single-family dwellings. “Minneapolis 2040” in the city of Minneapolis, Minnesota in the US “upzones” areas near transit and jobs allowing the construction of large multi-family apartment buildings suited to small households. It also reduces zoning that restricts smaller multi-family buildings such as duplexes and triplexes in low-density neighborhoods (Department of Community Planning and Economic Development, 2019; Schuetz, 2018). The policies, if successful, would enhance opportunities for people to move for jobs or schooling, and enable aging inhabitants to downsize without leaving their communities (Grabar, 2018). This could also increase housing density and reduce home size, contributing to a reduction in material consumption.

Local governments can promote smaller homes by allowing accessory dwelling units (ADUs), which permit additional dwellings to be built in open space on parcels with low-density or single-family housing. Constraints on lot size tend to make ADUs smaller and more energy efficient (StopWaste & Arup, 2018).

Infill development, a related strategy, allows for the use of open land within existing built-up areas and often leads to smaller dwellings per household. Smart growth advocates and the new urbanist movement have promoted infill development as a means of reducing sprawl, taking advantage of existing infrastructure, minimizing regional air pollution, and stimulating investment in neighborhoods (McConnell & Wiley, 2011). Neighboring residents frequently oppose infill development, however, due to concerns such as increased congestion, loss of open space, impact on local property values, and increased demand for city services. Efforts to remove barriers to neighborhood densification are not limited to the United States. A recent court decision in the German state of North Rhine-Westphalia confirmed land owners' rights in conflicts with neighbors regarding infill and top-up development facilitating densification of housing in neighborhoods (Marx, 2021).

6.5.2 | Policy toward shared mobility

Ride-sharing has historically been pursued to decrease congestion, emissions, and fossil fuel use by reducing vehicle miles traveled. A variety of strategies are used to encourage ride-sharing including support of infrastructure and access to public rights-of-way, such as high occupancy vehicle (HOV) lanes, park-and-ride facilities, and passenger loading zones (Chan & Shaheen, 2012; Shaheen & Cohen, 2019).

Policies on car-sharing often focus on zoning and parking issues such as provision of dedicated parking space for shared cars (NCSL, 2020). The policies vary in intent: in some communities, they aim to encourage adoption of car-sharing; in others, the objective is to manage competing demand for the use of parking spaces (A. Cohen & Shaheen, 2016).

Policies toward ride-hailing services are more regulatory than promotional, focusing on the behaviors of drivers and companies (Goodin & Moran, 2016). The regulations are aimed at non-environmental aspects of the operation of ride-hailing and do not explicitly consider ME-related impacts. A variety of other environmentally-related policies including zero-emission vehicle requirements, participant subsidies, and transit discounts, are also not aimed at material efficiency. However, policies that mandate or privilege shared rides, encourage integration with public transit, or restrict ride-hailing to reduce congestion may increase capacity utilization and potentially material efficiency (Kim et al., 2018; Schaller, 2018).

Policies aimed at fostering or regulating shared mobility can be hindered by issues of data availability.

Shared mobility companies are often reluctant to share data, impeding informed policy making (Cooper et al., 2015). Some ride-hailing companies have threatened to leave markets due to regulations requiring data sharing, while others have voluntarily offered data in exchange for reduced regulation, such as in Portland, Oregon.

6.6 | Rigorous quantitative ex post policy evaluation is uncommon

While sophisticated studies of the potential climate benefits of material efficiency are increasing (e.g., Ivanova et al., 2020; Pauliuk & Heeren, 2021; Scott et al., 2018, 2019), rigorous quantitative studies of effectiveness of ME-related policies are uncommon. The absence of such evaluation can reflect a lack of expertise and resources, or political incentives to avoid assessment. The novelty of some types of ME policy as discussed above (e.g., favorable parking and zoning for ride-sharing) is likely to play a role as well. Effective policy evaluation requires that programs reach an adequate level of maturity if reliable inferences are to be drawn. Governance systems also need to have appropriate methods and procedures for policy evaluation in place.

Material efficiency policy aiming to reduce GHG emissions must achieve both a reduction in the mass of materials used *and* a reduction in emissions. Evaluating the latter typically involves the use of LCA if system-wide impacts are to be quantified. It is important to know if the benefits of a policy to reduce material use or GHGs in one lifecycle stage are offset by increases in another stage.

Policies related to end-of-life management such as recycling mandates, landfill taxes, etc. are monitored in some jurisdictions. In many cases, however, tracking is limited to uptake of policies—how many jurisdictions have implemented policies. Tracking changes in the quantity of materials deposited in landfills or incinerated in waste-to-energy facilities is somewhat more meaningful. However, changes in the quantities disposed can be due to shifts in the economy, population, related policies, and a host of other factors. Even where policies are reviewed in detail (e.g., the evaluation of the EU End of Life Vehicles Directive; European Commission, 2021), use of analytic methods to estimate policy effectiveness is rare. Thus, ex post evaluations, counterfactual analysis, and experimental studies are needed in addition to GHG modeling.

7 | REBOUND EFFECTS

Like all efficiency strategies, material efficiency faces the challenge of rebound effects. Increases in efficiency can free up resources that increase demand leading to a net increase in consumption. As a result, to varying degrees, where a rebound occurs, the benefits of efficiency are partially or completely negated (Sorrell, 2007).

Ignoring rebound effects in policy assessments can thus lead to an overestimation of the materials, energy, and emissions saved through these measures (Font Vivanco et al., 2018; Zink & Geyer, 2017). Although some argue that energy or resource efficiency policies can "backfire," that is, lead to an overall increase in environmental burdens, studies suggest that microeconomic rebound effects often offset 20%–40% of the anticipated gains (Font Vivanco et al., 2018; Gillingham et al., 2016). To date, the impact of rebound effects on the effectiveness of ME measures has been ignored in most policy analyses.

Policy instruments that directly or indirectly raise the cost of production or consumption can reduce rebound effects (van den Bergh, 2011; von Weizsäcker et al., 2014). If ME strategies reduce the cost of materials, taxes can mitigate rebound effects by limiting savings. Cap and trade systems, which indirectly increase production or consumption costs, can also reduce rebound effects. However, the effectiveness of policies to counteract rebound is difficult to predict because many ME policies are relatively new, because rebound effects for resources other than energy are less extensively studied, and because the quantification of macro-level rebound effects is very complicated.

8 | THE NEED FOR POLICY DEVELOPMENT

If increased material efficiency is to contribute to climate change mitigation, many kinds of policy development are needed. The RECC modeling of ME strategies suggests that this is worth the effort—on the order of one third of emissions from housing or car travel can be saved according to the RECC report.

To contribute to the reduction of GHG emissions, material efficiency policy must both reduce material use and GHG emissions. This implies a need for greater understanding of the likely outcomes and efficacy of ME policies and a strategy for adoption. A good starting point is to better understand the impact of existing ME policies. Do the policies change the behavior of organizations and individuals? Waste-focused ME policy has been in place for decades. Yet, while there is considerable research on the outcomes of specific waste *strategies* in both mass and GHG terms, research that connects outcomes to specific *policies* is uncommon.

It is nearly a platitude to say that increased policy evaluation, especially ex post assessment, would help policy makers adjust policy strategies based on better understanding of outcomes. Ideally, LCA or related systems-level methods would be used to quantify changes in materials use and emissions through the product life cycle. The ODYM-RECC model, for example, addresses all steps of a product life cycle while modeling product cohorts at scale and over time, taking into account regional differences in electricity mixes and composition of the product cohorts (Hertwich et al., 2020; Pauliuk et al., 2021; Pauliuk & Heeren, 2020).

Experimentation where policies are tried and evaluated could benefit both existing and novel policies. By implementing policies with a deliberate focus on data collection, analysis, and detailed examination of outcomes, gaps in the understanding of the efficacy of ME policy could be reduced. Modeling of climate policy also needs to include the impact of macro-level instruments such as carbon taxes on material use and related GHG emissions.

In end-of-life management, the current focus on the diversion of waste from landfill needs to shift to the prioritization of GHG reduction. This would entail identification of wastes with a large carbon footprint and tailoring strategies to them. The State of Oregon has worked to move in this direction by integrating LCA in its development of waste policy (Lifset et al., 2023). Fees used to augment extended producer responsibility for packaging and paper reward evaluation and disclosure of life cycle environmental impacts. The largest 25 producers subject to EPR must also evaluate and disclose life cycle environmental impacts for 1% of their portfolio of covered products every 2 years.[15]

To realize the benefits of increased intensity of use of homes and cars, supportive policy is needed which in turn requires both political and social change. Efforts to change zoning in the United States in ways that are conducive to less floor space per person in dwellings face strong interest group opposition (Whittemore, 2021), deeply embedded norms equating single family homes and larger homes with social and economic success, and an array of laws and regulations generating contrary incentives. Rather than seeking an absolute reduction, directing policy interventions toward avoiding growth in dwelling size might be more politically feasible.

Policies that indirectly stimulate consumption related to land use and transport, such as commuter tax credits, tax treatment of mortgages, and subsidized parking that supports longer distances between home and work, bear scrutiny for their effects on material efficiency. Scholarship on the connection to material use is limited and the efficacy and unrelated consequences of altering such policies are unclear.

Economy-wide ME policies are needed. Many jurisdictions provide subsidies for their primary resource industries, particularly in economies dependent on mineral extraction. These subsidies often indirectly contribute to climate change impacts by hindering the market shift toward greener and more resource-efficient options. Much of the research on this topic has focused on subsidies for fossil fuels and stranded assets (McCarthy & Börkey, 2018; OECD, 2005). Subsidies for non-fuel, primary material extraction are nonetheless considerable (PCT, 2009). A broad range of direct and indirect subsidies for primary metals have been identified by the OECD, but a comprehensive cross-country database on government support detailing measures and commodities is lacking (McCarthy & Börkey, 2018). Improved understanding of non-fuel subsidies is needed as their removal could make a powerful contribution to material efficiency.

In addition to lowering or removing such subsidies, countries could impose taxes on primary materials. Such taxes are uncommon and are typically limited to minerals (Bahn-Walkowiak & Steger, 2015). Bibas et al. (2021) modeled a combination of a materials tax and subsidy for recyclers and found that such a tax could reduce primary materials use by approximately 7% with limited impact on global economic activity and achieve approximately a 6% reduction in global warming potential.

9 | CONCLUSION

The RECC report and related literature indicate that material efficiency can make a significant contribution to reducing GHG emissions. ME policies related to the end-of-life management of homes and cars are very common and focus on the diversion of waste from disposal. While some ME policies identify the reduction of GHG emissions as a rationale, very few organize the policies to maximize emissions reductions or employ quantitative targets for that purpose. Put another way, framing efficient use of materials as a measure *primarily* intended for climate mitigation is new and uncommon.

Because not all material efficiency strategies lead to emissions reductions, it is not sufficient to simply measure changes in material production and use. The carbon footprint of those activities must also be calculated. This in turn means that data must be systematically generated and analyzed from a systems perspective.

Many material efficiency policies are novel and untested, and much existing policy has not been subject to ex post policy analysis. If this addition to the portfolio of carbon reduction strategies is to be effective, policies not only need to be established and expanded, but the assessment of their impact must also become the rule, rather than the exception.

AUTHOR CONTRIBUTIONS

Reid Lifset: Conceptualization (lead); investigation (lead); project administration (lead); supervision (lead); writing—original draft (lead); writing—review and editing (lead). **Edgar Hertwich:** Formal analysis (lead); writing—review and editing (supporting). **Tamar Makov:** Investigation (equal); writing—review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

OPEN RESEARCH BADGES

This article has earned Open Data, Open Materials and Preregistered Research Design badges. Data, materials and the preregistered design and analysis plan are available at https://doi.org/10.5281/ZENODO.7789798.

DATA AVAILABILITY STATEMENT

Data used to calculate material and energy efficiency commitments in the second round of Nationally Determined Contributions for the G20 countries is available in Zenodo (Lifset, 2023). No other new data were created or analyzed in this study.

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ENDNOTES

[1] Some researchers have preferred the term material productivity (Scott et al., 2019) or (reduction of) material consumption.

[2] Descriptions of the related frameworks can be found in the Supporting Information.

[3] See https://resourcepanel.org.

[4] Light duty vehicles (LDVs), a category of vehicles defined as having maximum gross vehicle weight rating of less than 8500 pounds (≈3856 kg) were modeled in the RECC report. LDVs include passenger cars and smaller trucks. In the analysis described in this article, LDVs were modeled. Unless the specific composition of that category is being addressed, as in the modeling, LDVs are referred to as cars in this article for brevity.

[5] Unless otherwise noted, all tons mentioned in this article refer to metric tons (1 metric ton ≈ 1.102 short tons); 1 gigaton (Gt) = 1 billion metric tons.

[6] The numbers presented in this article, unless otherwise noted, are carbon footprints, that is, GHG emissions arising from production and use of a product or material. While the definition of carbon footprints varies among researchers, in this article it refers to the upstream portion of the product life cycle, from resource extraction to materials processing, product manufacture, distribution and use; It does not include end-of-life impacts. Similarly, consistent with cut-off allocation in life cycle assessment, where the costs and recycling credits are assigned to the next life cycle, the lifecycle emissions reported in the text do not include end of life unless otherwise noted.

[7] Developed by the climate change research community, the shared socioeconomic pathways (SSPs) describe plausible global developments that could result in different challenges for climate change mitigation and adaptation (Riahi et al., 2017). Five SSPs present differing futures with SSP1 depicting an ideal scenario, while SSP2 is considered a moderate one. The low energy demand (LED) scenario describes future change resulting in less energy demand (Grubler et al., 2018).

[8] https://www.resourcepanel.org/about/steering-committee.

[9] The UK is a pioneer in this respect. The UK Climate Change Committee discussed resource efficiency in 2020 as a means of climate mitigation as a part of its Sixth Carbon Budget (Climate Change Committee, 2020) and in 2023, the UK government estimated the reduction of GHG emissions through increased resource efficiency in support of proposed carbon policies (HM Government, 2023).

[10] INDCs refer to commitments proposed by countries before they formally join the Paris Agreement. Once they have done so, "intended" is dropped.

[11] Directive 2005/64/EC of the European Parliament and of the Council of 26 October 2005 on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability and amending Council Directive 70/156/EEC.

[12] Another form of shared mobility, ride-hailing, as in the familiar services of Uber and Lyft, is generally thought to increase GHG emissions because of a large of number of single passenger rides, dead-heading, that is, the need for vehicles to travel to passengers, and induced demand (i.e., Diao et al., 2021; Meshulam, Goldberg, et al., 2023; Schaller, 2021; Ward et al., 2021).

[13] See, for example, the International Code Council, an association responsible for setting the standards that govern the design and construction of buildings.

[14] See https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220AB2011 and https://www.oregon.gov/lcd/Housing/Pages/Choice.aspx.

[15] See ORS 459A.944 and https://www.oregon.gov/deq/recycling/Documents/recSB582Bsectsum.pdf.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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