



Pathways to a productive and inclusive net zero

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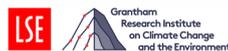


The Productive and Inclusive Net Zero Research Project

PRINZ is a collaboration between researchers from Imperial Business School, The London School of Economics, University of Oxford, the University of Leeds and NESTA.

The papers in this collection have been written by researchers from the Centre for Economic Performance, the Grantham Research Institute on Climate Change and the Environment, the Programme on Innovation and Diffusion, University of Leeds, the World Bank Group and the University of Surrey. The editors are Ralf Martin and Anna Valero.

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Introduction

Ralf Martin and Anna Valero

Now is a critical time for global action on climate. While the science is clearer on the urgency and the evidence on the economic opportunities stronger, the political challenges around net zero have become larger with a fracturing of consensus on net zero policy in some contexts.

At the same time, in many advanced economies – including the UK – improving productivity performance and hence living standards is an ever more urgent imperative. Boosting the UK's flatlining productivity and addressing longstanding regional inequalities requires increased investment in productive, resilient and sustainable assets across the country including in the innovation of clean technologies. Significant investment is also required in low- and middle- income countries (LMICs). These face significant adaptation and clean development challenges but also have the potential to build their own specialisms in clean innovation.

While specific opportunities and challenges will differ across and within countries, it is crucial that the economic and broader co-benefits of the net zero transition are realised and felt by citizens, and that displacements for businesses and people are actively managed.

In this context, timely research is needed to provide evidence for a productive and inclusive net zero transition. This has been the objective of the Productive and Inclusive Net Zero (PRINZ) programme funded by the Economic and Social Research Council. PRINZ has been a collaboration between researchers from Imperial Business School, the University of Leeds, the London School of Economics and Political Science's Centre for Economic Performance, the Grantham Research Institute on Climate Change and the Environment, the University of Oxford's Smith School of Enterprise and the Environment, and Nesta.

In this research programme, we have asked:

- How can we achieve the transition while ensuring equitable economic growth?
- Is it possible to make the economy cleaner while achieving regionally balanced growth?
- What kind of industrial policy is needed to facilitate the transition?
- How can we ensure there are good jobs for all?
- Which skills are needed to facilitate the transition and how can we provide for the necessary vocational training?

This collection of briefing notes summarises some of the key highlights from this research. Further results will be provided on the PRINZ Webpage (www.prinzproject.io) which we will maintain as an online repository on Productive and Inclusive Net Zero going forward.

Sectors, firms and innovators in the UK and other advanced economies

In “Informing industrial strategy for clean technologies in the UK: the Green Industrial Policy Matrix and beyond”, Ralf Martin, Maxwell Read, Arjun Shah, Anna Valero and Dennis Verhoeven set out key empirical results to inform industrial policy that seeks to seize UK growth opportunities in the net zero transition, with a focus on innovation. This work highlights specific technologies where the UK has comparative advantage, where the estimated returns to investment in innovation are particularly high in the UK, and regional patterns. A key finding is that the “returns” captured in the UK from investment in innovation are particularly high for clean energy technologies; and for such innovations in the north east, Wales and the West Midlands. This paper also presents new estimates of the “spillovers from science” into clean technologies, with university-level results for selected clean technologies. This shows that while so-called “Golden Triangle” universities of Cambridge, Oxford and Imperial tend to feature across all four technologies (offshore wind, nuclear, heat pumps, and carbon capture usage and storage), so does the University of Manchester. Other universities rank highly in specific technologies: for example, Nottingham for offshore wind, Southampton in nuclear and Liverpool in carbon capture usage and storage.

In “Do clean innovators create jobs?” Pia Andres, Ralf Martin and Anna Valero show that the bulk of clean innovation happens in larger firms that engage in both clean and non-clean innovation. While both clean and non-clean innovation boost employment, clean innovators tend to be larger meaning the total number of jobs associated with clean innovation is substantially higher on a per-innovation basis.

The briefing note “Cleaner energy, higher risk? Firm-level exposure to critical minerals and implications for UK industrial strategy” by Viet Nguyen-Tien considers supply chains and resilience. Dr Nguyen-Tien presents evidence that firms respond to exposure to critical minerals risks through recycling and reuse, material reduction and substitution, stockpiling and hedging or passing costs to customers.

In “Do common shocks drive changes in aggregate emissions intensity?”, Xiyu Ren, Fulvia Marotta and François Lafond investigate the extent to which changes in sectoral emissions intensity are driven by common shocks that impact all industries or by industry-specific forces and show that decarbonisation is primarily driven by industry-specific dynamics.

In “Firm- and sector-level decision-making on productivity and net zero”, Alice Owen considers how individual firms seek productivity improvements while meeting environmental obligations. She draws on two industry case studies, cement manufacture and Scottish whisky, to illustrate how firms go about this and how policy can support them.

Net zero and the labour market.

In “Measuring low-carbon work, skills, pay and places”, Aurélien Saussay, Misato Sato and Francesco Vona study trends and attributes of “low-carbon” jobs in the United States. They find that low-carbon jobs account for a relatively low share of total jobs advertised, but such jobs tend to be higher skilled, and to pay higher wages. Geographically, opportunities for low-carbon jobs overlap with places with a high intensity of high-carbon jobs, yet low-carbon vacancy shares are higher in richer areas. The briefing sets out how an inclusive net zero agenda will need to ensure training is available for high-quality jobs and embed place-based delivery, particularly in regions exposed to losses of jobs in high carbon activities and sectors.

In “Apprenticeships and low-carbon skills in England”, Chiara Cavaglia, Ilya Ilin, Sandra McNally, Misato Sato, Aurélien Saussay and Guglielmo Ventura analyse whether the UK’s apprenticeship framework is preparing young people for green jobs. They discover that 39 apprenticeship standards (6%), mostly in construction and transport, contain skills relevant for decarbonisation. The authors find that the supply of apprenticeships is not particularly reactive to prior changes in demand in local labour markets, though low-carbon ones are more responsive than other apprenticeships. These findings are discussed in the context of recent government reforms to introduce flexibility into the Growth and Skills Levy.

Net zero and competitiveness in low- and middle-income countries

“Green innovation – opportunities for developing countries” is the outcome of a collaboration between PRINZ researchers and the World Bank Group. In this paper, Ralf Martin, Golvine de Rochambeau and Trang Thu Tran examine measures of comparative advantage and spillovers in the knowledge economy across countries and technologies. This work introduces a new online tool to allow users to explore results for specific countries and technologies. This research finds that LMICs tend to specialise in green innovation and research; and green technologies in LMICs tend to generate relatively high spillovers. But there is huge variation across countries, technology fields as well as innovator types. Collaborations between LMIC and high-income country firms and innovators appear to be an important channel for emerging economies to kickstart innovation.

In “How renewable energy boosts economic productivity in the Global South”, Emilien Ravigné and Sam Fankhauser estimate how the clean transition is likely to benefit productivity in LMICs. They find that cheap renewables can generate a particularly large boost to productivity in the Global South by delivering more useful energy per dollar and lowering energy costs across the economy. They find that renewables create a new

comparative advantage for the Global South, with GDP gains of up to 9%-12% in some countries – well above those in advanced economies.

We hope that the evidence presented in this collection will shed light on the economics of how net zero, growth and labour market policies interact. This work is part of an ongoing research agenda, with future papers and datasets that will continue to inform policy for a productive and inclusive net zero transition.

Informing industrial strategy for clean technologies in the UK: the Green Industrial Policy Matrix and beyond

Ralf Martin, Maxwell Read, Arjun Shah, Anna Valero and Dennis Verhoeven

Executive summary

- The UK has set out an industrial strategy for Clean Energy Industries and other clean technologies, as part of its Modern Industrial Strategy. Alongside this, there are significant efforts underway to maximise the contribution to growth from the UK's excellence in innovation.
- This briefing note sets out key findings from a programme of research that seeks to inform policies that seize UK growth opportunities in the net zero transition, with a focus on innovation.
- We set out a number of high-level technology categories where the UK exhibits overall revealed technological advantage in innovation – including sectors such as offshore wind, carbon capture usage and storage (CCUS) and nuclear. While the UK is not specialised in some broad areas like technologies for decarbonising buildings, we do find that the UK has revealed technological advantage in specific technologies within the category, such as heat pumps.
- We present estimated “returns” for the UK economy from public investment in clean energy innovation, and find that such technologies generate above average returns.
- While in volume terms, a high share of clean energy innovation takes place in London and the southeast, estimated national returns are highest on average in the north east, Wales and West Midlands.
- We also consider the spillovers from science into technology development. The United States has high average spillovers (per scientific publication), second only to Switzerland, but it leads on the overall volume of spillovers given the high number of publications it produces. The UK generates a high volume of global spillovers, ranking third after the United States and Japan. But a relatively low share of those spillovers is retained within the UK compared to the United States and some of its peers.
- An examination of spillover patterns from science into specific clean technologies (offshore wind, nuclear, CCUS and heat pumps) reveals that universities across the country make varying contributions. For example, the “Golden Triangle” universities of Cambridge, Oxford and Imperial tend to feature across all four technologies, while Nottingham, Southampton, Manchester, Liverpool and others rank highly on the total spillovers they generate in specific areas – as well as universities in Scotland and Northern Ireland (eg Strathclyde and Queen's University Belfast for offshore wind).
- Our findings are relevant for informing investments in innovation and innovative clusters as part of the industrial strategy. Future research will continue to build on these methodologies and produce more granular evidence on clean energy and broader industrial strategy sectors.

Introduction

Governments are increasingly turning to industrial policy tools to boost investment, growth and resilience in key sectors, including those relevant for the net zero transition.¹ The UK Government published its Modern Industrial Strategy in June 2025, setting out a range of fiscal and non-fiscal policy levers to support eight key sectors across both manufacturing and services where the evidence suggests that the UK has current strengths and significant future growth potential.

At a high level, as well as boosting growth, the strategy seeks to “spread prosperity to all parts of the country, make us all more secure and seize the opportunities of net zero.”² More specifically in the context of net zero products and services, clean technologies presenting growth opportunities for the UK feature in the Clean Energy sector and Advanced Manufacturing sector plans, and sustainable finance products are highlighted in the Financial Services Competitiveness Strategy.

Our research summarised here, building on a longer-term research programme on sustainable growth at the LSE,³ has sought to inform a strategic approach to growth – where “green” industrial policies are nested within a broader strategy building on the UK’s comparative advantages (Valero and Van Reenen, 2023; De Lyon et al, 2022).

Innovation is central to this. For an innovative economy like the UK, building on the country’s significant research strengths, and improving the extent to which new ideas are converted to commercialised innovations, are key to improving productivity performance. And given how crucial innovation (via the invention and continued improvement of renewable energy and other clean technologies) is to the net zero transition, much of our analysis has sought to identify areas of comparative advantage and high economic payoff to investments in clean tech innovation. In this briefing note we summarise some key findings from PRINZ research and draw out implications for policy, and a future research agenda.

¹ See, for example, OECD analysis, here: <https://www.oecd.org/en/topics/sub-issues/quantifying-industrial-strategies.html>.

² See “The UK’s Modern Industrial Strategy”, UK Government, June 2025 https://assets.publishing.service.gov.uk/media/69256e16367485ea116a56de/industrial_strategy_policy_paper.pdf

³ See, for example, Curran et al (2022) for a broad assessment of the UK’s capabilities across a range of clean technologies; and deep-dives into specific technologies like zero-emission vehicles (Unsworth et al, 2020), carbon capture, usage and storage (Serin et al, 2021), tidal stream energy (Serin et al, 2023) and Greenhouse Gas Removals (Serin et al, 2025).

Key findings

Finding 1. There is evidence that the UK has strengths across clean technology categories, generating growth opportunities around the country

In our Green Industrial Policy matrix (Serin et al, 2024), we proposed a set of criteria for governments to consider when prioritising specific technologies for support as part of an industrial strategy. These are summarised in Table 1.

Table 1: Overview of criteria assessed under the green industrial policy matrix

Opportunities for growth	Strategic importance	Distributional aspects
<ul style="list-style-type: none">• Global tradeable market potential• Revealed comparative advantage (RCA) in trade• Revealed technological advantage (RTA) in innovation	<ul style="list-style-type: none">• Domestic demand under net zero• State of global supply chain	<ul style="list-style-type: none">• Job creation potential• Places – regional spread of opportunities

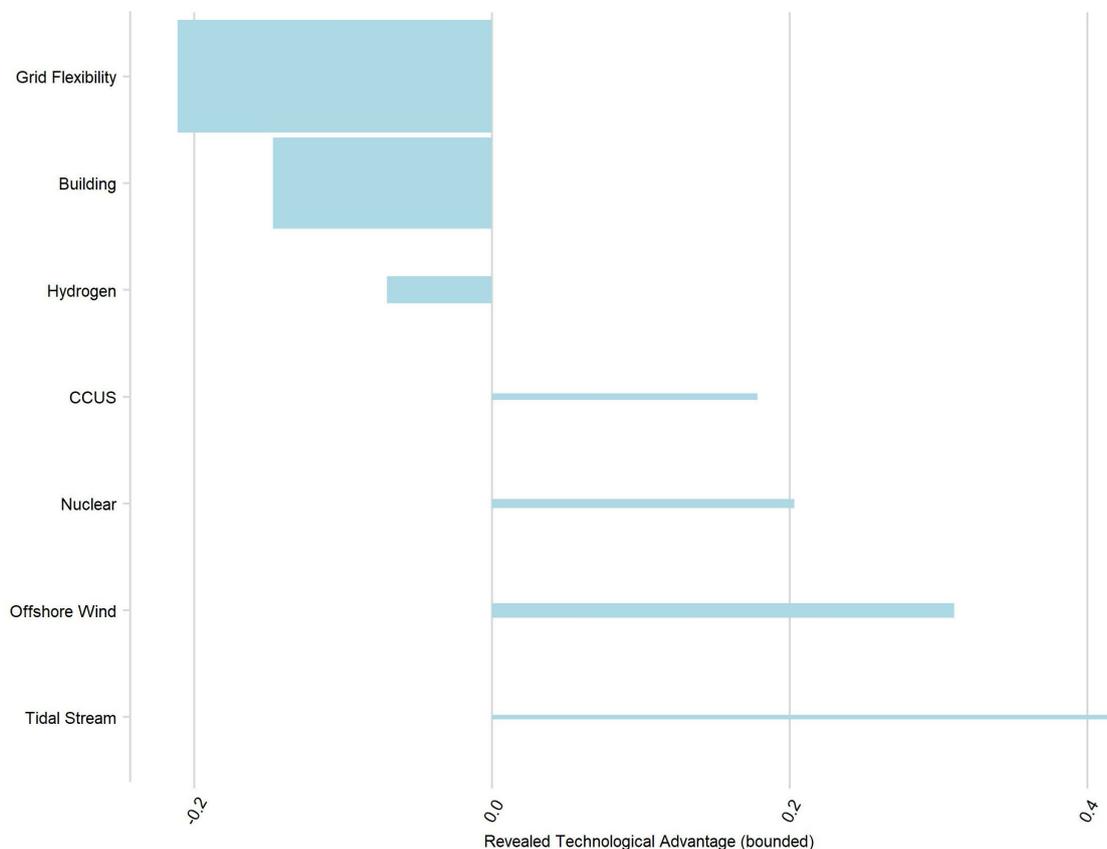
First, to assess overall growth potential we consider where there is evidence of UK comparative advantage in different technology areas and combine this with information on likely global growth. Given that clean technologies are not easily mapped in standard economic statistics, we consider granular data on traded goods and patents to construct measures of the UK's comparative strengths. More specifically, we calculate revealed comparative advantage (RCA) in traded goods mapped as being relevant for specific clean technologies, and revealed technological advantage (RTA) using more forward-looking innovation data, as measured by patenting in relevant technology classes. These measures are explained further in Annex 1.

We then consider the strategic importance of these technologies for meeting the UK's net zero commitments, and the extent to which UK supply chain capabilities are needed for resilience purposes given the geopolitical context. And finally, in the Green Industrial Policy Matrix, we consider the likely distributional aspects of growth in these technologies, in terms of both job creation potential and the regional spread of opportunities.

In this briefing note we outline the evidence on innovation strengths and associated growth opportunities, beginning with a high-level summary of RTA for seven key clean energy technologies in Figure 1. Here, the bar length shows RTA and the width represents the volume of innovations globally (number of patents). This measure shows that the UK has

RTA on aggregate in offshore wind, nuclear and CCUS (which all map to frontier sectors in the Clean Energy sector plan) as well as tidal stream.

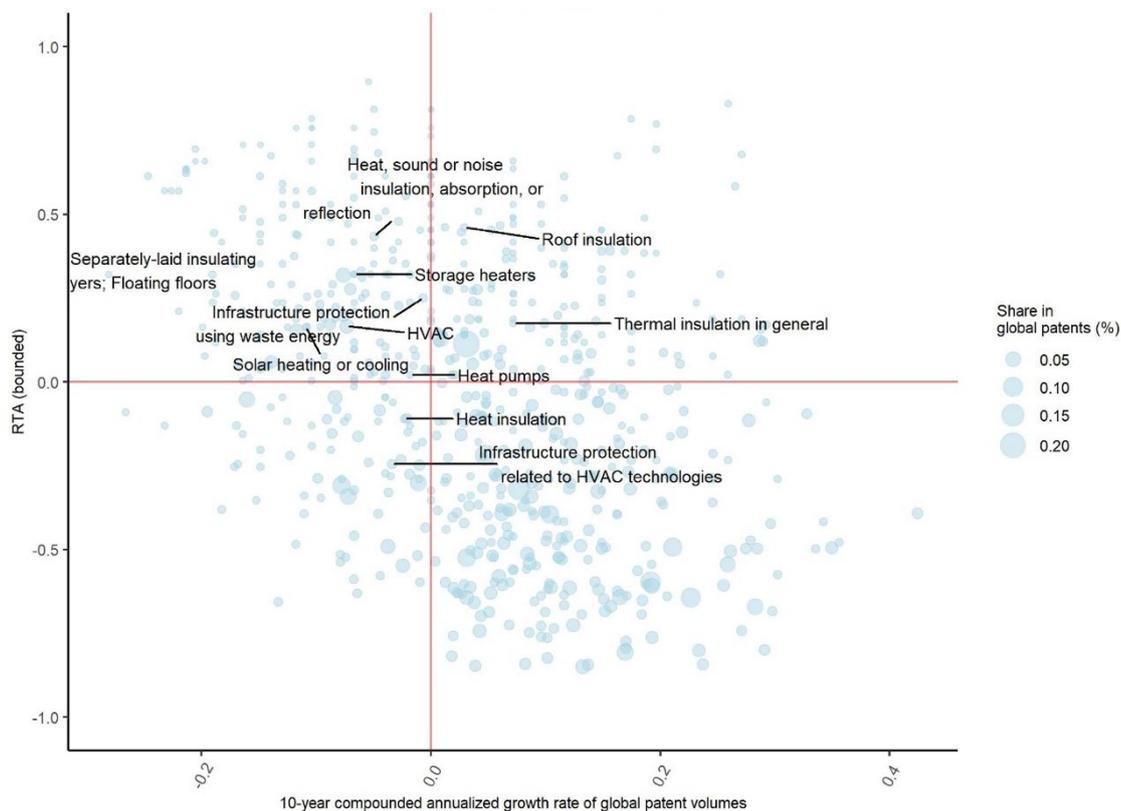
Figure 1: The UK's revealed technological advantage in aggregate technology categories (2016-2020)



Notes: Analysis based on PATSTAT Global 2023, Spring edition. Revealed technological advantage (RTA) compares a technology category's share in the country's total patenting to that technology category's share in global total patenting. RTA is bounded between -1 and 1, where values above 0 indicate specialisation. Bar widths reflect global patenting volume in the given category. **Source:** Serin et al (2024).

While there are some broad areas – notably Grid Flexibility and technologies relevant for reducing the carbon footprint of buildings – where the UK has an apparent comparative disadvantage, we can often identify narrower subcategories where the UK still has a relative advantage. This includes heat pumps (another frontier sector in the Industrial Strategy) within the broad category of heat and buildings (see Figure 2). Our broader analysis in the Green Industrial Policy Matrix (not reproduced here) highlights opportunities for regionally-balanced growth across many of these technologies, based on the location of businesses in relevant sectors.

Figure 2: The UK's revealed technological advantage in specific innovations relevant for low-carbon buildings (2016-2020)



Notes: Analysis based on PATSTAT Global 2023, Spring edition. Each bubble corresponds to a specific innovation within the category. The vertical axis denotes the UK's revealed technological advantage (RTA) in that innovation, bounded between -1 and 1, where values above 0 indicate specialisation. The horizontal axis represents the 10-year annualised growth rate of global patenting for that innovation (2010-2020), and the size of the bubbles represents the share of that specific innovation in global patenting activity between 2016-2020.

Source: Serin et al. (2024).

A successful industrial strategy should be informed by evidence on where government intervention can be most fruitful, and this is not necessarily or exclusively in areas with the highest comparative advantage. Innovation spillovers – where the benefits of innovation extend beyond the private benefits to the innovator – are a key justification for government investment in R&D and broader innovation policy. In the context of industrial strategy that seeks to boost domestic capabilities and growth, the extent to which spillovers are retained within a country is relevant. The following sections present new evidence on the estimated returns to investment in clean technologies in the UK, accounting for patterns of spillovers, as well as spillovers from the science that ultimately inspires clean tech innovation.

Finding 2. The 'returns' captured in the UK from investment in innovation are particularly high for clean energy technologies

RTA measures – as summarised in the previous section - give us an indication of specialisation in a given area of innovation, but tell us less about the economic value that can be generated from further R&D investments in particular technologies. The Industrial Strategy Index (IStraX) methodology provides a framework to provide evidence on this, while accounting for differences in direct and indirect knowledge spillovers between different technology types (Guillard et al, 2021). Using this methodology, returns for additional investments in specific types of innovation can be estimated accounting for spillovers at the global or national level or for specific regions. The scope of spillovers will matter for different policy objectives. For instance, the UK government will primarily be interested in R&D investments generating knowledge spillovers for UK innovators whereas the World Bank will be more interested in spillovers to innovators in developing countries.

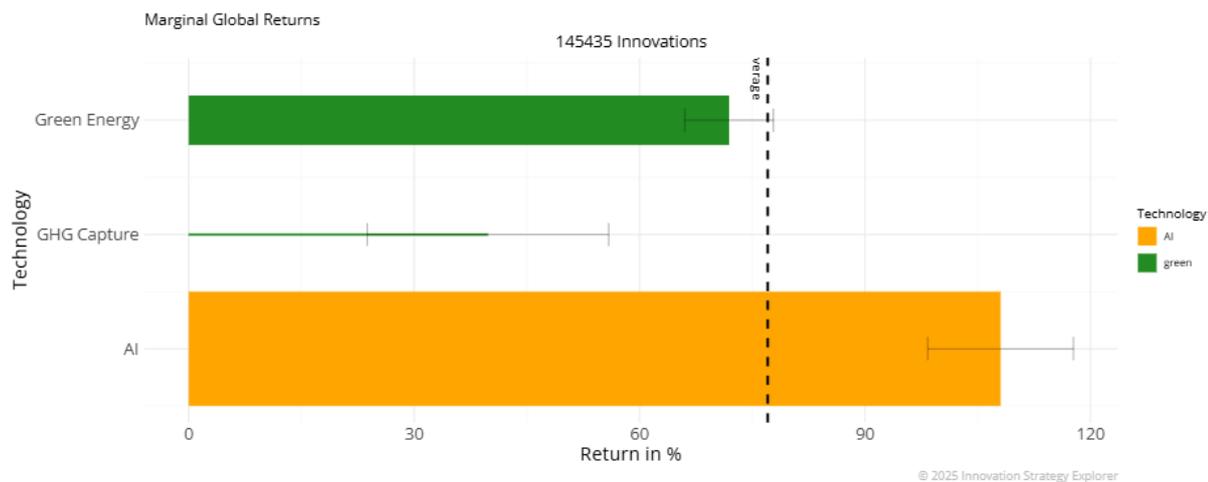
The basic idea is that the estimated “return” to investment in innovation for a type of technology reflects the difference between the expected increase in total economic value it generates (private value to the innovator, as well as the value created for others through knowledge spillovers) and the expected cost of the subsidy (for further detail on the methodology, see Annex A).

Figure 3 presents estimates of the marginal returns for UK innovations in selected technologies: green energy, greenhouse gas capture (CCUS technologies) or artificial intelligence (AI) for comparison. The width of the bars is proportionate to the volume of innovation over the sample period (2009-2018), while the length gives the estimated marginal returns, which are compared to the average across all technologies (dashed line).

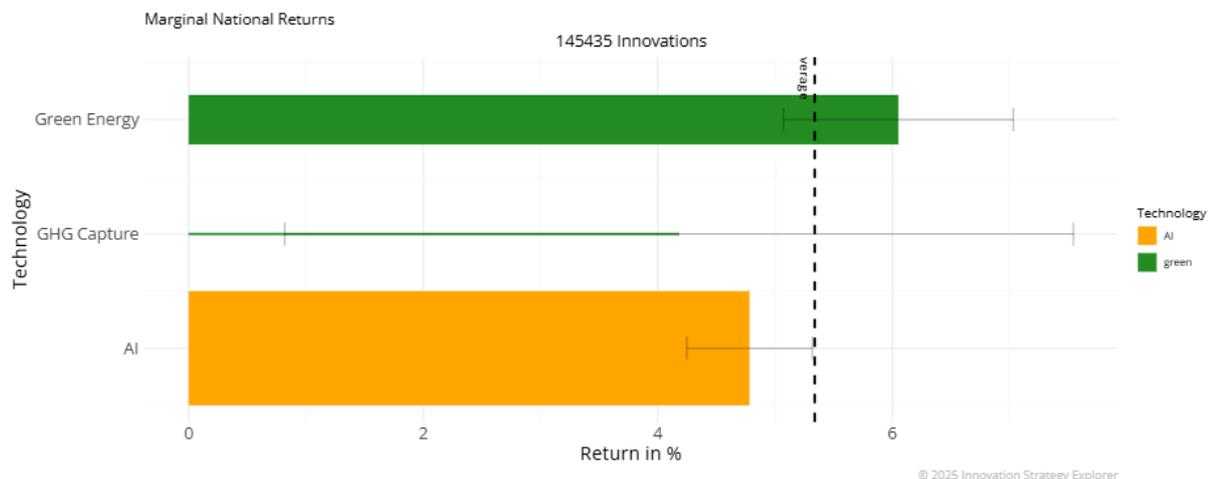
This analysis reveals that while UK green energy innovations generate below average *global* returns - when we consider *national* returns, we find that green energy is higher than average, and indeed higher than greenhouse gas (GHG) capture or AI respectively. This means that the potential to generate economic benefits in the UK is particularly high for green energy.

Figure 3: Estimated marginal global and national returns for selected technology categories in the UK

Panel A: Global



Panel B: National



Notes:

Results produced with the Innovation Strategy Explorer (ISE) - <https://www.prinzproject.io/iseapp>. Patents data are from PATSTAT Global 2021, and innovations over the period 2009-2018 are included. During that time, there were 145,435 innovations (“patent families”) across all technology classes in the UK. The dashed line shows the estimated marginal global (Panel A) and national (Panel B) return averaged across all of those innovations.

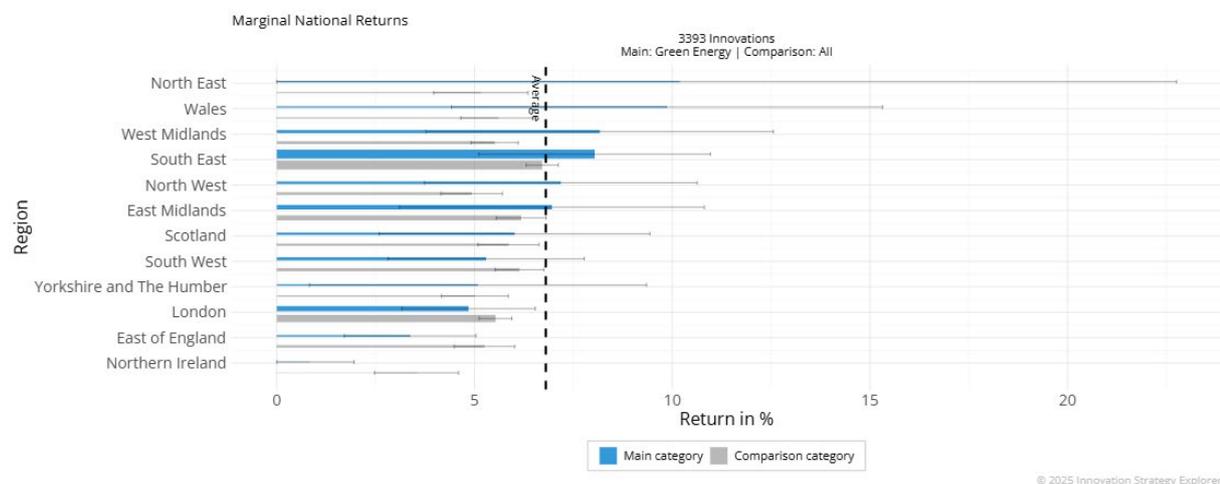
Finding 3. Spatial patterns in innovation and spillovers suggest that there are opportunities for regionally balanced growth through support for clean technologies development

The next step is to consider regional patterns in these metrics to inform place based industrial policies. In previous work, we show that in absolute terms green innovation – just like total innovation – tends to cluster in more productive places, but less productive places tend to be more specialised in green patenting and firms (Curran et al, 2022). We also applied the IStraX methodology to explore innovation between the Golden Triangle of

London, Oxford and Cambridge and the rest of the country. We show that investments in clean technologies can play an important role in improving growth outside the Golden Triangle – both directly via investments in those areas, and indirectly via spillovers from innovation occurring in the Golden Triangle to the rest of the country.

Here we extend that analysis, considering estimated returns to investment in innovation in green energy technologies for the UK’s 12 regions. The first step is to locate patents in specific regions and nations of the UK (which we could do for the majority of patents). The overall findings on the relative returns across broad classes documented in Figure 3 holds on this reduced subsample (see Annex B). Figure 4 considers how marginal returns to investments in green energy innovation compare across regions, and compare to the marginal returns across all technologies within each region. The width of the bars is proportional to volume, and this shows that the south east, London and the East Midlands account for the highest shares of green energy patents (and total patents) in absolute terms. However, estimated marginal returns are particularly high in the north east, Wales and West Midlands. In most regions, marginal returns to green energy are higher than the returns across all technologies. London is a notable exception.

Figure 4: Estimated marginal national returns for green energy innovations across the UK’s regions



Notes: Results produced with the Innovation Strategy Explorer (ISE) - <https://www.prinzproject.io/iseapp>. Patents data are from PATSTAT Global 2021, and innovations in “green energy” over the period 2009-2018 are included. During that time, there were 3,393 such innovations (“patent families”). The dashed line shows the estimated marginal national return averaged across these innovations.

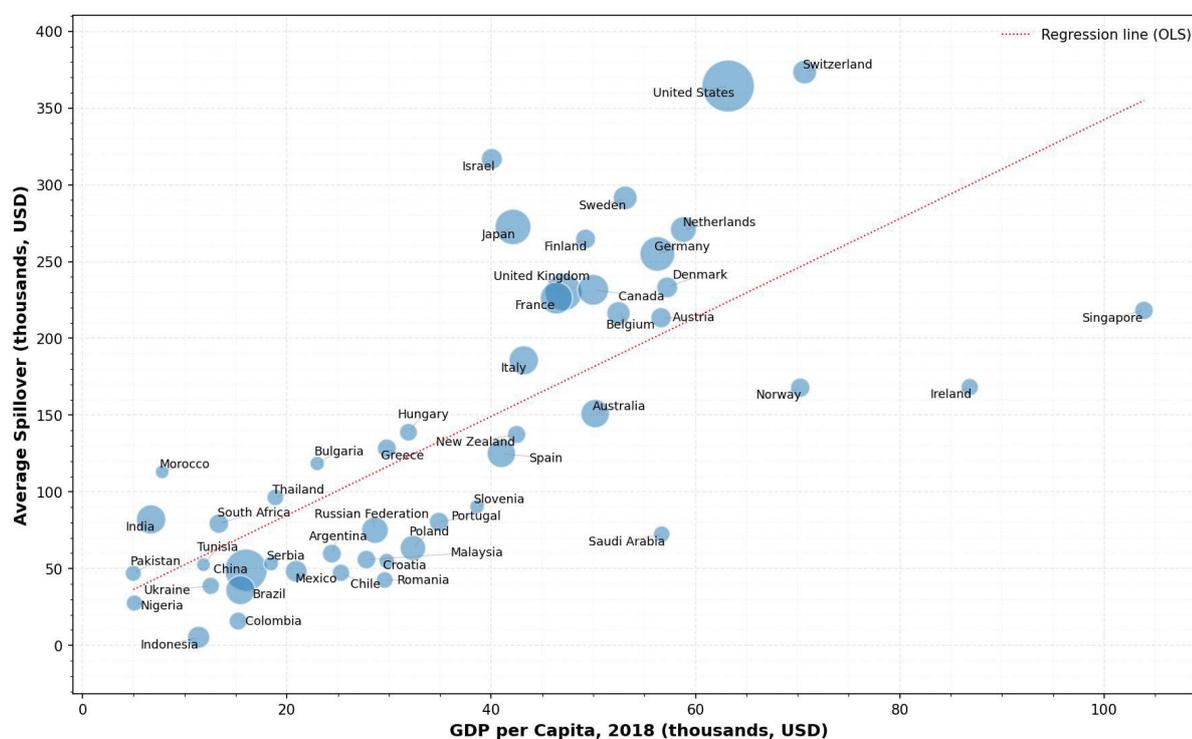
Finding 4. Estimates of the ‘spillovers from science’ provide another lens to inform innovation policy as part of an industrial strategy

Scientific knowledge creates value by serving as an input to the development of new technologies. This value varies across disciplines, institutions, and regions – and depends

on the type of technology being considered. Understanding this variation can help inform efficient targeting of science funding where growth is a key objective. In Martin et al (2026), we introduce a method (“Science Rank”) to measure the relative economic value of knowledge spillovers from scientific output into commercial innovations, using a large citation network⁴ to assign a portion of the private returns from patented innovations to the scientific work upon which it builds. Crucially, our method allows for both direct and indirect flows of value from scientific research to commercial innovations (see Annex A).

We summarise country level spillovers from science in Figure 5 which plots the average spillover for a scientific publication against GDP per capita. This shows that in general, more developed countries have higher spillovers on average. The United States has high average spillovers and also leads in volume terms (as shown by the bubble size). Average spillovers (per publication) are highest in Switzerland.

Figure 5: Global spillovers from science vs GDP per capita



Bubble area encodes publication count (square-root scaled).

Notes:

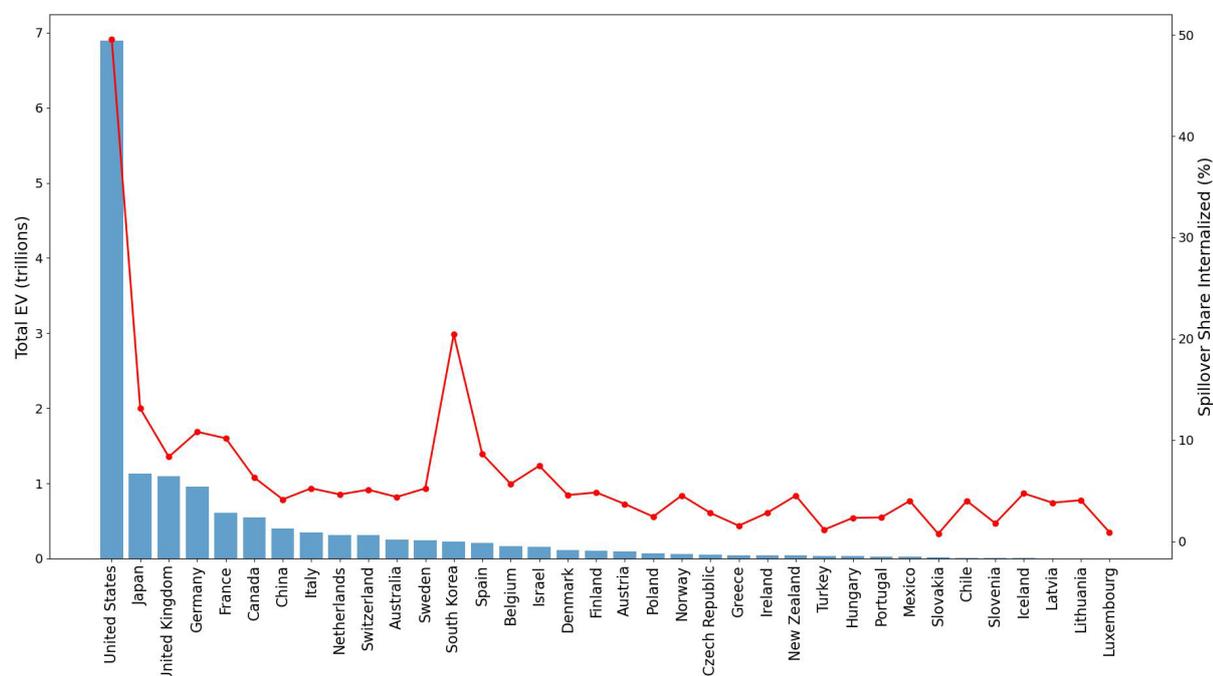
Bubble size represents the total count of academic publications in a country. The y-axis gives the average spillover across those publications, by country.

The relative ranking of countries in terms of total global spillovers is easier to discern in Figure 6, where we rank OECD countries plus China on this measure. As in our previous discussion, while global spillovers are of interest, perhaps more directly relevant for policymakers focused on industrial strategy is the extent to which spillovers from science

⁴ This network is built using three datasets: Open Alex, PATSTAT Global 2023 Spring Edition and the Reliance on Science dataset, for more detail see Martin et al. (2026). Our sample is constructed by limiting to citing innovations (academic publications and patents) from 1985 to 2018.

are “internalised” within national borders – ie spillovers from science benefit domestic rather than foreign innovation. Figure 6 plots this on the second y axis. This shows that the United States not only leads in terms of overall spillovers (given its high average spillovers and largest volume of publications shown in Figure 5), but it also internalises a far higher share (around 50%) compared to other countries – perhaps due to its overall technological development and capacity to apply the findings of science in commercial settings. Interestingly, the share internalised by the UK (below 10%) is lower than that in Japan, Germany and France. South Korea, while seeing lower total spillovers, stands out for internalising a high share of these (over 20%).

Figure 6: Internalisation of spillovers from science by country



Notes: The left y-axis gives total global spillovers generated by a country in trillions (USD). The second y-axis shows the percentage share of spillovers internalised by the country. The graph includes OECD countries and China.

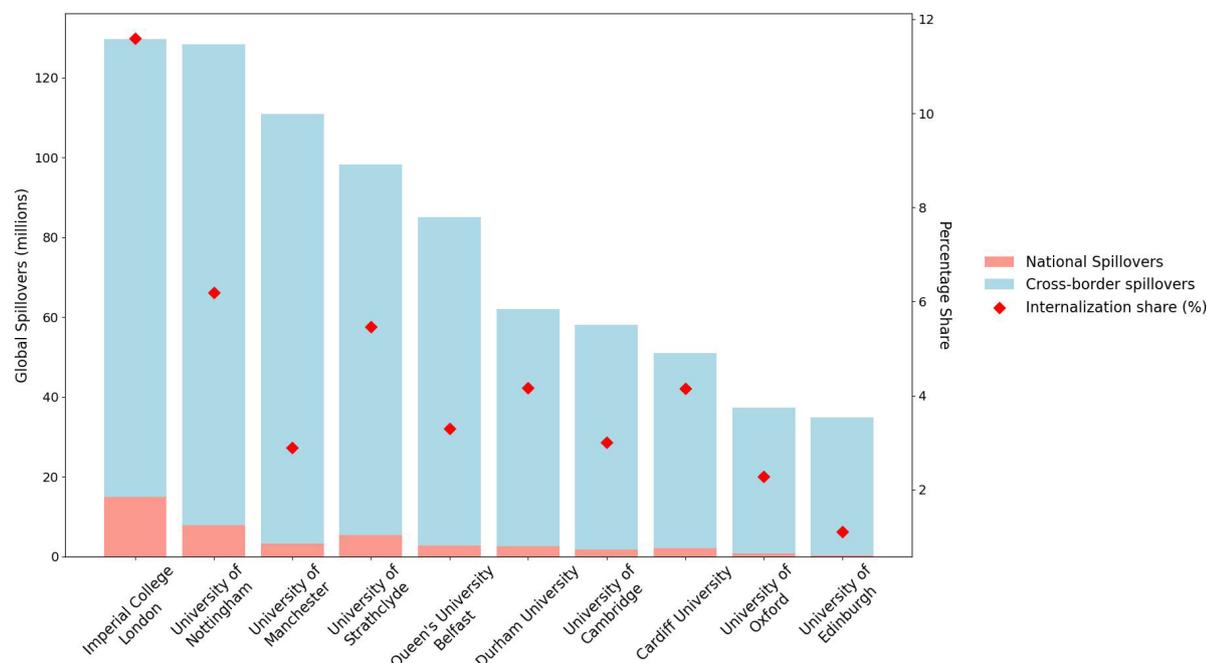
Using these measures, it is possible to consider the spillovers from science into specific technologies of interest, and to explore which countries, disciplines or even which institutions, are particularly important in generating spillovers. To illustrate this, our next step is to consider a selection of specific clean energy technologies that are priority subsectors in the Industrial Strategy: offshore wind, nuclear, CCUS and heat pumps. For each we consider the top 10 UK institutions in terms of the overall monetary value of spillovers generated into related innovation, as shown in Figure 7.

These charts show total global spillovers (blue), those retained within national borders (red), and on the right-hand vertical axis, the share of spillovers internalised. The first thing to note is that the scales differ – total spillovers for nuclear and CCUS are the highest, followed by offshore wind and then heat pumps. Across these technologies, this analysis highlights that different universities – in different parts of the country – lead across the different technologies. While Golden Triangle universities of Cambridge, Oxford and Imperial tend to feature across all four technologies, we find that Nottingham, Southampton, Manchester, Liverpool and others rank highly in specific technologies – as well as universities in Scotland and Northern Ireland (eg Strathclyde and Queen’s University Belfast for offshore wind).

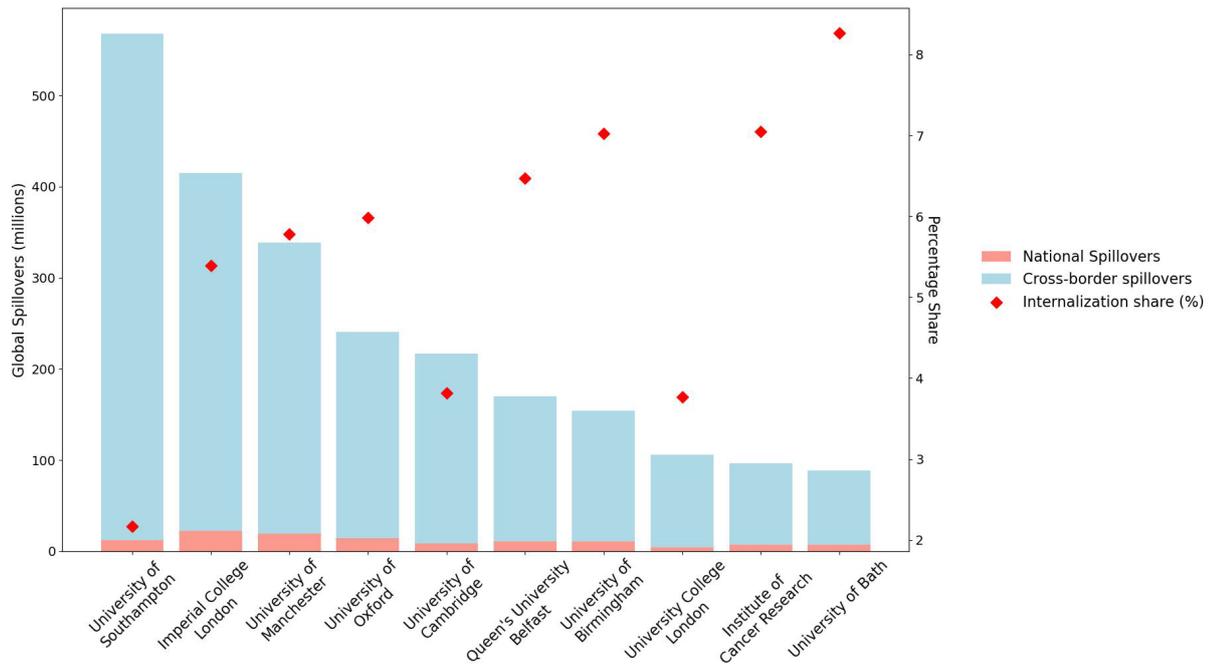
There is also wide variation in shares internalised. For example, both Imperial and Nottingham lead on offshore wind spillovers, but a higher share of Imperial’s spillovers is internalised (nearly 12% versus 6%). On nuclear, while Southampton leads on total spillovers and Bath ranks 10th, a far higher share of Bath’s spillovers is retained which means that the amounts of national spillovers generated by the two universities are similar.

Figure 7: Spillovers into specific clean tech innovations by UK institution

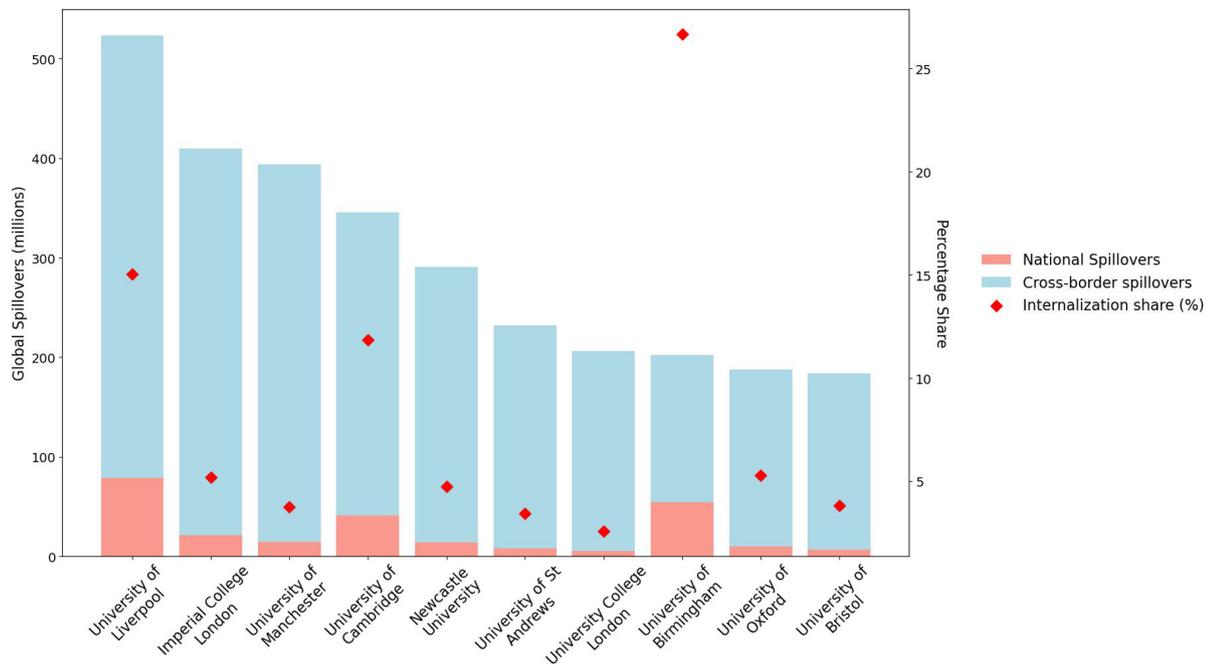
Panel A: Offshore wind



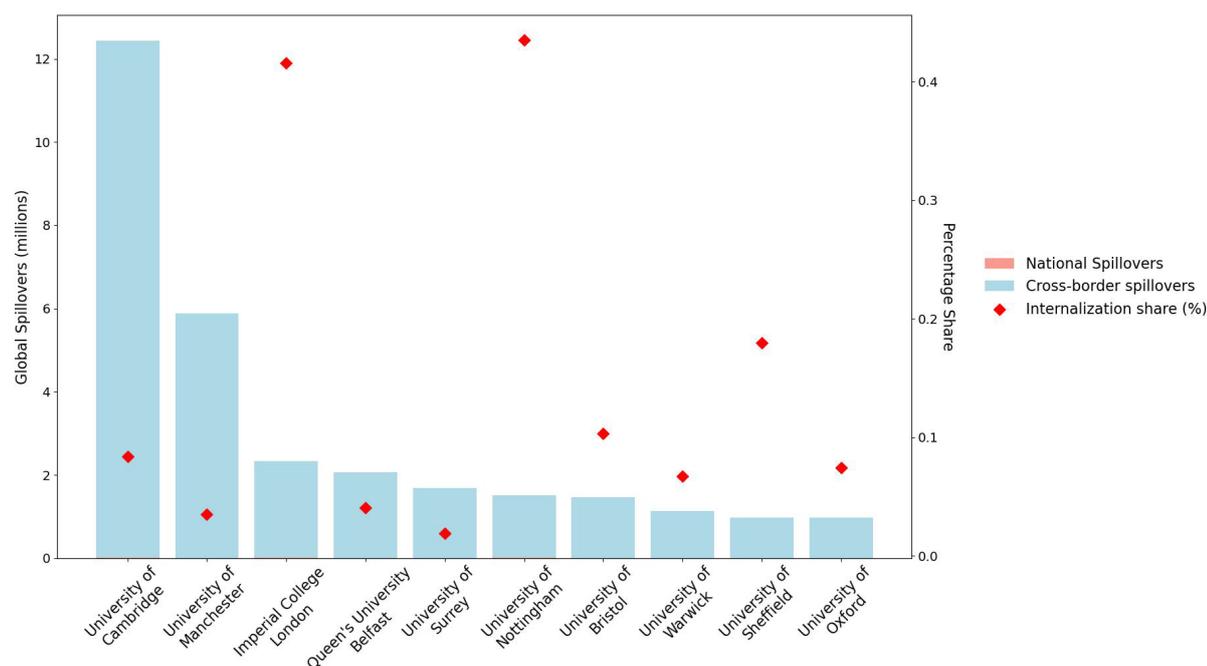
Panel B: Nuclear



Panel C: CCUS



Panel D: Heat pumps



Notes: The left y-axis gives total global spillovers in millions (USD) generated by an institution into the technology grouping specified for each panel. The second y-axis shows the percentage share of spillovers internalised by the institution. The graph includes the top ten UK institutions by global spillovers into each technology. Note that the scales differ across panels.

Conclusion

In this briefing note, we have summarised some findings that shed light on where the UK's comparative advantages in clean tech innovation lie, the extent to which economic benefits from investing in clean tech innovation are likely to be felt in the UK and regional patterns to this. Looking at patented innovation, we find that clean energy technologies generate higher than average national returns, and that these are particularly high for innovations in regions such as the north east and Wales.

We take a deeper look at the science that inspires specific clean technology innovation, showcasing a new methodology that shows how universities across the country are generating spillovers from science that benefit UK innovation. The UK's lower share of spillovers internalised relative to some other comparators provides another lens that suggests that the UK can do better at converting its excellence in science to economic benefits within the UK. And institution-level analysis highlights differences in spillovers from science into specific clean technologies, and the extent to which those spillovers are retained in the UK. Combining this with institutional knowledge and broader measures of effective structures for knowledge transfer and university – industry collaboration can help to build out industrial strategy clusters in priority sectors.

The work presented here is part of an ongoing research agenda to inform industrial strategy in the UK, with a focus on maximising innovation strengths, spillovers and likely returns to investments in innovation across the country. In particular, future research will seek to extend the analysis presented here to consider spillover flows across regions, and to consider more detailed technology classes across clean tech and broader industrial strategy sectors.

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Annex A: Methodologies for the measures and indicators in this note

This annex provides technical details for readers interested in understanding how our key measures are calculated. Please refer to the references for a more in-depth account of the methodologies used.

Revealed comparative advantage (RCA)

RCA is calculated as a product's share of a country's exports divided by the product's share in global exports. We adjust RCA values so that they lie between -1 and +1, with numbers larger than zero signifying that the country has RCA in a particular product. If a country has RCA in a product, it can be thought of as a specialised exporter of that product.

Revealed technological advantage (RTA)

A country is said to have RTA in a technology area if the area's share of the country's total patenting is larger than the area's share of total global patenting. We adjust RTA values so that they lie between -1 and +1, whereby numbers greater than zero indicate that the given country has innovative specialisation in that area. If a country has RTA in a technology, it can be thought of as a specialised innovator in that technology.

Private values of patents

In our methodology, the private value of an innovation to the innovator is captured only to the extent it translates into enhanced profit. Following the approach set out by Kogan et al. (2017), the private value of an innovation is assumed to be captured by the short-term response of the stock market price of innovating companies when a patent is granted. Private values of patents for non-stock-listed companies are extrapolated based on the most similar patents from stock-listed companies. See Guillard et al. (2021) for further explanation.

The Industrial Strategy Index (IStraX)

The IStraX (Guillard et al, 2023) is based on a model of the innovation process, which is fitted to global data on patenting and valuations of companies undertaking innovation. Resulting values therefore reflect the total economic value of an innovation in a certain field calculated as the difference between the expected increase in total value (private value as well as external values from knowledge spillovers) generated by that innovation and the expected cost of the subsidy, scaled by the expected cost of the subsidy.

The value of knowledge spillovers created by an innovation is calculated as a portion of the private value of all innovations that build upon it (as measured via citations). Since knowledge spillovers constitute value that is not internalised by the organisation that invests in R&D, they represent an externality that justifies government support for R&D.

We infer the average R&D investment required to generate an innovation from the observed shape of the private value distribution in a particular technology area. If we observe relatively few low value innovations, it is a sign that the costs of R&D projects in that area are higher; ie innovators will ensure that they can recover those higher costs – on average – by only pursuing the most promising ideas. If average R&D costs in a technology area are high, it will require more government funding to increase innovation.

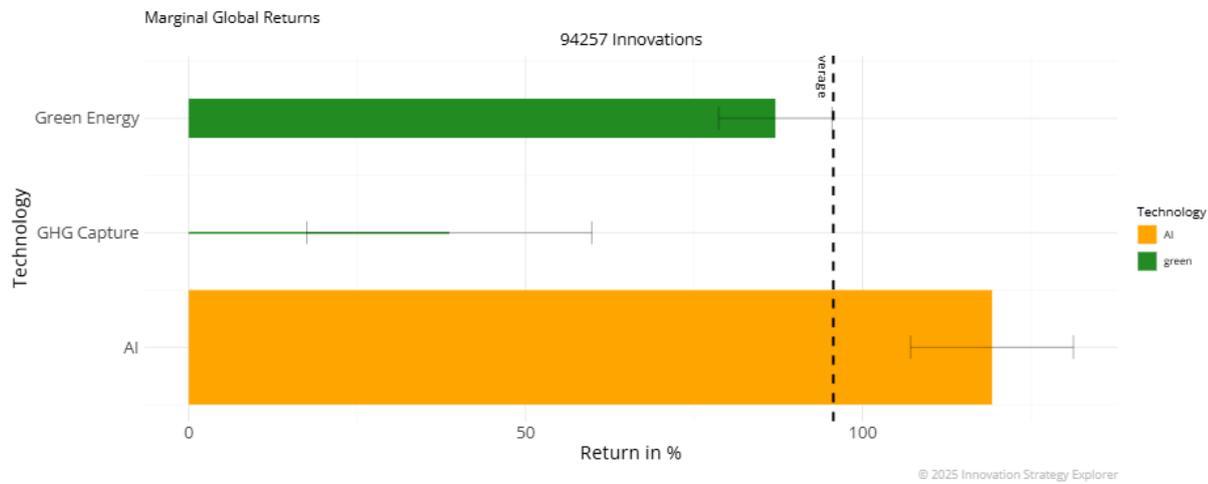
The Science Rank

The Science Rank is a methodology that estimates the spillovers from science (Martin et al., 2026). As in the ISTraX, patents are assigned a private value, and patents cited by future patents are assigned a portion of the private value of those future patents. Science Rank takes this approach back to the underlying science that inspires patented innovations. While the scientific publications are assumed to have zero private value themselves, we assign scientific publications a portion of the value of future patents that cite them directly or indirectly. As such, it is a measure of the value of knowledge spillovers produced by a scientific publication.

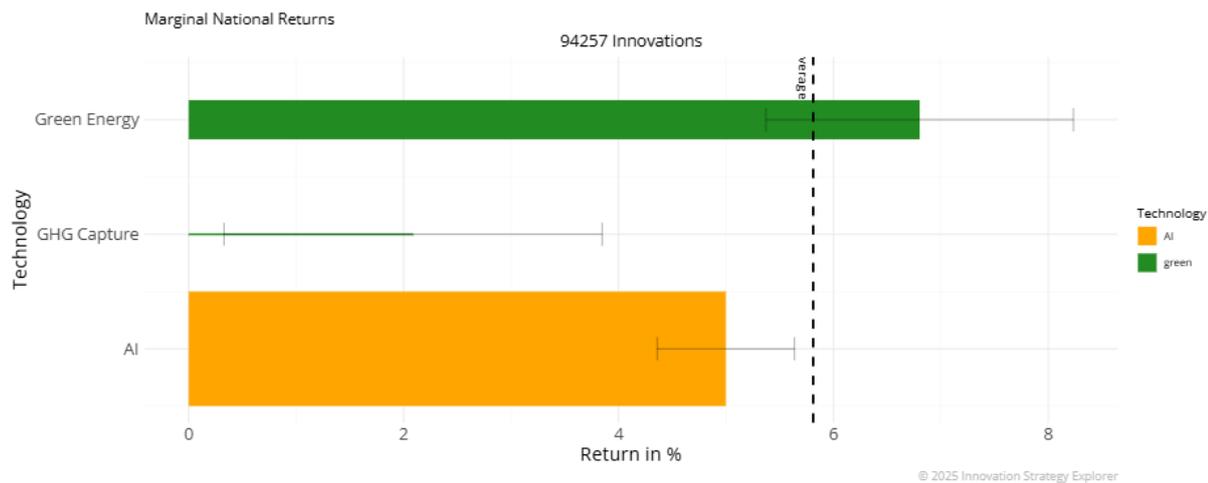
Annex B: Extra results

Figure B.1: Estimated marginal global and national returns for selected technology categories in the UK (sample mapped to region)

Panel A: Global



Panel B: National



Notes: Results produced with the Innovation Strategy Explorer (ISE) - <https://www.prinzproject.io/iseapp>. Patents data are from PATSTAT 2021, and innovations over the period 2009-2018 are included. During that time, there were 145,435 innovations (“patent families”) across all technology classes in the UK. Of these, 94,257 innovations have been mapped to region, and this chart summarises marginal global and national returns on that sample. The dashed line shows the estimated marginal global (Panel A) and national (Panel B) return across all of those innovations.

Green innovation: opportunities for developing countries

Ralf Martin¹, Golvine de Rochambeau² and Trang Thu Tran³

Executive summary

- To capture value from emerging green value chains, countries and firms need to be able to capture parts of the knowledge value chain – through the invention and development of new and improved green technologies.
- A recent report by the IFC/World Bank in conjunction with researchers from the Productive and Inclusive Net Zero (PRINZ) project examined measures of comparative advantage and spillovers in the knowledge economy across countries and technologies. This briefing note brings out key findings, and extends the analysis, to inform economic development strategies focused on green technologies.
- Overall, we find that low- and middle-income countries (LMICs) tend to be less represented in knowledge generation and research compared with high-income countries (HICs). But, looking at the composition of innovation, we find that they have a comparative advantage and tend to specialise in green innovation and research. For example, over 12% of patented innovations in LMICs are in green technology fields whereas the same figure is less than 9% in HICs.
- We also consider measures of the spillovers from innovation and find that green innovations in LMICs tend to generate higher spillovers than the average green (or non-green) innovation in HICs.
- This evidence suggests that making a push with policy and strategic investments in green technology fields and sectors could be part of a successful growth strategy for many emerging economies.
- But, we find the overall picture hides a lot of variation across countries, technology fields as well as innovator types. For example, for Vietnam we don't find high returns for green technology overall, but we find very high returns for green ICT technologies. For Indonesia we find high returns for Circular Economy technology which gets rather low returns in most other LMICs.
- Collaborations between LMIC and HIC firms and innovators appear to be an important channel for emerging economies to kickstart innovation. But, the amount of local spillovers this creates will vary across technologies and firm types. Hence, LMIC governments can be more effective if they seek out such partnerships strategically.

¹ World Bank Group and Imperial

² World Bank Group

³ World Bank Group

- The measures and indicators as suggested in the work described here can highlight potential broad technology fields where local talent already exists that generates virtuous feedback loops via spillovers. To aid policymakers with more granular case-by-case analysis we are building a new data tool: the [Innovation Strategy Explorer \(ISE\)](#).

Introduction

Many firms and governments are formulating strategies to secure participation in and the economic opportunities from global supply chains in green technologies. But, value tends to be captured by firms and countries that hold relevant intellectual property, especially in knowledge driven sectors involving advanced technologies. How are different countries placed to insert themselves into what we might call the Knowledge Economy Value Chain of the Green economy? Over the last 15 years or so we have seen China emerge as a leader in various clean technologies with a substantial impact on the overall growth of the economy.⁴ Are there other emerging economies where a growth strategy around innovation in green technologies might be likely or realistic? A recent report by the IFC/World Bank in conjunction with researchers on the Productive and Inclusive Net Zero (PRINZ) programme explored this question by looking at measures of comparative advantage and spillovers in the knowledge economy. This briefing note brings out key findings and extends the analysis to inform economic development strategies focused on green technologies.

Key findings

Finding 1. Low- and middle-income countries as a group have a comparative advantage in green research and innovation

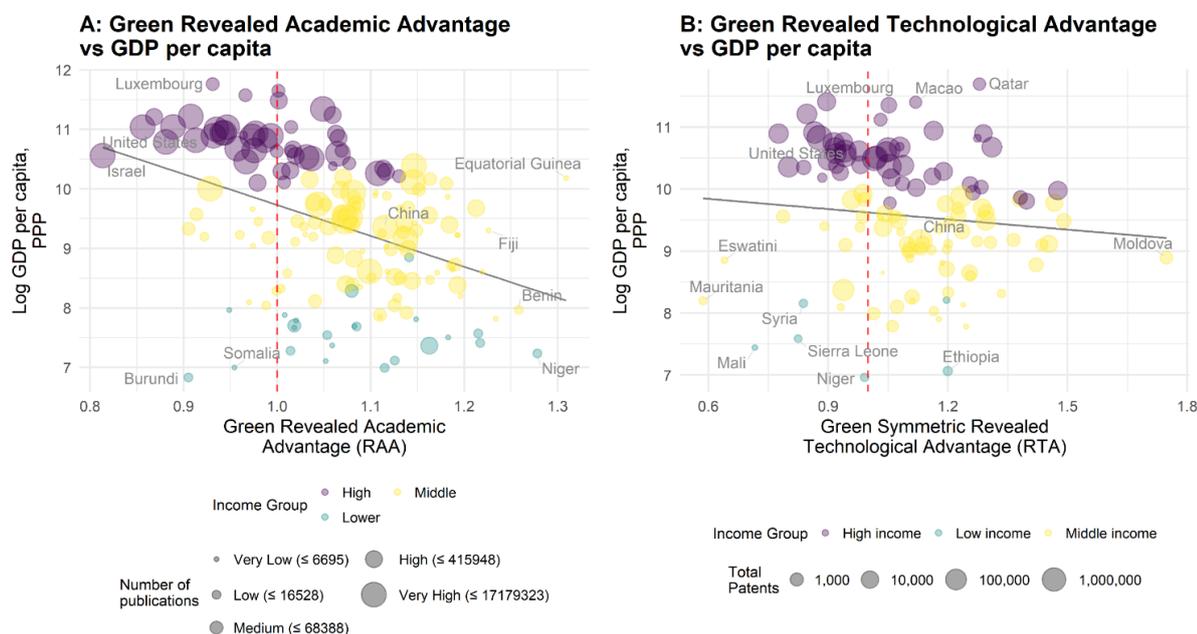
With trade data we explore comparative advantage by examining if a country's share in trade in a particular category such as green products is bigger than those of most other countries. We can do something similar with a country's activities in the scientific or innovation space. That is, we compute the relative activity shares in academic publishing – which we call revealed academic advantage (RAA), or innovation (based on patenting) – which we call revealed technological advantage (RTA).

Our analysis finds that, on average, low- and middle-income countries (LMICs) tend to have a comparative advantage in both academic research and innovation. This is shown in Figure 1 where there is a negative correlation between RAA (Panel A) and RTA (Panel B) respectively with country per capita GDP. Thus, while lower income countries generally produce much less innovation and research, a larger fraction of their innovation is green.

⁴ [Analysis: Clean energy contributed a record 10% of China's GDP in 2024 - Carbon Brief](https://www.carbonbrief.org/analysis-clean-energy-contributed-a-record-10-of-chinas-gdp-in-2024/)
(<https://www.carbonbrief.org/analysis-clean-energy-contributed-a-record-10-of-chinas-gdp-in-2024/>)

For example, over 12% of patented innovations in LMICs are in green technology fields whereas the same figure is less than 9% in High-Income Countries (HICs)

Figure 1: Revealed academic advantage and revealed technological advantage in green technologies, and GDP per capita



Source: IFC (2025). Based on OpenAlex, 2023 Patent Statistical (PATSTAT), European Union Intellectual Property Office (EUIPO), and World Bank Group’s World Development Indicators Database.

Notes: Each panel relates countries’ green symmetric revealed comparative advantage to GDP per capita, based on different knowledge measures. Panel A presents green revealed academic advantage (RAA) using academic publications, aggregated from 2000 to 2022. Panel B presents green revealed technological advantage (RTA) based on patents. The sample includes countries meeting two criteria: having at least 500,000 inhabitants, and total numbers of academic papers, patents, above 100 across all countries. GDP per capita is PPP, constant 2021 international dollars, averaged over the period. The size of each marker is larger the greater the country’s total number of papers, patents, startups or trademarks in the country. The grey solid line depicts fitted values from the unweighted OLS estimate of log GDP per capita on symmetric comparative advantage. See online appendix 1 in IFC (2025) for further details on sector classification.

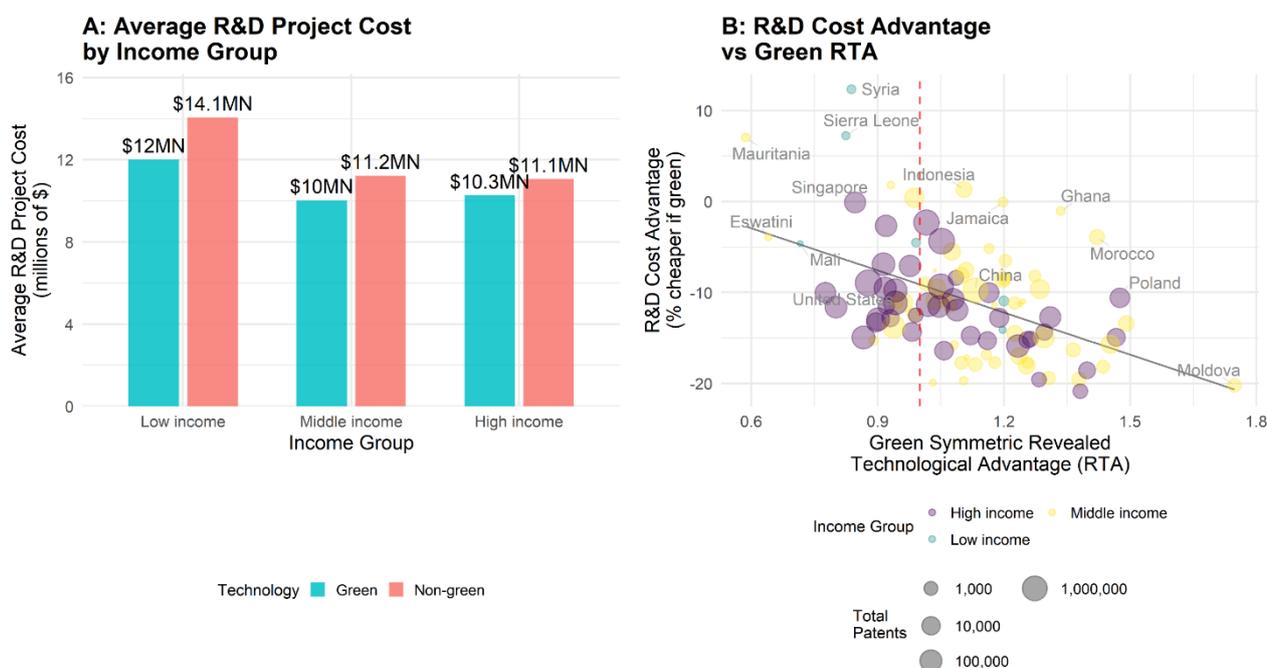
Finding 2. Drivers of LMIC green comparative advantage include the fact that, on average, green technology innovation is cheaper and thus more accessible for LMIC innovators

What could be the reason for these patterns of comparative advantage? We document two potential factors. Firstly, as a broad group, green innovations might be simpler or cheaper and thus more accessible for developing country innovators that are more resource constrained. To examine this, we rely on a method developed by Guillard et al (2021) that estimates the cost of creating an innovation across narrow technology classes. This analysis suggests that on average, innovation in green technologies is cheaper (Figure 2, Panel A). Also, the cost of green relative to the average innovation is closely related to RTA

in green technologies across countries. This is shown in Figure 2 (Panel B), where there is a negative correlation.

This could broadly be considered an innovation push factor in favour of green innovation in LMICs. It is the inherent characteristics of green technology innovation that make it more suitable or accessible for innovators in LMIC.

Figure 2: R&D Costs and revealed technological advantage



Source: Based on data from PATSTAT and Kogan et al. (2017).

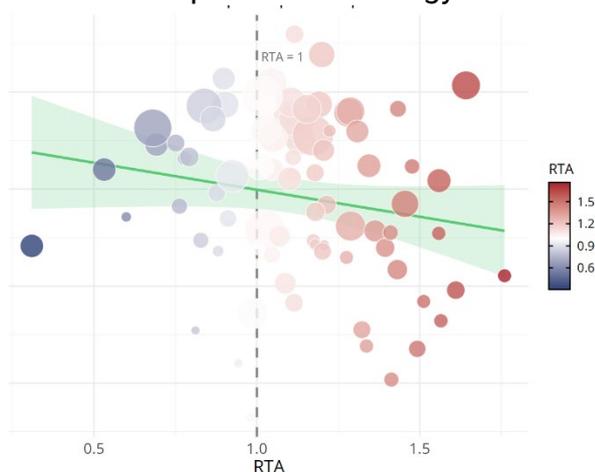
Notes: The figure explores the country level variation in an estimate of detailed technology-specific R&D costs from Guillard et al. (2021). Panel A shows that LMICs do not necessarily engage in lower cost innovation projects. But, across all income groups, green innovation involves lower fixed R&D costs. Panel B shows that this relative R&D cost is significantly associated with green RTA.

Finding 3. The LMIC green comparative advantage is particularly strong for adaptation innovation

We consider two subcategories within green technology: adaptation and green transport; and find that comparative advantage in LMICs is particularly strong in adaptation technologies which could be driven by higher exposure to the effects of climate change. For instance, Figure 3 contrasts adaptation technologies with green transport technologies, which are more dominated by HICs.

Figure 3: Revealed technological advantage and GDP per capita: adaptation and green transport

Panel A: Adaptation technology



Panel B: Green Transport Technology



Source: Based on data from PATSTAT and World Bank.

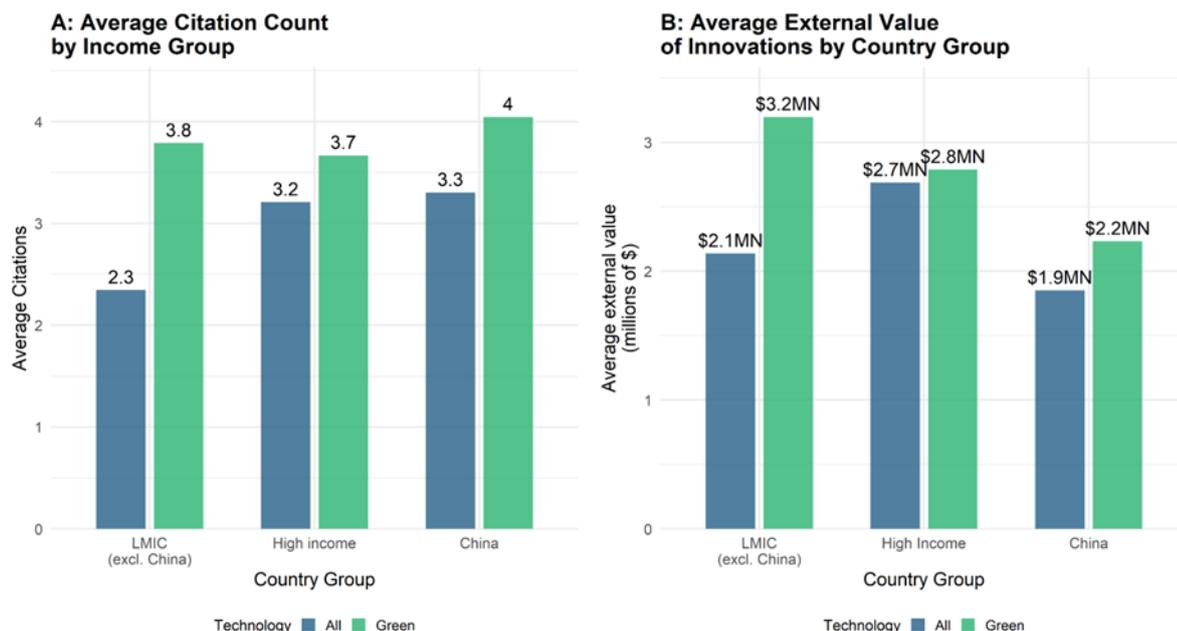
Notes: Panel A reports the relationship between GDP per capita and RTA in technology related to the adaptation to climate change. Panel C reports the same for RTA in green transport technology.

Finding 4. LMIC green innovation is on average of higher quality than other innovation

A strong comparative advantage in a specific technology is not necessarily a rationale for more investment. To derive such a rationale we need evidence of market failures. We explore one market failure in particular: knowledge spillovers measured via direct or indirect citations where we also consider the private (for the inventor) economic value of an innovation. This leads to an intriguing finding: while on average (across all technologies) innovations in LMICs generate lower levels of spillover than HIC innovations, green LMIC innovations have on average higher spillover values than HIC innovations across different categories: we estimate that the average spillover value of an LMIC green innovation is \$3.2mn whereas the average spillover value for all HIC innovation (across all technologies) is \$2.7mn (Figure 4).⁵ This suggests that LMIC green innovations are high quality but also that there is likely not enough R&D investments as private firms will not consider the value of these spillovers.

⁵ This calculation takes into account both direct and indirect knowledge spillovers inferred from patent citations. However, the high quality of green LMIC innovations emerges also from a simple citation count as reported in Panel A.

Figure 4: Citation counts and spillovers (Patent Rank) for green compared with all innovation across country groupings



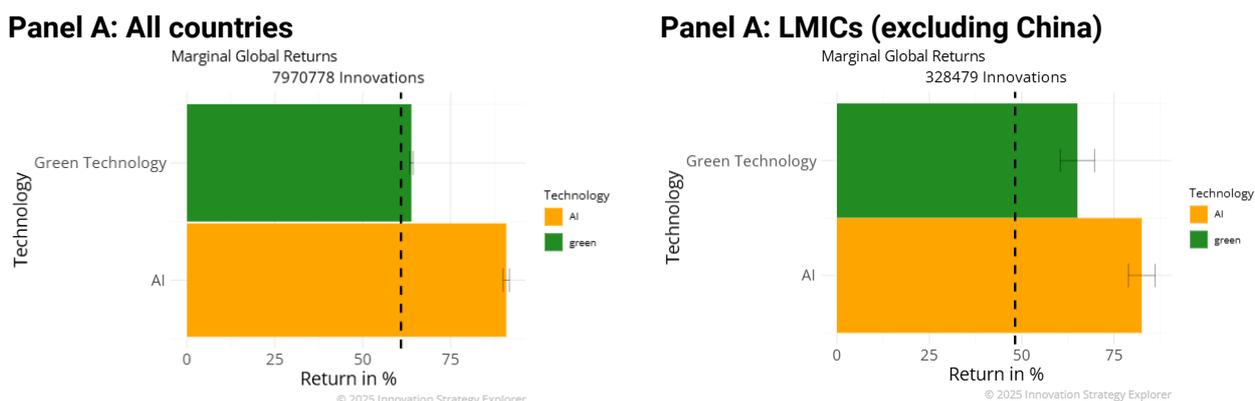
Source: IFC (2025). Calculations based on Guillard et al. (2021) using data from PATSTAT and Kogan et al. (2017). **Notes:** Panel A reports average citation counts of patented innovations across different regional groupings for all innovations as well as separately for green innovations. Panel B reports average values of Patent Rank following Guillard et al. (2021). This provides a method to assess the quality of patented innovations using citations while considering both direct and indirect citation and to account for economic value differences of the cited innovations.

Finding 5. Green innovation has above average internal and external returns from additional investment in R&D

To assess the impact of additional R&D investment more comprehensively we need to compare rate of returns to R&D investment taking into account the (marginal) value of these spillovers relative to the investment required to unlock it. To estimate such marginal rates of return we calibrate a model of the innovation process that allows for variation in R&D costs between different sectors⁶ as well as variation in the density of not yet exploited ideas across different sectors and technologies and countries. This leads to country and sector specific return figures. Estimated returns from green innovation are above average – although lower than for AI (as a comparison technology) – both for all countries combined but specifically so for LMICs (Figure 5).

⁶ The innovation cost estimates in Figure 2 are also derived from this.

Figure 5: Marginal global returns for green technologies and AI



Notes: Results produced with the Innovation Strategy Explorer (ISE) – <https://www.prinzproject.io/iseapp> – or Click on the figures to navigate to ISE. In each chart, the dashed line represents the average returns across all green and non-green technologies.

Finding 6. There is considerable heterogeneity in R&D returns across countries, technologies (including green sub-technologies) and across inventor types

There is considerable variation in returns across green technology subfields and across countries. To facilitate examining this on a case-by-case basis we have developed a tool – the Innovation Strategy Explorer (ISE)⁷ that allows exploring these return figures and similar measures for different countries and technology groupings. The tool also allows for browsing of specific examples of high value innovations.⁸ Figure 6 illustrates this for a selection of countries. For example, in Indonesia (Panel A), we find high returns for circular economy technology which gets rather low returns in most other LMICs. In Vietnam (Panel B), Green technology overall has lower than average returns (shown by the dashed line), but we find very high returns for green ICT technologies.

⁷ <https://www.prinzproject.io/iseapp>

⁸ In the appendix we show some examples.

Figure 6: Marginal global returns across selected countries and technologies

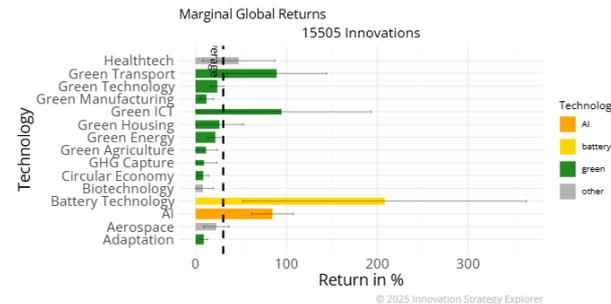
Panel A: Indonesia



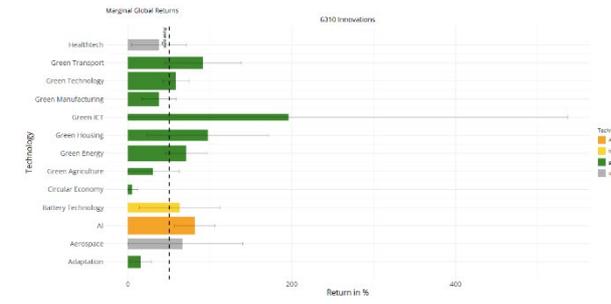
Panel B: Vietnam



Panel C: Mexico



Panel D: South Africa



Notes: Results produced with the Innovation Strategy Explorer (ISE) – <https://www.prinzproject.io/iseapp>. Click on the figures to navigate to ISE. In each chart, the dashed line represents the average returns across all green and non-green technologies. The width of the bars present the (log of 1 plus) number of innovations.

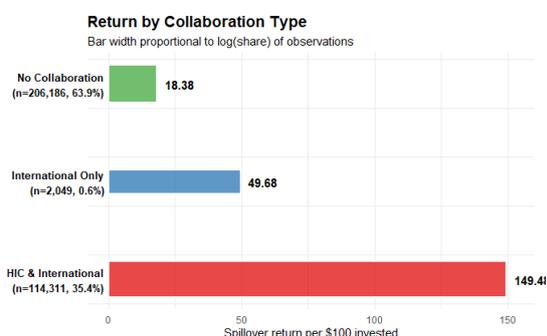
There is also substantial heterogeneity in returns by inventor type (Figure 7). We find that high spillover returns in LMICs derive primarily from innovations where LMIC innovators collaborate with HIC innovators. Around one third of LMIC innovations involve this type of collaboration. But, it is those innovations that generate the highest returns on average. As we show in Figure 7, the average is nearly 10 times higher. Thus, the strategy for LMICs innovators to create high quality high return innovations might involve collaborations and investments by and with HIC innovators and firms.

We might be concerned that this reflects an extractive dynamic, where LMICs intellectual capabilities are re-directed to benefit HIC firms rather than developing countries. This could be particularly the case because some innovations behind these figures could be suspected of being associated with “brain drain” where individuals born in lower income countries migrate to study or work abroad and some if not all commercially valuable innovation happens abroad. It could also be the case that innovators while being employed by foreign MNEs – sometimes in dedicated R&D labs – continue to stay in LMICs and move between various firms there, including from MNEs to domestic firms. We might suspect that such a scenario creates more benefits for LMICs than a brain drain. But there might still be concern that employment by MNEs leads to R&D output that benefits the domestic economy less.

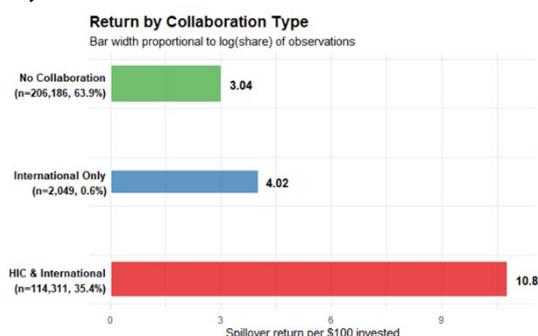
We can examine these questions using a modified version of our framework where we only take into account spillovers within LMIC innovators. Panel B of Figure 7 repeats panel A while focusing on within-LMIC spillovers only when computing returns. This leads to the same pattern as before, with LMIC-HIC collaborations having yet again the highest returns. This means that returns to innovations from LMIC innovators are higher when LMIC innovators collaborate with HIC innovators, even when only returns to LMICs are considered. But, we note that the return gap relative to national only innovations is somewhat smaller (a ratio of three rather than nearly 10) suggesting that there is a certain pro-HIC bias in such collaborative ventures.

Figure 7: Global spillover returns by collaboration type

Panel A: Global spillover returns



Panel B: Spillover returns within LMICs (excl. China)

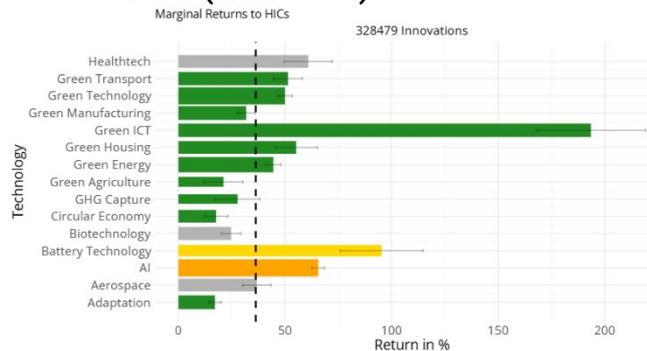


Notes: The figure reports the returns to further R&D investment (Marginal Returns) for innovations from LMICs (excluding China) with different kinds of innovator collaborations. HIC & international are innovator teams where at least one innovator or the assignee from a HIC and at least one innovator from a developing country. International Only are innovator teams from multiple LMICs. No collaboration are innovations where all innovators and assignees are based in the same LMIC.

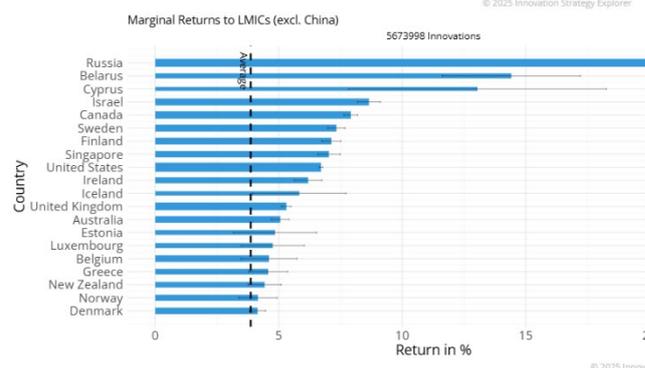
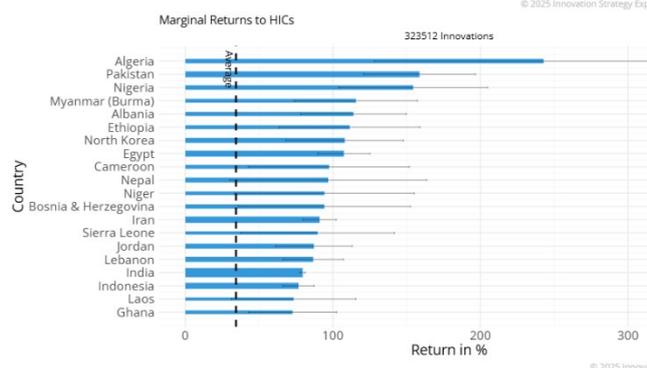
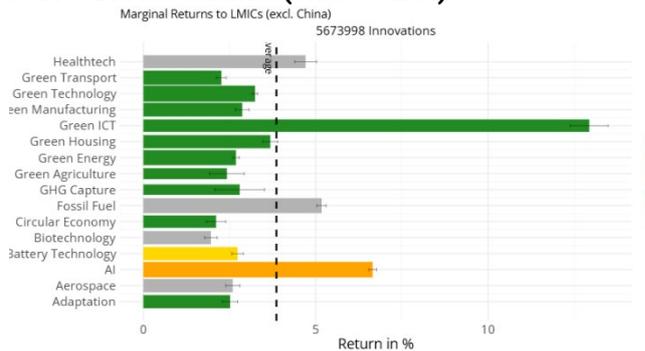
More broadly, we can use this approach to study spillover flows between technologies and country groups. For instance, we can study how investments in LMIC innovators in specific technologies or countries lead to returns in HICs (Figure 8, Panel A). We see there that returns are relatively high for AI. But, they are also above average for a range of “green” categories such as green ICT but also green transport and energy.

Figure 8: Return flows between LMICs and HICs by technology and country

Panel A: LMIC (excl. China) → HIC



Panel B: HIC → LMIC (excl. China)



Notes: The Figures reported here consider spillover return flows to HICs from R&D investments in LMIC (Panel A) and spillover return flows to LMICs from investments in HICs. The top row examines flows from different technology areas, whereas the bottom row averages the marginal return flows across all technology areas from specific countries. The width of the bars present the (log of 1 plus) number of innovations.

We also investigate the reverse flow of knowledge spillovers to developing country innovators from HIC R&D investments (Figure 8, Panel B). Green ICT yet again generates high returns. Other green categories tend to be below average, and AI generates high returns once more. There is also substantial variation across countries. Investment in Russia exhibits high returns presumably because of its links to former Soviet countries. But, there is also substantial heterogeneity across more comparable advanced economies. For instance, external returns from Israel are nearly twice as high as those from Denmark.

Conclusion

Emerging economies with ambitions to grow into high-income countries will need to develop innovation-driven growth. This will be a process of trial and error, but not all technologies and sectors will be equally suited. If government resources are being used to support innovation limited resources need to be targeted to strategic areas while not being so targeted that competition is stifled – eg by supporting a single national champion.

The measures and indicators as suggested in the work described here can highlight potential broad technology fields where local talent already exists that generates virtuous feedback loops via spillovers.

Collaborations with HIC firms and innovators appear to be an important channel for emerging economies to kickstart innovation. But, the amount of local spillovers this creates will vary across technologies and firm types. Hence, LMIC governments can be more effective if they seek out such partnerships strategically.

Such strategic collaboration can also go both ways: some HIC firms and countries are more likely to benefit from collaborations with LMICs and HIC governments can be proactive in identifying and supporting such opportunities. Analysis as developed here can support this process.

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Annex A: Methodologies

Inferring the cost of innovation

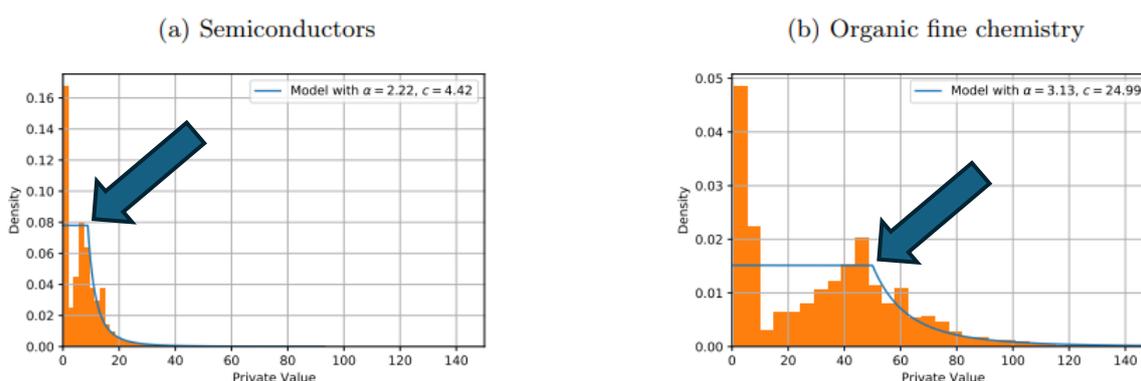
While patent data are readily available as a measure of innovation outputs, there is much less information on innovation inputs and associated costs. Guillard et al. (2021) develop a method to infer the average cost of an innovation in different technology areas.

For different technology fields, they examine the distribution of the present discounted value of innovations for the innovating firm. They follow Kogan et al. (2017) to estimate those values from the stock market response when the firm's patent related to the innovation is first granted. They develop a model where the realised value of an inventive step is determined by two parameters: First, the shape of an underlying idea generation process which is typically skewed – some technologies are more skewed with many ideas

of little value and the occasional “superstar” idea that generates very high profits for the innovating firm. Second, before an idea can be turned into a commercially valuable innovation it requires investment in R&D, the cost of which varies by technology. Only after incurring the sunk R&D cost will the actual value of the idea be known. If all ideas succeeded, we would expect to see only high-value innovations, those above the minimum value needed to justify the R&D cost. Ideas below that threshold would not be developed. But innovation is uncertain. Some ideas that look promising end up with low realized value, and so some low-value innovations will still be observed below the threshold. This creates a kink in the distribution of innovation values at the cutoff point.

By fitting observed data to this pattern, we can infer R&D costs across technology fields: the further to the right the kink is, the higher the underlying R&D cost as illustrated below (Figure A.1). Here, costs are estimated by granular technology categories. In Figure 2, they are aggregated at the country and broad technology type level.

Figure A.1 The value distribution of innovations in semiconductors and organic chemistry



Notes: The figure illustrates how Guillard et al. (2021) derive estimates of R&D costs across different technology areas by a modelled distribution function (Model) to the actual distribution of (private) innovation values derived using the Kogan et al. (2017) approach – that is, by examining the shock on share prices of stock listed innovators.

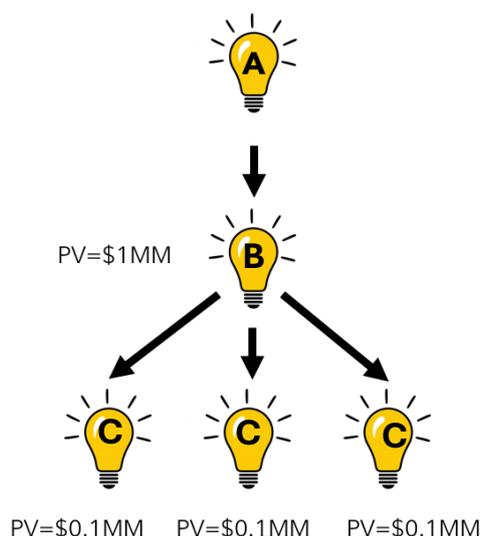
Computing returns and spillover flows from innovation

Guillard et al. (2021) highlight several shortcomings of simple citation counts as a measure of innovation spillovers – namely, that a simple count of citation does not consistently differentiate between being cited by an innovation that is highly cited itself compared with an innovation that is not. Moreover, citation counts do not account for the potentially large differences in the commercial value of innovations irrespective of their ability to generate citations. For instance, counting citations suggests that a citation by patent USD618677S1, which describes design features of Apple’s iPhone, holds the same value as being cited by

patent JP2007016376A, which seeks patent protection for a head cooling device incorporating a fan into a builder’s hard hat.

Guillard et al. (2021) propose a new approach to assess the value of innovations by adapting Google’s Page Rank algorithm to patents. By combining Page Rank with estimates of the private value of patents, they show that it can be interpreted as the total economic value of an innovation comprising the private value of an innovation to the inventor and a fraction of the private of all other (subsequent) inventors who cite the innovation directly or indirectly. They call this new indicator Patent Rank. To estimate the private values of individual innovations they follow Kogan et al. (2017), who infer the value of specific patents by studying the stock market response to the patent when first granted by the patent authorities. By assuming that stock-listed innovators are similar to non-stock-listed innovators within narrow technology classes, they can extend this approach to all patented innovations.

Figure A.2 Illustration of Patent Rank (P-Rank)



Notes: The Patent Rank approach by Guillard et al. (2021) ranks an innovation A based on direct citations such as innovation B as well as indirect citations C. In doing so they also take into account the (private) value of these innovations.

Formally, to derive the P-Rank we need to solve the equation system⁹ defined by

$$V_i = PV_i + \sum_{j \in F_i} \phi_{ji} V_j \tag{1}$$

⁹ While simply a linear equation system due to its consisting of several millions of innovations, we solve it using a recursive approach proposed in Google’s page rank algorithm.

where V_i is the P-Rank of innovation i , PV_i is the private value of innovation i to its inventors and $\sum_{j \in F_i} \phi_{ji} V_j$ is a weighted average of the P-Ranks of all innovations j citing innovation i . Several ways to define weights ϕ_{ji} are plausible. Guillard et al. (2021) propose¹⁰ as a benchmark to use $\phi_{ji} = \frac{\sigma}{N_{Bj}}$ where N_{Bj} is the number of backward citations of innovation j . This assumes an innovation i contributes more to j if there are fewer citations by j and all innovations cited by j contribute uniformly – in the same amount – to j . σ is an arbitrary scale factor set to 0.5. While V_i would measure the global social economic value¹¹ we can also examine how much value is generated for specific geographical subsets – such as say LMICs country innovators – by only accounting for private values PV_j of innovators falling into that subset and setting all other private values to zero.

Guillard et al. (2021), further derive ISTRAX, an indicator that allows assessing the marginal return of increasing innovation funding for specific technology subsets by fitting a simple model of the innovation process to the available data which was also used to derive the R&D cost figures discussed in the previous section. The underlying idea is the following: if we increase funding in a particular technology area this will lead to the implementation of more innovation projects. But what is the likely value of those additional projects? We should *not* expect them to be like the value of the average project of the past. Rather, those additional projects will disproportionately be drawn from the area to the left of the kink in Figure A.1; i.e. the projects that were previously below innovators' profitability threshold. What's more, how many such projects innovators have in their pipeline will vary between technology areas. However, we can estimate the probability mass of such projects by examining the shape of the value distribution to the right of the threshold. Moreover, we allow for the possibility that the spillover those below threshold projects generate might be different (most likely lower) from the spillover of the average project. Finally, we compare those additional benefits with the additional cost of an innovation which we derive as explained in the previous section. Guillard et al (2021) derive the following formula to capture all this in an index as

$$IstraX_a = \frac{1}{\#A} \frac{1}{c_a} \sum_{i \in A} SV_i \times I\{PV_i < 2c_a\} (1 + \alpha_a) \quad (2)$$

where A_i is the set of innovations that fall into a particular category (e.g. green innovations in LMICs), c_a is an estimate of the cost of an R&D project in category a , $I\{\cdot\}$ is the indicator function, and α_a is the curvature of the idea generation function from our simple model of innovation that determines how ideas are distributed across a quality measure. A high α_a implies that the idea generation function is more left skewed with more probability mass

¹⁰ Thereby following PageRank.

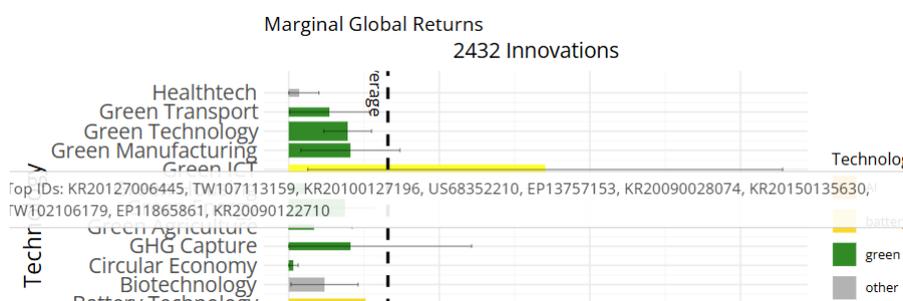
¹¹ This would account only for knowledge externalities but not for instances of any negative environmental damages of an innovation.

close to zero and less likelihood of “superstar” ideas with an extremely high quality and thus potentially high private economic value for the inventor. $SV_i = V_i - PV_i$ is the social value of an innovation. So, $IStraX_\alpha$ is the average of the social value part of P-Rank below the kink in the value distribution, scaled with innovation cost and curvature parameters of the idea generation distribution. Note that the basic qualitative features of expression 2 are intuitive: The marginal response to further investment in an area will be higher if costs are small because a given amount of R&D will simply go further. It will also be higher if the curvature is more skewed towards zero (α_c is larger) because a greater mass of ideas can readily be turned into R&D projects with some extra funding. Like for for P-Rank, we can compute various versions of IStraX depending on whose private values we want to consider. In this way we can for instance compute the return to a given amount invested in – say – an LMIC to innovators in HICs and vice versa.

Annex B: Innovation deep dives

Green ICT in Vietnam

The ISE Tool features a tool that facilitates deep dives into the underlying patent documents. For instance, consider Figure 6b, showing a high return for Green ICT in Vietnam. Which patents exactly are driving this result? We can explore by hovering over the relevant bar of the bar chart:



This reveals the application numbers of the top patents behind the statistic. Clicking on the bar leads to the listings on these patents on Espacenet, the European Patent Office’s online patent viewing website:

10 results found

1. MULTIPATH TCP WITH END-TO-END ENERG...
 KR20120065867A • 2012-06-21 • UNIV KYUNG HE...
Earliest priority: 2010-12-13 • Earliest publication: 20...
 PURPOSE: A multi-path TCP network using end-to-end energy saving technique for network which has great multiplication of delay-band width and an energy saving method are provided.

2. SPECTRUM SENSING METHOD, AND COGN...
 KR101450351B1 (A) • 2014-10-14 • UNIV ULSAN F...
Earliest priority: 2009-12-10 • Earliest publication: 20...
 PURPOSE: A spectrum sensing method is provided to enable one second user to participate in a spectrum sensing.
 CONSTITUTION: A receiver(110) receives a beacon signal

3. Device for Wireless Network and Computer Re...
 KR102430900B1 (A) • 2022-08-10 • 삼성전자주식회사
Earliest priority: 2015-09-24 • Earliest publication: 20...
 The present invention relates to upper and lower node devices which communicate with each other in a wireless network, and a computer readable recording medium including a program.

4. INTERFERENCE MITIGATION BY PUNCTURI...
 KR101460671B1 (A) • 2014-11-11 • QUALCOMM IN...
Earliest priority: 2009-08-11 • Earliest publication: 20...
 In the different kind wireless communications network, disclosed is the easy systems and methods the interference is controlled. It can be punctured in the physical broadcast

Global Dossier

Applicants QUALCOMM INC [US] +

Inventors SEONG KI BEOM [KR]; LUO TAO [CA]; YOO TAE SANG [KR]; ZHANG XIAOXIA [CN]; DOAN DUNG N [VN] +

Classifications

IPC H04J11/00; H04W52/32; H04W52/34; H04W72/54;

CPC H04L1/0045 (KR); H04L1/0069 (EP,KR,US); H04L1/0072 (EP,KR,US); H04W52/244 (EP,KR,US); H04W52/322 (EP,KR,US); H04W52/34 (KR); H04W72/544 (KR); H04W84/045 (KR); +

Priorities US2010045196W-2010-08-11; US23310709P-2009-08-11; US85316810A-2010-08-09

Application KR20127006445A-2010-08-11

Publication KR101460671B1-2014-11-11

Published as CN102474829A; CN102474829B; EP2465307A2; EP2465307B1; EP2536225A2; EP2536225A3; EP2536225B1;

One of the patents is focused on interference mitigation in the transmission of mobile phone signals. One implication of the patent is a reduction in energy intensity of mobile networks. The patent holder is the US firm Qualcomm. The team of innovators includes at least one person who is based in Vietnam.

Green transport in Mexico

We can do a similar exercise for Mexico. From Figure 6c we see that green transport generates above average returns. Which patents are driving this?



One of the top patents driving this is an innovation related to EV charging filed by [Leviton Manufacturing](#) a US headquartered firm supplying electrical, lighting and data network solutions. One of the inventors was, at the time of patent filing, based in Mexico.

9 results found

List view List content Sort by
 Text only All Relevance

(0 patents selected) Select the first 9 results

6. エンジン排気ガス後処理システム
 JP2016514799A • 2016-05-23 • テネコ オート...
Earliest priority: 2013-04-10 • Earliest publication: 20...
 An exhaust gas passage and the exhaust gas processing component housing which is open for free passage to an exhaust gas passage, A plurality of exhaust gas

7. ELECTRIC VEHICLE SUPPLY EQUIPM...
 US2011169447A1 • 2011-07-14 • LEVITON M...
Earliest priority: 2010-01-11 • Earliest publication: 20...
 An electric vehicle charging system includes a portable housing having an integral holder to hold a connector for an electric vehicle supply circuit. An electric vehicle supply

8. ELECTRIC VEHICLE SUPPLY EQUIPM...
 US2011172839A1 (B2) • 2011-07-14 • LEVITO...
Earliest priority: 2010-01-11 • Earliest publication: 20...
 An EVSE system includes an electric vehicle supply circuit, and a timer adapted to automatically control the electric vehicle supply circuit. The timer may be adapted to

☆ US2011172839A1 ELECTRIC VEHICLE SUPPLY EQUIPMENT WITH TIMER

Bibliographic data Description Claims Drawings Original document Citations Legal events Patent family

Global Dossier ↗

Applicants LEVITON MANUFACTURING CO [US] +
Inventors BROWN KENNETH J [US]; RAMIREZ CARLOS E [MX]; SOTO VICTOR [US] – BROWN KENNETH J.; RAMIREZ CARLOS E.; SOTO VICTOR

Classifications

IPC **G06F1/28;**

CPC

B60L3/0069 (EP,US); B60L3/0092 (EP,US); B60L53/00 (EP,US); B60L53/16 (EP,US); B60L53/18 (EP,US); B60L53/305 (EP,US); B60L53/31 (EP,US); B60L53/34 (EP,US); B60L53/55 (EP,US); B60L53/68 (EP,US); B65H75/4473 (EP,US); B65H2701/34 (EP,US); Y02T10/70 (EP,US); Y02T10/7072 (EP,US); Y02T90/12 (EP,US); Y02T90/14 (EP,US); Y02T90/16 (EP,US); Y02T90/167 (EP,US); Y04S30/12 (EP,US);

Priorities US68560910A-2010-01-11; US82210010A-2010-06-23

Application **US82210010A**-2010-06-23

Publication US2011172839A1-2011-07-14

Published as US2011172839A1, **US2014015487A1; US8558504B2; US9073439B2**

EN

Measuring low-carbon work, skills, pay and places

Misato Sato, Aurélien Saussay and Francesco Vona

Executive summary

- Low-carbon work is visible in vacancy data but remains small, around 1% of the United States workforce across the decade 2010–2019, roughly 1.3 million workers.
- Sharper measurement matters for policy: a skill-based approach using online job vacancy data identifies low-carbon roles within occupations, avoiding inflated counts from broad firm or occupation labels.
- Low-carbon hiring growth is concentrated in lower-skilled occupational groups (notably construction and installation/maintenance), while shares fall within higher-skilled groups over 2010–2019 – implying delivery depends heavily on the trades and work-based pathways.
- Low-carbon jobs demand more skills and more diverse skills compared to non-low-carbon roles in the same occupation (especially management, social and technical skills), indicating a reskilling challenge in the green transition.
- Job quality and place are binding constraints: low-carbon wage premia are positive but modest and declining once firm/occupation differences are controlled for, while low-carbon vacancies overlap with high-carbon places yet tilt toward richer areas, supporting the case for policies that build career ladders and co-locate training with investment in at-risk regions.

Introduction

Delivering net zero plans depends on people as much as capital. Renewables, electrification, and efficiency upgrades need workers who can design, install, operate and maintain new systems. Policy and investment will fail to deliver climate and social objectives if firms cannot hire or if workers face long spells out of work and lasting pay cuts during the transition to a low-carbon economy.

Measurement is a persistent problem. “Green job” counts vary according to the definition, scope and classification used (Vona 2021). Occupation- or firm-based classifications can over-estimate green employment, especially if failing to account for the fact that only a subset of tasks or jobs within occupations relate to decarbonisation. This is problematic because broad occupational categories such as car mechanics may include both low-carbon roles (eg electric vehicle mechanic) and fossil-fuel roles (eg diesel mechanic) as well as generic roles (eg auto glass mechanic).

Instead here, we use job-level data, and separate low-carbon jobs from non-low-carbon jobs within the same narrow occupational codes. For example, among electrical engineers, we

can isolate renewable grid integration engineers; and among installation, maintenance, and repair occupations, we can isolate wind turbine service technicians. While excluding roles within low-carbon sectors or firms that do not directly contribute to decarbonisation such as office and administrative support occupations. Specifically, we use online job vacancy data from Lightcast, covering all United States online job adverts spanning 2010 to 2019. Low-carbon jobs are identified using a skill-based strategy, where we first use Natural Language Processing techniques to identify 389 “low-carbon skills” which we define as skills that contribute directly to emissions-reducing activity (Saussay et al, forthcoming). A vacancy is considered low-carbon if it mentions at least one of these skills, yielding around 1.8 million postings out of roughly 200 million during the 10-year sample period. Comparing low-carbon and non-low-carbon roles within narrow occupational codes allows us to more accurately characterize the unique nature of low-carbon jobs. Better understanding within-occupation transitions matters for policy because workers moving into green jobs are more likely to do so within their existing jobs or by moving jobs within the same occupation.

The vacancy data here ends in 2019, before the Inflation Reduction Act brought a major green investment push in the United States from 2022. This strategic direction was subsequently reversed by the second Trump administration. In the UK and EU, growth and industrial strategies emphasise the importance of generating job opportunities from net zero investments and ensuring the right skills are in place. The method developed in this paper can be applied to other countries and later years, and can continue to inform such policy. For example, Sato et al. (2023) apply a comparable vacancy-based approach to the UK and compare patterns across the two labour markets. Tracking how low-carbon hiring responds as those policies roll out, will be documented in upcoming research by the LSE Green Skills Lab.

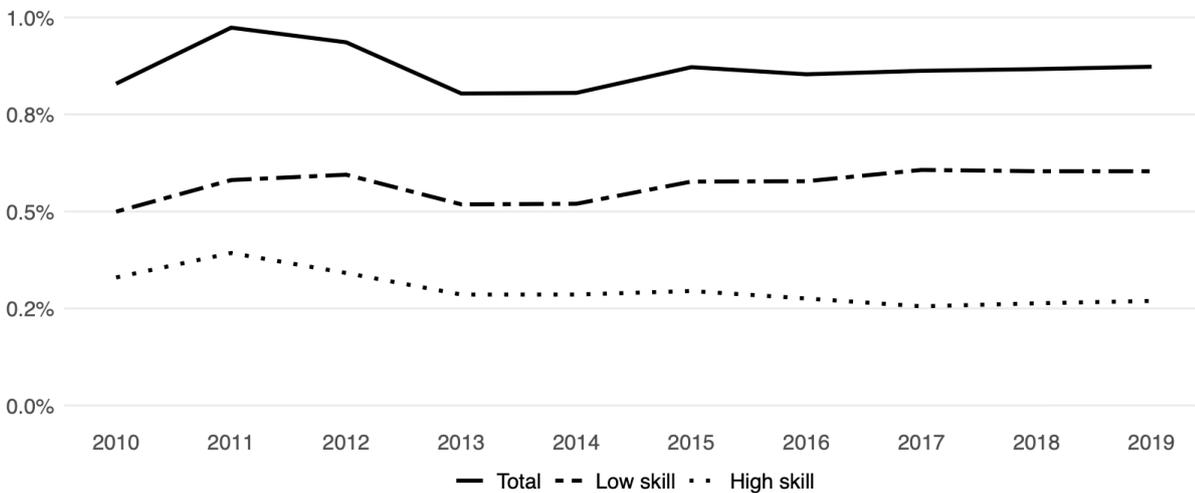
In this brief, we summarise seven new findings around wage gaps, skill gaps and spatial gaps that the low-carbon transition may entail before concluding with implications for policy.

Key findings

Finding 1. Low-carbon hiring is visible, but it remains a small share of the labour market

On an employment-weighted basis, low-carbon jobs average about 0.9% of the United States workforce in 2010–2019, roughly 1.3 million workers. Vacancy shares sit close to 1% through the decade of our analysis (Figure 1). This estimate is lower than many headline “green jobs” figures because we focus on climate change mitigation-related activity and identify low-carbon jobs at the job advert level rather than counting all jobs within low-carbon related firms or occupations as low-carbon jobs.

Figure 1: Evolution of low-carbon vacancy shares in the United States (2010–2019)



Source: Saussay et al. 2025

Finding 2. Low-carbon vacancies grew within low-skilled occupations and fell within high-skilled ones

Figure 1 shows divergence in trends across broad groupings of high- and low-skilled occupations over the 10-year period. Within high-skilled occupations, low-carbon vacancy shares fell, while within low-skilled occupations, the shares rose. Focusing on the six occupations where low-carbon jobs are concentrated (Business Specialists; Engineers; Engineering & Mapping Technicians; Physical Scientists, Construction & Extraction and Installation & Maintenance), we also find divergent trends. For example, low-carbon shares declined for business specialists and engineers but increased in construction and in installation and maintenance during this period.

Finding 3. Low-carbon skills gaps are larger than previously estimated

We calculate a “skill gap” between low-carbon and generic jobs, which is the difference in the skill content required by low-carbon jobs relative to otherwise comparable non-low-carbon jobs within the same occupation. This captures how much reskilling is needed to move into low-carbon roles. We calculate the skill gap from online job ads by representing each posting by its skill vector (aggregated into broad groups such as technical/managerial/social/IT/cognitive), then estimating the average difference in skill intensity/complexity between low-carbon and non-low-carbon postings within occupation (and with controls such as time effects, and in some specifications firm fixed effects). Prior work using occupation/task-based measures also finds greener work is more skill intensive. Examples include Vona et al. (2018) and Marin and Vona (2019) using O*NET green-task intensity at the occupation level; Consoli et al. (2016) emphasising training needs in green jobs; and Bluedorn et al. (2023) documenting that green-intensive occupations are held disproportionately by higher-skilled (often urban) workers. Because we are able to identify low-carbon jobs within broader occupations, our data allows us to decompose this gap into a between-occupation component (driven by the fact that low-carbon work is concentrated in different occupations) and a within-occupation component (due to different skill requirements for low-carbon jobs within the same occupation).

Table 1 decomposes the skill gap into within-occupation and cross-occupation components for five broad skill families. The within-occupation component captures skill differences between low-carbon and non-low-carbon jobs that share the same occupational code, while the cross-occupation component reflects differences arising from low-carbon work being concentrated in different occupations.

Within-occupation differences are non-trivial, especially for management, social, and technical skills. Across broad skill groups, low-carbon jobs show positive skill gaps throughout, meaning that on average, low-carbon jobs require *more* skills than comparable non-low-carbon jobs. For cognitive skills, the total skill gap of 21.03% means that, on average, low-carbon jobs require about 21% more cognitive skill content than comparable non-low-carbon jobs. Most of this difference, 18.45%, comes from between-occupation variation, reflecting how low-carbon jobs are disproportionately located in occupations that are, in general, more cognitively intensive. The remaining 2.59% comes from within-occupation variation, meaning that even within the same occupation, low-carbon roles demand additional cognitive skills relative to non-low-carbon roles. This suggests some retraining may be needed even when workers do not switch occupations, and this adjustment was not captured by previous research that focuses only on occupational switching.

Table 1: Skill gaps between low-carbon and non-low-carbon jobs, within and between occupations

	Total	Within-occupation	Cross-occupation
Cognitive	21.03%	2.59%	18.45%
IT	26.70%	2.47%	24.23%
Management	35.34%	8.29%	27.05%
Social	38.96%	7.44%	31.53%
Technical	32.73%	8.68%	24.05%

Source: Saussay et al. 2025

Finding 4. Management, social, and technical skills drive much of the skills gap seen within occupations

Within occupations, low-carbon job adverts are more likely to ask for management and people skills as well as technical skills compared to their non-low-carbon counterpart.

The within-occupation component of the skills gap is largest for managerial, social, and technical skills, and can account for up to around a third of the overall gap. Our findings also highlight social skills as a distinctive feature of low-carbon jobs relative to generic ones.

In job adverts, “management” skills include project planning and mentoring; “social” skills include client communication and coordination across teams; and “technical” skills include work such as mechanical engineering, technical specification or documentation and the use of specialised engineering software.

In practice, this fits the nature of retrofit and deployment work: coordination across teams, supervision, documentation, quality and safety processes, and communication with clients and regulators.

Finding 5. Low-carbon job adverts bundle more skills per vacancy

We use “skill vector length” (the number of skills mentioned in an advert) as a measure of skill breadth. Across all occupations, generic adverts list 9.3 skills on average; low-carbon adverts list 14.1.

Table 2 reports the same pattern within each of the six key occupations. The gap persists when comparing postings within the same firm, which reduces the risk that it reflects different advertising styles rather than different requirements. This analysis suggests that

low-carbon roles come with broader skill bundles, which is likely to raise hiring and training requirements.

Table 2: Skill vector length of generic, low- and high-carbon jobs by occupation

Occupation	Generic	Low-carbon	High-carbon
13-1 – Business Operations Specialists	11.5	14.8	
17-2 – Engineers	11.9	16.2	10.6
17-3 – Engineering and Mapping Technicians	9.5	14.5	
19-2 – Physical Scientists	10.9	15.7	
47 – Construction and Extraction	6.3	10.0	7.9
49 – Installation, Maintenance, and Repair	8.4	13.4	
All occupations	9.3	14.1	9.2

Source: Saussay et al. 2025

Finding 6. Wage offers are higher for low-carbon roles, but firm rents explain much of the gap

We estimate wage regressions and find a small positive association between low-carbon vacancies and posted wages that is declining over time. When we compare low-carbon and generic roles within the same firm by adding firm fixed effects, the implied premium reduces by more than one third. Under this model, the estimated premium is modest: about 5.2% in 2010–2012, 3.0% in 2017–2019, and 3.7% overall. These are associations in posted wage offers, not causal estimates.

This pattern is consistent with UK evidence using worker-level survey data, which finds that green jobs tend to exhibit a wage premium, particularly at lower skill levels, while selection and occupational mix remain relevant (Sato et al, 2023; Valero et al, 2021; Broome et al, 2022).

Table 3 reports the headline wage results.

Table 3: Relationship between low-carbon job and wage-offer

	2010-2012		2017-2019		2010-2019	
	(1)	(2)	(3)	(4)	(5)	(6)
Job is low-carbon	0.079*** (0.010)	0.052*** (0.010)	0.045*** (0.005)	0.030*** (0.004)	0.065*** (0.005)	0.037*** (0.004)
Mean wage (\$2019)	66,352	70,019	58,823	57,410	60,461	59,554

Observations	759,507	273,544	2,418,12	1,600,34	4,748,66	2,578,40
R^2	0.27	0.74	0.23	0.69	0.21	0.66
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Skill vector length FE	Yes	Yes	Yes	Yes	Yes	Yes
Commuting Zone FE	Yes	Yes	Yes	Yes	Yes	Yes
SOC (3-digits) FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE		Yes		Yes		Yes

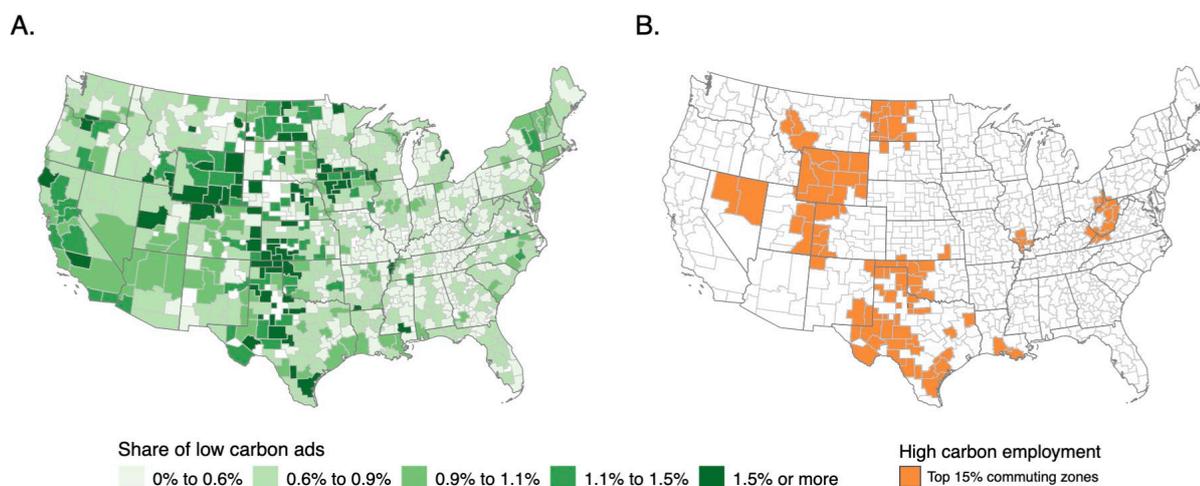
p < 0.1, **p < 0.05, *p < 0.01*

Source: Saussay et al. 2025 **Notes:** We stack the data for the 6 key listed above, weighting them by BLS employment. Skill vector length fixed effects are grouped as follows: 1-4, 5-8, 9-12, 13-16 and 17+ skills per job ad. Standard errors are clustered at the commuting zone level.

Finding 7. Low-carbon hiring overlaps with high-carbon employment, but tilts toward richer areas

We examine spatial patterns in low-carbon hiring activity. We find that low-carbon vacancies in low-skilled occupations are more geographically dispersed than high-carbon employment, which is highly concentrated in resource-extraction regions. Across commuting zones, low-carbon vacancy shares are positively correlated with high-carbon employment shares. In weighted estimates, a 1% higher high-carbon employment share is associated with a 0.07% higher low-carbon ad share. We also find a positive correlation between income and low-carbon hiring: a 1% higher per-capita income is associated with roughly a 0.2% higher low-carbon ad share. This analysis suggests that while opportunity from the low-carbon transition, and exposure to it overlap, more policy effort might be required to manage transitions for workers in lower-income places. Figure 2 visualises the spatial distribution of low-carbon vacancies relative to high-carbon employment.

Figure 2: Spatial distribution of (A) low-carbon vacancies and (B) high-carbon employment in low-skilled occupations



Source: Saussay et al. 2025 **Notes:** These maps show the intensity of low and high-carbon jobs by commuting zone, averaged over the period 2010-2019, for all low-skilled occupations (SOCs 31 to 53). Panel A shows the average share of low-carbon job vacancies; panel B shows the the top 15% commuting zones with the highest shares of high-carbon employment.

Conclusion

The net zero transition is, in practice, a labour-market transition. Its pace and political durability will depend not just on the number of “green jobs”, but on whether workers can move into low-carbon tasks without large earnings losses, long spells out of work, or forced relocation. A persistent barrier has been measurement: standard occupation and firm labels miss the fact that low-carbon roles sit alongside non-low-carbon roles within the same occupation, obscuring the true reskilling challenge and the quality of jobs on offer.

This evidence shifts what “workforce policy for net zero” should target. First, because skill demands rise within occupations, generic upskilling is unlikely to be cost-effective. Training offers need to be occupation-specific and built around the skill bundles that low-carbon roles actually combine—including managerial and social skills alongside technical skills—and structured to work also for those in employment. Second, job quality cannot be assumed. In 2010–2019, low-carbon work was around 0.9% of employment (about 1.3 million workers) and advertised wage premia were positive but much smaller once firm pay differences are accounted for, and they decline over time — pointing to an “attractiveness gap” that policy must address through clearer progression routes, job design, and complementary measures that raise job quality in low-carbon projects and firms.

Third, place matters for both delivery and fairness. Low-carbon hiring overlaps with high-carbon employment, but it is stronger in higher-income areas. Managing reallocation costs and avoiding regional scarring may therefore require place-based packages that co-locate training, investment, and support in at-risk communities.

Finally, the wider value of this approach is operational: vacancy-based metrics can be embedded in modelling and monitoring systems to improve the calibration of transition costs and inform the sequencing of climate, industrial, and workforce policies, and can be updated beyond 2019 and extended across countries as net zero strategies evolve. The LSE Green Skills Lab is building tools and data to support this agenda.

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Apprenticeships and low-carbon skills in England

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Executive summary

- In this policy briefing, we study the alignment of low-carbon apprenticeship provision in England with the emerging low-carbon skill needs in the economy.
- We analyse the detailed skill content of apprenticeships' training plans (apprenticeship standards) to understand whether they can deliver the low-carbon skills needed to decarbonise different sectors (ie energy sector, buildings and transport).
- We find that 39 apprenticeship standards (6%) contain skills relevant for decarbonisation. These are concentrated in engineering and technical roles in Construction and Transport. Only few seem related to clean energy.
- Low-carbon apprenticeships are most common at Level 3 (comparable to A-levels in the national qualification framework). Low-carbon apprentices are much more likely to be aged under 25, male and white British and a little less likely to be based in London and the south-east.
- We find that the share of low-carbon skills supplied through apprenticeships has increased over three-fold from 2018 to 2021 (from 0.2% to 0.7% of skills).
- This rapid growth in low-carbon skills is mainly attributable to apprenticeships that teach "decarbonising buildings" skills. No equivalent growth was observed in apprenticeships delivering "decarbonising transport" or "energy" skills.
- Demand for low-carbon skills over this period has also increased. It has grown the most for "decarbonising transport" skills and "decarbonising energy", and not by much in "decarbonising buildings", in marked contrast with what we see for low-carbon skills supply.
- When we relate changes in the supply of low-carbon skills through apprenticeships, with prior changes in demand within the same local labour market, we find that apprenticeships are not particularly reactive, though low-carbon ones respond more than non-low-carbon ones.
- Finally, we discuss whether recent reforms aimed at making apprenticeship provision more flexible and accessible to small and medium enterprises (SMEs) could improve the system's reactivity and whether more targeted interventions may be needed.

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Introduction

A successful net zero transition hinges on the country's ability to adopt low-carbon technological and economic processes at scale in a timely way across different sectors: from building renewable energy plants to retrofitting poorly insulated homes. This transformation requires substantial investment in skills. Yet, workers and firms may hesitate to invest in training due to costs and uncertain returns, even if society as a whole is set to benefit from having a skilled workforce capable of delivering decarbonisation and securing international competitiveness in green industries. The role of government in solving co-ordination issues and driving investments in low-carbon skills is therefore key.

In England, apprenticeships have been the main vehicle for publicly-funded training. In 2023/24, £2.5bn supported over 700,000 apprenticeships⁶. Apprenticeships are intended to deliver transferable occupation-wide skills as they deliver mandated training content set out in apprenticeship standards by industry leaders and regulated by Skills England. In this respect, apprenticeships emerge as a potentially important vehicle to support and co-ordinate skill investment in strategic low-carbon industries. This is set out clearly in the government's recent Clean energy job plan (Department for Energy Security and Net Zero, 2025). But, the evidence base on the supply of low-carbon skills in general, and the role of apprenticeships in meeting emerging skill demands, remains limited.

This policy brief assesses whether and how apprenticeships have contributed to the provision of low-carbon skills in recent years. We assess this against recent trends in employers' demand for low-carbon skills. We provide some early evidence on the responsiveness of low-carbon skills supply through apprenticeships to demand. Finally, we discuss what this means in the current policy context and draw out key insights.

We define low-carbon skills as those that contribute directly to decarbonising the economy. Major low-carbon activities centre around the development of renewable sources for power generation, as well as the reduction of fossil fuel use, especially in transportation and buildings sectors. We apply a large language model (LLM), initially developed by Cass et al. (forthcoming), to identify low-carbon related content in the detailed training plans provided by 650 apprenticeship standards in England (active by December 2024). Each standard lists the "skills, knowledge, and behaviours" that apprentices are expected to develop throughout their training, and on which they are formally assessed. Using the LLM-based algorithm we classify skills by whether they are low-carbon (and of which type).

⁶ According to the Department for Education's statistics release on Apprenticeships for academic year 2023/24 ([link](#)).

Key findings

Finding 1. Apprenticeships contribute to low-carbon skills supply

There are 39 apprenticeship standards (or 6%) that contain skills relevant for decarbonisation, predominantly in Transport and Construction. We find few apprenticeship standards related to energy decarbonisation (and they are mostly in the nuclear industry). Almost half of the low-carbon apprenticeship standards started in the five-year period studied (2018-2022) were within “Plumbing and domestic heating technician”, while “Maintenance and operations engineering technicians” accounted for around a tenth (Table 1).

Table 1: Top 10 Low-carbon apprenticeship standards started (2018-2022)

Apprenticeship Standard name	Share of low-carbon apprenticeship starts
Plumbing and domestic heating technician	49%
Maintenance and operations engineering technician	11%
Refrigeration air conditioning and heat pump engineering technician	6%
Passenger transport driver – bus and coach or tram	4%
Dual fuel smart meter installer	4%
Nuclear scientist and nuclear engineer (integrated degree)	4%
Gas engineering operative	3%
Travel consultant	3%
Bus and coach engineering technician	2%
Civil engineering technician	2%

Notes: List of the 10 most popular apprenticeship standards classified as low-carbon on the basis of their skills content. This is based on the number of starts observed in the 2018-2022 period. **Source:** Own computation based on the Individualised Learners Record (ILR) held by Department for Education (DfE).

Finding 2. Low-carbon apprentices tend to be young, male and Level 3

Low-carbon apprenticeships are most common at Level 3 (an “advanced apprenticeship” with an average duration of 18 months and comparable to A-levels in the national qualifications framework). Within this level, low-carbon (LC) apprentices are much more likely to be aged under 25, male and white British and a little less likely to be based in London and the south-east. But when we compare characteristics of apprentices within Construction and Engineering (which accounts for most of the low-carbon apprenticeship activity), the characteristics of LC and non-LC apprentices are far more similar (Table 2).

Table 2: Characteristics of low-carbon apprentices at Level 3 compared with non-low-carbon ones in different sectors

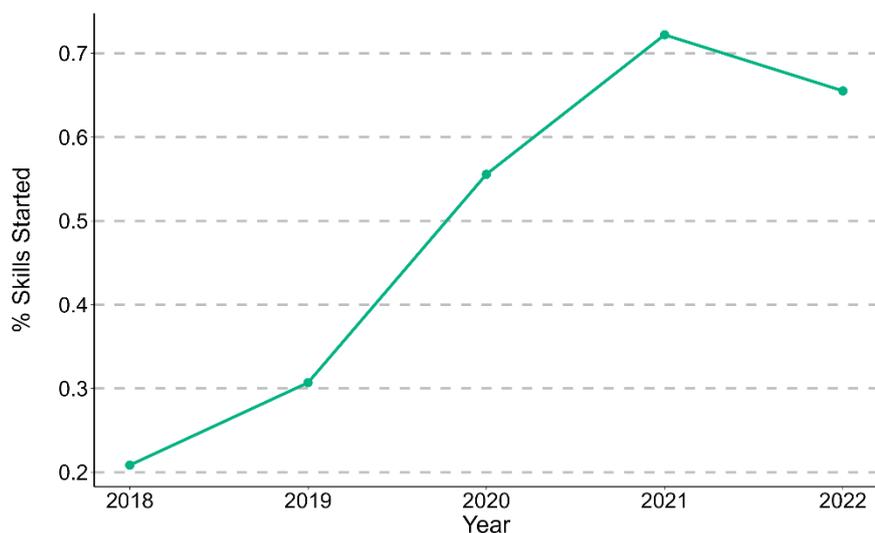
	All sectors		Engineering sector		Construction sector	
	Not LC	LC	Not LC	LC	Not LC	LC
Under 25	56%	88%	71%	65%	82%	88%
Male	49%	93%	90%	87%	90%	95%
White British	80%	90%	84%	80%	89%	89%
London and South East	26%	20%	25%	28%	21%	21%

Source: Own calculations from Individualised Learners Record (ILR), 2018-2023.

Finding 3. The supply of low-carbon skills through apprenticeships has increased rapidly over recent years

Based on the figures published by the DfE on apprenticeship starts, we find that the number of low-carbon skills in apprenticeships has increased over three-fold from 2018 to 2021 (from 0.2% to 0.7% of skills) followed by a small dip in 2022 (Figure 1). These shares appear low but are proportional given that low-carbon employment accounted for around 1.4% on average across the UK between 2012 and 2021 (Sato et al, 2023) and the proportion of low-carbon skills advertised by employers was below 0.12% between 2018 and 2022. We find that most of the increase was due to the higher uptake of the existing apprenticeship standards, rather than the approval of new ones.

Figure 1: Change in the provision of low-carbon skills through apprenticeships (2018-2022)

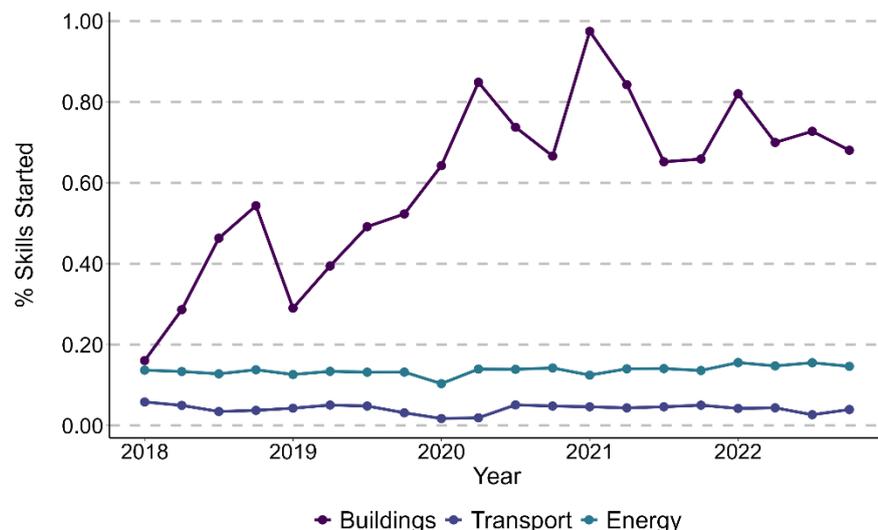


Notes: Percentage of apprenticeship skills started in a given year that are classified as low-carbon. **Source:** Own calculation from DfE published figures.

Finding 4. Increase in low-carbon skills provision within apprenticeships is driven by 'decarbonising buildings' skills

The rapid growth in low-carbon skills supply within apprenticeships is mainly attributable to “decarbonising buildings”. Within this sector, low-carbon related skills have increased from below 0.2% to over 0.8% between 2018 and 2022 (Figure 2). No equivalent growth was observed in decarbonising transport or energy, even though apprenticeship standards in related occupations exist.

Figure 2: Change in the provision of different types of low-carbon skills through apprenticeships (2018-2022)



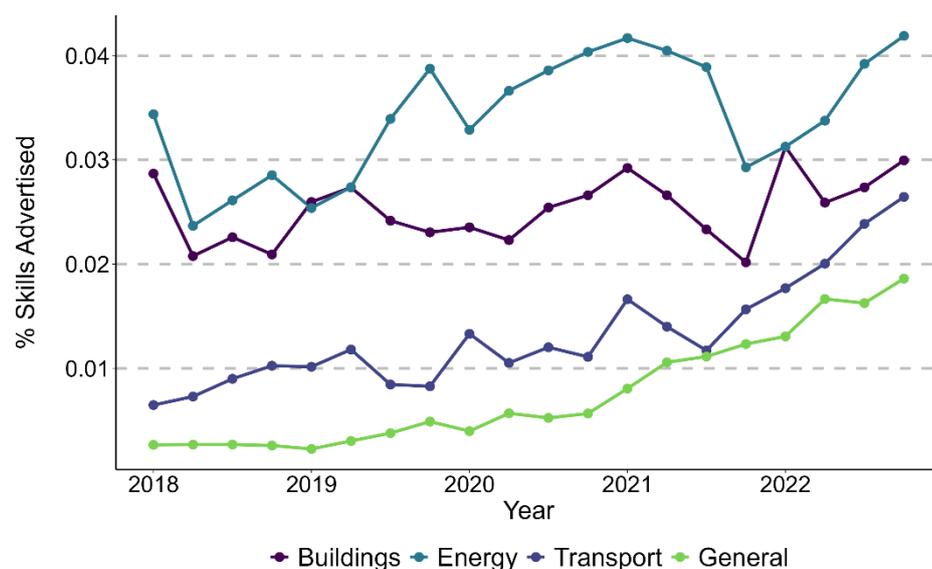
Notes: Percentage of apprenticeship skills started in a given quarter classified as different types of low-carbon. Figures are de-seasonalised. **Source:** Own calculation of DfE published figures.

This suggests that apprenticeships have become a popular way of providing skills related to heating, plumbing and the installation and maintenance of energy-saving technologies such as heat pumps or smart meters. The increased provision of apprenticeships boosting green building sector skills is welcome news as skill gaps in Construction, including in heating, have been highlighted in a recent Skills England report (Department for Education, 2025a).

Finding 5. Demand for low-carbon skills has also increased over the same period

To assess the demand for low-carbon skills, we apply the same LLM-based approach to Online Job Vacancy (OJV) data for England from Lightcast. The share of job ads that contain relevant low-carbon skills grew over our sample period (Figure 3). Demand for low-carbon skills increased markedly for “decarbonising transport” skills and “decarbonising energy”, while it remained relatively stable for “decarbonising buildings”. This contrasts from the patterns we see (as described above) for low-carbon skills provided through apprenticeships.

Figure 3: Change in demand for low-carbon skills in online job ads (2018-2022)



Notes: Percentage of skills advertised online by employers classified as different types of low-carbon. Advertised skills exclude those related to Managerial and Professional occupations. Job ads are reweighted to be representative of the occupational composition in England. **Source:** Lightcast data.

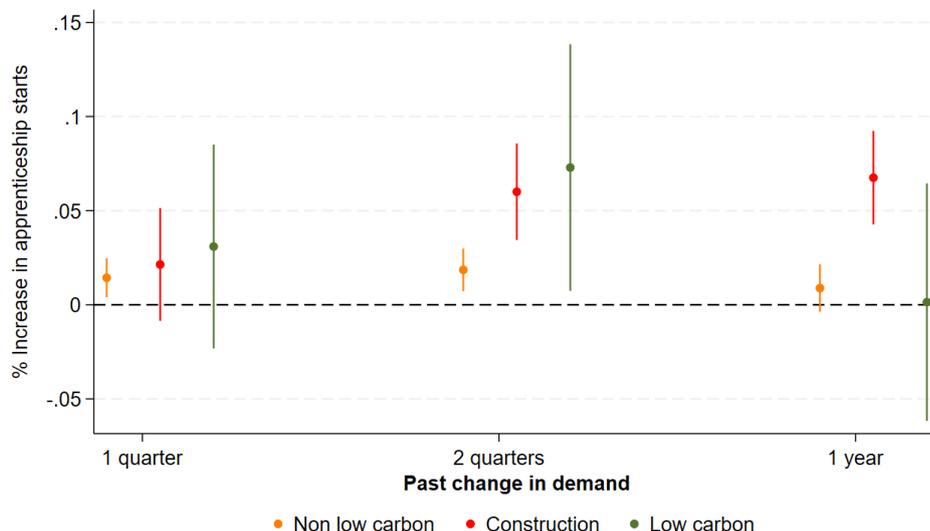
Finding 6. Low-carbon apprenticeships are more responsive to changes in related skills demand than non-low-carbon apprenticeships

We use regression analysis to associate changes in the number of low-carbon apprenticeships to changes in demand for relevant skills. For each apprenticeship standard, we build a measure of relatedness to the different types of skills that appear in the online job ads data. This gives us a common metric to compare demand and supply of skills. We use variation over time and across area (ie travel to work areas).

We are mostly interested in how the supply of low-carbon apprenticeships responds to previous changes in demand. We benchmark this against the responsiveness of non-low-carbon apprenticeships and the subgroup of apprenticeships in the Construction sector, as these are more directly comparable with low-carbon apprenticeships.

Figure 4 shows that the provision of low-carbon apprenticeships is moderately responsive to increases in demand *that* occurred up to two quarters before. A one standard deviation increase in low-carbon-related skill demand is associated with a 7.5% increase in the number of low-carbon apprenticeships. This is in line with what we observe more generally in the Construction sector, and is much higher than what we observe for non-low-carbon apprenticeships. This association, however, is short-lived and the increase in supply is not permanent.

Figure 4: Strength of reaction of skill supply to past changes in demand



Notes: Estimates and 95% Confidence Intervals of a Poisson regression of number of apprenticeship starts on apprenticeship-related demand for skills measured at different points in the past. Estimates are obtained from separate regressions including: Non-low-carbon apprenticeships (in any sector), non-low-carbon apprenticeships in Construction, and low-carbon apprenticeships (in any sector). **Source:** Own calculation of DfE published figures and Lightcast data.

Conclusion

In this analysis we show that low-carbon skills have increased through apprenticeships. But the increase has been partial and limited to certain sectors. Changes in supply have not been very responsive to national-level changes in demand for low-carbon skills, as revealed by job ads.

A possible reason for slow responsiveness could be that suitable standards are not available for firms to deliver training. The creation of apprenticeship standards is “bottom up” by groups of employers and co-ordination costs may hold back their development in some areas. Even when apprenticeship standards are in place for low-carbon apprenticeships to be delivered, firms may underinvest if costs exceed expected benefits.

In a report about Clean Energy Industries (Department for Education, 2025b), feedback from stakeholders suggests that existing funding bands for some apprenticeships does not meet the cost of delivery – particularly at Levels 2 and 3. There have also been concerns that training providers face substantial upfront costs for setting up the required equipment and

facilities. Alongside shortages of skilled training personnel, this may reduce the availability of suitable training providers for firms (and push up the cost). Policy efforts to increase retention of science, technology, engineering and mathematics trainers and the extra capital funding for providers made available through the Skills Mission Fund may help with this.

Furthermore, government subsidies exist to compensate for the direct costs of off-the-firm training but not for indirect costs (ie on-site training or time off-site). For this reason, SMEs are typically more reluctant to provide training, which may restrict the supply of skilled workers in low-carbon sectors such as retrofitting or low-carbon heating installation. Also, there may be differential risks of competitors poaching trained workers, and it is plausible that this might be greater in occupations with high skill shortages. There may therefore be a case for creating more firm-level incentives that encourage take-up of apprenticeships in shortage areas. Recent tweaks to apprenticeship funding are going to free up more funding for SMEs but, as these only target direct costs, it is unclear how far they will go.

Recent government reforms to apprenticeships are expected to make the system more flexible and therefore responsive to changes in demand. This includes shortening the duration of certain apprenticeships, allowing employers to deliver modular training and integrating aspects of the end point assessment into the training itself. It should be noted that this does have risks to the extent that shortening of apprenticeships makes them less holistic for individuals (in the sense of training them for a career rather than a specific job) but it could help employers target workers who are already experienced but need reskilling.

Besides improving incentives, one could also think of conditionality (to take on apprenticeships) being imposed as part of wider investment subsidies and public procurement strategies (similarly to the mandated apprenticeship quotas for firms benefiting from tax credits introduced by the Inflation Reduction Act in the United States). Finally, while the focus in our analysis has been on apprenticeships (as the largest publicly supported training programme), future research should also consider how alternative training programmes (such as sectoral training programmes or Skills Bootcamps) and higher provision at Level 4 and 5, funded through the Lifelong Learning Entitlement can further help growing demand for low-carbon skills.

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Cleaner energy, higher risk? Firm-level exposure to critical minerals and implications for UK industrial strategy

Viet Nguyen-Tien

Executive summary

- The transition to net zero is transforming demand for materials as well as the energy sector itself. Clean technologies, such as electric vehicles, batteries, wind turbines and solar panels, depend on critical minerals (lithium, cobalt, nickel, copper and rare earths) which are far more geographically concentrated than fossil fuels, increasing exposure to supply disruptions, geopolitical shocks and export restrictions.
- This note presents new firm-level evidence which shows that these risks are economically meaningful and highly uneven. Analysis of the text from earnings calls in large companies shows that mentions of critical minerals spike during periods of price volatility, and firms involved in EVs, batteries and renewables activities are significantly more likely to reference the minerals they rely on.
- More than 80% of variation in mineral-related risk occurs at the firm level, over and above common shocks at the industry or country level, underscoring the importance of a more granular approach. Mineral-related risk can be statistically and economically meaningful: for example, a one standard deviation increase in lithium risk reduces the revenue growth of an average global firm by roughly 0.25 percentage points. Within the studied period, US firms appear more sensitive to copper and European firms more sensitive to lithium.
- Firms respond to such risks through diverse strategies: recycling and circular economy approaches, material substitution, stockpiling and hedging, and passing costs to customers. Circularity is particularly used for lithium and cobalt, while stockpiling and substitution are most frequent overall.
- The UK's Vision 2035: Critical Minerals Strategy recognises the need for resilient and diversified mineral supply chains. Firm-level evidence suggests that effective policy requires granular, data-driven monitoring, targeted interventions and coordination between public and private actors.
- Innovative data sources, such as textual analysis of earnings calls, can provide early warnings of emerging vulnerabilities and inform evidence-based solutions. Further research should explore how these tools can be refined, scaled and embedded into industrial strategy approaches to anticipate risks across technologies and supply chains. Successfully addressing these challenges will require sustained interdisciplinary collaboration across economics, materials science, engineering, data science and other relevant fields.

Introduction

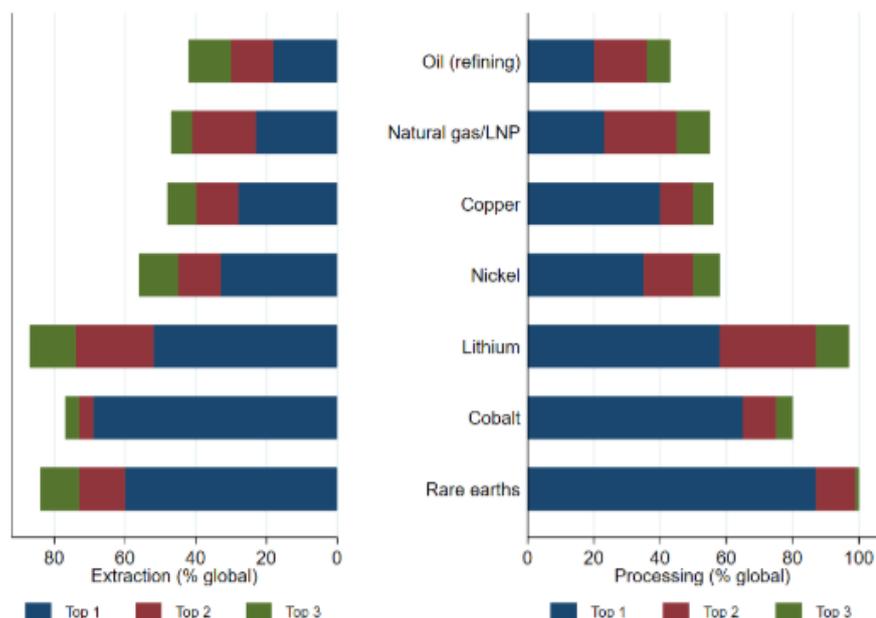
The UK has a long history of industrial leadership, from the Industrial Revolution to the Age of Steam and Rail, when mastery of energy and infrastructure systems underpinned global economic and technological advantage (Chollet and Kapnick, 2025). Today, the world faces a new energy security challenge: the transition to low-carbon technologies is reshaping not only energy systems but also the material foundations of economic growth and resilience.

Clean-energy technologies, including electric vehicles (EVs), solar panels, wind turbines and energy storage systems, require minerals such as copper, lithium, cobalt, nickel and rare earth elements. These inputs are classified as critical minerals due to their economic importance and the risks associated with supply constraints (World Bank, 2017). Structural trends such as digitalisation, AI-driven industrial processes and renewed rearmament are further intensifying demand.

The scale of this transformation is unprecedented. EVs require three to four times more copper than traditional vehicles; wind and solar infrastructure consume two to seven times more copper per unit of capacity than fossil-fuel plants; lithium, cobalt, and nickel are essential for batteries and energy storage; and rare earth elements underpin permanent magnets in wind turbines and electric motors (Jones et al, 2020; IEA, 2022; IRENA, 2023).

Historically, energy-related economic risk was largely shaped by fuel price volatility. Today, however, risk increasingly arises from the supply of minerals embedded in long-lived products and infrastructure. Figure 1 shows that critical minerals are more geographically concentrated than fossil fuels, both in the mining and processing phases, as measured by the share of production accounted for by the top three countries.

Figure 1: Top three countries producing fossil fuels vs critical minerals (2019)



Source: This is a work derived by Nguyen-Tien (2025) from IEA material (IEA 2022) and Nguyen-Tien (2025) is solely liable and responsible for this derived work. The derived work is not endorsed by the IEA or its Member countries in any manner.

This concentration creates new structural vulnerabilities with key examples including:

- **Cobalt:** Approximately two-thirds of global production comes from the Democratic Republic of Congo, where political instability and governance challenges are endemic (Jones et al, 2023).
- **Rare earths:** China dominates both mining and processing, and export policies – such as the recent “0.1% rule” (Nguyen-Tien and Harper, 2025) – can disrupt global markets.
- **Nickel:** Supply was sharply affected following Russia’s invasion of Ukraine.
- **Copper:** Chile and Peru have repeatedly experienced production shocks due to strikes and social unrest.

These vulnerabilities have intensified over time. Between 2009 and 2023, the number of export restrictions on critical minerals increased more than fivefold, with China, Russia, and five other countries accounting for the majority of new restrictions (OECD, 2025). Countries and regions are now developing new approaches to secure supply – for example, the EU’s Critical Raw Materials Act (European Commission, 2023) and the UK’s Vision 2035 Critical Minerals Strategy (HM Government, 2025). Both reflect a growing recognition that a successful net zero transition requires not only decarbonisation but also resilient, responsible supply chains.

This briefing note summarises new evidence on how firms perceive and respond to critical mineral-related risks. A major challenge in assessing mineral-related risks and the effectiveness of policy responses is that traditional economic data struggle to capture the rapid emergence of clean tech firms, novel business models and complex global supply chains. To address this, recent research (Nguyen-Tien, 2025) combines firm-level performance data for nearly 14,000 publicly listed companies across more than 90 countries (2010–2022; Compustat Global) with textual evidence from earnings call transcripts.

Earnings calls, held shortly after reporting periods, contain management remarks interpreting recent results and provide timely, firm-level signals of exposure to critical-mineral constraints when these issues materially affect operations. The subjective nature of prepared remarks is partly mitigated by the live Q&A, in which analysts frequently elicit operationally relevant information not disclosed elsewhere.

The study employs textual analysis of earnings call transcripts to construct several key measures:

- **Mineral and technology exposure:** Binary indicators capturing whether minerals or clean-technology terms are mentioned, reflecting their relevance to the firm's business activities.
- **Mineral risk and sentiments:** Three sets of measures capture the perceived impact of mineral-related shocks: risk, positive impact and negative impact. Standardised word lists (Oxford Dictionary, Loughran and McDonald, 2011) identify language indicating risk or sentiment, with intensity reflecting perceived shock magnitude.
- **Mitigation strategies:** Indicators capture firm discussions of methods to address mineral price shocks, including:
 1. Circular economy solutions (such as recycling and reuse).
 2. Material substitution.
 3. Stockpiling or hedging.
 4. Passing costs to customers.

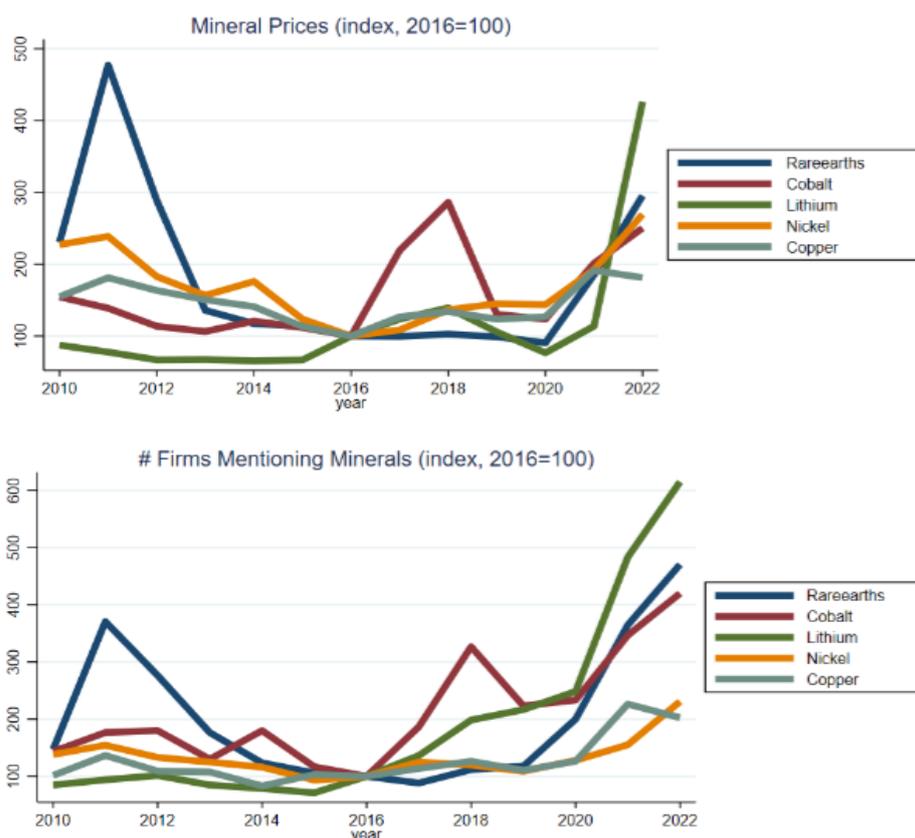
This policy brief draws on these insights from novel measures to explain how firm-level evidence on critical-mineral exposure can inform UK industrial strategy, support resilient supply chains.

Key findings

Finding 1. Textual data capture firm-level responses to critical-mineral price surges

Analysis of earnings call transcripts from thousands of firms worldwide shows that companies increasingly reference critical minerals during periods of price volatility. This demonstrates that textual data captures meaningful, timely signals of exposure and concern at the firm level. For example, relative to the reference price in 2016 (used to normalise all series), mentions of rare earths surged in 2011 (Figure 2) to around four times that level following China's export restrictions. In 2018 cobalt mentions rose to nearly three times that levels amid growing expectations for EV adoption. By 2022, references to lithium were more than six times higher, rare earths and cobalt were around five times higher, and copper and nickel mentions had more than doubled. These increases correspond with commodity price rallies driven by supply disruptions during the Covid-19 pandemic, Russia's invasion of Ukraine and the global acceleration of the clean-energy transition.

Figure 2: Mineral mentions and mineral prices



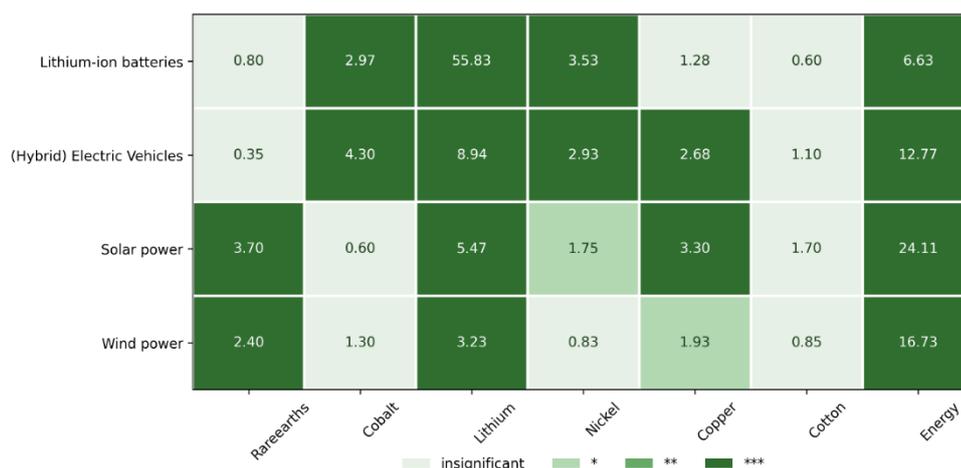
Notes: This figure presents a comparison of critical mineral price series (Panel A) and the count of listed firms mentioning these minerals in their earnings conference calls (Panel B). **Sources:** Price data sourced from IMF (2023), with linear imputation for lithium and rare earths using USGS data for the years 2010–2011, and computation based on earnings conference call transcript data.

Finding 2. Firms' mineral mentions align with energy-transition technologies

Building on the evidence of firms' heightened mineral awareness in Figure 2, textual analysis reveals a clear link between critical minerals and energy-transition technologies, consistent with engineering and materials-science expectations (Figure 3), validating the usefulness of this approach. Transcripts referencing lithium-ion batteries (LiBs) and EVs are significantly more likely to mention lithium, nickel and cobalt, reflecting firms' direct or indirect exposure to these inputs.

Copper, widely used in EV motors, batteries, inverters, wiring and charging infrastructure, is also significantly more likely to be mentioned in EV-related calls. Mentions of lithium alongside solar and wind reflect these technologies' reliance on energy storage. While rare earth mentions are less frequent, the model robustly detects a strong association with wind technology, consistent with permanent-magnet use in turbines.¹

Figure 3: Co-occurrence between critical mineral exposure and technology exposure at the transcript level



Notes: This table reports coefficients indicating the correlation between the occurrences of critical minerals and energy technologies in the earnings conference call transcripts conditional on firm size (log of total assets), firm fixed effects and time fixed effects. Standard errors are clustered at the firm level. *, **, *** denote estimates significant at 10%, 5%, 1% respectively. "Cotton" and "energy" are included as placebo tests, with expected insignificant and significant associations, respectively, with all selected technologies.

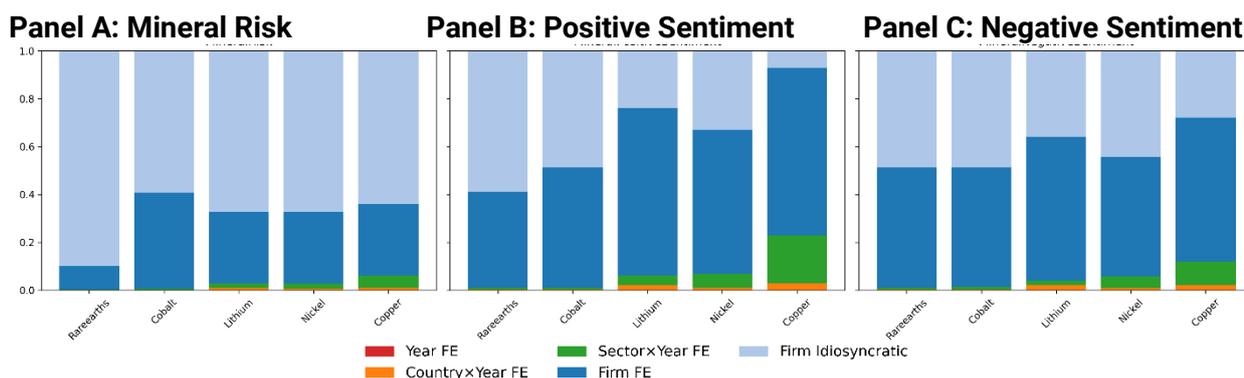
Finding 3. Most variation in mineral risk perception is driven by firm-specific factors

A variance decomposition analysis shows that the majority of differences in firms' perceived risks and sentiments about critical minerals are firm specific, perhaps reflecting

¹ The observed positive association between solar and rare-earth mentions attenuates when conditioning on wind co-mentions, suggesting the link is driven partially by co-discussion of wind rather than by a direct technological dependence of solar on rare earths. For EVs, although rare-earth magnets play a critical role in many electric-motor designs, the material and economic scale of lithium-ion battery minerals is substantially larger and more central to firms' business strategies, so corporate discussion is dominated by batteries and any average EV-rare-earth signal is muted.

the early stages of the transition, rather than being driven by country- or sector-specific factors. As shown in Figure 4, country- or industry-level shocks explain less than 1% of overall variation in estimated mineral risk (Panel A), and under 20% of positive sentiment (Panel B) under 10% of negative sentiment (Panel C). Most of the variation arises from firm-specific factors, either time-invariant firm characteristics (rather than location and industry) and time-varying factors at the firm level (for example the engagement in electrification).

Figure 4: Variance decomposition of mineral risk and sentiment variables



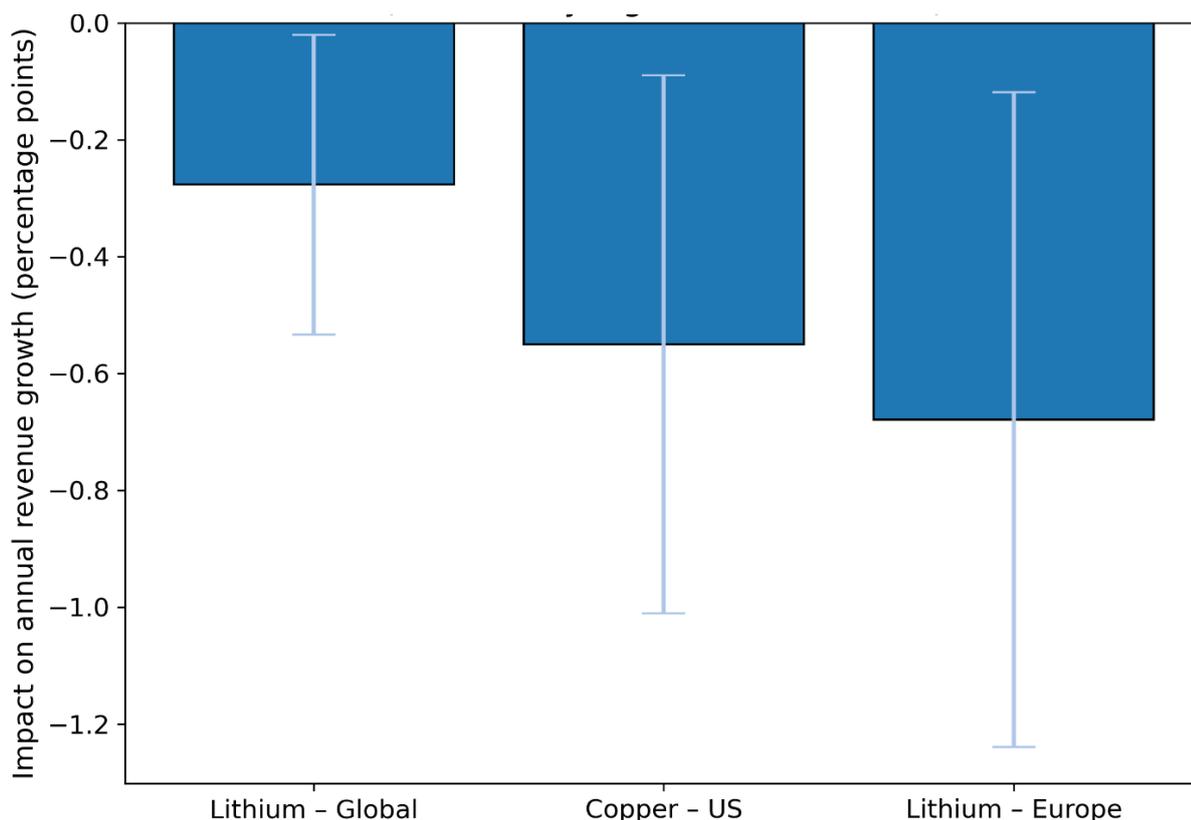
Note: This figure shows the R^2 from a projection of text-based Risk and Sentiment variables on various sets of fixed effects. **Source:** Derived from Table 7 of Nguyen Tien (2025).

Finding 4. Critical-mineral risk could hinder firm growth

Having examined how risks and sentiments vary across firms, the next step is to explore how perceived critical-mineral risk can influence firm performance. Results vary across commodities and regions, with some key results shown in Figure 5. Globally, only lithium-related uncertainty is a significant predictor of revenue growth, controlled for confounding sentiments, with a modest impact: a one standard deviation increase in lithium risk reduces growth by around 0.25 percentage points, compared with a sample mean of 7.5%.

Regional differences reflect supply-chain positioning. US firms are sensitive to copper risk (coefficient = -0.55), while European firms are more sensitive to lithium risk (coefficient = -0.68). These patterns align with classical profit-uncertainty models, where price volatility raises perceived input costs or reduces expected returns, prompting risk-averse firms to reduce output.

Figure 5: Impact of mineral risk on revenue growth (statistically significant estimates) and 95% confidence intervals



Source: Derived from Panels C, D, E in Table 8 of Nguyen Tien (2025).

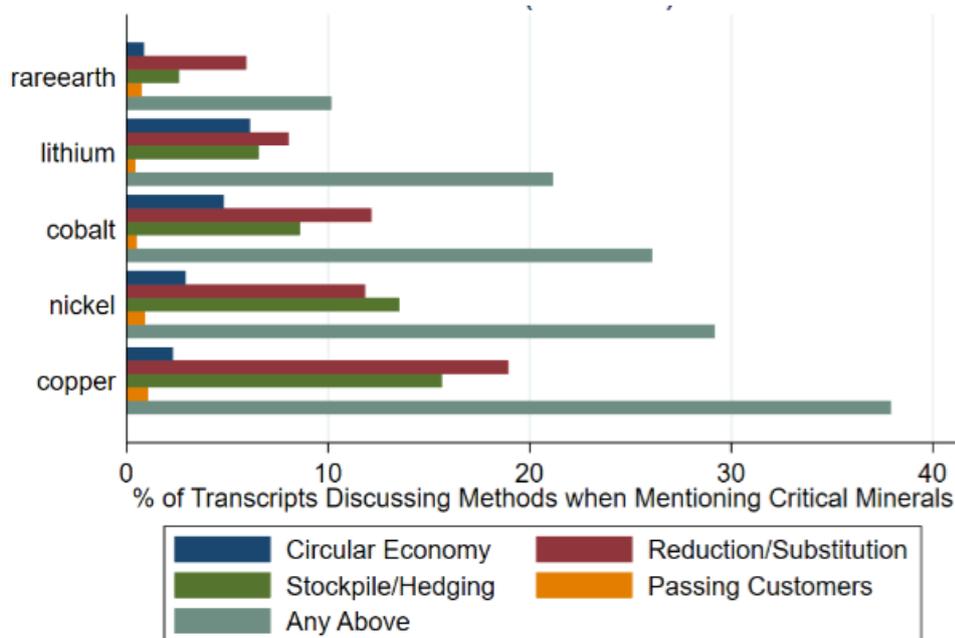
Finding 5. Firms respond to critical-mineral price surges through operational and innovation strategies

Textual evidence also allows us to explore how firms are responding to rising prices and uncertainty in critical-mineral markets (Figure 6). Price surges create ambiguity about future costs and supply, as it may be unclear whether increases are temporary or sustained. Four main mitigation channels were identified:

1. Circular economy solutions – recycling and reuse.
2. Material reduction and substitution – alternative inputs or product redesign.
3. Stockpiling and hedging – inventory management or financial hedges.
4. Passing costs to customers – adjusting pricing to maintain margins.

Between 2010 and 2022 (Figure 6), discussions of stockpiling, hedging and material reduction/substitution were most frequent. Circular economy strategies were cited more often for lithium and cobalt, reflecting the higher value and relative scarcity of these newer commodities.

Figure 6: Managing critical mineral prices



Notes: This figure illustrates the share of transcripts mentioning methods for managing critical mineral prices when earnings conference call participants mention critical minerals in my full sample covering 2010-2022. Each transcript can reference multiple methods.

Policy implications

The responsiveness captured in earnings call language suggests that firms worldwide monitor critical-mineral markets closely and adjust operational expectations accordingly. This highlights the potential of textual data as a real-time, globally informed – and UK-relevant – tool for identifying supply-chain vulnerabilities, informing industrial strategy and guiding targeted resilience planning in the UK’s net zero transition.

This approach demonstrates the potential of textual analysis to monitor material–technology linkages in a business context, complementing traditional engineering perspectives by revealing how these relationships evolve in economic and strategic terms. Such insights can help anticipate resource competition across clean-technology portfolios – as well as digital and defence technologies, identify emerging bottlenecks, and inform targeted interventions to strengthen UK supply chains in support of the net zero transition and broader national security objectives.

Risk and sentiment around critical minerals are firm specific and globally heterogeneous, highlighting the importance of a firm-level perspective. Traditional sector- or country-level indicators may miss emerging vulnerabilities, while textual analysis provides a granular, timely lens on firm behaviour relevant for policy.

Even moderate impacts on firm revenues – potentially reflecting the early stages of the low-carbon transition – can propagate through global supply chains. Reducing uncertainty

around critical minerals not only supports progress toward net zero targets but also strengthens the UK's green growth strategy, enhances industrial resilience and safeguards economic competitiveness in emerging clean-technology, digital and defence sectors.

Textual data provide insights into how firms expect to manage critical-mineral prices through operational and innovation strategies. Such information can help policymakers align public measures with business behaviour, supporting targeted interventions, supply-chain resilience and the UK's broader net zero and industrial strategy objectives.

Conclusion

The transition to net zero is not only necessitating an energy transformation, but also a transformation in the demand for materials, reshaping the foundations of industrial competitiveness and economic security. As clean technologies scale, exposure to critical minerals has emerged as a growing risk that warrants close monitoring. Firm-level evidence shows that companies actively track mineral markets, that mineral-related risks can affect firm growth – as evidenced in the cases of copper and lithium – and that firms employ a range of strategies to mitigate the shocks.

The UK's *Vision 2035: Critical Minerals Strategy* sets out four core objectives:

- increasing domestic production and recycling of critical minerals.
- limiting reliance on any single foreign supplier to no more than 60% of supply by 2035.
- leveraging international partnerships to secure resilient supply chains.
- supporting industrial growth and regional employment through strategic mineral development.

For the UK, these findings highlight the limits of aggregate or sector-level approaches to industrial strategy. Most variation in critical-mineral risk arises at the firm level – at least during the transition phase – even within the same industry, implying that broad-based policies risk missing key vulnerabilities while diluting public support. An effective strategy requires firm-level, data-driven analysis to identify which technologies, supply-chain positions and companies are most exposed to mineral-related uncertainty, where protection is most urgently needed, and how private and public mitigation measures can be effectively coordinated.

Addressing these challenges will require sustained interdisciplinary collaboration. Economic analysis must be combined with materials science, engineering and supply-chain expertise to anticipate bottlenecks, assess the feasibility of substitution and recycling pathways and align innovation policy with physical resource constraints. Closer coordination between government, industry, and research institutions will be essential to

ensure that advances in clean-energy deployment are matched by progress in material efficiency, circularity and resilience. Embedding this interdisciplinary perspective within UK industrial strategy will be critical to ensuring that the material foundations of the net zero transition are as robust as the UK's climate ambitions.

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Firm- and sector-level decision-making on productivity and net zero

Alice Owen¹

Executive summary

- Just as the UK government is seeking to drive stronger growth alongside its commitment to net zero emissions by 2050, individual firms seek productivity improvements while meeting environmental obligations.
- This briefing note considers how firms go about this, and how policy can support them, drawing on two industry case studies: cement manufacture and Scottish whisky. The intention of this research was to illustrate difference, not fully to represent entire sectors, or to represent the economy. These two industries are similar in the way they are suited to particular places, but they are different in being either business to consumer (B2C) or business to business (B2B), with products that are either a commodity or a luxury where brand is important.
- We found that firms select innovations, and invest in innovation, based on criteria that make sense for their strategy, which may not align with policy goals for economic growth. Market share, firm reputation and cost reduction all play a part.
- Firms' decisions that affect progress towards net zero may have two separate productivity-related motivations: either to increase added value as perceived by their customers (increasing price or market share and therefore revenue), or to reduce costs (increasing margin, if prices are maintained, and therefore increasing revenue).
- Firms' behaviour in adopting innovations depends on whether the innovation requires capital investment, or whether it involves changes in standards and behaviour. The latter can be adopted more rapidly, but such innovations are difficult to track.
- At the sector level, innovations that cannot be patented are important, specifically *innovations in codes and norms* that set expectations or requirements for low carbon products and services. Policy must recognise the power of sector-wide standards rather than relying on firm-level initiatives.
- Where whole sectors are constrained by customer expectations or technical requirements, there can be a first-mover disadvantage in innovation. Regulation does not have to be a burden for business: it can be a route to clarifying the rules of the game and ensuring a level playing field.

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Introduction

The UK as a whole wants economic growth and the UK government is committed to achieving net zero carbon emissions by 2050. Individual firms also want productivity improvements that will make their businesses more profitable, and they want to deliver on environmental obligations as well as their promises to shareholders. How do they go about it – and how can policy support them?

Economy-wide actions are made up of thousands of individual business decisions. To complement the economic models that generate insights into trends and relationships, some understanding is needed of what shapes decisions at the firm level. Individual business decision-makers are no more wholly economically rational than humans in any other context.

Furthermore, the relative weight given to productivity, and to net zero, in firm-level decision making changes over time and in response to sector-specific pressures and opportunities. Looking at firms within sectors helps identify the factors that affect decision-making, which then makes the insights more transferable between firms. For example, if aspects of firm location, whether it be in a limestone-rich national park for cement or in the Scottish Highlands for whisky, affect decision-making, then what is it about that location that is important?

National, regional and sectoral policies aim to provide incentives and stimulus to firms to meet multiple goals. This research sought to understand how firms respond to those different signals and chart their own path between those goals.

Over six months, case studies were constructed using data from site visits and interviews (two firms in each sector) as well as wider stakeholder interviews, publicly available information and records of publicly funded projects. Interviewees were asked about innovations they had made that they believed contributed to the carbon emissions of their business, allowing them to identify what they considered innovation. Innovations included changes to products, processes, packaging, standards and customer information/marketing.

Cement manufacturing

Cement is an example of a “foundational industry”, as set out in the UK’s Industrial Strategy 2025. Cement manufacturers directly employ 89,000 people across the mineral products sector with cement manufacture generating £1.4bn in 2023 (MPA, 2025). The government’s mission to build new homes and to encourage investment and renewal of transport infrastructure depend on the construction industry, which in turn relies on essential construction materials including cement. As such, the sector receives some relief from electricity costs, reflecting the dominance of energy-intensive manufacturing processes and limited proven technologies allowing

alternative production processes. Changes to manufacturing processes are usually capital-intensive but yield little in the way of revenue benefits as cement prices are competitive, and the requirement to meet technical specification on strength and durability are non-negotiable for most users. Cement manufacture is “place-based” for supply chain reasons ie production is usually located close to a source of limestone.

Scottish whisky production

Food and drink production does not feature in the UK’s industrial strategy, but whisky production has a comparative advantage that is difficult to replicate. Whisky exports worth £6.2bn represent 77% of Scotland’s food and drink exports (Scottish Food & Drink Partnership, 2023). Whisky production is place-based for resources and brand reasons; brands are tied directly to perceived attributes of rural Scotland and whisky production plays a distinctive role in the Scottish economy, underpinning 41,000 jobs in the nation (and 66,000 across the UK as a whole) (Scottish Whisky Association, 2024) many of which are part-time roles in rural economies. The energy-intensive distillation process and lengthy timescales to product maturity mean that managing working capital is a key consideration shaping investment decisions around innovation. There has been public funding support for innovation in green hydrogen energy in Scotland over the past five years, with significant technology piloting and investments in whisky production sites.

Key findings

Finding 1. Firms select innovations (and investment in innovations) based on customer preferences, and requirements

Whisky brands generate value by identifying with the “clean” Scottish environment, including pristine water supplies. Thus, capital investment that strengthens those brand values is given a more generous weighting in decision-making. On-site biomass/biodigestion energy plants, using local organic waste, speak to the “natural” attributes of whisky that customers prize – and for which they will pay a premium. Investment in green energy offers a double dividend of cost reduction and (some) brand enhancement. Customer preference is for green and natural products, rather than carbon reduction per se, but the firms we spoke to were alive to the opportunity to combine the two.

Customer preference is also reported as affecting investment decisions by cement manufacturers, although the timescales and complexities to implementation are longer in this industry than they are for whisky. Property and infrastructure developers using debt may demand low carbon cement to help with the developers’ environmental, social and governance (ESG) reporting to finance houses providing debt. ESG reporting is voluntary

and there is little clear assessment as to if and how ESG reporting reduces financial risk. In the absence of industry-wide consensus about the preferred innovations to reduce climate changing emissions from cement production, cement customer demand is a weak pressure for change.

Finding 2. Decision-making has constraints/parameters

Factors external to the business constrain decision-making on product or process innovation.

Standards and regulations: for cement manufacture, product attributes such as strength and durability, often assessed by product composition as much as performance, are defined through industry and engineering standards. This constrains the product and process innovation a firm can undertake alone. For a firm in a foundational industry such as cement, where the performance of other industries literally rests on the performance of the foundational material, any innovations that threaten compliance with technical standards cannot be pursued.

Locational assets/constraints: logistics determine where cement manufacture, and investment in cement manufacture, is viable; the fundamentals of the production process must involve a quarried limestone feedstock, and the product must be stored dry before being transported to where it is wetted and used. For whisky, logistics are also a concern, with feedstock being moved from maltings to distillation to large warehouses, with oak barrels imported often from France, Spain or the southern United States, but such considerations do not outweigh the value added through association with rural Scottish locations, and the premium associated with flavour from the pre-used barrels.

Finding 3. There is no simple relationship between productivity and net zero drivers in firm-level decision-making

Our case studies identified 13 distinct, firm-level innovations with net zero effects being adopted, as shown in Table 1.

Table 1: Innovations with carbon reduction impacts, identified by case study interviewees

Innovation description	Sector	Main reported driver
Energy storage	Whisky	Net Zero
Carbon capture and storage	Cement	Net Zero
Energy generation by biodigestion of byproducts	Whisky	Net Zero
Updating product use standards to allow flexibility in parameters	Cement	Net Zero
Updating production process standards	Whisky	Net Zero

Updating product standards from composition to performance	Cement	Net Zero
Changing packaging material – plastic to paper	Cement	Net Zero
Changing packaging material: glass to plastic	Whisky	Productivity
Proprietary equipment for distribution / product use makes switching suppliers more difficult for customers	Cement	Productivity
Branding enabling premium pricing	Whisky	Productivity
Heat recovery	Whisky	Combined
Bringing additional energy generation on site	Cement	Combined
Product diversification – pea gin	Whisky	Combined

This list excludes innovations that lie outside individual firms’ decision-making. For example, cement manufacturers are aware that innovation in building codes to allow more timber construction may reduce sector carbon emissions, but individual firms cannot currently engage positively with such sector-wide innovation.

Business viability concerns mean that firm-level decision-making is likely to focus on net zero innovation as a way of improving productivity – either by increasing value added or reducing costs. For one whisky producer, diversifying production by using the existing stills and using legumes for premium gin distillation increased income and improved the productivity of existing capital assets, while also speaking to the net zero narrative through avoiding waste and improving carbon capture in soil. In that example, measuring the net zero contribution in CO₂ equivalent terms is not straightforward, and carbon reduction is considered a side benefit of the diversification.

Finding 4. Firms assess technological/process innovations differently to how they adopt code or behavioural innovations, valuing intangible issues and customer perception

Technology and process innovations – carbon capture, renewable energy generation, energy storage – require capital. This means they are evaluated by firms in a particular way, scrutinising financial payback, although payback might be achieved through cost reduction, or from new income from increased market share or product diversification.

But an innovation in standards that does not require capital investment, such as the way in which stills are cleaned, or the packaging and storage of products, is evaluated on criteria that extend beyond cost considerations, including the “fit” of the innovation with the firm’s culture or with consumer expectations. Packaging whisky in plastic pouches rather than glass bottles may reduce carbon costs associated with transport by reducing the weight of the product, but the effects on consumer perception and brand or traditions must also be understood.

Conclusion

At the firm level, innovations for net zero must also contribute to productivity improvements if those innovations are to be adopted successfully. There are two routes to doing this:

Innovating to add value to the product increasing market share and/or unit prices that the consumer will accept; these case studies showed evidence that there can be green preferences in both consumer and industrial markets that drive firm investment decisions.

Innovating to reduce costs, particularly material or energy/resource costs.

Therefore, net zero policy needs explicitly to recognise how firms can meet their own requirements for improving productivity through implementing a net zero action.

At the sector level, innovations that cannot be patented are important, specifically *innovations in codes and norms* that set expectations or requirements for low carbon products and services. Policy must recognise the power of sector-wide standards rather than relying on firm-level initiatives.

Where whole sectors are constrained by customer expectations or technical requirements, there can be a first-mover disadvantage in innovation. Regulation does not have to be a burden for business: it can be a route to clarifying the rules of the game and ensuring a level playing field.

Research should connect quantitative and qualitative insights, providing information to shape policy that is both quantitatively rigorous, but also reflects the realities that businesses recognise. Once complex data sets have been mined to identify patterns of behaviour, eg individuals who repeatedly engage in entrepreneurship and start-ups which promise greener outcomes like carbon emission reductions, qualitative research can then test the attributes and conditions that create, allow or enhance that behaviour.

While there can be synergies between growth and net zero objectives, there are also tensions that vary by sector, location, supply chain and history/development. For sectors where energy intensity of products appears to be intractable, particularly in foundational industries, technological research exploring routes to decarbonisation should be matched by social science research which examines the business models for, and impacts of, reducing or displacing demand for energy-intensive products and services.

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Do common shocks drive changes in aggregate emissions intensity?

Xiyu Ren¹, Fulvia Marotta² and François Lafond³

Executive summary

- Climate policy can be conceived either at the macro-level, affecting all industries simultaneously, or at the industry-level, where different industries have different patterns of emissions reduction. Net zero commitments and transition plans now often include detailed industry-level pathways.
- In this note we summarise research (Ren, Marotta, and Lafond, 2025) that seeks to understand whether industry-level emissions intensity is driven by common shocks that impact all industries, or by idiosyncratic, industry-specific forces. To do so, we use industry-level emissions intensity data for the UK from 1990 to 2022, at the level of more than 100 industries.
- We decompose industry-level yearly changes in emissions intensity into a part due to each individual industry, a part due to groups of industries, and a part due to global, common variation. While macro-economic policy, economy-wide or societal factors may play a role in the future, historically they have not left a strong footprint in the form of a common factor that impacts all industries. The predominant force remains at the industry level, with some dynamics explained at the level of larger industry groups.
- The research also contributes to the policy evaluation toolkit of environmental macro policy actors. While macro-environmental policies would in principle be expected to create co-movement between emissions intensities in different industries, we show that such co-movement does not isolate the effect of macro policies alone. Other sources, such as common inputs, can create co-movement.

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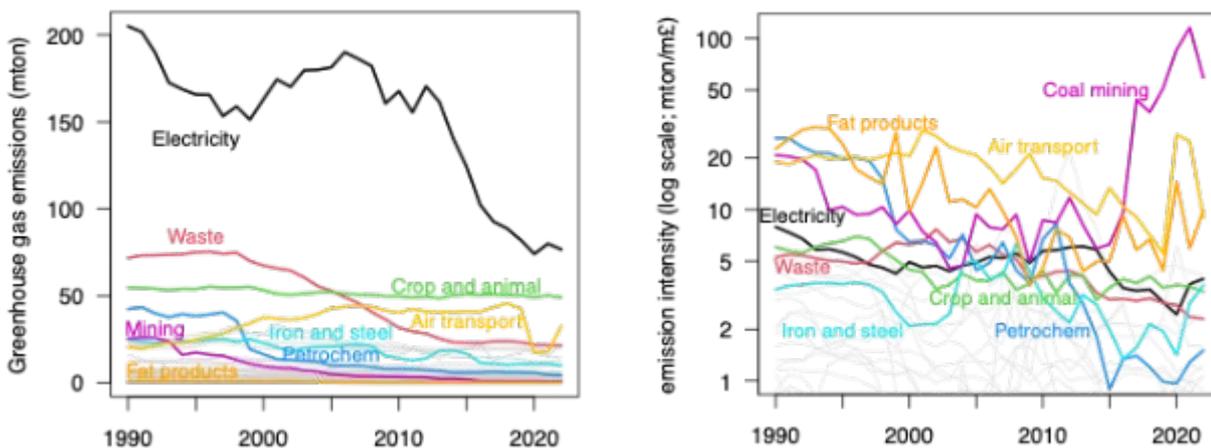
Introduction

In the UK, aggregate emissions intensity, the amount of CO₂-equivalent emitted per unit of value added, has more than halved over the past three decades.

Part of this decoupling reflects a shift in domestic production, away from heavy industry and towards services, which tend to emit less per unit of value added. Recent work has evaluated this channel and concluded that most of the decline in aggregate emissions intensity over the past three decades comes from within-sector changes, that is, individual industries becoming cleaner, rather than the economy simply shifting toward cleaner industries (Agarwala and Martin, 2022). The composition effect appears relatively minor compared to industry-specific technological progress, although this is partly because the data is not granular enough to capture the shift away from coal within the electricity generation sector.

Since reallocation across industries is not the major channel of aggregate emissions intensity reduction, the key question is what drives emissions intensity reduction within each industry. Climate policy frameworks have become increasingly granular (e.g. Fankhauser et al, 2022), with net zero commitments and transition plans now often formulated at the industry- or firm-level, implicitly assuming that this is the right level of decision making and analysis. But when we observe emissions reductions within an industry, we need to consider whether they really reflect industry-specific dynamics. After all, macro-level incentives, such as shared infrastructure, broad regulatory pressure or changing societal norms, can affect multiple industries at the same time, albeit to varying degrees. Industry-level decarbonisation patterns may very well be, in principle, driven by broader, economy-wide forces.

Figure 1: Industry-level Greenhouse gas emissions and Greenhouse gas intensity.



Notes: Top industries (based on 1990) shown in colours, with manually shortened labels.

The left panel of Figure 1 shows that while electricity generation has been a dominant source of emissions, other industries are important too, so there is potential for macro

policy to affect aggregate emissions by affecting several industries at the same time. But the right panel shows that emissions intensity of the large emitters, while often trending downward, are not synchronised, in the sense that they do not feature the simultaneous ups and downs that would indicate that they are driven by a common force.

In Ren, Marotta, and Lafond (2025), we examine this using a factor model, which allows us to assess the extent to which industry-level emissions intensity are driven by common shocks or idiosyncratic, industry-specific forces. We use data on industry-level emissions intensity in the UK from 1990 to 2022, at the level of more than 100 industries.

Key findings

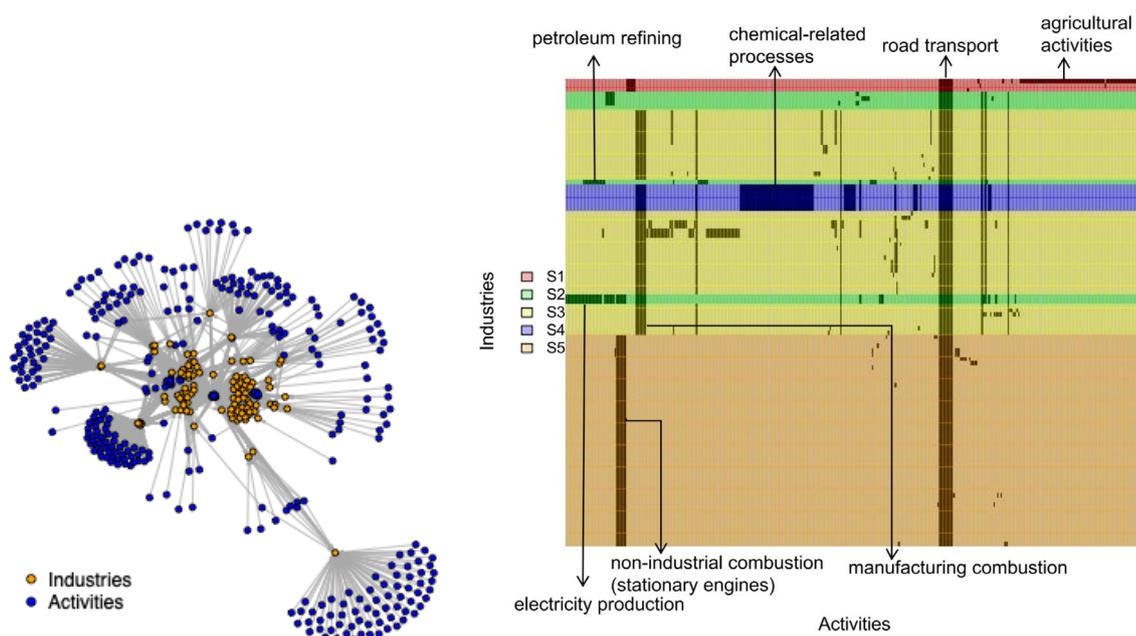
Finding 1. There is a common factor, but it's not necessarily macro policy

A naive investigation of our data, using a factor model, revealed a non-negligible role for a common factor. In other words, several time series do go up and down at the same time, in a statistically significant way. But, as a lively literature in econometrics has revealed, it is easy to pick up a common factor when none exists (Foerster et al, 2011). In studies of production networks, for instance, the diffusion of purely idiosyncratic shocks across the supply chain creates co-movement, and this co-movement could be picked-up as a significant common shock by a naive factor model. Against this backdrop, and motivated to understand what actually creates co-movement in industry-level emissions intensity, we dived into the nature of the data and how it is collected.

In practice, data is collected on emissions at the activity level (for instance, petrol used driving a petrol car) and then mapped onto industries using assumptions on the extent to which an industry uses an activity. Figure 2 shows the industry-activity map used by Eurostat. Some activities are performed by all industries, such as driving cars, while others are highly specific, such as specific cases of land use, which are only performed by the agriculture industry.

Thus, co-movement between industries can arise partly because they have activities in common. Activities that are common to all industries would create a genuine common factor, but there might be subtle patterns of “local” or block-level co-movement induced by partial overlaps of activities between sub-groups of industries. We do not know exactly the contributions of each activity to each industry, so we cannot estimate a model that would do justice to these patterns. Instead, we group industries based on how many activities they have in common, using a standard algorithm for community detection in networks (see Figure 2, left panel and Table 1). We then estimate a “block-level” factor model, which lets each group of industries have its own common factor, in addition to the economy-wide common factor.

Figure 2: Mapping activities to industries to allocate emissions



Notes: Emissions are estimated at the level of activities, and activities are then allocated to industries. The figures show two different representations of the correspondence table according to the Eurostat Manual for Air Emissions Accounts – 2012 edition (correspondence between SNAP97 – CRF/NFR and NACE Rev.2.). The left panel shows the bipartite network where an edge exists if an industry uses an activity. The right panel shows the incidence matrix, where a square is dark if the industry from y-axis uses the activity from the x-axis. The industries are ordered based on the initial ordering of SIC07. The activities are ordered based on SNAP code classification. The colours represent blocks chosen by our community detection algorithm, which we use in our block-level factor model (see Table 1). The labels are manually created by us by inspecting the activity’s name.

Table 1. Classification of industries into blocks.

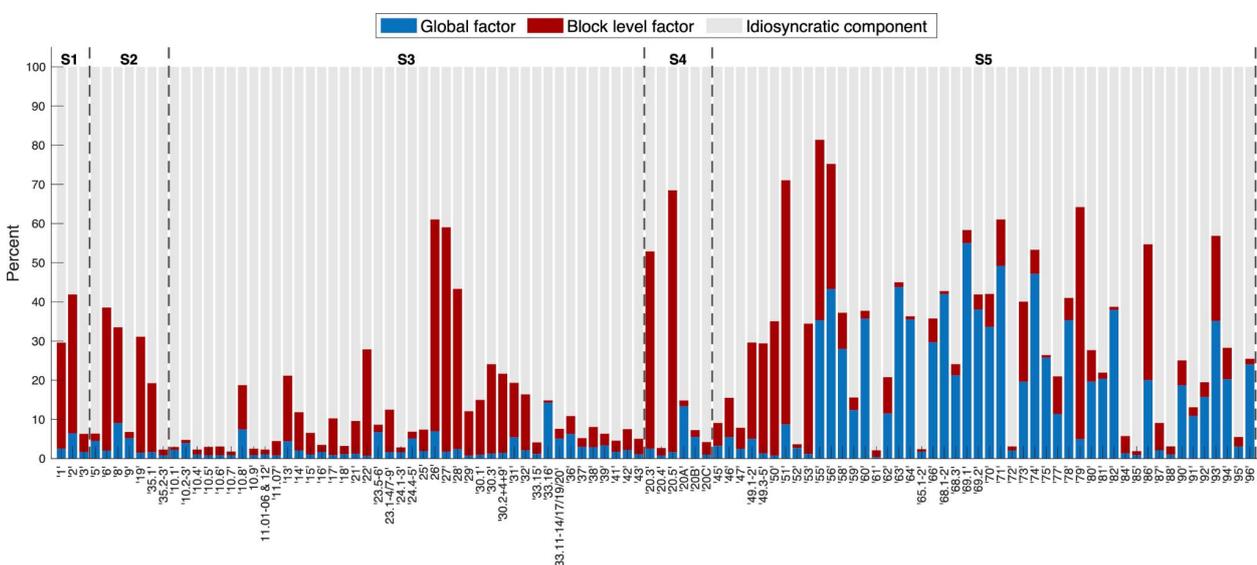
Block	General Description of Industries
S1	Agriculture and related industries
S2	Oil, gas, electricity and petroleum production
S3	General manufacturing, waste management and construction
S4	Chemical-related manufacturing
S5	Transportation and service industries

Notes: This classification is based on a Louvain community detection algorithm applied to a network where nodes represent industries and links indicate the number of activities two industries have in common. It differs from broader industry groupings. We have labelled each block manually.

Finding 2. Industry-specific factors remain the main driver of changes in emissions intensity

The results (Figure 3) show that after controlling for these block-level patterns of co-movement, the economy-wide common factor explains little of the variance of emissions intensity changes. The service sector is an exception (block S5 in Figure 3), as a large part of emissions come from universal inputs, such as road transport. Figure 3 also shows that the block-level factor can be substantial, indicating that certain blocks of industries, eg energy-related (block S2) feature strong co-movement, likely due to their co-allocation of activities.

Figure 3: Variance explained by the block-level factor model.



Notes: The block-level factor model allows us to decompose the volatility of each industry's emissions intensity into parts due to a global common factor, a block-level common factor, and idiosyncratic (industry-specific) shocks. The x-axis shows SIC codes, organised by block of industries as described in Table 1.

In summary, we find that idiosyncratic shocks remain the dominant driver of changes in emissions intensity. But both a global common factor and block-level factors can explain a meaningful share of the emissions intensity volatility in some industries. The global factor exhibits significantly higher loadings in service industries, suggesting that these sectors are more responsive to broad, economy-wide influences or to universal inputs such as road transport.

We also aggregate these industry-level results, to understand how idiosyncratic and common shocks each contribute to aggregate emissions intensity fluctuations (more precisely, to the part that comes from within-industry changes). We find that the global factor contributes very little, because service industries (in which the global factor has the most impact) emit very little. The block-level factors, in contrast, can explain a substantial

amount of aggregate volatility, as they contribute to explaining volatility in the Agriculture, Energy and Chemicals blocks, sectors with substantial emissions.

Conclusion

Our results confirm that decarbonisation is primarily driven by industry-specific dynamics. While macro-economic policy, economy-wide or societal factors may play a role in the future, historically they have not left a strong footprint on the short-run co-movement of time series of changes in emissions intensity.

Our paper is the first exploration of co-movement in emissions intensity. Our key insight is that to properly interpret the results, one should pay attention to the way data is collected, and should distinguish carefully between the results of the factor model and what they imply for aggregate emissions intensity. This contributes to the policy evaluation toolkit of environmental macro policy actors. While macro-environmental policies would, in principle, be expected to create co-movement between emissions intensities, we show that such co-movement does not isolate the effect of macro-policies alone. Other sources, such as common inputs, can create co-movement; in practice this is the case in low-emissions industries.

While very much an initial exploration, it points to interesting follow-ups both on the technical side (e.g. using better representations of the activity-industry maps, or characterising trends instead of volatility), and on the applied side, where similar models could be developed to evaluate whether firm-level emissions are driven by firm-specific efforts or simply follow economy-wide patterns.

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How renewable energy boosts economic productivity in the Global South

Emilien Ravigné and Sam Fankhauser

Executive summary

- Cheap renewables can boost productivity in the Global South by delivering more useful energy per dollar and lowering energy costs across the economy.
- Energy sector productivity could more than double by 2050 in many Global South countries under a rapid renewables transition, with especially large gains in sub-Saharan Africa.
- Economy-wide productivity gains are strongest in energy-intensive countries, and when solar and wind make up a large share of the energy mix.
- Renewables create a new comparative advantage for the Global South, with GDP gains of up to 9-12% in some countries – well above those in advanced economies.
- Fossil-fuel pathways deliver much less productivity growth, making renewables a key driver of long-term economic development.

Introduction

By 2030, roughly half of the global electricity demand could be met by renewable energy, chiefly solar and wind (IEA, 2024). While the transition entails upfront investment costs and economic dislocations for some sectors and communities, the net economic benefits of this transition are increasingly clear (OECD and United National Development Programme, 2025). Renewables materially enhance energy provision by offering more equitable access to more affordable energy. They are an important source of inward investment, boosting the local economy through increased activity along the supply chain. As the sector grows, it is becoming an increasingly important employer.

Perhaps most consequentially, this policy brief provides evidence that progressively cheaper renewables will also boost economic productivity. Far from being a drag on the economy, the falling costs of renewables means they are now driving future productivity

growth. For the solar-rich countries of the Global South, renewables can be the source of important, new cost advantages and help to finally close income gaps.

Drawing on a broader report on the economic benefits of renewable energy (Fankhauser et al, 2025), this policy brief quantifies the economic productivity benefits that the clean energy transition could bring to low and middle-income countries in the Global South. The analytical framework builds on methods originally developed for the UK under the Productive and Inclusive Net Zero (PRINZ) programme, which are used here as a benchmark to ensure consistency and comparability across country contexts. Ongoing and forthcoming research will explore these UK-specific implications in greater depth, including work on innovation, industrial strategy, and green skills and employment, helping to inform future policy discussions with policymakers.

Key findings

Cheap renewables raise productivity in two main ways. First, they make energy production more efficient: more electricity is generated for every dollar invested, with fewer losses when compared with fossil fuels or biomass. Second, these gains spill over into the wider economy, lowering energy costs for households, businesses and industries that depend on affordable power. When factories can run for longer hours at lower costs, the entire economy benefits.

Finding 1. What matters for the transition is the useful energy

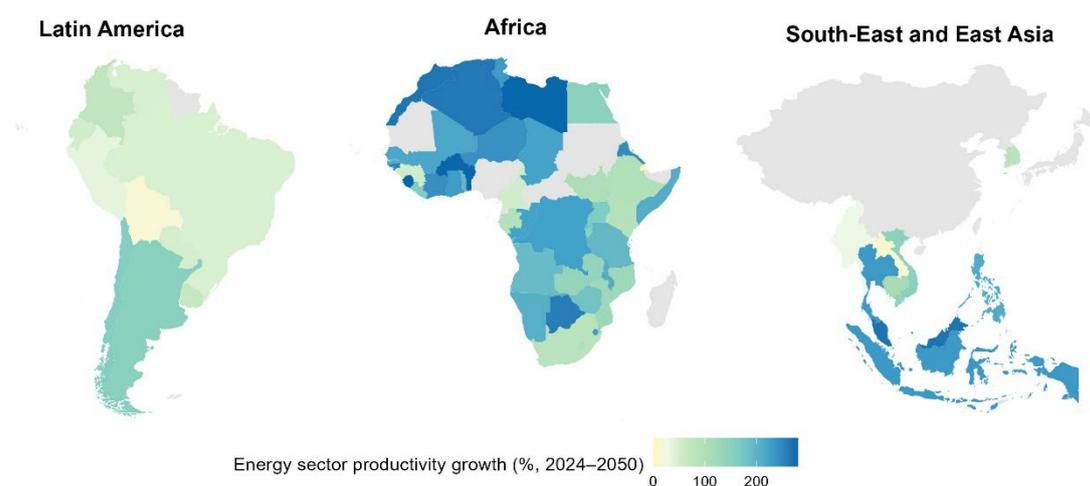
What ultimately matters for economic activity is not energy produced, but useful energy – the portion of energy that is effectively available to perform a task, after accounting for conversion and efficiency losses. For example, it is useful energy in petrol that moves the car forward, rather than energy being lost as heat. Clean energy technologies typically deliver higher shares of useful energy per unit of primary energy.

Economists use the concept of total factor productivity (TFP) to summarise how efficiently an economy (or sector) turns inputs (such as labour and capital) into output. This means that shifts in the energy mix that raise the supply of useful energy can support higher productivity, even if total energy inputs or investment costs increase during the transition. In our framework, these productivity gains are inferred from the joint evolution of energy quantities and prices: improvements in efficiency are reflected in a combination of higher useful-energy output and lower unit costs, which we map into sectoral TFP using a reduced-form relationship calibrated on historical data.

Finding 2. A switch to renewables could more than double energy sector productivity

Figure 1 reports projected changes in energy sector TFP (on a useful-energy basis) from 2024 to 2050 under a rapid transition scenario. The results show the evolution of energy sector productivity along a net zero pathway, generated using the open-source OSeMOSYS energy system model (Howells et al, 2011), in which climate policies drive emissions reduction, relative to today's fossil-based energy system.

Figure 1: Projected change in energy sector productivity (useful-energy basis), 2024–2050.



Notes: Based on a method developed by Ravigné and Lafond (2024) and using the open-source energy model OSeMOSIS (Howells et al, 2011) with data from the CCG Starter Data Kit (Gardumi et al, 2018). Energy cost projections are from Way et al. (2022).

The results are striking. For most countries in the Global South, the gains in energy sector productivity are close to or in excess of 100%. That is, under a rapid transition to renewables, TFP in the energy sector could double within 25 years. Importantly, productivity gains are positive for all countries in the sample, with particularly dramatic improvements in Sub-Saharan Africa, where energy systems still rely heavily on traditional energy sources, such as firewood and agricultural residues.

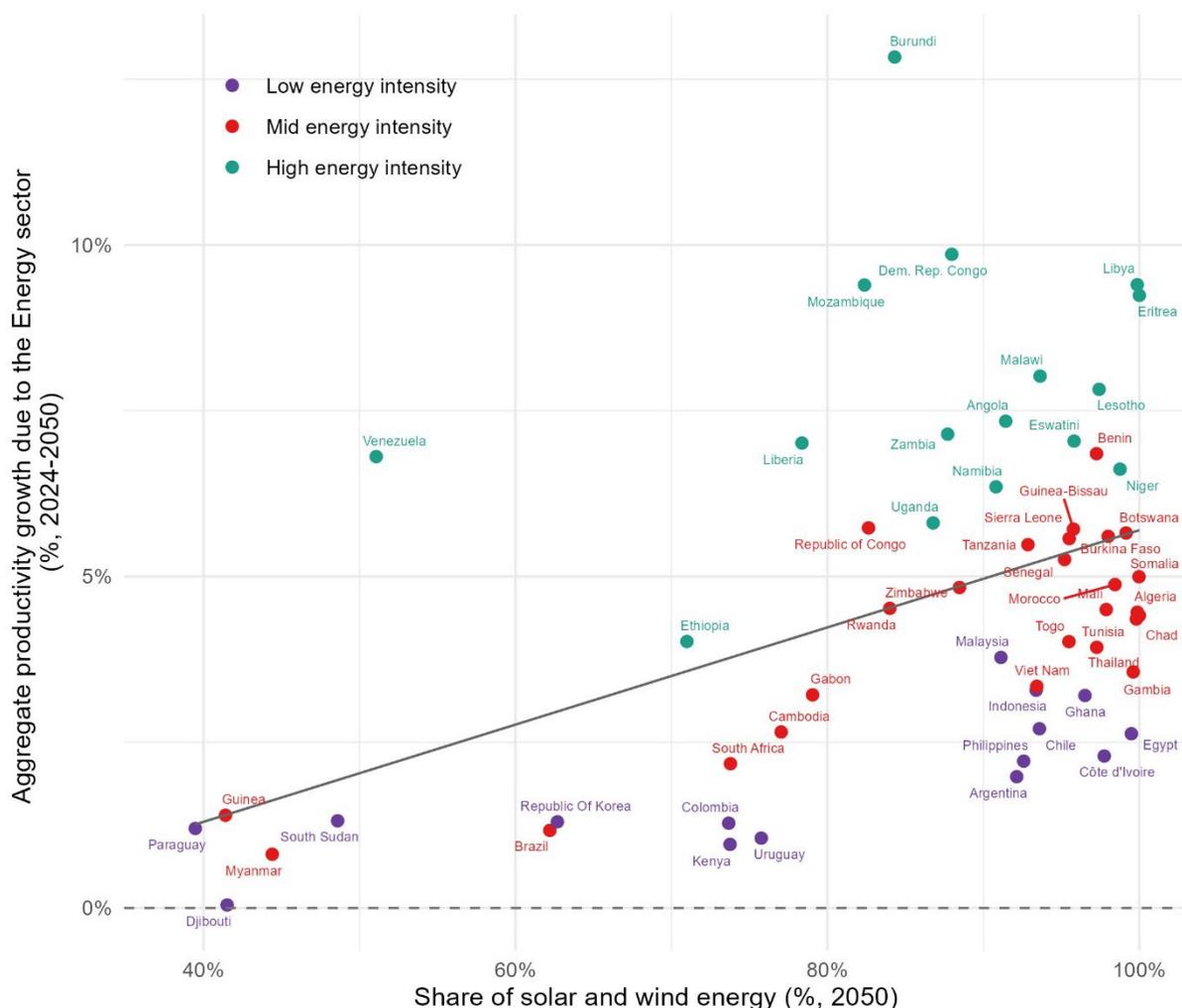
This is because traditional energy sources and clean electricity both offer useful energy for a task like heating but electricity requires much less primary energy to provide this useful energy because there are fewer losses in combustion and fuel extraction.

Finding 3. Energy-intensive economies with a large renewables share will benefit most

As energy use is so ubiquitous, an increase in energy productivity will translate into an aggregate (or economy-wide) increase in productivity. For example, renewable energy firms in East Africa do not just sell electricity. They are bringing to rural areas energy-as-a-service solutions like cold storage, water pumping and irrigation systems that lift agribusiness productivity (Fankhauser et al, 2024).

The extent to which energy productivity gains translate into aggregate productivity gains depends on two factors. The first factor is the magnitude of the energy productivity boost, which in turn is driven by the share of renewables in the energy mix. The second factor is the country’s energy intensity, that is, how big the energy sector is as a share of the economy.

Figure 2: Projected aggregate-economy productivity due to the energy transition



Notes: The y axis depicts aggregate (economy-wide) change in TFP between 2024 and 2050 (useful energy basis) under the OSeMOSIS fast transition pathway. Each dot is a country; colour indicates energy

intensity (low/mid/high). Low, Mid and High intensities are energy sales to GDP ratio being respectively 0-3%, 3-5%, >5%. Countries with a low share of solar and wind rely on nuclear, hydro or geothermal. Based on a method developed by Ravigné and Lafond (2024).

Figure 2 shows the relationship. Aggregate productivity growth rises in proportion to the share of renewables (solar and wind) in the energy mix, as shown by the upward sloping trend line. Countries with a high renewables share in 2050 will see bigger aggregate productivity gains.

The colour coding highlights how this positive relationship is amplified in energy-intensive economies. In countries where energy is a major input or demand is rising – such as Burundi, Mozambique and the Democratic Republic of the Congo – energy productivity growth is translated into above-average aggregate productivity growth. In contrast, countries where the energy sector carries relatively less weight, such as the Philippines, Indonesia and Malaysia, may enjoy strong energy productivity growth but this does not translate into equally large economy-wide gains.

Finding 4. Switching to renewables gives the Global South a new comparative advantage

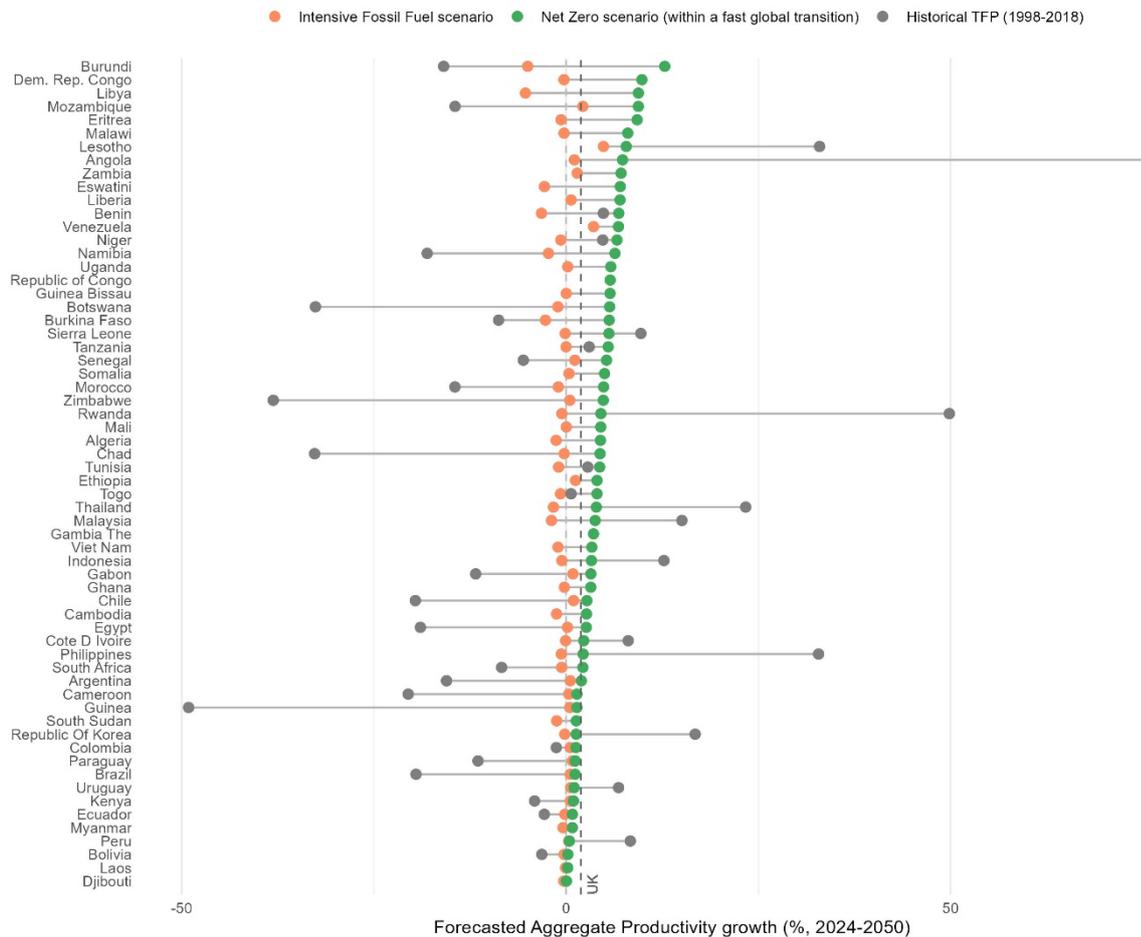
Figure 3 compares the aggregate productivity gains from a fast transition to renewables with those under a fossil-fuel intensive pathway. Under a fossil fuel scenario, aggregate productivity growth between now and 2050 is broadly flat. Economic growth would have to come from non-energy intensive sectors or be driven by increased capital accumulation.

In contrast, under a renewable energy pathway almost all countries, but particularly those with a high energy intensity, enjoy substantial aggregate productivity growth. Notably, the productivity boost arising from the energy sector alone is typically larger than the economy-wide productivity growth observed over the past 20 years (see the grey dot in Figure 3). In the case of Burundi, DR Congo, Libya and Mozambique TFP could rise by as much as 9-12%. As productivity directly translates into economic growth, we can expect GDP to grow by the same amount.

The productivity gains in most countries in the Global South also far exceed those of the UK and other developed countries under the same scenario, around 2 per cent by 2050 (see dotted vertical line in Figure 3). While this represents a meaningful productivity gain for the UK, we project much larger improvements in many countries in the Global

South. In other words, comparative advantages could shift in favour of the Global South. Compared to energy productivity in a fossil fuel world, the renewables-rich countries of the Global South can expect to have a distinct cost advantage in the net zero economy.

Figure 3: Aggregate-economy productivity under a fossil fuel and renewable energy scenario



Notes: The chart depicts TFP growth (useful energy basis) between 2024 and 2050 under the OSeMOSIS fossil fuel scenario (orange) and fast transition scenario (green). Grey markers show historical productivity growth (1998–2018, World Bank), with the UK’s fast transition case shown as a benchmark (dotted line). Based on a method developed by Ravigné and Lafond (2024).

Conclusion

Renewables are not just a cleaner way of meeting growing energy needs. Cheap renewable energy is also key to sustained economic development. Done well, the transition to renewables can expand affordable energy access, attract investment and create new jobs. Crucially, it can also increase productivity both in the energy sector and for the entire economy.

This policy brief calculates that a rapid switch to renewables will double energy sector productivity in low and middle-income countries, translating into economy-wide GDP gains as high as 9–12% for some countries.

These productivity gains are much higher than those in UK and other European countries, giving the Global South an important structural advantage in the global net zero economy. This economic opportunity is driven by:

- Abundant solar resources – solar is already the cheapest form of power generation and costs continue to fall.
- Leapfrogging potential – rising demand can be met directly with clean energy, without having to replace an entrenched fossil infrastructure.
- Energy intensity – in countries where energy makes up a large share of total output, productivity improvements will ripple through the economy more strongly.
- Replacing inefficient fuels – transitioning from biomass and coal to clean electricity eliminates wasteful and polluting energy use, reducing costs and yielding major productivity gains.

Countries that pursue these avenues can lock in a substantial productivity dividend. But, deliberate policy interventions and industrial policies will be needed to realise it. There is also a need for further research applying similar analysis to other sectors, comparing alternative technological solutions and transition pathways, and assessing the implications for trade and competitiveness.

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Do clean innovators create jobs?

Pia Andres, Ralf Martin and Anna Valero

Executive summary

- Innovation drives long-term growth and is key to creating high-quality jobs.
- We study innovation and employment among UK firms, and in particular, the role of clean innovation in driving employment growth.
- We find that while overall patenting among UK firms declined between 2005 and 2020, patenting in clean technologies remained more stable, and now comprises a share of almost 10% in overall UK innovation.
- Innovating firms tend to be larger and employ more people than non-innovators; especially those which innovate both in clean and non-clean technologies.
- Innovation is associated with higher employment growth. Employment growth rates for clean and non-clean firms are comparable. But, in absolute terms, an average clean innovation is associated with greater job creation than non-clean innovation as firms innovating in clean are on average larger.
- We conclude that policy incentivising clean innovation can support job creation.

Introduction

Innovation drives long-term growth, and thus also growth in employment and labour income. But, through waves of technological change, some innovations have been more conducive to workers' ability to benefit from growth than others.

At the firm level, much of the research studying these relationships has been focused on the adoption of new technologies. For example, if a supermarket adopts self-checkouts (Acemoglu and Restrepo, 2019, 2022), this replaces workers, while adopting an e-commerce platform will greatly augment the scope of an existing sales team and likely lead to its expansion. Today, debates are centered upon the impacts of AI adoption on the demand for workers of different types, with some studies already seeing significant changes in demand for certain workers (see, for example, Brynjolfsson et al, 2025). Similarly, analyses of the impact of the net zero transition on the labour market tend to be focused on how the adoption of "clean" technologies and practices in the energy sector and across the economy will impact workers (see Riom and Valero (2024) for a summary).

By contrast, Autor et al (2020) stress the relevance of superstar firms with high markups but often much lower employment intensities in explaining a declining share of income from labor. They also suggest at the sector level the link between innovation and the emergence of superstar firms. Following on from this in a new study we examine the link between innovation and jobs focusing on innovating firms in the UK. We consider how the invention of clean technologies relates to employment in inventing firms and whether the

relationship differs across clean and non-clean technologies. While we might expect that firms inventing new technologies which they take to market will need to hire more people, there has been concern that especially in recent internet based technological waves there was “scaling without mass” (Brynjolfsson et al, 2008) where the biggest innovators grow market share orders of magnitude faster than jobs. There are similar concerns in the context of recent clean innovations where some have argued that the automotive sector will create fewer jobs in the future, as electric vehicles are much simpler to assemble than internal combustion engine cars.¹

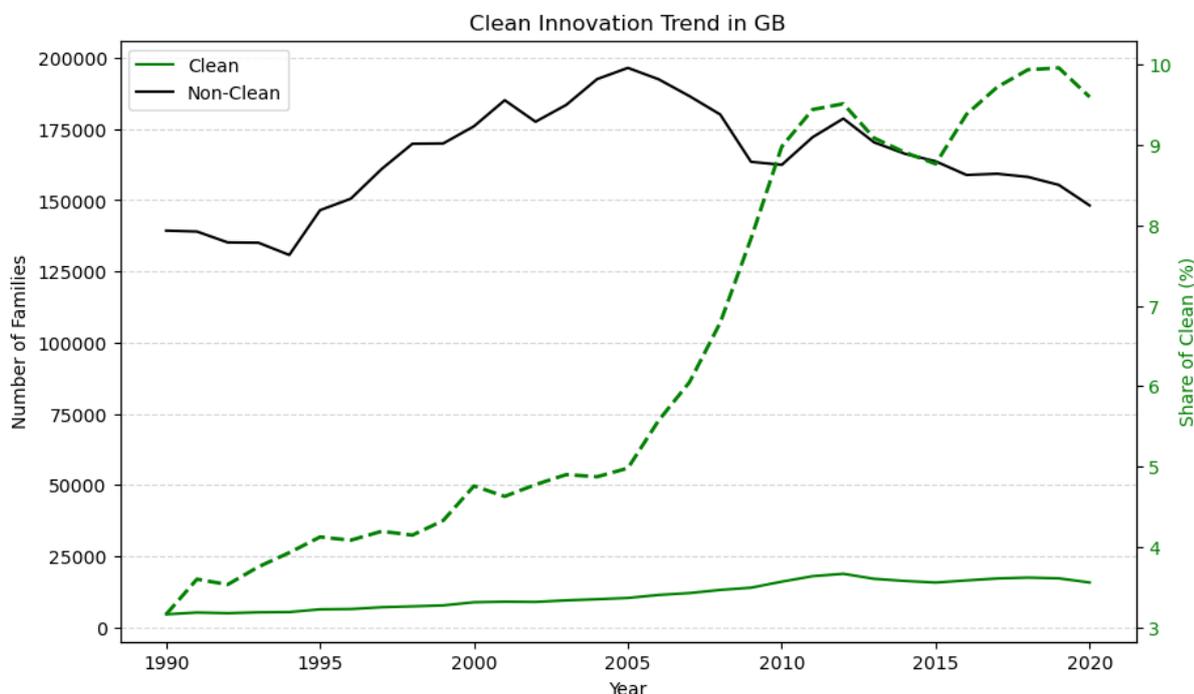
Our analysis is based on data on employment and other financials on UK firms from Bureau Van Dijk’s ORBIS Historical database. We match these data to firm patenting using ORBIS IP and draw on PATSTAT Global (2024 Spring Edition) to count clean innovations² and non-clean innovations at the firm level, annually, over a period of 20 years.

Key findings

Finding 1. While overall patenting in the UK declined between 2005 and 2020, the share of clean patenting rose rapidly and stabilised in the 2010s

We begin by considering trends in UK patenting (Figure 1). Overall patented innovation in the UK peaked in 2005 and has declined since then (with some short-term fluctuations). Clean innovation was just 3% of total innovation in 1990 and this share rose sharply between 2005 and 2010, after which it stabilised between 9% and 10%.

Figure 1: Patenting trends: clean and non-clean technologies



¹ <https://news.climate.columbia.edu/2023/09/18/protecting-workers-as-we-shift-to-electric-vehicles/>

² Defined as those classified within the Y02 class of the Cooperative Patent Classification: Technologies or Applications for Mitigation or Adaptation against Climate Change.

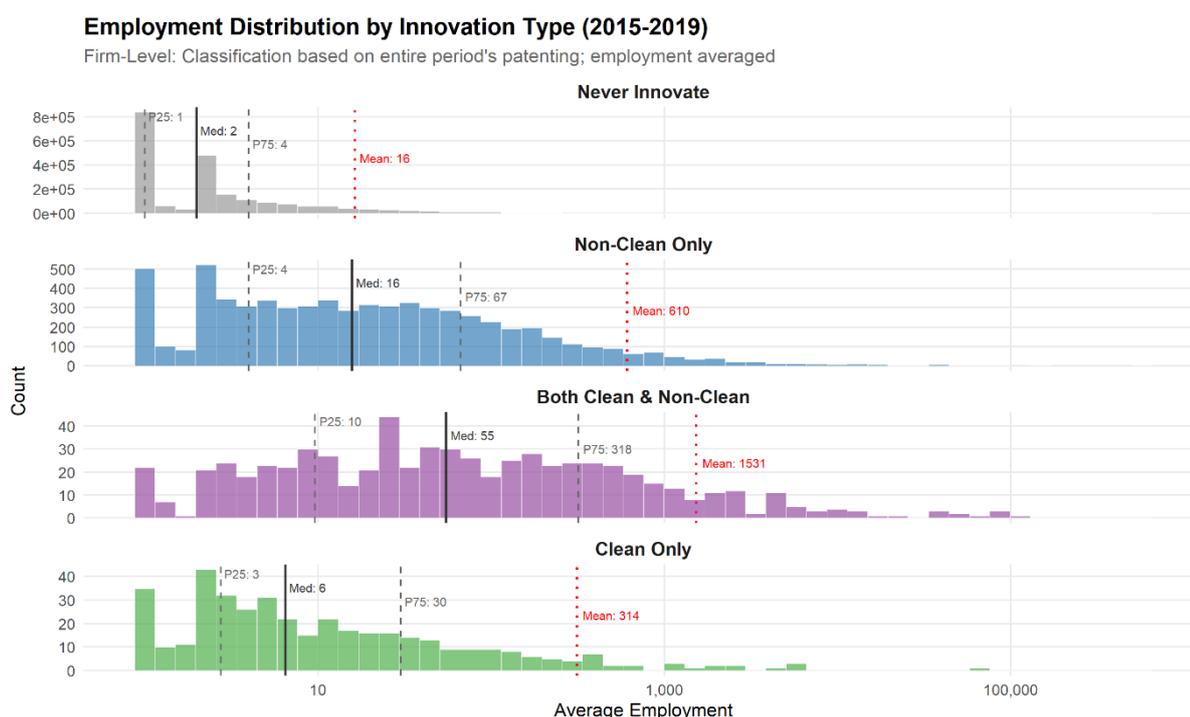
Notes: The figure plots the annual number of new patent families associated with UK-based applicants. Patent families group together multiple filings relating to the same underlying invention, including re-filings, division, and continuation applications, as well as filings across jurisdictions. The solid green line shows the number of new patent families classified under CPC code Y02, while the solid black line shows the number of new patent families not classified as Y02 (left axis). The dashed green line reports the share of Y02 patent families in total UK patenting (right axis).

Finding 2. Innovating firms tend to be larger than non-innovators, particularly those that combine clean and non-clean innovations

To understand the relationship between patenting and firm size, we first explore the employment distribution of firms that innovate in different technology classes (and those that do not innovate at all). This analysis is focused on the period from 2015 as our data benefits from coherent sampling rules over this period.

Figure 2 shows that the vast majority of firms never innovate, but these firms tend to be quite small relative to innovating firms. The average size of firms innovating only in non-clean technologies (“non-clean only”) is 610 employees. Innovators active in both “clean” and “non-clean” fields are larger still, with an average of 1,531 employees. By contrast, clean-only innovators are smaller, with an average of 314 employees.

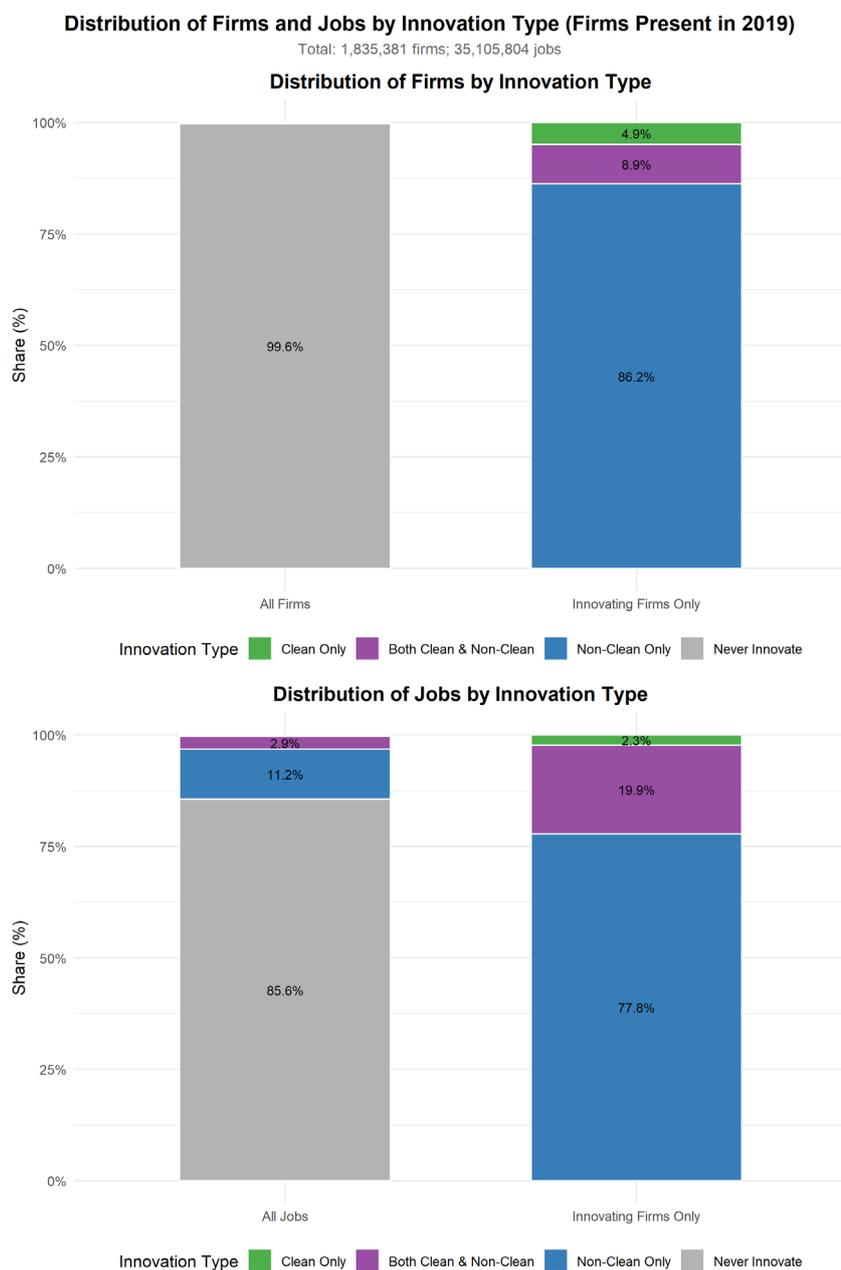
Figure 2: Employment distribution by types of innovation (2015-2019)



Notes: Firms are grouped based on their patenting over the period 2015-2019. Firms in the top panel (grey) have no patents over the period. Firms in the second panel (blue) have only non-clean patents. Firms in the third panel (purple) have both clean and other patents. Firms in the bottom panel (clean) have only clean patents. Employment for a firm is calculated as the average across all years from 2015-19 where it is active. The figures show the number of employees for each type of firm (annual average) in each bin. The bold black line indicates the median for each distribution. The dashed black lines indicate the 25th and 75th percentile. The dashed red line marks the mean.

Figure 3 summarises the share of firms and jobs innovating in different technologies. We note that in the aggregate, firms in the “both clean and non-clean” group punch above their weight: while representing less than 0.5% of firms and just under 9% of innovating firms, they account for 3% of total jobs and 20% of jobs in innovating firms (as shown in the bottom panel).

Figure 3: Share of firms and jobs innovating, and innovating in clean vs non-clean technologies

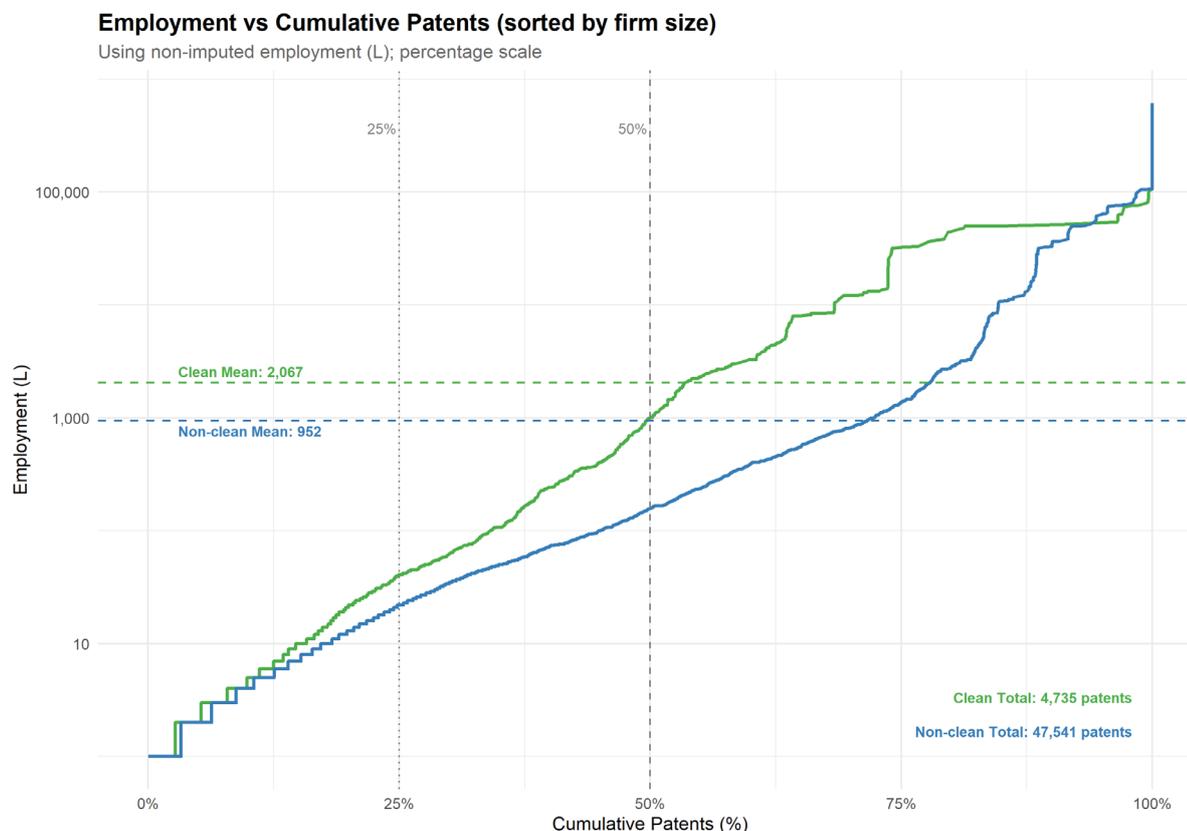


Notes: Firm level technology classifications are based on patenting over the period 2015-2019. Average employment for a firm is calculated as the average across all years from 2015-19 where it is active. This figure plots the distribution of firm sizes across all innovations in our sample of UK firms between 2015 and 2019.

We find that all innovation groups include a broad range of firms, ranging from those with only a few employees to large firms with more than 1,000 employees. The higher average

size of the "both clean and non-clean" innovation group is not driven only by extremely large firms. Indeed, the "non-clean" group is smaller on average, despite consisting of more firms with extremely high employment (Figure 4).

Figure 4: Firm size distribution across types of innovation



Notes: The Figure plots the employment size gradient for clean and non-clean patents. We see that a larger share (nearly 75%) of non-clean patents are produced in smaller firms with less than 1,000 workers, whereas only about 50% of clean patents are in such firms. However, despite this, non-clean patents also dominate among very large firms with around 100,000 employees. Average employment figures are different from Figure 2, as this Figure reports employment in the year when patenting happens, whereas Figure 2 reports average employment across a 5-year period. This suggests that patenting happens when firms are already somewhat larger.

These findings are consistent with the idea that policies incentivising further clean innovation could have broader direct effects on worker outcomes than in other innovation areas. To further investigate this hypothesis, we study the relationship between the emergence of new innovation and jobs.

Finding 3. Clean innovation tends to be followed by employment growth

We explore the relationship between innovation and subsequent employment growth in businesses in firm-level panel regressions. We have to be cautious in interpreting regression results as causal, but we take several steps to mitigate concerns related to reverse causality and omitted variables in our estimations.

First, all regressions include controls for observable firm characteristics (like firm size), as well as firm fixed effects that allow us to control for time-invariant firm-specific characteristics. We examine the relationship between last year's patenting and this year's employment growth.³ We also include controls for past employment and investment. Using lagged variables minimises the potential for reverse causality and confounding. For instance, it might be the case that an increase in employment such due to the hiring of R&D workers or support workers as part of an investment in an R&D lab are causing the emergence of innovations rather than the other way round.

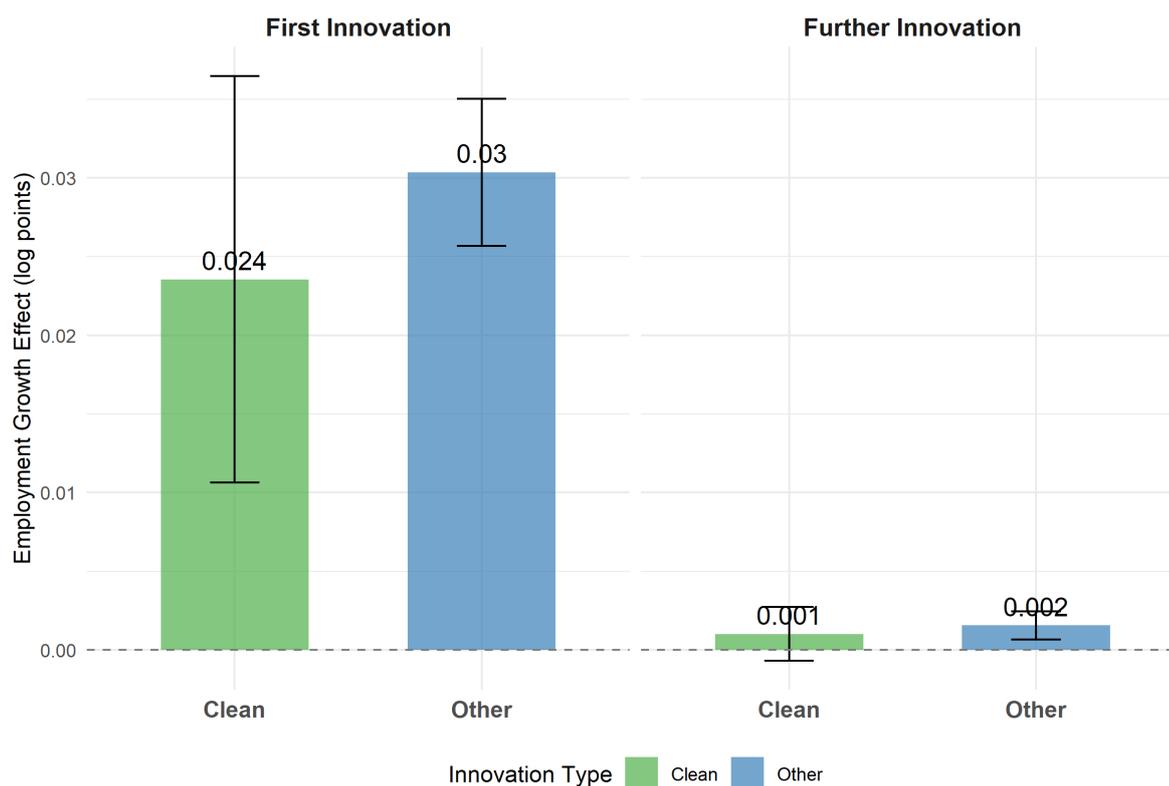
Figure 5 plots coefficient estimates and 95% confidence intervals for our most sophisticated model. Results from other model specifications are of similar order of magnitude and reported in the Annex. We distinguish between the effect of a first innovation and the effects of further innovation. We also distinguish between the effects of clean vs other innovation. We find that firms that innovate in clean in the previous year have additional employment growth of 2.4 percentage points (0.24 log points). For "non-clean" patents the increase is a bit larger (an additional 3 percentage points), but the difference is within the margin of error. The intensity of patenting does not matter as much with additional growth of only 0.1 to 0.2 percentage points for additional patents (further innovation) after the first.

Hence, what matters most is if a firm is engaged in innovation, not how many innovations it produces in a given period. This could be the case because multiple innovations are often less significant extensions of one main innovation. It could also reflect the fact that firms with multiple innovations are often larger more established firms, whereas single patent innovators are smaller startup firms where the emergence of a patent has a more dominant impact on the firm's fortunes. We are exploring these potential heterogeneities in ongoing research.

Annex B includes a detailed discussion of all alternative regression specifications, as well as a full regression table.

³ We also explore specifications where we examine the relationship between this year's employment growth and this year's patenting. Our various specifications are discussed in more detail in the Annex.

Figure 5: Associations between innovation and employment at the firm level



Notes: We regress the change in logged employment on the number of patents in each category (Clean and Other), using a range of econometric models detailed in the Annex. Estimates are of similar order of magnitudes. The results of our preferred, most comprehensive, model are shown here. The coefficients are in the mid-range of our estimates.

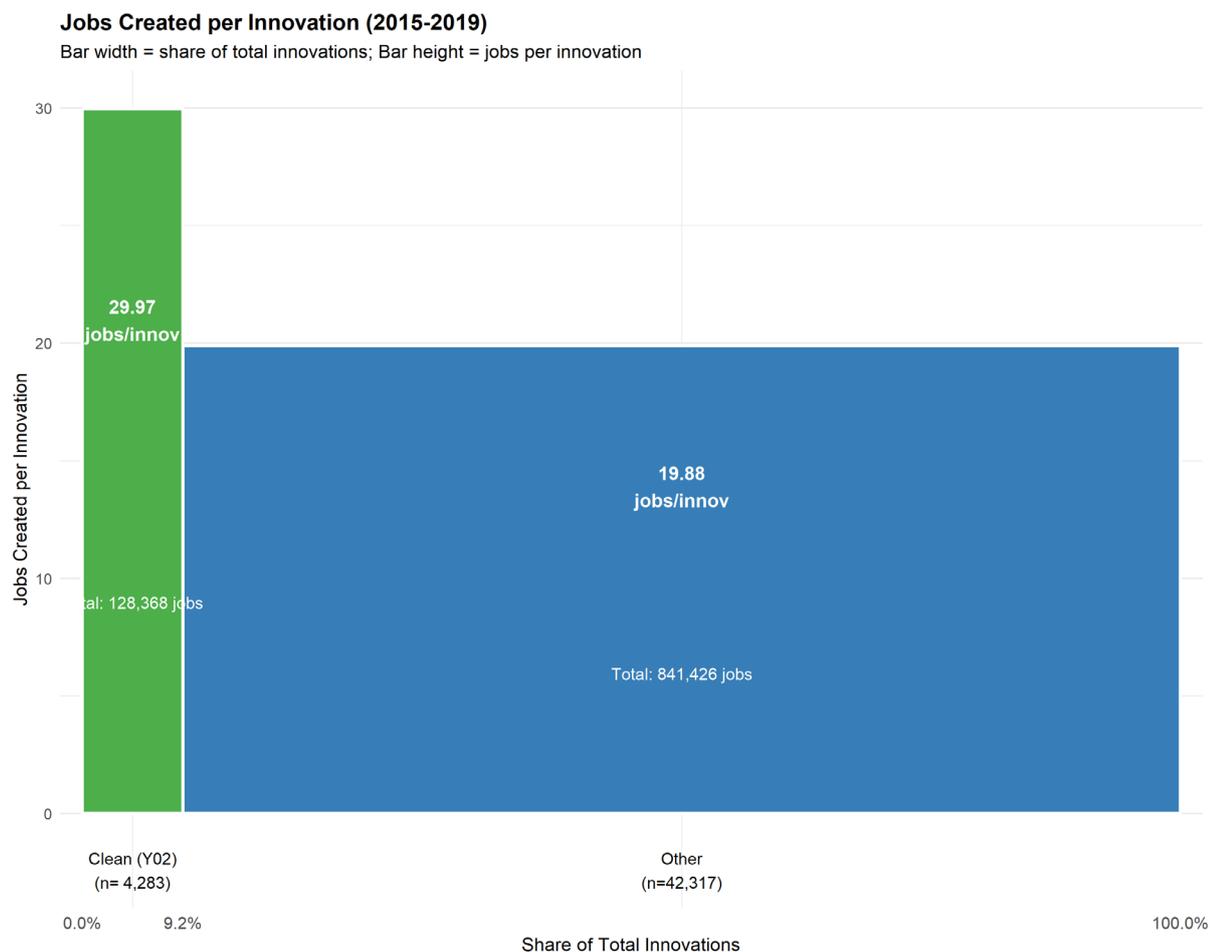
While our results do not suggest much difference between clean and non-clean innovation, the varying differences in firm size between the two groups discussed above could still imply substantial differences in the aggregate relevance of these effects. We explore this in the next section.

Finding 4. Job creation associated with a clean innovation is higher than non-clean, on average

We conduct a counterfactual exercise, in which we use the results from regression Model 4 to estimate the number of new jobs associated with an innovation for each innovating firm.⁴ This suggests that over the 2015-2019 period, nearly 1 million jobs created were associated with (patented) innovation in the UK. Most of those were linked to non-clean innovation. But, in per innovation terms, clean innovations have tended to punch above their weight, with over 30 jobs per innovation on average compared with nearly 20 for non-clean innovations.

⁴ We chose Model 4 because the results are in the middle of our spectrum of estimates.

Figure 6: Jobs created per innovation, clean vs other technologies



Notes: Bar height shows model-implied average jobs created per innovation in the period 2015–2019. Predicted job creation is obtained by aggregating firm-level employment effects implied by the regression estimates from Model 4, where predicted employment changes are computed using a nonlinear transformation of the linear predictors and scaled by firm employment. Bar width is proportional to the number of innovations of each type (normalised to the maximum), such that bar area reflects total predicted job creation.

Conclusion

The bulk of clean innovation happens in larger firms that engage in both clean and non-clean innovation. The job growth associated with innovation is comparable across the innovation types examined here. But, because firms innovating in clean technologies tend to be larger, the total number of jobs associated with clean innovation is substantially higher on a per-innovation basis.

Further research is needed to understand mechanisms and effects, including differences across a greater range of technologies and firm types. In addition, employer-employee data could shed more light on the type and quality of jobs that are being created. And further research is needed to establish robust causal relationships. But, our results support the idea that the clean transition is associated with a relative increase in labour demand in the

firms innovating in clean technologies. Our results also highlight that while much policy focus is on small firms (where financial barriers to investment tend to be higher), larger firms innovating in clean technologies are a likely to play a key role in job creation.

These results are also consistent with a view that building out clusters of clean tech firms via incentives for clean innovation (such as R&D subsidies directed at clean technologies, or impact investment strategies focusing on clean innovation) could support job creation – in addition to creating new technologies to address climate change. This relies on the assumption that the cost of additional innovation is comparable across technologies. In related work (International Finance Corporation, 2025) we show that on average and at the global level, advances in clean technologies are less costly than for non-clean technologies. This would reinforce the conclusion that support for clean innovation has higher returns in terms of jobs compared with non-clean technologies. In future work we will examine more closely to what extent this applies to specific green technologies in the UK. We also will consider to what extent there are further employment effects via knowledge spillovers, following the approach developed in (Guillard et al, 2021).

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Annex - further detail on regression analysis

We estimate regressions of the form

$$\Delta l_{it} = \beta_C C_{it} + \beta_{NC} NC_{it} + \beta_{\#C} \#C_{it} + \beta_{\#NC} \#NC_{it} + \beta_X X_{it} + \alpha_i + \delta_t + \epsilon_{it}$$

where C_{it} a variable equal to one if a firm i conducts clean innovation in year t , $\#C_{it}$ is a variable counting the number of clean innovations. O_{it} and $\#O_{it}$ record the same for other innovations. While our analysis does not support a clear causal claim, our aim is to establish whether there is a statistically significant relationship between employment growth (the outcome) and a firm's innovation behaviour, proxied by patents in clean and non-clean technology groups (the regressors).

Specifically, we estimate the following four models:

$$\Delta l_{it} = \beta_C C_{it} + \beta_{NC} NC_{it} + \alpha_i + \delta_t + \epsilon_{it} \quad (1)$$

$$\Delta l_{it} = \beta_C C_{it} + \beta_{NC} NC_{it} + \beta_{\#C} \#C_{it} + \beta_{\#NC} \#NC_{it} + \alpha_i + \delta_t + \epsilon_{it} \quad (2)$$

$$\Delta l_{it} = \beta_C C_{it} + \beta_{NC} NC_{it} + \beta_{\#C} \#C_{it} + \beta_{\#NC} \#NC_{it} + \beta_l l_{it-1} + \beta_k k_{it-1} + \alpha_i + \delta_t + \epsilon_{it} \quad (3)$$

$$\Delta l_{it} = \beta_C C_{it-1} + \beta_{NC} NC_{it-1} + \beta_{\#C} \#C_{it-1} + \beta_{\#NC} \#NC_{it-1} + \beta_l l_{it-1} + \beta_k k_{it-1} + \alpha_i + \delta_t + \epsilon_{it} \quad (4)$$

Where:

Δl_{it} is the log change in employment in firm i between time t and $t - 1$

C_{it} is a binary variable indicating whether firm i had at least one Y02 patent family at t

NC_{it} is a binary variable indicating whether firm i had at least one non-Y02 patent family at t

$\#C_{it}$ is the number of Y02 patent families by firm i at time t

$\#NC_{it}$ is the number of non-Y02 patent families by firm i at time t

l_{it-1} is lagged, logged employment in firm i

k_{it-1} is lagged, logged total assets in firm i

α_i are firm fixed effects

δ_t are year fixed effects

ϵ_{it} is the i.i.d. error term

Table A1: Regression results

	(1)	(2)	(3)	(4)
Y02 Patent Indicator (C_{it} or C_{it-1})	0.0175*** (0.0055)	0.0153*** (0.0056)	0.0360*** (0.0063)	0.0225*** (0.0066)
Non-clean patent indicator (NC_{it} or NC_{it-1})	0.0184*** (0.0021)	0.0174*** (0.0021)	0.0467*** (0.0025)	0.0288*** (0.0025)
Number of Y02 patents ($\#C_{it}$ or $\#C_{it-1}$)		0.0003 (0.0005)	0.0018*** (0.0006)	0.0010 (0.0009)
Number of non-clean patents ($\#NC_{it}$ or $\#NC_{it-1}$)		0.0005** (0.0002)	0.0021*** (0.0005)	0.0016*** (0.0005)
Employment (Lag, Log) (l_{it-1})			-0.1580*** (0.0009)	-0.1638*** (0.0010)
Total Assets (Lag, Log) (k_{it-1})			0.0432*** (0.0004)	0.0477*** (0.0005)
Num.Obs.	4150232	4150232	4055283	3697161
R2	0.395	0.395	0.456	0.449
R2 Adj.	0.045	0.045	0.137	0.130
R2 Within	0.000	0.000	0.093	0.095
R2 Within Adj.	0.000	0.000	0.093	0.095
Std. Errors	Clustered (firm_id)	Clustered (firm_id)	Clustered (firm_id)	Clustered (firm_id)
FE: firm_id (α_i)	X	X	X	X
FE: year (δ_t)	X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Notes: Table A1 reports the results of our 4 regression specifications, as Equations (1)-(4) above. Dependent variable: annual change in log employment. Models (1), (2) and (3) use contemporaneous patent indicators, while in Model (4), patent indicators are lagged to mitigate the risk of reverse or simultaneous causality. All specifications include firm and year fixed effects. Standard errors are clustered at the firm level.

The impact on aggregate jobs

We compute the number of jobs created due to clean innovation in firm i in period t as

$$\Delta \widetilde{L}_{it}^C = L_{it} \times (1 - \exp[-\beta_C C_{it} - \beta_{\#C} \#C_{it}])$$

Thus, we compute how much lower employment in a given firm would be if the firm had not produced any of their clean innovations as suggested by our fitted regressions model. We can compute the same figure considering what would happened to jobs without any of a firm's non-clean innovations:

$$\Delta \widetilde{L}_{it}^{NC} = L_{it} \times (1 - \exp[-\beta_C NC_{it} - \beta_{\#C} \#NC_{it}])$$

Figure 6 then reports the share of the implied employment change in actual innovation for either innovation type ie: $\frac{\sum_{it} \Delta \widetilde{L}_{it}^Z}{\sum_{it} Z_{it}}$ where $Z \in \{C, NC\}$

About the authors' organisations

The **Centre for Economic Performance (CEP)** is an interdisciplinary research centre at the London School of Economics. It was established by the Economic and Social Research Council in 1990 and is now one of the leading economic research groups in Europe. It carries out policy-focused research on the causes of economic growth and effective ways to create a fair, inclusive and sustainable society.

<https://cep.lse.ac.uk/>

The **Programme on Innovation and Diffusion (POID)** carries out cutting-edge research into how to boost productivity through nurturing innovation – ideas that are new to the world – and how to diffuse these ideas across the economy. The programme is funded jointly by the Economic and Social Research Council and the London School of Economics. <https://poid.lse.ac.uk/>

The **Grantham Research Institute on Climate Change and the Environment** was established in 2008 at the London School of Economics and Political Science. The Institute brings together international expertise on economics, as well as finance, geography, the environment, international development and political economy to establish a world-leading centre for policy-relevant research, teaching and training in climate change and the environment. It is hosted by the Global School of Sustainability at LSE and is funded by the Grantham Foundation for the Protection of the Environment. www.lse.ac.uk/granthaminstitute

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