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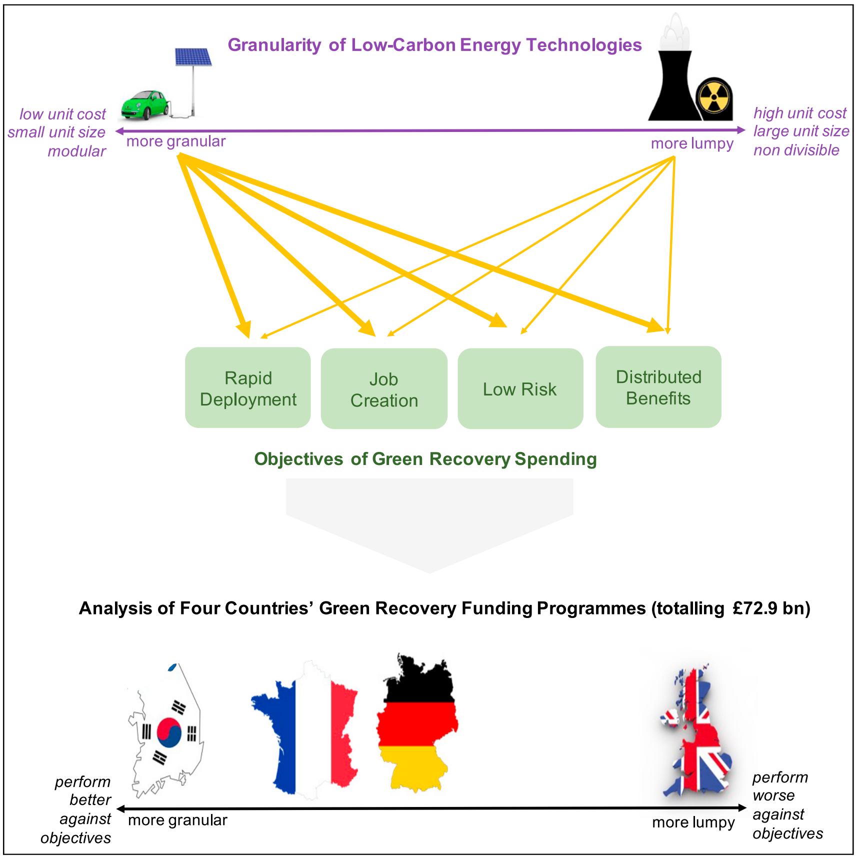

Building back better after the COVID-19 pandemic means public investment in low-carbon technologies that deploy rapidly, create jobs, and distribute benefits widely. These desirable criteria are all associated with small-scale "granular" technologies like solar panels with relatively low unit investment costs—compared with large-scale "lumpy" technologies like carbon capture and storage. Countries vary widely in the technological granularity of their green recovery funding programs, with the UK as an outlier in the lumpiness of its investment choices.

Highlights

Size matters for green recovery: smaller-scale energy technologies perform better

Technological granularity is an important design criterion for investment programs

Green recovery funding priorities vary widely by country and by sector

Concentrating public monies on a small number of megaprojects is risky

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Building back better: Granular energy technologies in green recovery funding programs

Charlie Wilson,[1,2,4,*] Simon De Stercke,[2,3] and Caroline Zimm[2]

SUMMARY

Granular energy technologies with smaller unit sizes and costs deploy faster, create more jobs, and distribute benefits more widely than lumpy large-scale alternatives. These characteristics of granularity align with the aims of fiscal stimulus in response to COVID-19. We analyze the technological granularity of 93 green recovery funding programs in France, Germany, South Korea, and the UK that target £72.9 billion for low-carbon energy technologies and infrastructures across five emissions-intensive sectors. We find that South Korea's "New Deal" program is the most technologically granular with strong weighting toward distributed renewables, smart technologies, electric vehicle charge points, and other relatively low unit cost technologies that are quick to deploy. The UK has the least granular portfolio, concentrating large amounts of public money on small numbers of mega-scale energy projects with high implementation risks. We demonstrate how technological granularity has multiple desirable characteristics of green recovery: jobs, speed, and distributed benefits.

INTRODUCTION

Following the 2007–2008 global financial crisis, governments around the world mobilized massive fiscal stimuli to pull economies out of recession. From a climate perspective, the great hope was that public investment would be aligned with decarbonization objectives. This largely failed to happen.[1] Only 16% of the spending was on green measures,[2] although green stimulus projects performed well in terms of job creation compared with traditional fiscal measures.[3–5]

In the fifteen years since the global financial crisis, political support for decarbonization and energy transition objectives has strengthened, creating more favorable conditions for low-carbon investment and spending.[6] Following COVID-19-induced economic contractions in 2020, oft-heard calls to "build back better" echoed those made over a decade ago to align fiscal stimulus with decarbonization.

In simple terms, "building back better" means green recovery spending that acts quickly to support or boost employment and economic activity while helping reduce greenhouse gas (GHG) emissions over both short and long terms.[7]

Different indicators have been proposed for assessing "betterness." These include the following: employment, economic activity, timeliness, impact on government budgets, GHG emissions, other environmental benefits, and social benefits including reduced poverty and inequality (Table 4.1 in Höhne et al.[7] compiled from data in IEA,[8] World Bank,[9] Hepburn et al.,[10] Jotzo et al.,[11] O'Callaghan et al.,[12] and Vivid Economics[13]). Similar sets of indicators are provided in Watkins et al.[14] and OECD.[15]

CONTEXT & SCALE

Governments mobilized trillions of dollars of public money to help economies recover from COVID-19. This was a unique opportunity to align massive fiscal stimulus with the urgent need to rapidly decarbonize energy systems. Did countries seize this opportunity to "build back better"? We show how the answer lies in the size of low-carbon technologies targeted by recovery funding. Small-scale "granular" technologies like solar panels or electric vehicles with relatively low unit investment costs deploy more rapidly, create more jobs, and distribute benefits more widely than large-scale "lumpy" technologies like nuclear power or carbon capture and storage. Against this technological granularity criterion, South Korea performed well and the UK poorly, choosing to concentrate a large amount of money on a small number of low-carbon megaprojects. Embedding granularity in the design of low-carbon investment programs can help accelerate progress on climate change mitigation.

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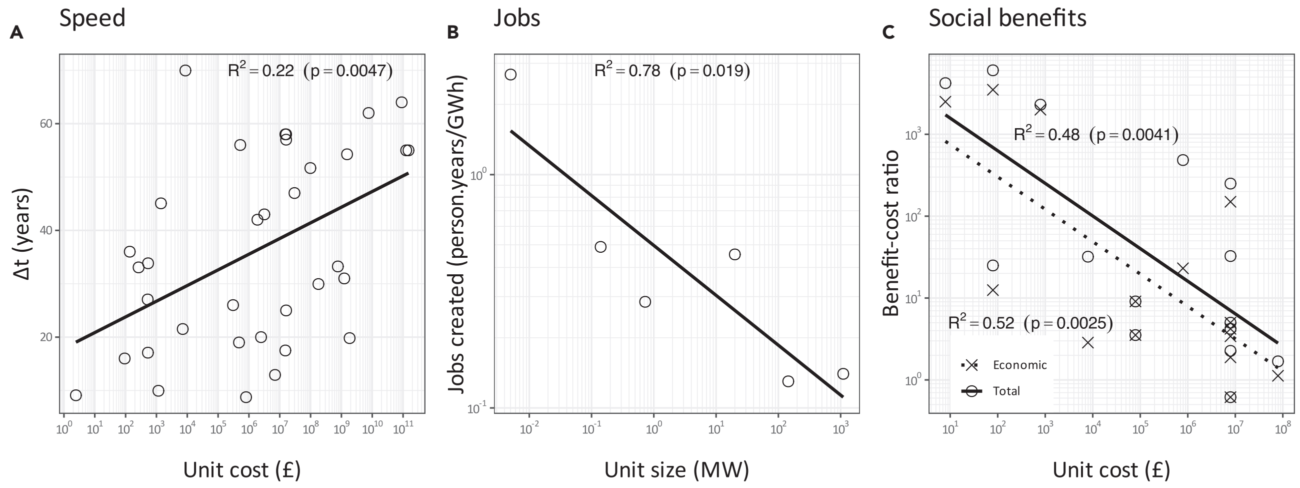

Figure 1. Three benefits of technological granularity for green recovery spending

Left panel (A shows shorter diffusion timescales; middle panel (B) shows more net jobs created; and right panel (C) shows higher social returns on investment. Unit cost and unit size are strongly correlated and interchangeable as measures of granularity (x axis). Each point represents an energy technology. Best fit lines (with R^2s and p values from bivariate models fitted to the data) show general relationships averaged over diverse energy technologies (listed in full in supplemental information).

Source: adapted from Wilson et al.[16]

See also Data S1.

In this article, we propose, test, and analyze an additional metric of "build back betterness," drawing on recent research that demonstrated the advantages of granular energy technologies for accelerated decarbonization.[16] Granularity means low unit costs, low unit sizes, modularity, and growth through replication (e.g., solar panels and home insulation). In contrast, lumpy means high unit costs, large unit sizes, indivisibility, and growth through upscaling (e.g., nuclear power plants, and whole-home retrofits). By unit, we mean the lowest functional specification of a technology before the inclusion of infrastructure or other conditions required for its operation (see Experimental procedures).

Drawing on a wide range of historical data, Wilson et al.[16] showed empirically that more granular technologies deploy faster, create more net jobs, and provide higher social returns on public investment. Figure 1 shows these three benefits with each data point representing an energy technology, ordered from left to right along the granular to lumpy continuum (for which unit cost and unit size are interchangeable as a metric). The historical technology dataset spanned energy supply, energy end use (transport and buildings), industry, and manufacturing, generalizing across both deployment and manufacturing contexts (or consumption and production type activity).

Additional benefits of more granular technologies not shown in Figure 1 are that they have lower implementation risks, they learn more rapidly, i.e., improve faster in cost and performance (see also Sweerts et al.[17]), they are less susceptible to lock-in, they are more widely distributed and accessible, and they have larger potentials for efficiency improvements.[16]

Granularity is a relative, not an absolute measure. In each of the major GHG-emitting sectors of the economy, mitigation options span the granular to lumpy continuum. In the building sector, smart thermostats or insulation panels (£10^{2-3}/unit) are more granular than whole-building deep energy retrofits (£10^{5-6}/unit). In the energy

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Table 1. Summary statistics of green recovery funding programs in four countries

	France	Germany	South Korea	United Kingdom	Total
Total recovery funding (£bn)	21.7	18.8	24.4	8.0	72.9
Recovery funding programs (#)	24	21	23	25	93
Average program size (£bn)	0.90	0.89	1.06	0.32	0.78
Min-max program size (£bn)	0.05–4.18	0.02–3.03	0.01–3.50	0.01–2.00	–

The full dataset is available in supplemental information.

sector, solar panels or battery storage (£10^{3-4}/unit) are more granular than a nuclear power plant or carbon capture and storage (CCS) facility (£10^{9-10}/unit). In transport, electric vehicles (EVs, £10^4/unit) are more granular than public transit systems (£ > 10^5/unit). In industry, hydrogen electrolyzers (£10^{4-7}/unit) are more granular than steam-reformed hydrogen production with CCS (£10^8/unit). All these examples are targeted by green recovery funding programs.

We use technological granularity as a single indicator associated with multiple desirable characteristics of green recovery (Figure 1): more rapid deployment of low-carbon technologies with higher employment multipliers, higher environmental and social returns on public funds invested, and more widely distributed and accessible benefits.[16]

Our aim is to provide a simple and transparent approach for comparing and contrasting green recovery spending against energy transition and climate change policy needs in the aftermath of the COVID-19 shock. We demonstrate this approach by evaluating the granularity of low-carbon technologies and infrastructures targeted in the COVID-19 recovery funding programs announced in 2020 by four countries: France, Germany, South Korea, and the United Kingdom (Table 1). These countries accounted for 46% of all green recovery spending at that time[12]; see supplemental information for details of country selection.

Our research approach uses novel estimates of granularity (£/unit) for each of the low-carbon technologies and infrastructures identified in these four countries' green recovery funding programs. This approach is sensitive to uncertainties in our definition of a "unit" as the lowest functional specification of a technology. For example, a wind turbine and a hydrogen electrolyzer are technological units analyzed in green recovery funding programs targeting offshore renewables or green hydrogen production, respectively, but both technologies can vary in unit size (see Experimental procedures).

RESULTS

Types of economic activity targeted by green recovery funding programs explain differences in the technological granularity of countries' overall funding portfolios

Figure 2 shows the technological granularity of each country's green recovery funding programs, ordered left to right from most granular to most lumpy. Recovery funding in all four countries targets low-carbon technologies and infrastructures spanning the granular to the lumpy continuum (y axis). However, curves that rise more slowly (e.g., South Korea) indicate portfolios with a more granular weighting compared with curves that rise more steeply and that are weighted more toward lumpy technologies and infrastructures (e.g., the UK).

Across their full portfolios of green recovery programs, South Korea, France, and Germany have a similar overall technological granularity. If the average unit cost

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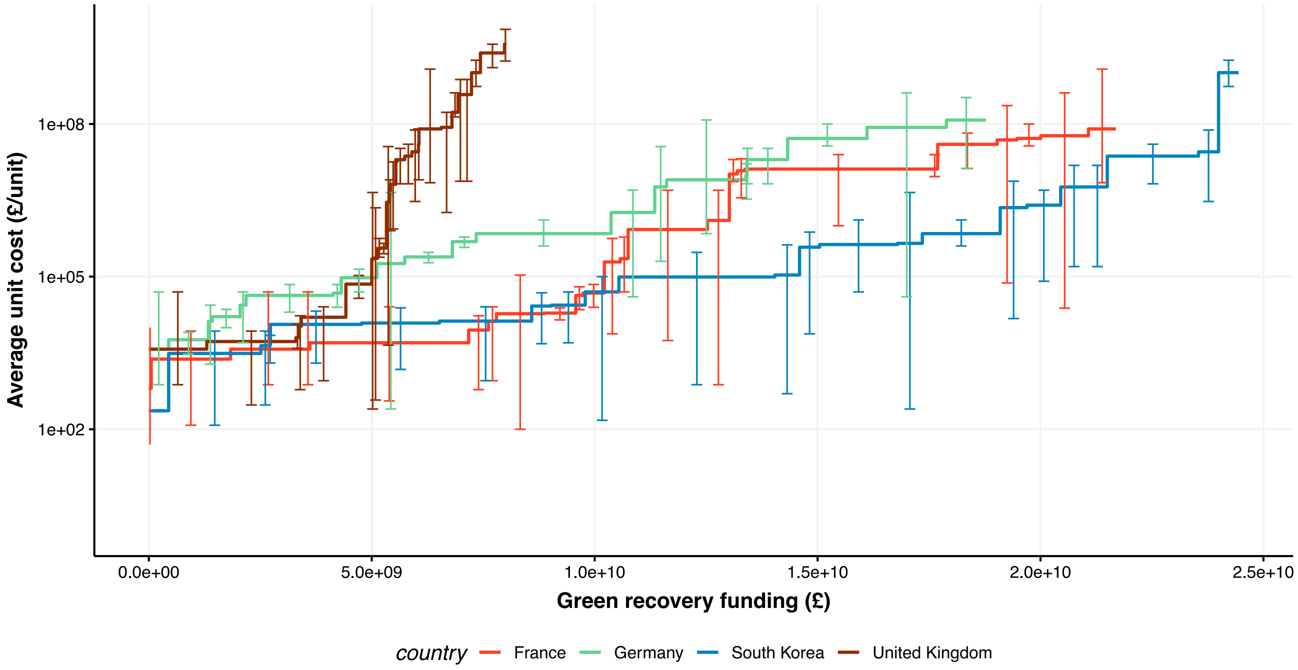

Figure 2. Green recovery funding (£, x axis) for low-carbon technologies and infrastructures of varying unit costs (£/unit, y axis) for four countries
Vertical error bars show low-high uncertainties around unit cost estimates due to variation in the specification of discrete technologies (e.g., different size wind turbines) and variation between technologies within a given funding program (e.g., energy efficiency in buildings); see experimental procedures for details.

of each technology targeted is weighted by the size of its corresponding funding program, all three countries have an average granularity in the range of £13–22m per unit investment (i.e., seven orders of magnitude, or O.M. £10^7). The UK is strikingly anomalous: average unit costs are an order of magnitude higher around £238m (O.M. £10^8).[18]

The UK announced some relatively large funding programs targeting granular technologies in the buildings and transport sectors, including £2bn for residential efficiency measures, heat pumps, and rooftop solar photovoltaics (PV) and £1.3bn for EV charging points in urban areas. However, the overall UK portfolio is skewed by a concentration of funding programs targeting large-scale energy and industrial facilities including nuclear power, CCUS (carbon capture, utilization, and storage), and blue hydrogen (steam-reformed natural gas with CCS) with unit costs in the range O.M. £$10^{8\text{-}9}$.We explore these issues further below.

Countries vary in their relative emphasis on the supply or demand-side stimulus. Recovery funding can directly incentivize consumer spending on low-carbon technologies (“consumption”), support the production and manufacturing of low-carbon technologies and resources (“production”), or invest in infrastructure or capital formation as an enabler of low-carbon technology deployment (“infrastructure”).[19] A systemic approach to green recovery funding would see balance across all three types.[20]

Although consumption-side spending typically incentivizes deployment through the final adoption of technologies by end users (e.g., EV purchase subsidies),

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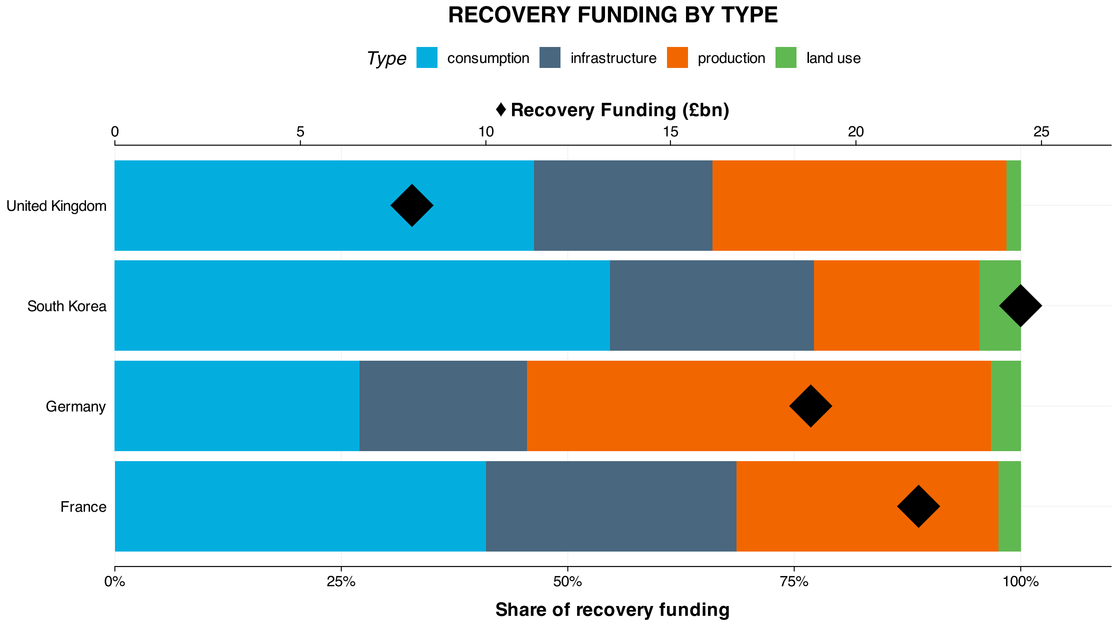

Figure 3. Total amounts of green recovery funding programs targeting consumption or production activity in four countries

Diamonds show total per country (upper x axis), bars show % of the total for consumption, production, infrastructure, and land use (lower x axis).

infrastructure and production-side spending invests in construction activity (e.g., EV charging networks), and manufacturing facilities (e.g., EV production lines). We use the term "materialization" to capture these different ways in which recovery funding increases the stock of low-carbon technologies and their enabling infrastructures. This is consistent with the historical data (Figure 1) and with the green recovery funding programs, as both span consumption and production-side technologies.

Across all four countries, 43% of green recovery spending targets consumption (with end users as direct beneficiaries), 31% targets production (with generally large manufacturers and other firms as direct beneficiaries), and 23% targets infrastructure. However, this varies between countries (Figure 3). The South Korean portfolio is weighted more toward consumption (55%), whereas the German portfolio is weighted more toward production (51%).

These weightings in turn help explain differences in the technological granularity of each country's overall portfolio of green recovery funding programs. Unit costs are lower in consumption sectors with households and firms as the direct beneficiaries of demand-pull recovery funding, and unit costs as low as O.M. £10^2. Hence, consumption-oriented portfolios like South Korea's are more granular. Conversely, unit costs are higher in production and infrastructure sectors, strengthening supply-side conditions for technology development and deployment, with firms, manufacturers, industrial plants, energy utilities, and national infrastructure operators as the direct beneficiaries of recovery spending, and unit costs up to O.M. £10^9. The UK is anomalous as its green recovery funding programs are weighted toward consumption (46%), but the very lumpy characteristics of its production-side investments (32%) markedly reduce the overall technological granularity of its portfolio.

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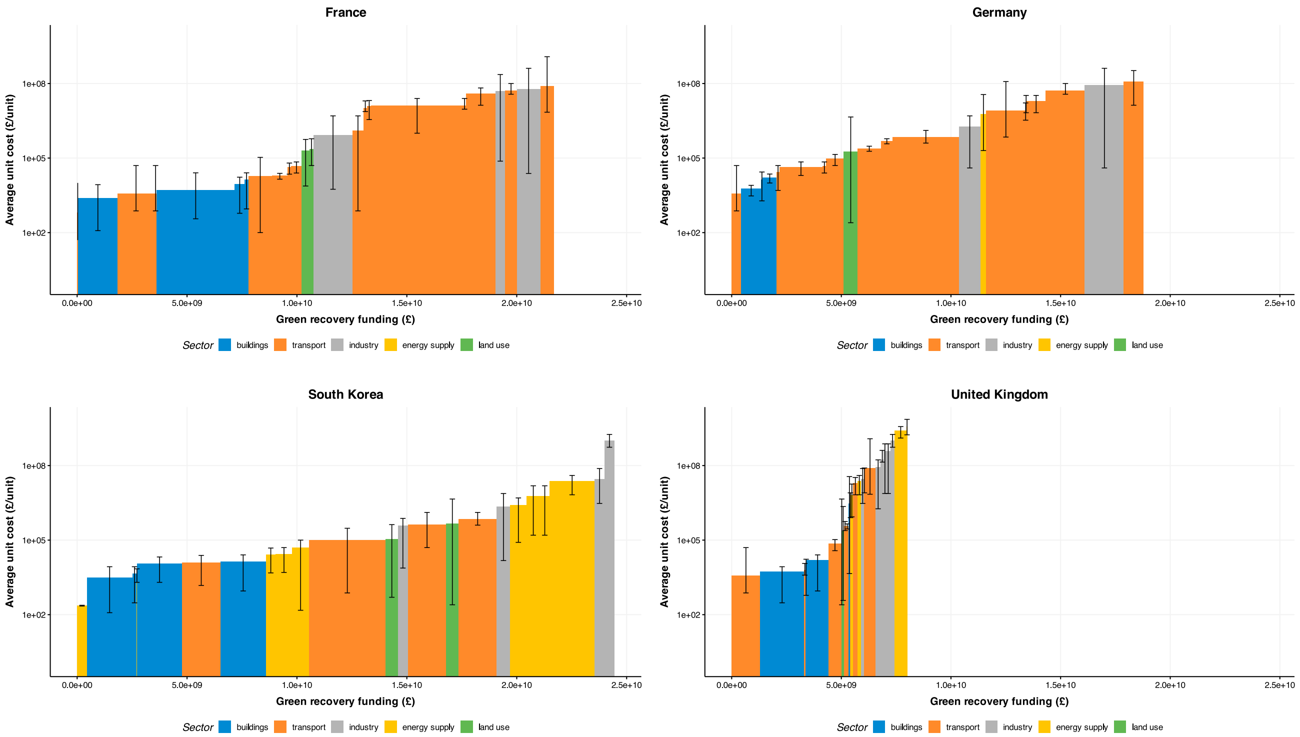

Figure 4. Green recovery funding (x axis) for low-carbon technologies and infrastructures of varying unit costs (y axis)
Colored blocks correspond to different sectors. Note that the x axis (not the area of each block) shows cumulative total funding. Vertical error bars show low-high uncertainties around unit cost estimates due to variation in the specification of discrete technologies and variation between technologies within a given funding program (see experimental procedures for details).

Emissions-intensive sectors targeted by green recovery funding programs explain differences in the technological granularity of countries' overall funding portfolios

Figure 4 breaks down each country's green recovery funding programs by sector. Average unit costs of low-carbon technologies and infrastructures vary across countries in some sectors but not others. Variation is low for land use and industry, high for transport and buildings, and very high for energy supply.[21] This is due to variation in the technologies targeted within a sector.

As an example in the transport sector, Germany's funding programs include R&D activity and manufacturing scale-up for low-carbon aviation and shipping (unit costs of O.M. £$10^{7\text{-}8}$) as well as automotive and hydrogen production facilities (O.M. £10^{7}). In contrast, South Korea's funding programs predominantly target LPG conversions, EV purchases, and distributed recharging infrastructure with average unit costs in the range of O.M. £$10^{3–4}$.

As another example in the energy supply sector, South Korea's funding programs target smart meters and rooftop solar (O.M. £$10^{2–4}$) as well as smart control systems in water, energy, and sewage systems (O.M. £10^{5}). In contrast, the UK has four funding programs in this sector that target clean heat networks (O.M. £10^{6}), port infrastructure for offshore wind farms (O.M. £10^{7}), and a new generation of nuclear power plants (O.M. £10^{9}).

Overall, across all four countries, the transport sector accounts for 51% of the total green recovery funding, followed by buildings (23%), industry (12%), energy supply

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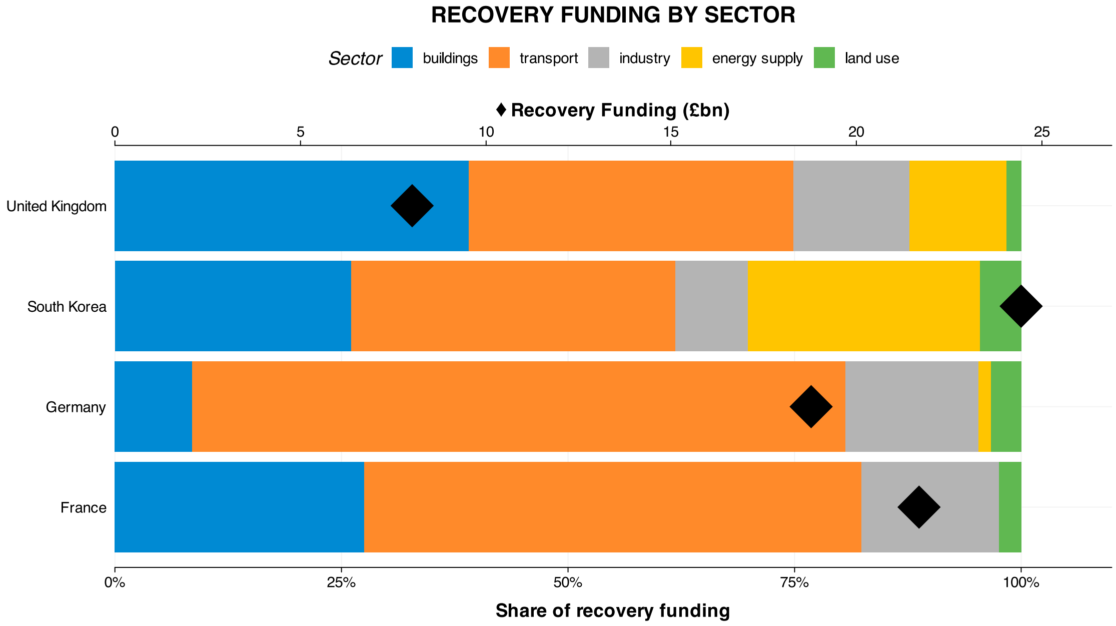

Figure 5. Total amount of green recovery funding programs across five economic sectors in four countries

Diamonds show total per country (upper y axis), bars show % of total for buildings, transport, industry, energy supply, and land use sectors (lower x axis).

(10%), and land use (3%) (Figure 5). That the transport sector dominates is unsurprising as it was particularly hard hit by policy responses to COVID-19 that restricted physical mixing and travel. However, the breakdown of countries' funding portfolios by sector reveals their characteristic policy needs and economic strengths. Three differences are particularly striking.

First, the German portfolio is strongly weighted toward transport (72%), reinforcing the country's strategic leadership in the automotive industry, vehicle electrification, and hydrogen infrastructure development.

Second, the UK portfolio has the highest share allocated to the buildings sector (39%), reflecting the characteristic inefficiency of the UK building stock and the lack of effective sectoral policies prior to the pandemic.[22]

Third, the South Korean portfolio is the only one with a significant share (26%) invested in energy supply resources and infrastructure (microgrids, power networks, smart meters, offshore wind, and other renewables). South Korea has a national grid unlike the increasingly interconnected European electricity network, and progress on power sector decarbonization is less well-advanced. Around two-thirds of South Korean electricity is generated by fossil fuel combustion compared with less than half in Germany and the UK and significantly less in France.[8]

These different sectoral emphases are shaped by countries' political, economic, and institutional conditions—what Geels et al.[20] call "critical antecedents." The economic importance and competitive advantage of domestic industries and sectors explain Germany's emphasis on EVs[23] and hydrogen[24] as potential export growth industries. Longstanding economic concerns over unemployment explain France's emphasis on building retrofit, particularly in the public sector to signal state leadership. Legally binding climate mitigation targets coupled with weak policies and

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progress in the buildings sector explain the UK's emphasis on retrofit but largely in the private sector, given the strong associations between property market activity and economic growth.[20]

Alongside these differences, a striking similarity between all four countries is that the land use sector received less than 5% of the total green recovery funding, despite the significant potential for near-term climate mitigation benefits. For example, the recent Dasgupta Review noted: "Large-scale and widespread investment in 'Nature-Based Solutions' would help significantly contribute to climate change mitigation and adaptation, not to mention wider economic benefits, including creating jobs. As part of fiscal stimulus packages in the wake of COVID-19, investment in natural capital has the potential for quick returns."[25]

The sectoral breakdowns of the four countries' green recovery funding programs further explain their respective granularity. Low-carbon technologies and infrastructures in the building sector tend to be more granular (with unit costs in the range of O.M. £$10^{3–4}$) as they predominantly target efficiency upgrades and renewables through discrete measures such as solar PVs, heat pumps, insulation, and light-emitting diode (LED) lighting. These adoption incentives to homeowners or social housing providers stimulate the deployment of low-carbon technologies. Green recovery funding programs in the buildings sector tend not to target supply chains or production systems with higher unit costs such as the offsite manufacturing of whole-home retrofit solutions (O.M. £$10^{5–6}$).[26]

In contrast, transport sector funding programs target not just the deployment of low-carbon technologies through consumer adoption but also the design, development, manufacture, and integration of low-carbon technologies by producers and infrastructure providers. Consequently, average unit costs in the transport sector are much higher as ranges for consumer technologies like EVs (O.M. £10^5) are pulled up by the two to three orders of magnitude higher unit costs of investment in EV production and assembly lines, scaling up battery manufacturing, and building hydrogen refueling infrastructures (O.M. £$10^{7–8}$).

Green recovery funding programs in the energy supply sector similarly target both consumption and production. Unit costs range from O.M. £10^2 (single smart meter installations in apartments) through to O.M. £$10^{5–6}$ (microgrids) up to O.M. £10^7 (offshore wind) and O.M. £10^9 (nuclear reactors).

As the industry sector only has production-side investments, average unit costs as a measure of granularity are the highest of all the sectors, and all beneficiaries are necessarily firms (rather than consumers). Unit cost estimates for industry are also the least certain, as reported costs and variability for discrete investment targets like "automotive manufacturing production line" are less readily available than for consumer goods like EVs. Discrete investments supported by recovery funding in industry vary widely in terms of unit costs from O.M. £$10^{4–6}$ for hydrogen electrolyzers or air pollution controls in manufacturing plants all the way up to O.M. £10^9 for large-scale new-build CCUS facilities.

DISCUSSION

Our analysis of the technological granularity of green recovery funding programs shows marked variation within and between sectors and countries. In this discussion, we interpret these results in light of the three evidenced benefits of granularity noted earlier and summarized in Figure 1: shorter diffusion timescales, more net job creation, and more widely distributed social returns on investment. We also contrast each country's performance against these criteria for green recovery spending. Our basic assertion is that more granular funding programs are better aligned with green recovery objectives, such that technological granularity serves as a useful single indicator of "building back better." Against this indicator, South Korea performs strongly and the UK weakly. There are many other potential advantages to a funding portfolio weighted toward more distributed, modular, smaller-scale investments in low-carbon technologies and infrastructures that we do not discuss here. Examples include the following: resilience against extreme weather impacts on energy networks provided by distributed and end-use efficient system architectures[27] and lower risks of lock-in to suboptimal long-lived infrastructure with high sunk costs.[28,29]

More granular technology portfolios diversify risk and speed up the materialization of low-carbon technologies and infrastructures by distributing funding over larger numbers of units

More granular technologies diffuse faster (Figure 1, left panel). This is a general finding applicable to the materialization of technologies in a range of adoption environments, from households to cities to industrial facilities. Large numbers of building retrofits, distributed renewables, EV charging points, and small-scale hydrogen electrolyzers (unit costs in the range of O.M. £10^{2-5}) can be rolled out rapidly in the absence of supply chain constraints. In contrast, lumpy new nuclear power plants, blue hydrogen production facilities, and other industrial infrastructure (unit costs of O.M. £10^{8-9}) take many years if not decades to build.

The average relationship between granularity and diffusion timescales observed historically is shown in the trend line in Figure 1A (left panel):

$$\Delta t \;=\; 1.28\,\ln(\mathit{unit\ cost}) + 17.6$$

in which $\varDelta w$ is the diffusion timescale in years (from 1% to 50% of the S-shaped diffusion curve) and unit cost is the measure of granularity (£/unit). This relationship is generalized over a diverse sample of energy supply and end-use technologies that span power plants, refineries, household appliances, industrial processes, manufacturing facilities, transport infrastructures, and pipelines (see supplemental information). As a coarse average across these different adoption contexts, an increase in unit cost by an order of magnitude extends the overall diffusion timescales by 2.9 years.

It is important to note that this general relationship describes the speed with which technologies and infrastructures are materialized through deployment, manufacture, or construction and does not account for differences in the quality or quantity of the useful functions served by those technologies (e.g., thermal comfort of buildings and GWh of electricity generated).

Recovery funding programs targeting more granular technologies also distribute investment over larger numbers of more modular technological units and so, *ceteris paribus*, are less exposed to technology and project risks.[16] Conversely, recovery funding that targets small numbers of non-divisible lumpy technologies are more likely to be delayed and overrun in cost.[30,31]

We estimate the total number of discrete technological units targeted in green recovery programs by dividing total funding by average unit costs per program (Figure 6A). Using this crude measure, we find that South Korea has the most extensive

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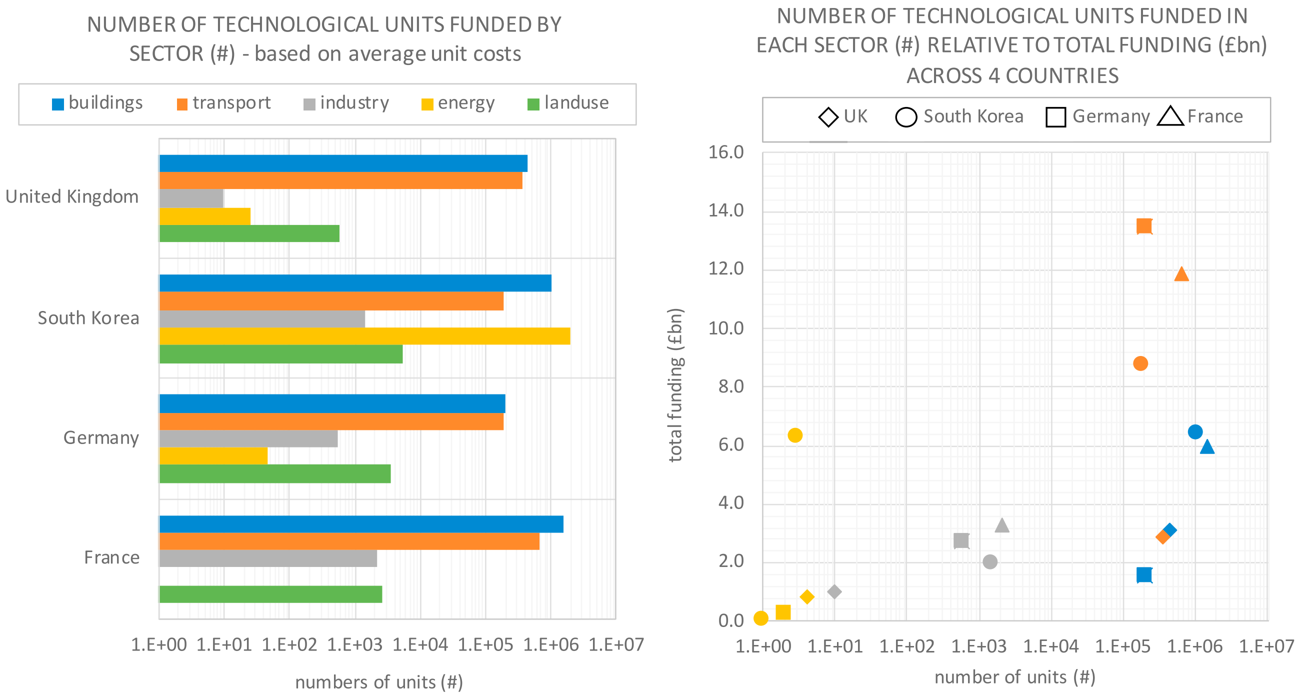

Figure 6. Estimated numbers of technological units funded by green recovery programs in four countries

Left panel (A) shows number of units by sector; right panel (B) shows number of units as a function of total program funding. Note log-scale x axes in both panels.

diversification of funding across large numbers of technological units (3.2 million) followed by France (2.2 million) and the UK (0.8 million). Germany has noticeably the highest concentration of funding across the smallest numbers of units (0.4 million). These differences are explained by the weighting of Germany's portfolio toward more lumpy industrial technologies and its relatively weak emphasis on more granular building retrofit measures (like in France and the UK) or distributed renewables (like in South Korea).

Although the UK's portfolio does include building retrofit programs, its overall concentration over relatively few numbers of units is caused by large funding allocations to very lumpy technologies. In the industry sector, for example, £0.9bn of funding for large-scale H_2 production with CCS, CCUS using direct air capture (DAC), and material reuse in heavy industry would only cover the cost of five technological units (based on our estimated average unit costs). This is shown by the variation across the four countries in how the total £bn of funding translates into numbers of technological units (Figure 6B). Wide variation is seen particularly in the industrial sector with the UK as the low outlier (high concentration) and in the energy sector with South Korea as the high outlier (high diversification).

Diversification of funding across larger numbers of more granular technologies speeds up deployment and so near-term progress on decarbonization: both desirable characteristics of building back better.

More granular technology portfolios widen accessibility by distributing recovery funding to larger numbers of direct beneficiaries

Larger numbers of more granular units are not only associated with faster diffusion and diversified technology and adoption risks but also with a wider distribution of

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benefits across social, geographic, and economic interest groups. Again, these are all desirable characteristics for building back better.

Concentrating funding on a small number of large-scale ''winners'' (e.g., CCS in the UK and hydrogen in Germany) offers larger potential payoffs but with the risk that future markets fail to materialize. Concentration of funding on lumpy technologies also exposes programs to critiques of ''pork barrel'' politics favoring specific firms, sectors, or geographies.[32]

However, more granular portfolios that spread funding over large numbers of discrete units also have downside risks, including increased coordination and program delivery challenges (discussed further below in the section on limitations). More granular portfolios may also have a more diluted, diffuse, and so harder to quantify effect on low-carbon transformation by virtue of being highly distributed.[16]

Beneficiaries receiving incentives, investments, or other forms of recovery funding can broadly be grouped into final consumers for demand-pull incentives (e.g., EV purchase subsidies), and firms or service providers for technology-push incentives (e.g., infrastructure investments in EV production lines or battery manufacturing facilities). Larger numbers of beneficiaries in each of the consumption and production sectors mean the seeds of recovery funding are sown more widely across a more diverse range of technological actors.

From our data, we cannot estimate the number of beneficiaries of each funding program: owners of residential, commercial, or public buildings may install more than one efficiency or renewable energy measure; automotive manufacturers may receive funding support for more than one R&D program or production line upgrade; and so on. For consumption-side funding, a crude assumption of one technological unit funded per beneficiary is reasonable as the beneficiary is the final user, not the installer or manufacturer. However, the same final user may benefit from more than one unit; hence, a 1:1 ratio will overestimate the number of beneficiaries. For production-side funding, a crude 1:1 assumption also broadly holds as the larger unit investment sizes of green recovery funding are unlikely to be captured multiple times by the same firm within the same program. However, at the lumpy end of the technology spectrum, very large unit investments are likely to target consortia or partnerships of firms; hence, a 1:1 ratio will underestimate the number of beneficiaries. If the numbers of beneficiaries (consumers, firms, and service providers) directly receiving recovery funding follow the numbers of technological units targeted (Figure 6), South Korea is the clear leader in distributing accessibility to public spending on green recovery through its granular energy and buildings programs.[33]

More granular technology portfolios create more jobs by targeting technologies with higher average employment multipliers

More granular technologies create more net jobs (Figure 1B, middle panel). Using data from Blyth et al.,[34] Wei et al.,[35] Meyer and Sommer,[36] and Wilson et al.[16] shows that more granular energy technologies tend to have higher average employment multipliers normalized per unit of output over their lifetimes. This takes into account both direct effects (e.g., jobs for constructing and operating facilities) and indirect effects (e.g., jobs displaced from one sector of the economy to another) and so allows for a direct comparison between different types of jobs in the materialization of low-carbon infrastructure at different scales.

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The generalized relationship between granularity and job creation is shown in the trend line in Figure 1, middle panel:

$$jobs = 0.50 \times unit\ size^{0.21}$$

in which jobs is the direct and indirect employment effect over the lifetime of an energy technology or facility (person.years/GWh) and unit size is the measure of granularity (MW/unit). As with the diffusion timescale relationship, this is a coarse average over diverse energy technologies including power plants and energy-using processes and devices (see supplemental information). However, it is indicative that an increase in unit size by six orders of magnitude from 0.001 MW (solar panels) to 1,000 MW (thermal power plants) decreases job creation by 2 person.years/GWh output over the lifetime of the technology or facility. This generalized effect of unit scale on job creation does not account for qualitative characteristics of employment including permanence. However, various studies show modular renewable technologies perform well relative to lumpy fossil fuel plants not just on construction-related jobs but also enduring operational and service-related jobs.[35,37–39]

Studies comparing clean energy investments (renewables and efficiency) against fossil investments consistently find higher job multipliers per dollar spent on clean energy. For example, Garrett-Peltier[40] analyzes direct and indirect job creation effects and finds that $10m spent on renewables or efficiency creates 75 or 77 jobs, respectively, whereas the same amount spent on fossil fuels creates 27 jobs. A recent machine learning-assisted synthesis of 908 different documents also confirmed that green investments resulted in higher job creation than non-green investments.[41] Pai et al.[39] apply job creation data across technology classes to future scenarios in which warming is limited to 2°C and show an overall increase in energy sector jobs.

Through a granularity lens, funding programs targeting distributed renewables (e.g., South Korea) and energy efficiency improvements such as building retrofits (e.g., France) invest in the materialization of technologies with lower unit sizes and costs.[42] This has clear advantages for job creation, a highly desirable characteristic for building back better. Investments in solar power perform particularly well against combined job creation and decarbonization outcomes.[43] In contrast, Engström et al.[44] found that lumpy investments in R&D or large-scale green infrastructure projects were less likely to generate the jobs needed to overcome the recessionary impact of COVID-19.

Limitations of technological granularity as a singular metric for evaluating green recovery funding programs

Granularity is not a panacea. There are other important design considerations for green recovery funding programs that a single granularity metric does not capture. We consider four issues that limit our comparative assessment of granular versus lumpy technologies: strategic objectives, scale economies, substitutability, and implementation risks.

Strategic objectives

Large public investments to enable the construction of a small number of technological units may serve other objectives such as the development of export industries (e.g., blue hydrogen production), new industrial clusters or manufacturing capacity (e.g., CCUS, e-automotive production), or the improvement of public services (e.g., rail transport infrastructure). Green recovery funding may also specifically seek to derisk large-scale materialization of low-carbon infrastructure by demonstrating its technical or financial viabilities.[45]

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Scale economies

Cost-reducing innovation is an important explanation of the rapid diffusion observed for more granular technologies (Figure 1). Dramatic declines in unit costs are particularly evident recently in the trajectory of solar PVs[46,47] and batteries.[48] Green recovery funding may seek to both exploit and further stimulate cost reduction by scaling up deployment or manufacturing of technologies that are standardized.[49] Balance-of-system costs that are less amenable to learning or scale-driven cost reductions may mean that highly granular installed units are more costly on a per kW basis than larger installations, for example, residential versus commercial solar PV systems.[50] However, scale economies at the unit, plant, or facility level are more characteristic of more lumpy technologies. Upscaling to increase the size or performance capacity of a technology (Luiten and Blok[51]) is a powerful heuristic, driving the search for technological and infrastructural solutions.[52] As an example, upscaling of plant sizes explained around 75% of cost reductions observed in US coal power production over much of the 20th century[53] and may similarly be an objective of green recovery funding for technologies like CCS.

Substitutability

In some contexts, there are limited or no substitutable alternatives to lumpy technologies or infrastructures (e.g., steel and cement manufacturing and Passivhaus buildings). However, in many contexts, technologies on the granular-lumpy continuum in the same domain of application may serve a similar function (e.g., generating MWh electricity from nuclear power or from solar PV modules with battery storage) or may provide a similarly useful service albeit with different qualitative characteristics (e.g., intra-urban passenger mobility from light transit or from e-bikes). In these more directly comparable contexts, the benefits of granularity are more directly evidenced.

Implementation risks

Lumpy investments have well-documented implementation risks, with time and cost overruns amplified by long construction lead times.[30] Although typically less susceptible to delays, more granular investments require coordination that can increase transaction costs, given that adoption or manufacture of large numbers of low-carbon technologies takes time and effort. Strategies for managing transaction costs include aggregation, standardization, third-party management, and performance contracting (e.g., energy service companies).[16] Ineffectual management compounds implementation risks, as evidenced by the abrupt cancellation of the UK's £2bn Green Homes Grant scheme with most of its funds still unallocated (see supplemental information). However, this was not inherently due to the program's technological granularity, and different examples of delivery failures are similarly evident in very lumpy investment programs in the UK (e.g., high-speed rail and nuclear power).

In sum, alongside general considerations of diffusion timescales and investment risks related to unit size, other issues affect the materialization of low-carbon technologies in deployment contexts (e.g., non-substitutability, service quality, and heterogeneous consumer preferences) or in production contexts (e.g., project management, strategic policy objectives, and regulatory uncertainty). These will affect granular and lumpy technologies differently and hence limit their direct comparability using a simple granularity metric.

Conclusion: Building back granular

Our analysis of green recovery funding programs announced in 2020 in the UK, France, Germany, and South Korea demonstrates the usefulness of technological granularity as a design criterion. Granularity (£/unit) characterizes technologies, plants, facilities, and infrastructures that can be more rapidly materialized, with more direct beneficiaries and with more net jobs created. As such, it encompasses three desirable characteristics of green recovery for building back better.

Across the four countries analyzed, South Korea's funding programs have a more granular technological emphasis, aligning well with the need for accelerated low-carbon transformation that creates jobs and distributes benefits widely to help recover from the effects of COVID-19. The granularity of France's portfolio is improved by the emphasis on relatively low-cost and geographically distributed building retrofit measures, whereas Germany's portfolio is made lumpier by its weighting toward automotive manufacturing and export-oriented industrial clusters in line with national economic priorities. The UK's green recovery funding programs perform worst on the granularity criterion, with a significant proportion of the total funds allocated to energy and industrial technologies with unit costs exceeding hundreds of millions of pounds. Not only do these mega-scale projects have significant implementation risks and delayed benefits to decarbonization but also they deliver fewer net jobs and incentivize fewer beneficiaries compared with granular alternatives.

One similarity across all four countries is that granular nature-based measures to enhance carbon sinks (e.g., tree planting and urban green spaces) play only a very minor role in green recovery funding programs, although they are an effective, quick, and job-creating decarbonization strategy.

There is clear path dependence in specific countries' recovery spending programs.[6,20] The four countries in our sample have variously prioritized national industries (e.g., German automotive sector), protected existing jobs (e.g., French public transport sector), aligned with national policy priorities (e.g., South Korean energy supply decarbonization), and used recovery spending to fill gaps in national policy landscapes (e.g., UK building retrofits). Emphasizing granularity in recovery spending is an opportunity to "bend" these path dependencies toward accelerated progress on decarbonization.

However, overall recovery spending in response to the COVID-19 pandemic has so far not been consistently used to shift economies onto low-carbon trajectories.[2,54,55] The underlying imperative to rapidly scale-up low-carbon investment to achieve net-zero targets under the Paris Agreement remains.[56]

EXPERIMENTAL PROCEDURES

Our research approach uses novel estimates of granularity (£/unit) for each low-carbon technology and infrastructure identified in country-level portfolios of green recovery funding programs.

Resource availability

Lead contact

Further information and requests for resources should be directed to the lead contact, Charlie Wilson (charlie.wilson@eci.ox.ac.uk)

Materials availability

Data and assumptions on unit cost estimates (technological granularity) and green recovery funding programs are summarized in supplemental information in pdf

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format and in Data S1 as excel tables: Data and assumptions on unit cost estimates for technologies and infrastructures in green recovery funding programs.

Data and code availability

Python code used for figure plots is available from the authors.

Method (1): Selection criteria for green recovery funding programs

Green recovery spending within the overall COVID-19-related fiscal stimulus included emergency loans, firm or sectoral bailouts, employment support packages, and other measures that were not technology-specific. We identified the subset of recovery funding programs targeting specific low-carbon technologies, infrastructures, activities, or resources. This is consistent with the main categories of green recovery spending defined by Höhne et al.[7] and O'Callaghan et al.[41] It also aligns with transformative recovery policies that go beyond near-term fiscal stimulus to provide longer-term support for low-carbon infrastructure and private sector innovation.[57]

We excluded from our analysis the following:

(1) General green funding announcements lacking any specifics on which low-carbon technologies or infrastructures were being targeted,
(2) support packages for economic subsectors (e.g., the airline industry) and bailouts for specific firms (e.g., Air France) unless specific low-carbon technology development programs were cited (e.g., R&D investment in low-carbon aviation fuel),
(3) green recovery spending that was unambiguously not additional (i.e., specifically and distinctively for green recovery), for example, because the measures were announced before COVID-19 struck in early 2020.

Method (2): Compiling data on green recovery funding programs

We compiled data on recovery funding that targeted specific low-carbon technologies and infrastructures in four countries: France, Germany, South Korea, and the United Kingdom. In late 2020, these four countries were the clear leaders in terms of announced green recovery spending as a proportion of gross domestic product (GDP) according to the UNEP Emissions Gap Report 2020 (see Figure 4.2 in Höhne et al.[7]) based on data current to August–November 2020 from Climate Action Tracker,[58] IMF Policy Tracker and Fiscal Monitor Database,[59–61] Vivid Economics Green Stimulus Index,[62,63] and the Oxford University Economic Recovery Project.[12,64] Geels et al.[20] also select France, Germany, and the UK for a comparative analysis of green recovery funding, given these countries' early leading positions.

Based on data for 2020 in the Oxford Global Recovery Observatory for the 50 largest national economies, the four countries in our sample represent 46% of all green recovery spending (£138.9bn of £304.8bn) and 33% of all announced green recovery spending policies or programs (118 of 362). Although not representative, our four countries do reflect a good share of all green recovery spending worldwide in 2020.[12]

Applying the selection criteria set out above, we compiled data on green recovery funding programs announced prior to 31 December 2020 in France, Germany, South Korea, and the United Kingdom. Our primary resource was Carbon Brief's Green Recovery Policy Database that lists summary details of announced funding programs from media and government sources.[65] For each entry in the Carbon Brief database, we cross-referenced with national government sources, and national media or research reports, to confirm each policy's scope and funding and to compile further details of the specific low-carbon technologies and infrastructures targeted. We cross-checked our final dataset with the Oxford Global Recovery Observatory current to end 2020 (see supplemental information for details).[66] When identifying green recovery funding programs, we do not account for how and when monies are disbursed. In line with O'Callaghan and Murdock,[67] our analysis takes at face value each country's announcements of recovery spending. In some cases, this may overstate funding available if specific programs were amended or cut following initial announcements.

Overall, across the four countries, we compiled data on 93 discrete green recovery funding programs totaling £72.9bn of funding (Table 1). We excluded a further 30 funding programs totaling £42.6bn of funding, 18 of which did not clearly specify low-carbon technologies,[68] 9 of which were sectoral or company bailouts, and 3 of which were not clearly additional (see supplemental information for details).

We do not consider potential or targeted emission-reduction outcomes of each funding program; hence, we make no comment on mitigation effectiveness. We simply treat all announced programs as having "low-carbon" characteristics if they align with the definition of green measures set out above.[7]

We report all data in GBP (£) using fixed conversion rates representative of 2020 market exchange rates (1 USD = 0.75 GBP, 1 EUR = 0.89 GBP, and 1 SKW = 0.000667 GBP). This approximation serves our interest in broad patterns of granularity in green recovery funding programs across countries based on O.M. estimates of unit cost (see below).

Total spending across all the green recovery funding programs in our dataset ranges from £8.0bn for the UK across 25 funding programs to £24.4bn for South Korea across 23 funding programs (Table 1). The single largest program was £4.2bn funding to improve the French rail network "to offer an attractive and efficient alternative to road transport" for both passenger and freight services. The single smallest program was £10m funding to support UK manufacturing scale-up of EV batteries, motors, and electronics.

Method (3): Defining a technological "unit" targeted by green recovery funding programs

By technological "unit," we mean the lowest (non-divisible) functional specification of a technology as a discrete investment. This is consistent with our interest in the granularity of how public monies are invested in the materialization of low-carbon technologies and infrastructures through green recovery funding programs.

Our definition of technological units follows the concept of an "operational principle" that is the highest level of operational aggregation of component parts necessary to serve a useful function or provide a useful service, but before the inclusion of infrastructure and other material or institutional conditions required for operation.[69,70]

This functional or operational specification means units of wind turbines rather than wind farms, insulation panels rather than buildings, and EV production lines rather than whole car manufacturing plants.

However, within this general definition, our identification of technological ''units'' for which we estimate investment costs is strongly guided by the green recovery funding programs that specifically identify them as investment targets.

Production-side funding programs in manufacturing and industrial sectors may target investments in units of production lines or whole industrial facilities. Consumption-side funding programs in final demand sectors typically target investments in units of consumer goods, efficiency measures, or distributed energy supply technologies.

Our full dataset of technological units is provided in supplemental information.

Method (4): Estimating unit costs of discrete technologies and infrastructures targeted by green recovery funding programs

We estimated unit costs (£/unit) for each low-carbon technology, infrastructure, activity, or resource targeted in the 93 funding programs in our dataset by searching peer-reviewed and gray literature using technology name and ''unit cost'' as search terms.

In all cases, we estimated averages and low-high ranges for unit costs to reflect ''within-technology'' variation due to technological specification (e.g., different types of hydrogen production with CCS), due to the capacity or size (e.g., different MW wind turbines) or due to geography (e.g., nuclear power plant construction costs in different countries). Tables S4 and S5 in supplemental information give examples of each case.

For some technological units for which cost data were not readily available, we made simplifying assumptions based on other similar technological units (e.g., aircraft engines as 10% the cost of an aircraft). All data estimates, assumptions, and sources are provided in supplemental information.

All our unit cost estimates are expressed as indicative O.M. For example, O.M. £$10^{2–4}$ denotes unit costs ranging from two to four orders of magnitude (hundreds to tens of thousands of pounds). Limiting the resolution of our granularity analysis to the O.M. level is faithful to uncertainties in the data, and our assumptions in interpreting the technological specificity of funding programs (see below).

Method (5): Estimating unit cost ranges for each green recovery funding program

Almost all the green recovery funding programs in our dataset target investment in one or more types of low-carbon technology or infrastructure. This adds ''between-technology'' variation to our estimates of granularity (£/unit) at the program level, on top of the within-technology variation noted above. In some cases, multiple technologies within a single funding program are only specified with limited detail. This further amplifies uncertainties.

As an example of between-technology variation, the French hydrogen funding program targets investment in fuel cells (O.M. £$10^{3–4}$/unit), refueling stations (O.M. £$10^{5–6}$/unit), and electrolyzers (O.M. £$10^{4–6}$/unit). Within-technology unit cost variation is therefore O.M. £$10^{3–4}$ for fuel cells alone, but between-technology unit cost variation is O.M. £$10^{3–6}$ for the funding program overall.

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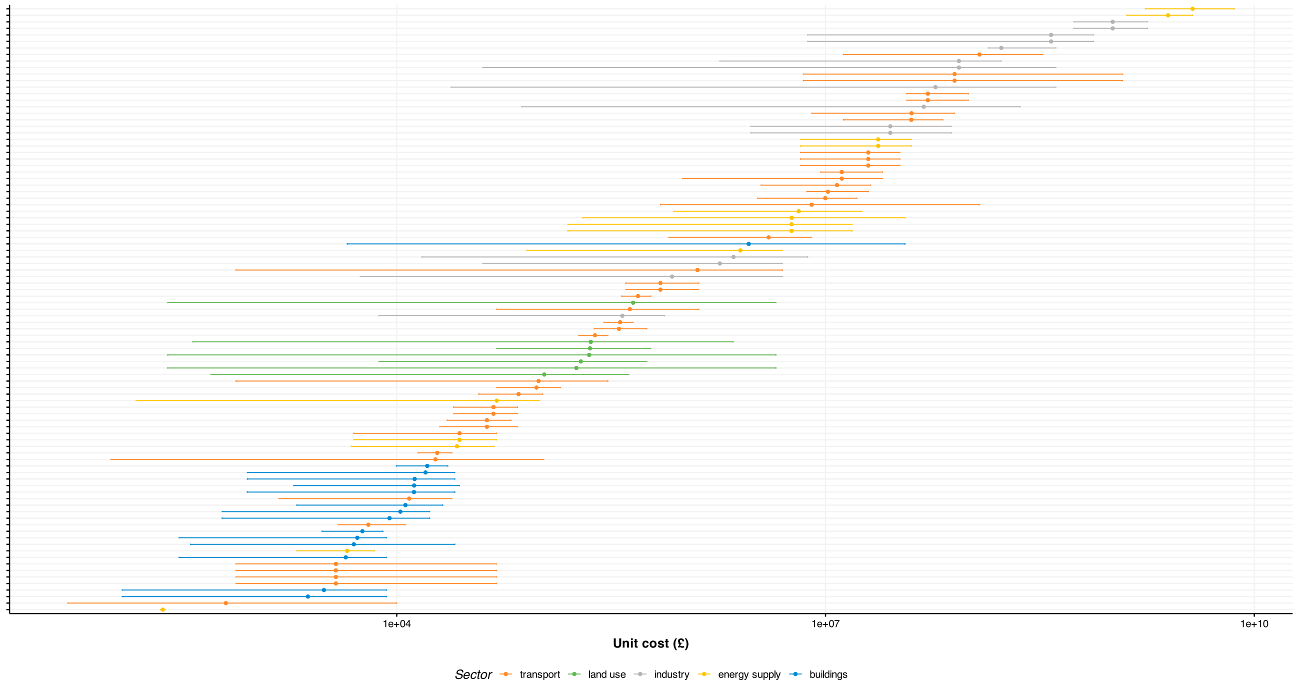

Figure 7. Rank-ordered unit cost estimates for low-carbon technologies and infrastructures targeted in 93 green recovery funding programs
Horizontal error bars show low-high uncertainties around unit cost estimates due to variation in the specification of discrete technologies and variation between technologies within a given funding program. Note log-scale axis that accentuates lower range of uncertainty. Colors denote sectors.

The full distribution of unit cost estimates for green recovery funding programs in our dataset ranges from a low of O.M. £10^2 for a program deploying smart meters to a high of O.M. £10^9 for a program targeting new-build single-reactor nuclear power plants (see Figure 7 and supplemental information for the full dataset).

Method (6): Sectoral disaggregation of unit cost estimates

We classify each funding program by both type of economic activity (consumption, production, and infrastructure) and sector (buildings, transport, industry, energy supply, and land use). Our sectoral classification corresponds with those used in national GHG emission inventories: final demand sectors (buildings and transport), supply and intermediate production sectors (industry and energy supply), and land use (agriculture, forestry, other land use, or nature). Each sector is further disaggregated into a number of subsectors. For example, buildings are disaggregated into residential, social housing, commercial, and public (see supplemental information for details).

Figure 8A shows that unit cost estimate ranges are widest in the energy supply sector (yellow line, O.M. £$10^{2–9}$) and narrowest in in the buildings sector (blue line, O.M. £$10^{3–6}$).

The average of these unit costs also varies by sector (unweighted or weighted by the size of each funding program) (Figure 8B). Average unit costs are lowest for buildings (O.M. £$10^{4–5}$), then transport (O.M. £10^7), with the highest for industry and energy supply (O.M. £10^8). Land use sits toward the low end (O.M. £10^5) but with fewer data points and less certain unit cost estimates; hence, we do not analyze this sector further.

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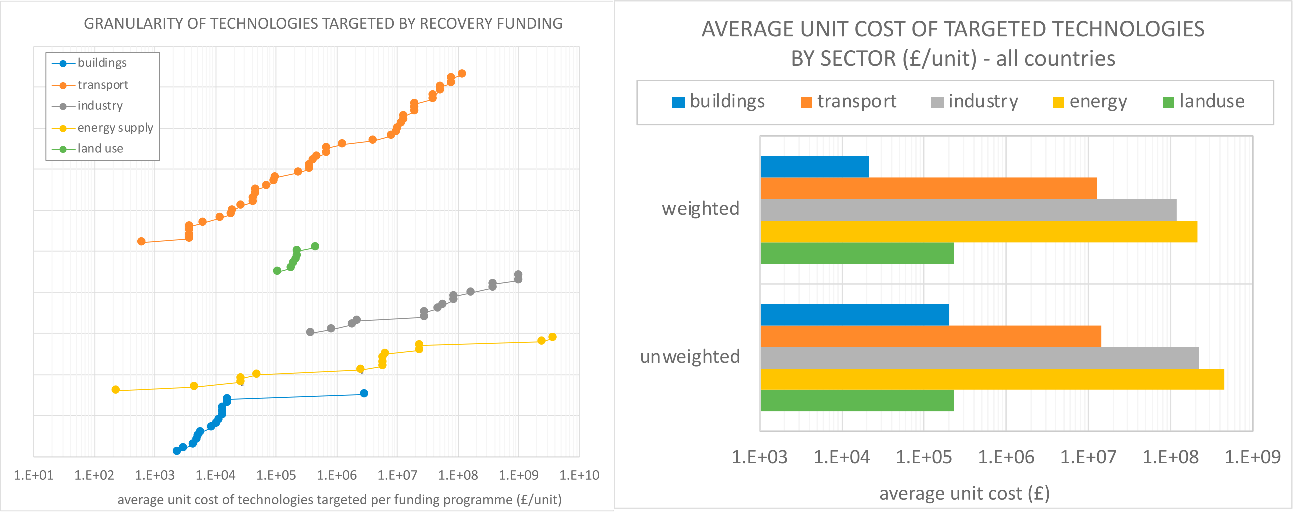

Figure 8. Sectoral comparison of unit costs of technologies targeted by funding programs in four countries
Left panel (A) shows unit cost ranges; right panel (B) shows average unit costs expressed unweighted and weighted by the size of each program.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.05.012.

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AUTHOR CONTRIBUTIONS

C.W. designed the study and methodology; C.W., S.D.S, and C.Z. collected and analyzed data; S.D.S. generated the figures; C.W. wrote the manuscript; C.W., S.D.S, and C.Z. reviewed and edited the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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19. Nahm et al. (2022) distinguish measures that will cut emissions directly (27% of total spending) such as grants to install low-carbon heat systems in homes, from measures that will cut emissions indirectly (72% of total spending) such as EV charging or railway infrastructure investments. This corresponds to our distinction between consumption and production-side investments.

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21. Variation in average unit costs per sector across countries is high for industry (x9 from lowest in France to highest in United Kingdom), higher still for transport (x53 from lowest in South Korea to highest in Germany) and buildings (x99 from lowest in France to highest in United Kingdom) and extremely high for energy supply (x372 from lowest in South Korea to highest in United Kingdom).

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24. Germany, France, and the UK all allocate green recovery funding for hydrogen, but Germany has a much larger production base linked to its chemicals and steel industries (e.g., 4.5 bn m^3 production in 2019, compared to 0.97 and 0.26 bn m^3 in France and UK respectively) (Geels et al. 2022). However, Germany and France focus on green hydrogen (using electrolysers) but UK also includes blue hydrogen (using fossil fuels with CCS). Green hydrogen strategies use more granular production technologies.

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