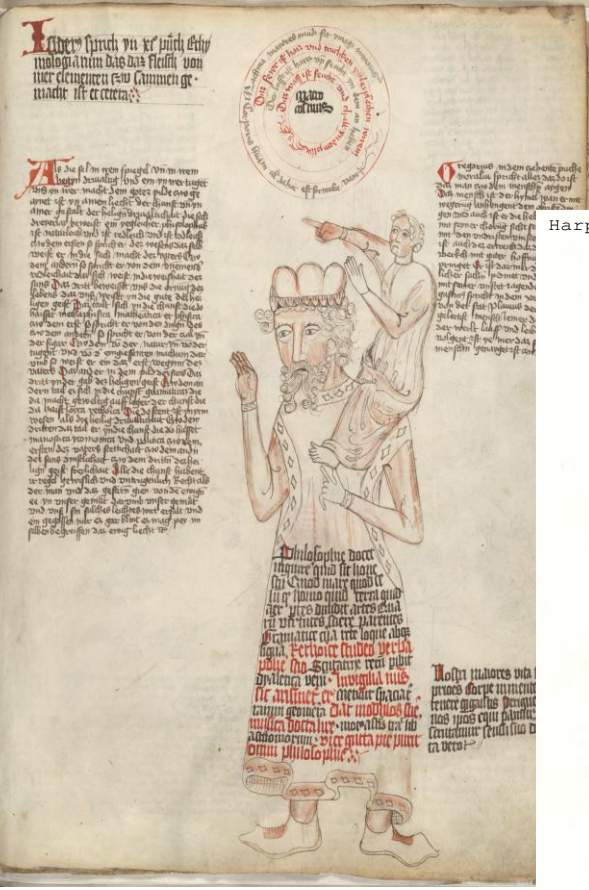


DEEP SCIENCE, THE ULTIMATE KNOWLEDGE LEVER

Koenraad Debackere, KU Leuven

May 21nd, 2026

Materinex Annual Event, Antwerp



Harpers, issue 179, June/November 1939

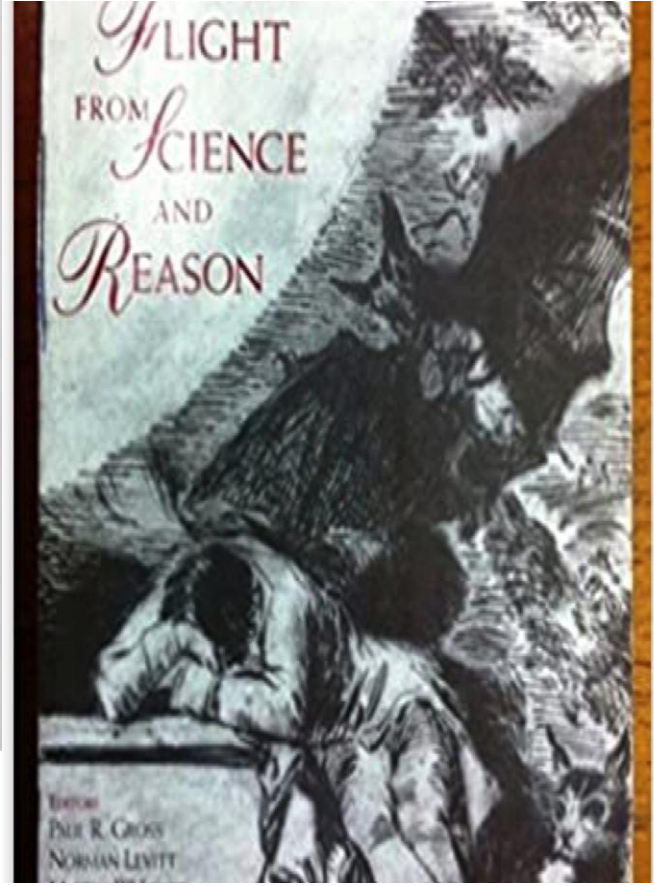
THE USEFULNESS OF USELESS KNOWLEDGE

BY ABRAHAM FLEXNER

It is not a curious fact that in a world steeped in irrational hatreds which threaten civilization itself, men and women—old and young—detach themselves wholly or partly from the angry current of daily life to devote themselves to the cultivation of beauty, to the extension of knowledge, to the cure of disease, to the amelioration of suffering, just as though fanatics were not simultaneously engaged in spreading pain, ugliness, and suffering? The world has always been a sorry and confused sort of place—yet poets and artists and scientists have ignored the factors that would, if attended to, paralyze them. From a practical point of view, intellectual and spiritual life is, on the surface, a useless form of activity, in which men indulge because they procure for themselves greater satisfactions than are otherwise obtainable. In this paper I shall concern myself with the question of the extent to which the pursuit of these useless satisfactions proves unexpectedly the source from which undreamed-of utility is derived.

We hear it said with tiresome iteration that ours is a materialistic age, the main concern of which should be the wider distribution of material goods and worldly opportunities. The justified outcry of those who through no fault of their own are deprived of opportunity and a fair share of worldly goods therefore diverts an increasing number of students from the studies which their fathers pursued to the equally important and no less urgent study of social, economic, and governmental problems. I have no quarrel with this tendency. The world in which we live is the only world about which our senses can testify. Unless it is made a better world, a fairer world, millions will continue to go to their graves silent, saddened, and embittered. I have myself spent many years pleading that our schools should become more acutely aware of the world in which their pupils and students are destined to pass their lives. Now I sometimes wonder whether that current has not become too strong and whether there would be sufficient opportunity for a full life if the world were emptied of some of the useless things that give it spiritual significance; in other words, whether our conception of what is useful may not have become too narrow to be adequate to the roaming and capricious possibilities of the human spirit.

We may look at this question from two points of view: the scientific and the humanistic or spiritual. Let us take the scientific first. I recall a conversation which I had some years ago with Mr. George Eastman on the subject of us. Mr. Eastman, a wise and gentle far-seeing man, gifted with taste in music and art, had been saying to me that he meant to devote his vast fortune to the promotion of education in useful subjects. I ventured to ask him whom he regarded as the most useful worker in science in the world. He replied instantaneously: "Marconi." I surprised him by saying, "Whatever pleasure we



SCIENCE TECHNOLOGY MARKET

*DANCING CHEEK-
TO-CHEEK, BUT ON
THEIR OWN
RHYTHM (C.
FREEMAN, 1981)*

RESEARCH IMPACT

The dual frontier: Patented inventions and prior scientific advance

Mohammad Ahmadpoor^{1,2} and Benjamin F. Jones^{1,2,3*}

The extent to which scientific advances support marketplace inventions is largely unknown. We study 4.8 million U.S. patents and 32 million research articles to determine the minimum citation distance between patented inventions and prior scientific advances. We find that most cited research articles (80%) link forward to a future patent. Similarly, most patents (0%) link backward to a prior research article. Linked papers and patents typically stand 2 to 4 degrees distant from the other domain. Yet, advances directly along the patent-paper boundary are notably more impactful within their own domains. The distance metric further provides a typology of the fields, institutions, and individuals involved in science-to-technology linkages. Overall, the findings are consistent with theories that emphasize substantial and fruitful connections between patenting and prior scientific inquiry.

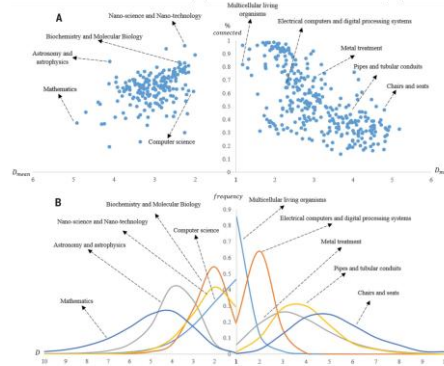


Fig. 2. Application to fields. (A) Distance metric. The mean distance, D_{mean} , to the paper-patent boundary is presented for each field (x-axis) together with the percentage of knowledge outputs in that field that are connected to the integrated citation network (y-axis). (B) The full D distribution for several fields.

TECHNICAL CHANGE AND THE AGGREGATE PRODUCTION FUNCTION*

Robert M. Solow

IN this day of rationally designed econometric studies and super-input-output tables, it takes something more than the usual "willing suspension of disbelief" to talk seriously of the aggregate production function. But the aggregate production function is only a little less legitimate a concept than, say, the aggregate consumption function, and for some kinds of long-run macro-models it is almost as indispensable as the latter is for the short-run. As long as we insist on practicing macro-economics we shall need aggregate relationships.

Even so, there would hardly be any justification for returning to this old-fashioned topic if I had no novelty to suggest. The new wrinkle I want to describe is an elementary way of segregating variations in output per head due to technical change from those due to changes in the availability of capital per head. Naturally, every additional bit of information has its price. In this case the price consists of one new required time series, the share of labor or property in total income, and one new assumption, that factors are paid their marginal products. Since the former is probably more respectable than the other data I shall use, and since the latter is an assumption often made, the price may not be unreasonably high.

Before going on, let me be explicit that I would not try to justify what follows by calling on fancy theorems on aggregation and index numbers.¹ Either this kind of aggregate economics appeals or it doesn't. Personally, I belong to both schools. If it does, I think one can

* I use a debt of gratitude to Dr. Louis Lefler for original and other assistance, and to Professor Fisher, Leonard, and Solida for stimulating questions. ¹Men. Robinson in particular has ordered many of the problems considered "all right in the way of giving one peace meaning to the quantity of capital" (The Production Function and the Theory of Capital, *Review of Economic Studies*, Vol. 11, No. 1), and I have thrown up still further obstacles (ibid., Vol. 21, No. 2). Were the data available, it would be better to apply the results to some precisely defined production function with many precisely defined inputs. One can at least hope that the aggregate analysis gives some notion of the way a detailed analysis would lead.

[317]

draw some crude but useful conclusions from the results.

Theoretical Basis

I will first explain what I have in mind mathematically and then give a diagrammatic exposition. In this case the mathematics seems simpler. If Q represents output and K and L represent capital and labor inputs in "physical" units, then the aggregate production function can be written as:

$$Q = F(K, L, t). \quad (1)$$

The variable t for time appears in F to allow for technical change. It will be seen that I am using the phrase "technical change" as a shorthand expression for any kind of shift in the production function. Thus slowdowns, speed-ups, improvements in the education of the labor force, and all sorts of things will appear as "technical change."

It is convenient to begin with the special case of neutral technical change. Shifts in the production function are defined as neutral if they leave marginal rates of substitution untouched but simply increase or decrease the output attainable from given inputs. In that case the production function takes the special form

$$Q = A(t)F(K, L) \quad (1a)$$

and the multiplicative factor $A(t)$ measures the cumulated effect of shifts over time. Differentiate (1a) totally with respect to time and divide by Q and one obtains

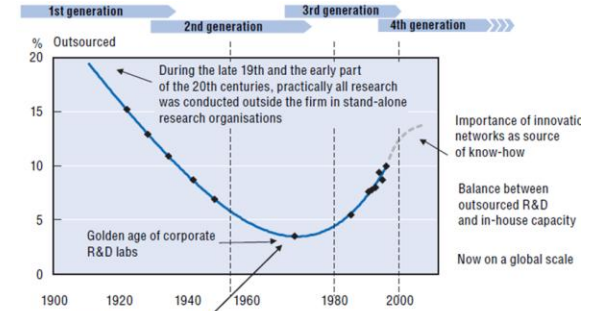
$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + \alpha \frac{\partial Q}{\partial K} \frac{\dot{K}}{K} + \beta \frac{\partial Q}{\partial L} \frac{\dot{L}}{L} \quad (2)$$

where dots indicate time derivatives. Now define

$$w_1 = \frac{\partial Q}{\partial K} \frac{K}{Q} \quad \text{and} \quad w_2 = \frac{\partial Q}{\partial L} \frac{L}{Q}$$

the relative shares of capital and labor, and substitute in the above equation (note that $\partial Q / \partial K = A \partial F / \partial K$, etc.) and there results:

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + w_1 \frac{\dot{K}}{K} + w_2 \frac{\dot{L}}{L} \quad (2')$$



"Roughly 3% of research is bought outside the firm" - EIRMA study

source: European Commission (2005a).

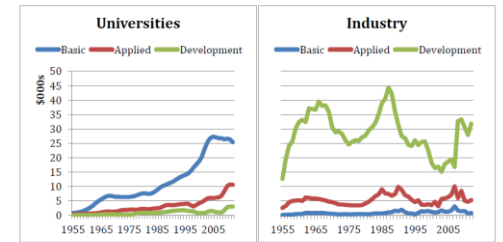


Figure 2. Character of federal research spending. All amounts in \$M, expressed in 2015 dollars. (Data from the American Association for the Advancement of Science.)

THE DEEP RESEARCH SPECTRUM (SOURCE: LSE, DYEUVRE, 2024), IMPACT OF “DEEP SCIENCE” ON INTRODUCTION OF NEW USPC PATENT CLASSES

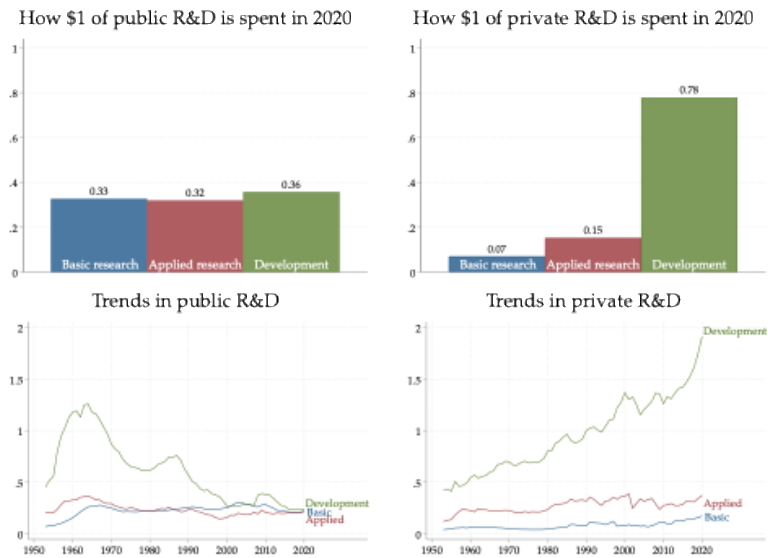


TABLE A.10. How public R&D differs from private R&D and trends over time

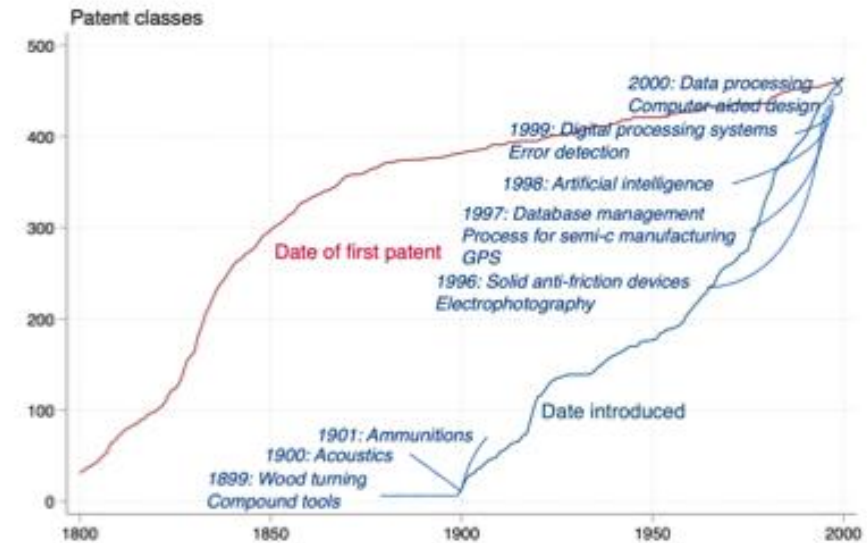


FIGURE 14. Timeline of the introduction of new USPC patent classes

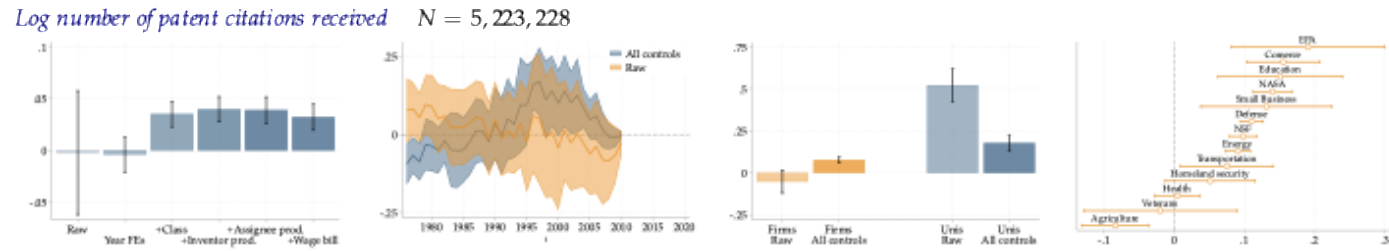
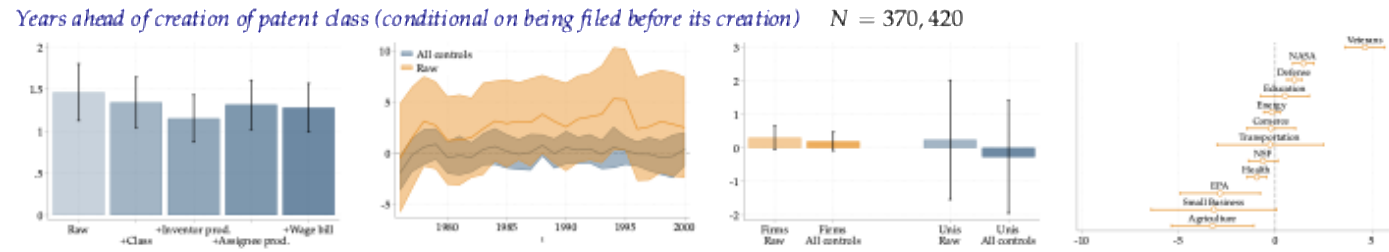
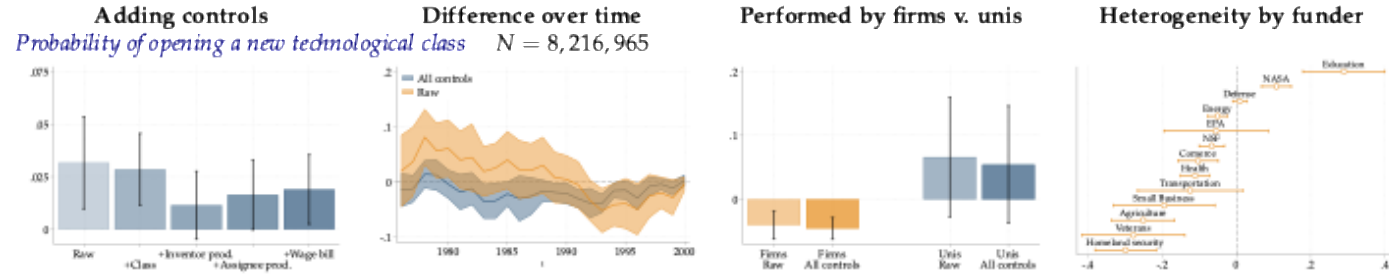


TABLE C.13. Fact 2 – Publicly-funded patents are more impactful (all results)

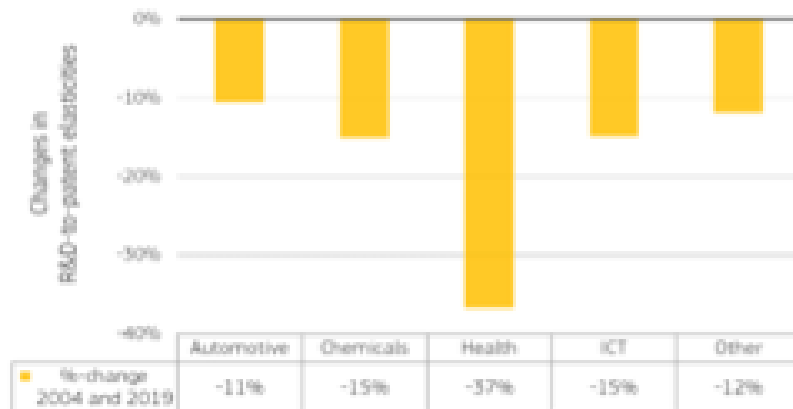
Notes: The unit of analysis is a patent. Coefficients and 95% confidence intervals come from a regression of an outcome of interest (y_i) on a dummy equal to one if the innovation protected by the patent benefited from public funding. Formally: $y_i = \alpha + \beta \times 1[\text{patent } i \text{ is publicly-funded}] + X_i\gamma + \varepsilon_i$. Standard errors are clustered at the class and year levels. Graphs in the first column show how β varies when successively more exhaustive arrays of controls are used. Graphs in the second column report β coefficients for different years. Graphs in the third column show how the β coefficient varies within performers of R&D: universities or firms. The last graphs report coefficient heterogeneity across R&D funders.

IMPACT OF PATENTS RESULTING FROM PUBLICLY FUNDED “DEEP SCIENCE”, FUNDAMENTAL SCIENCE

EUROPEAN R&D PRODUCTIVITY DECLINES, FIRM-LEVEL CHALLENGES >< CHINESE DARK FACTORIES



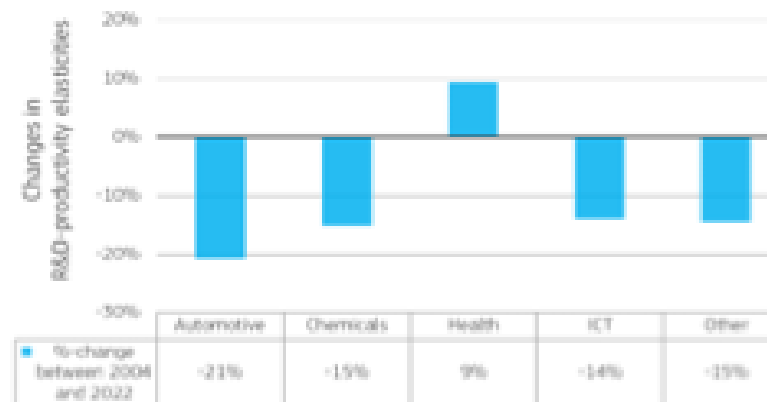
Figure 2 – Estimated total decline in R&D–patent elasticity across sectors, 2004–2019 (*) (%)



(*) The first observation from China is from 2008 instead of 2004 because of data availability.

Source: EU Industrial R&D Investment Scoreboard.

Figure 3 – Estimated total decline in R&D–labour-productivity elasticity across sectors, 2004–2022 (*) (%)



(*) The first observation from China is from 2008 instead of 2004 because of data availability.

Source: EU Industrial R&D Investment Scoreboard.

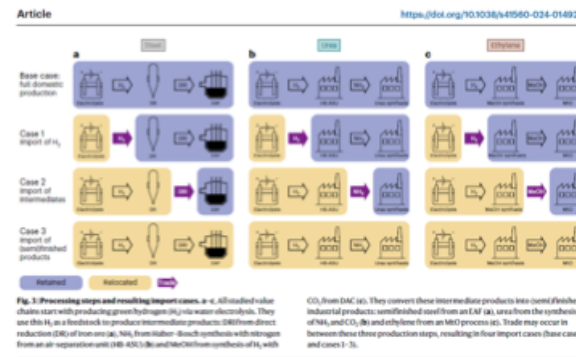


R&D productivity: Are ideas harder to find or does Europe suffer from a commercialisation gap?

R&D productivity in terms of patents has been falling globally, but most strongly in the United States and the EU. Coupled with the EU's persistent weakness in transforming its R&D into commercially successful product innovations, as the estimated R&D–labour-productivity elasticities show, that seems to warrant urgent policy action to bring the EU back on a growth path that secures its long-term global competitiveness.

RECONFIGURING EUROPEAN CHEMISTRY-ENERGY VALUE CHAINS?

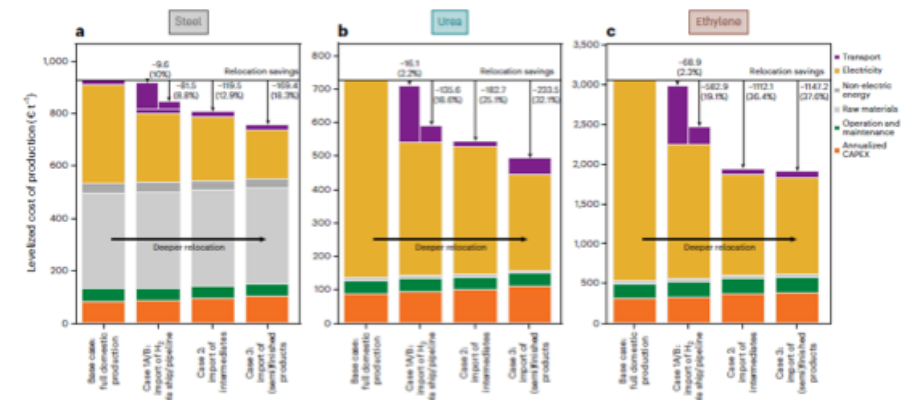
Shipping of intermediates (e.g. ammonia, methanol and reduced iron ore) from 'renewable rich' areas to 'renewable poor' areas may be cheaper than shipping H₂



‘Conserving today’s production patterns by shipping hydrogen is substantially costlier, whereas trading intermediate products could save costs while keeping substantial value creation in renewable-scarce importing regions.’



Verpoort, P.C., L. Gast, A. Hofmann and F. Ueckerdt, 2024. Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. *Nature Energy*, 9, 491–503



assumes a higher WACC of 8% in the RE-rich region compared to 5% in the RE-scarce region over a lifetime of 18 years, resulting in higher levelized capital cost, yet this effect appears to be small compared to the renewables pull. For a detailed composition, we encourage readers to view this figure in the online webapp or download the accompanying spreadsheet file (see ‘Data availability’).

MATERIALS AS THE ABSOLUTE PRIORITY IN TRANSITION ECONOMICS

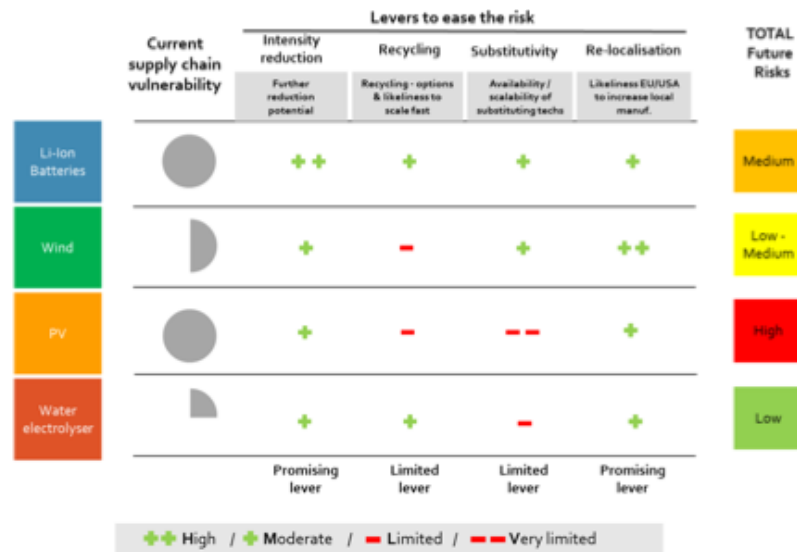
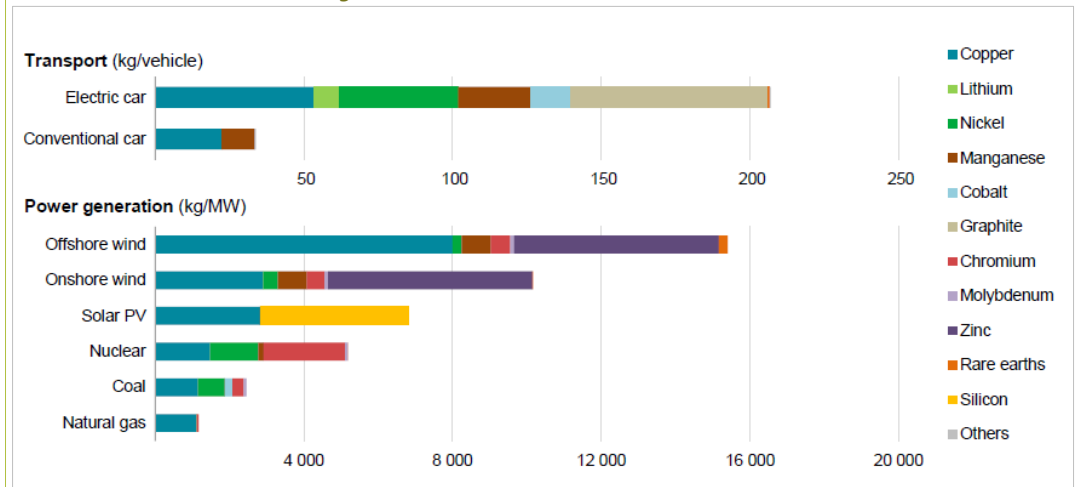


Fig. 3 Qualitative estimation of the current CRM supply chain vulnerability and the effect that the four mitigation levers could have on reducing it for the four clean energy technologies considered in this

study: (i) Li-ion batteries for large-scale electricity storage, (ii) wind turbines, (iii) silicon-based PV and (iv) water electrolysis

Materials used in selected technologies



subatomic particle, can convert into an electron without extra particles being formed. Once construction is complete, the Fermilab team will have to spend time tuning up the magnets. Data collection is expected to begin in 2027.

Trump's second year

The shockwaves from US President Donald Trump's return to office will continue in 2026. His first year brought sweeping policy changes that will continue to affect US science this year. Battles between the White House and the Congress over cuts to science funding look set to rumble on. Changes to public-health policy that have drawn criticism from researchers – including rolling back vaccine

recommendations, promoting unproven medical claims, cuts to international aid and reduced participation in global health schemes – will have broad consequences, and the country's climate policy could be watered down.

US universities must grapple with immigration restrictions that could limit the movement of international students and scientists. Institutions will deal with continued court battles over terminated federal grants and jobs.

The Trump administration has moved to refocus national research priorities on AI and quantum technologies. Although some researchers welcome this, others are concerned that it will draw resources away from other fields.

The results reflect a drastic reversal. At the beginning of this century, the United States led more than 90% of the assessed technologies, whereas China led less than 5% of them, according to the 2024 edition of the tracker.

"China has made incredible progress on science and technology that is reflected in research and development, as well as in publications," says Ilaria Mazzocco, who researches China's industrial policy at the Center for Strategic and International Studies, a non-profit research organization in Washington DC.

Mazzocco says the general trend identified by the ASPI is not a surprise, but it is "remarkable" to see that China is so dominant and advanced in so many fields compared with the United States.

This might have something to do with the types of technology that are tracked, says Wang Yanbo, a science-policy researcher at the University of Hong Kong. The country is more likely to be a research leader in new technologies, where it has focused its efforts, than in established fields, such as semiconductor chips, where other countries lead, he notes.

Tracking high-impact research

The ASPI team based its analysis on a database that contains more than nine million publications from all around the world. It ranked nations in each technology by identifying the top 10% of the most-cited papers produced by researchers in a country over a five-year period, between 2020 and 2024, and calculated that country's global share.

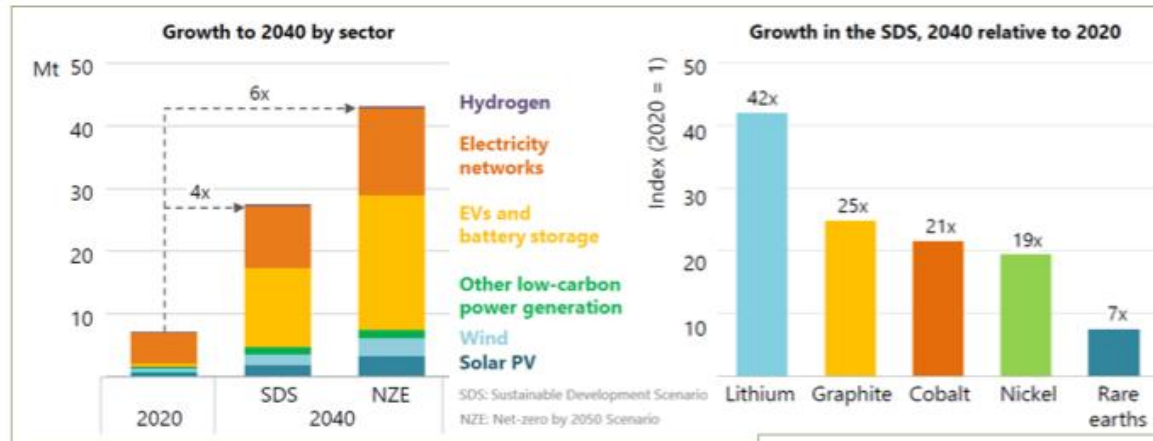
One noteworthy finding is that China is outpacing the United States in cloud and edge computing, according to David Lin, a national security and technology strategist at the Special Competitive Studies Project, a non-profit organization based in Arlington, Virginia. Cloud computing enables artificial-intelligence companies to train models and process data without the need for physical infrastructure, whereas edge computing processes data locally. China's research intensity in these fields "probably reflects the urgency with which Beijing is moving AI from the lab into deployment", Lin says.

The analysis should not be interpreted as "a collapse of American power", says Steven Hai, a political economist focusing on technology innovation at Xi'an Jiaotong-Liverpool University in Suzhou, China. In general, the United States is still an important player globally in these technologies, Hai says.

Jenny Wong-Leung, a data scientist at ASPI who participated in the study, warns that the findings show democratic nations risk losing "hard-won, long-term advantages in cutting-edge science and research" in a range of essential sectors, which is crucial for the development and advancement of the world's most important technologies.

Although the ASPI's tracker is good for

The transition to a climate-neutral world relies on critical minerals



Source: IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021.



China produces the largest share of high-quality research for 66 technologies.

CHINA LEADS RESEARCH IN 90% OF CRUCIAL TECHNOLOGIES

The United States tops the remaining areas in an assessment of 74 technologies.

By Xiaoying You

China is leading research in nearly 90% of the crucial technologies that "significantly enhance, or pose risks to, a country's national interests", according to a technology tracker run by the Australian Strategic Policy Institute (ASPI) – an independent think tank.

The ASPI's Critical Technology Tracker evaluated high-quality research on 74 current and emerging technologies in 2025, up from the 64 technologies it analysed in 2024. China is ranked number one for research on 66 of the technologies, including nuclear energy, synthetic biology and small satellites, and the United States topped the remaining 8, including quantum computing and geoen지니어링.



More than 300 new mines required to meet battery demand by 2035

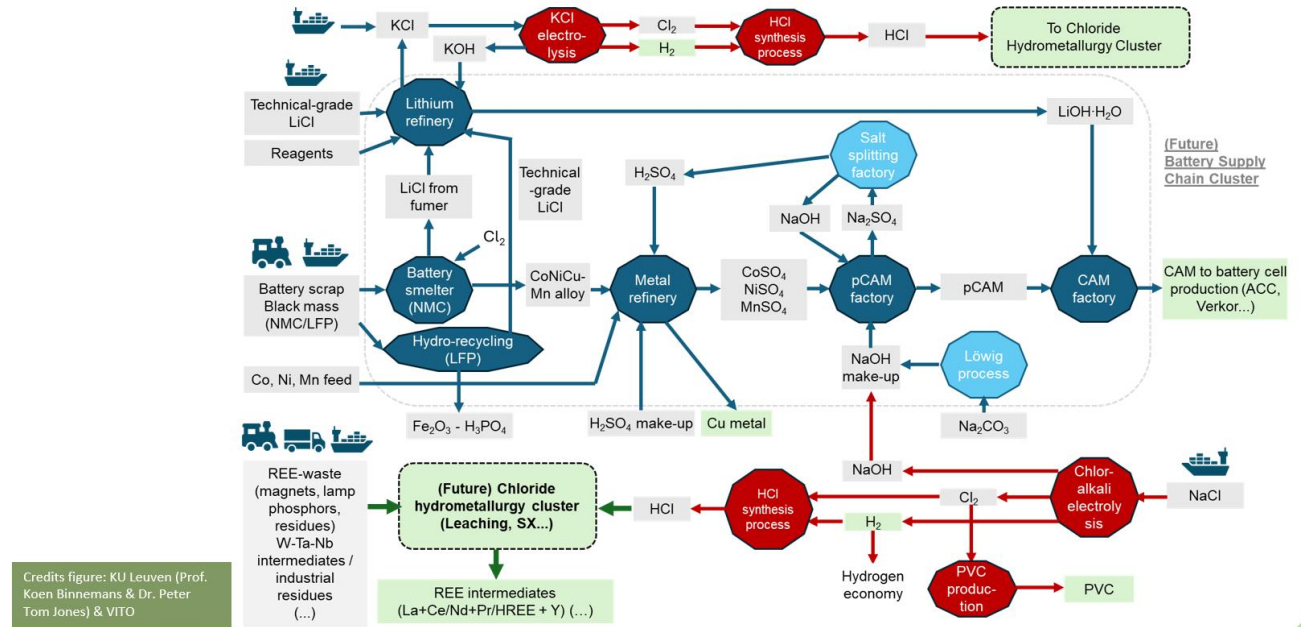


Source: Benchmark Minerals

AN ECONOMIC TRIAD:

*CHEMISTRY
&
ENERGY
&
MATERIALS*

The importance of industrial symbiosis – A Leitbild/vision for a (future) CRM Hub



Credits figure: KU Leuven (Prof. Koen Binnemans & Dr. Peter Tom Jones) & VITO



BUT ... CULTURE EATS STRATEGY FOR BREAKFAST (P. DRUCKER)

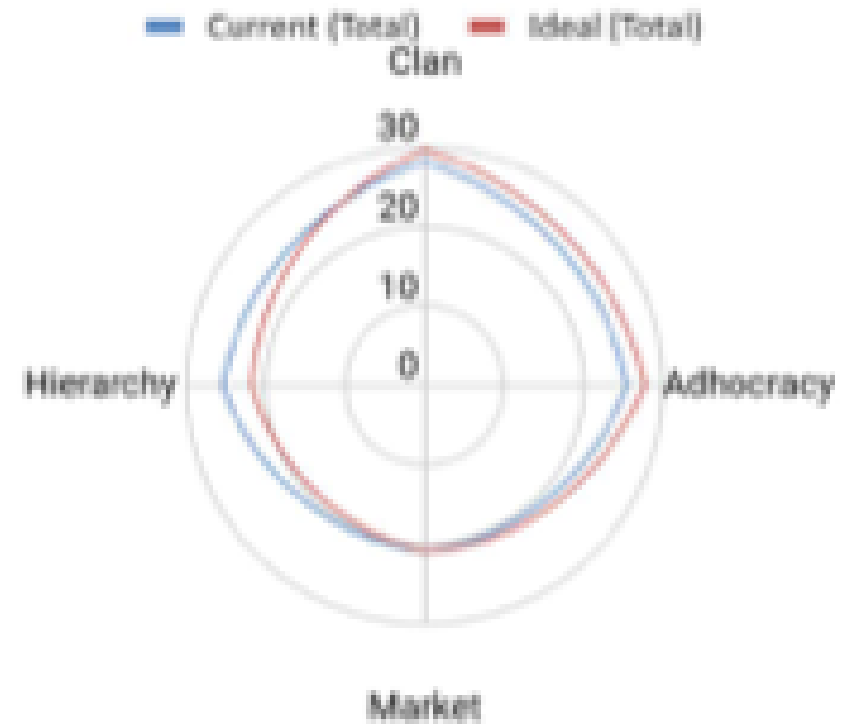
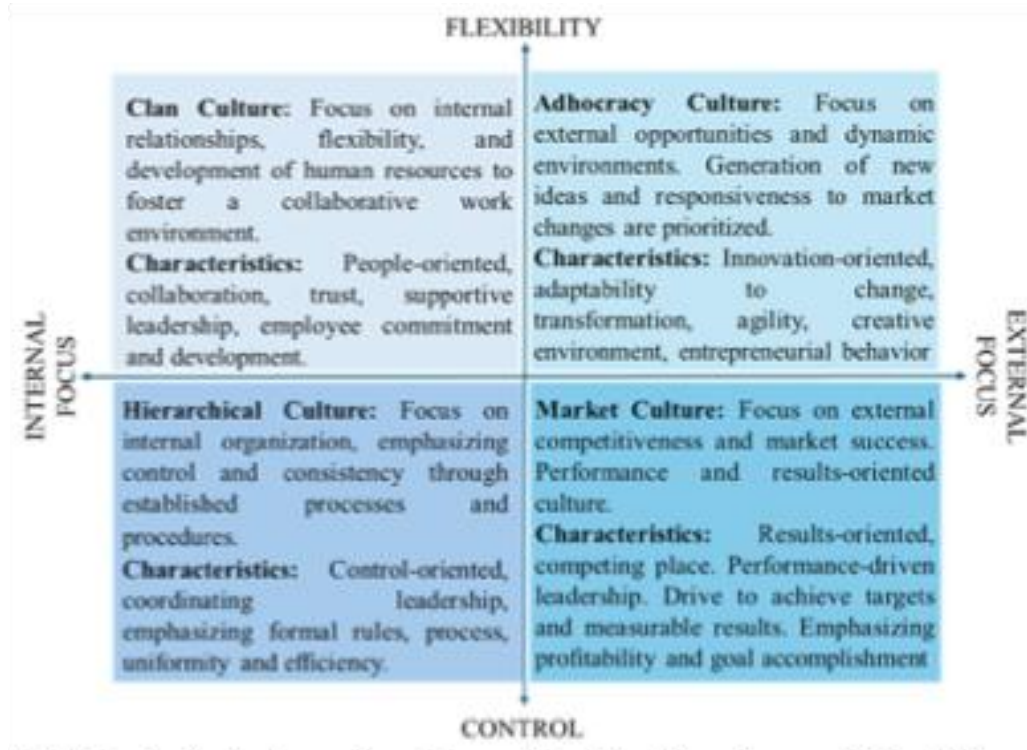


Fig. 1. Organizational culture profiles and characteristics (Adapted from Cameron and Quinn, 2006)

BREAKTHROUGHS ARE ROOTED IN DEEP SCIENCE



KU LEUVEN

Metals for Clean Energy:
Pathways to solving Europe's raw materials challenge

27

Here in the newsroom at *MIT Technology Review*, reporters and editors constantly debate which emerging technologies will drive progress or incite the most change—define our future. Once a year, we take stock and share some educated guesses with our readers. Here are 10 advances that we think will drive progress or incite the most change—for better or worse—in the years ahead.

Hyperscale AI data centers	Sodium-ion batteries	Base-edited babies	Mechanistic interpretability	Next-gen nuclear
Embryo scoring	AI companions	Gene resurrection	Generative coding	Commercial space stations

10 Breakthrough Technologies

NEWS | IN DEPTH

Check for updates

IBNL's fully automated A-Lab can churn out new materials 24/7 without human intervention.

heads IBNL's Materials Project and announced the new A-Lab.

Previous automation efforts randomly mixed compounds in search of new materials, Ceder says, but the new AI-driven approach is more akin to the way traditional chemists do their jobs. The AI starts by coming up with a plausible way to synthesize a material, using its understanding of chemistry. It guides robotic arms to select among nearly 200 different powdery starting materials, containing elements such as lithium, nickel, copper, iron, and manganese. After mixing the precursors, another robot parcels out the mix into a set of crucibles, which are loaded into furnaces where they can be mixed with gases such as nitrogen, oxygen, and hydrogen. The AI then determines how long to bake the different mixes, the temperatures, drying times, and so on.

After the baking, a gumball-like dispenser adds a ball bearing to each crucible and shakes it to grind the new substance into a fine powder that's loaded onto a slide. A robot arm then grabs each sample and slides it into an x-ray machine or other equipment for analysis. Results are fed back into the Materials Project database of materials structures and properties, and if the outcome isn't what was predicted, the AI setup iterates the reaction conditions and starts anew.

IBNL researchers have spent the past several months working out the kinks in their system and testing it. In the process, the A-Lab has produced more than 40 target materials—about 70% of the compounds it has set out to produce. "I have made more new compounds in the last 6 weeks than my whole career," Ceder says.

IBNL's AI materials lab may not be alone for long. In a 3 April preprint, researchers from the Samsung Advanced Institute of Technology reported that they, too, have set up a computer-driven robotics lab to search for new electronic materials. Results from that report show their setup performed more than 200 reactions to make 35 inorganic compounds, including certain oxides commonly used in battery electrodes, solid oxide fuel cells, and superconductors. In each stage of their robotic experiments "AI is used to some degree," says Samsung's Jeong-Ju Cho.

Ceder notes that despite the move to fully automated synthesis and analysis, researchers are just as likely as ever to make unexpected discoveries. "That's no different with the A-Lab." Except now, the hits and the surprises will likely come faster. ■

MATERIALS SCIENCE

AI-driven robotics lab joins the hunt for materials breakthroughs

Setup is the first fully automated effort seeking novel inorganic materials for emerging technologies

By Robert F. Service, in San Francisco

Imagine a cookbook with 150,000 tempting dishes—but few recipes for making them. That's the challenge facing an effort at the Lawrence Berkeley National Laboratory (LBNL) known as the Materials Project. It has used computers to predict some 150,000 new materials that could improve devices such as battery electrodes and catalysts. But the database's users around the globe have managed to make just a fraction of those for testing, leaving thousands omitted. "Synthesis has become the bottleneck," says Gerbrand Ceder, a materials scientist at LBNL.

Now, Ceder and his colleagues have married artificial intelligence (AI) and robotics to eliminate that bottleneck. The AI system makes a best guess at a recipe for a desired material and then iterates the reaction conditions as robots try to create physical samples. The new setup, known as the A-Lab, is already synthesizing about 100 times more new materials per day than humans in the lab can manage. "This is the way to go," says

Ali Coskun, a chemist at the University of Freiburg who isn't involved with the A-Lab, but attended the Materials Research Society meeting here last week, where the new AI approach was announced.

AI-driven robotics labs are becoming commonplace among pharmaceutical companies searching for new drugs and even some academic materials labs (Science, 13 December 2019, p. 1095). But these efforts primarily use liquid precursor compounds that are relatively straightforward to mix and process. "It's a lot more difficult to do this with solid materials," Coskun says. Synthesizing these materials typically requires mixing solid powders together and then adding different combinations of solvents, and experimenting with heat, drying time, and other inputs to try to get them to crystallize into the predicted material.

The number of recipes is essentially infinite, Ceder says. Although computers can predict which final compounds should lead to better devices, "there is no theory for synthesis that tells us what can and cannot be made," says Kristin Persson, who

THANK YOU

Koenraad Debackere, KU Leuven

May 21nd, 2026

Materinex Annual Event, Antwerp