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A study of energy in transition

The role of research and innovation in the world's shift to sustainable energy sources

Author biographies

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Ed is a thought leader in innovation measurement and forecasting, and is the head author of the Top 100 Global Innovators™ and Top 100 Best Protected Global Brands programs from Clarivate. A twenty-year veteran of Clarivate and its forebears, Ed has a technical background in electronic engineering, instrumentation and particle/plasma devices.
Ed has spent most of his career developing new methods of analyzing innovation ecosystems and advised hundreds of corporations, institutions and governments with technology data investigations.

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Mihnea has a decade of experience in the field of intellectual property. He has a background in business economics having studied at the Solvay Brussels School of Economics and Management and is a data scientist by training. Mihnea is the data guru behind programs such as the Top 100 Global Innovators and Top 100 Best Protected Global Brands from Clarivate. Mihnea has a track record in delivering data and analytics products that help both corporations and governments accelerate innovation and change the future.

A study of energy in transition

At Clarivate, we are passionate about championing sustainable advancement. We've woven sustainability into everything we do and it is fundamental to every decision we make.

We know that in order to drive measurable business and societal impact, we need to embrace a holistic approach and we are constantly looking at new and meaningful opportunities for our data, intelligence and experts to make a positive impact on the world's sustainability efforts.

This study is part of our contribution towards the UN Sustainable Development Goal 9: Industry, Innovation and Infrastructure. It looks at the relationship between global research and innovation in the roll out and development of sustainable energy sources. It identifies current gaps, trends and needs of further research concentration, while looking at where capabilities lie, by sustainable energy source and geography.

Throughout this report, we harnessed our resources to deliver an analysis of the role of research and innovation in the world's shift to sustainable energy sources, providing valuable insight to policy makers, corporations, funders and the world's scientists.

Governments, business, research organizations and public bodies need to work together to find technical and creative solutions to the crisis – and they need to do so rapidly.

One of the challenges facing us as a society is to fully understand the scale and context of the problem across different research areas and industries using data. It is only through accurate data that we can fully comprehend and start to tackle the challenges in a meaningful way.

Data must be selective, structured, rigorously maintained and updated, and used in a compatible way with other data sets of similar quality in order to allow us to extract the right insights.

The time between an original discovery, published in a scientific journal, and the application of the technology in the real world, is approximately 12-17 years. Sometimes one discovery will influence multiple technologies; often you find they are applied in many products across industries. Our data has been curated on the same basis for over 40 years – that's what allows us to spot new trends, new networks and to understand how the landscape has changed.

It is only through better understanding of our efforts to date through data and intelligence that we can help propel progress.

Together with our colleagues, customers and partners, we look forward to playing a critical role in driving real change and enabling meaningful progress in the world's journey to a sustainable future.

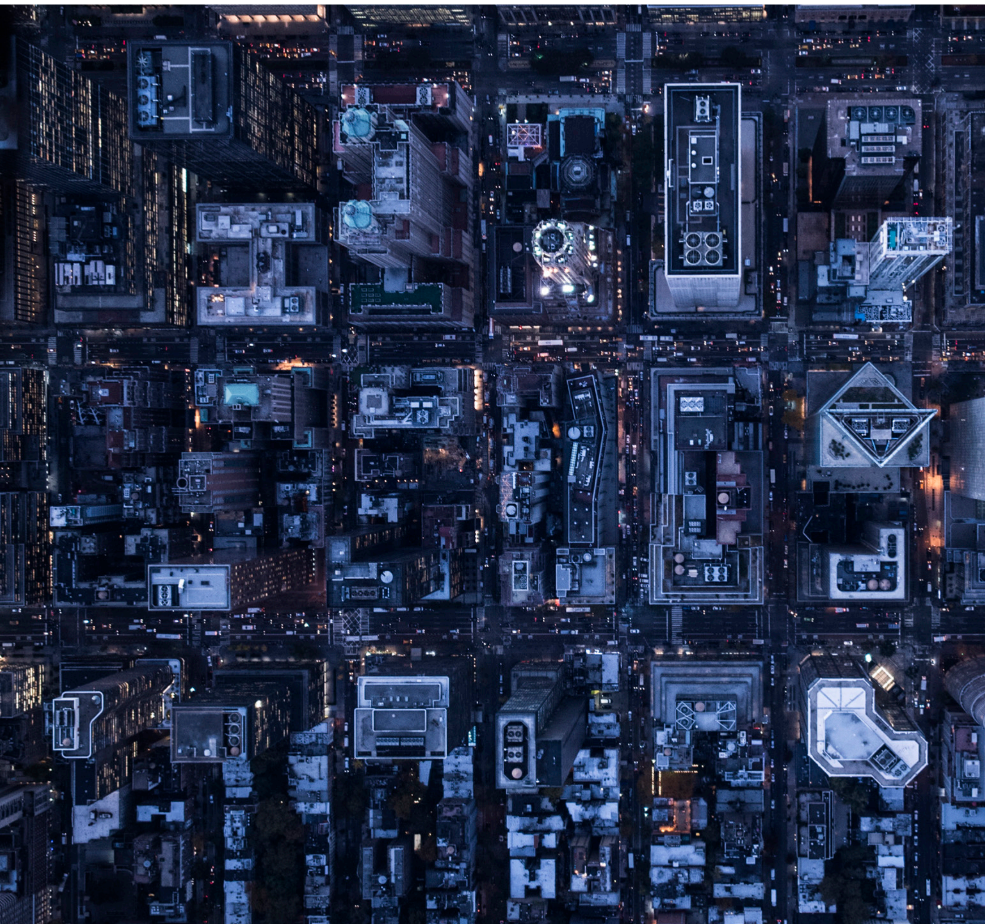
Tiffani Shaw
Chief of Staff and Sustainability Sponsor, Office of the CEO, Clarivate

Contents

Setting the scene for sustainable energy sources

It took a global public health crisis to bring about an encouraging drop in carbon emissions in 2020 but as economies and societies sprung back to life, so too have global energy consumption and carbon emissions levels.

Governments around the world shored up their economies with fiscal and stimulus packages to remarkable effect and global economic growth rebounded in 2021, expanding by 6%.[1] However, so did CO_2 emissions by a similar percentage,[2] setting the world back in the goal to decrease emissions by 45% by 2030. We are once more marching towards an unsustainable future, the goal of net zero by 2050 hanging in the balance and the world's transition to sustainable, renewable energy not progressing fast enough, despite the use of renewable energy posting its biggest increase to date in 2021.[3]



The imperative for sustainable energy sources is clear. Scientists agree that a third of the projected world population could face un-livable conditions by 2070, if the current rate of global warming persists. Indeed, significantly reducing emission levels could halve the number of people exposed to such living conditions.[4] If the world is to have any chance of achieving net zero by the middle of this century and securing a livable earth, efforts to implement sustainable energy need to be accelerated – and it needs to happen now.

The challenge facing policy makers, scientists and engineers is to match ambition with tangible action – and balance the environmental, economic and practical imperative for accelerating the uptake and eventual full transition to sustainable energy sources. Indeed, solar and wind plants are cheaper to build and run today compared to fossil fuel power plants.[5] How can sustainable, renewable energy sources such as solar photovoltaic, wind power and green hydrogen be implemented so that they address modern society's energy needs and leverage and integrate with existing energy grids?

Governments are under pressure to juggle competing demands, from delivering continued economic recovery and providing support to populations and businesses in the face of soaring energy prices, to implementing a sustainable transformation of their economies. Renewable energy sources could play a big role as they are inherently local, unlike their fossil fuel counterparts, and therefore cheaper and more energy secure. The recently passed Inflation Reduction Act (IRA) in the United States is one such example of legislation aimed at addressing cost of living pressures and tackling the climate agenda. The IRA includes $370 billion in climate and sustainable energy provisions including tax credits and increased funding and focus to accelerate research and development of clean technologies and sustainable energy.[6]

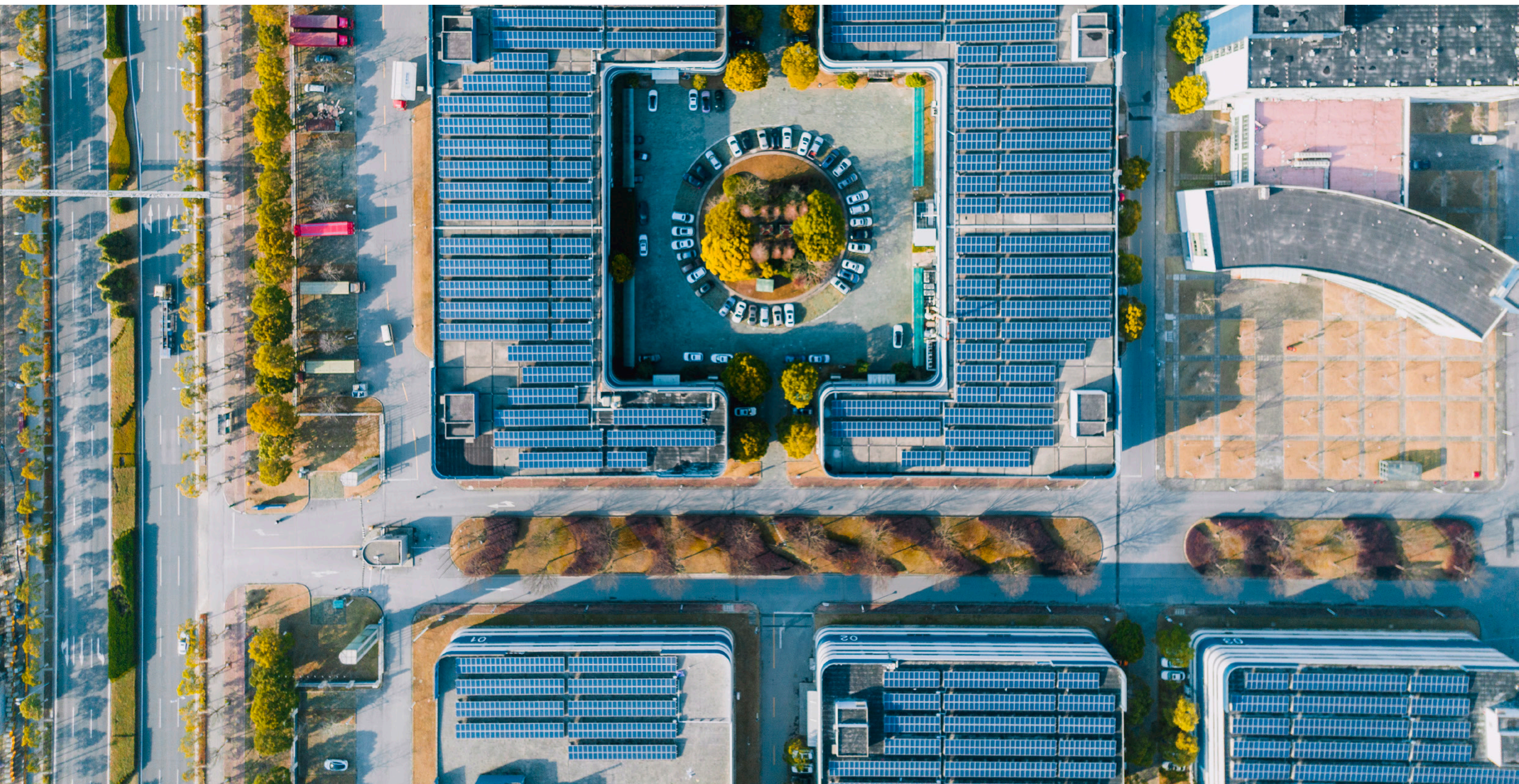
Sustainability, however, has an inherent information gap – between the ambition of governments and corporations and the concrete actions undertaken. The ecosystem of capital investment for renewable energy needs information on not just desire and ambition, but measures of actual outcome and capability.

This study looks at the relationship between global research and innovation in the roll out and development of sustainable energy sources, and identifies current gaps, trends and needs of further research concentration. It also looks at where capabilities lie, by sustainable energy source and geography.

We do so by collating and curating rigorous data surrounding global research and innovation, bringing together the deep content of our Web of Science™ publisher independent global citation database, the Derwent World Patent Index™ (DWPI™), our curated source of global patent data, the Derwent Patents Citation Index™ and Darts-ip™ global IP case data to assess research and invention holistically.

In doing so, we aim to create a modern-day 'great library,' one that creates a store of the current scientific and engineering knowledge of humanity, but structuring it for interrogation by funders, governments, corporations and researchers themselves. So that they may better understand the state of the current research and innovation ecosystem, as well as its likely future shape not just for sustainable energy sources, but indeed any sector.

Click here to view the full methodology.



Overview of the state of scientific research and inventive activity for renewable energy sources

Curiosity. Ingenuity. Discovery.

Scientists the world over have asked questions, made new discoveries and created new knowledge that have contributed to the advancement of society. Hence many nations invest significantly in fundamental scientific research, through agencies such as the National Science Foundation in the U.S., the Federal Ministry of Education and Research in Germany and the National Research Foundation of Korea. Recognizing the value of basic research, corporates and philanthropic organizations are increasingly supporting basic science funding.[7] In fact, "much of what we take for granted today is a result of an interplay of fundamental science and technology, with each driving the other forward," said Nobel Prize-winner Sir Venki Ramakrishnan.[8]

This interplay is very much at play in the renewable energy space. The assumption of an expected lag, from the more fundamental research inherent to the scientific peer review publication process, and the more applied and commercial technology development that is intrinsic to patent protection is apparent in sustainable energy research and innovation, with a lag of approximately 10 years between overall inflexion point to fast development growth.

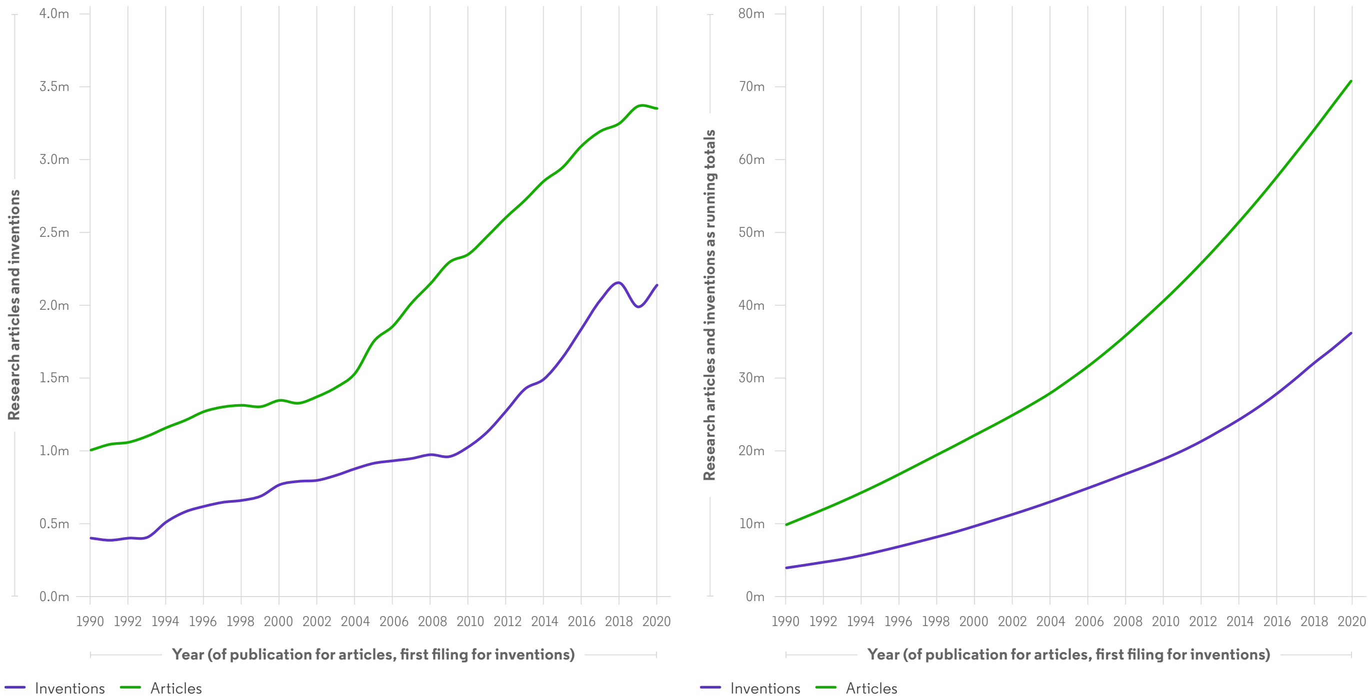
"Much of what we take for granted today is a result of an interplay of fundamental science and technology, with each driving the other forward."

Sir Venki Ramakrishnan, Nobel Prize-winner

Figure 1: Global research and innovation, 1990 to 2020

Global research and innovation, per year
Research articles and inventions* per year, 1990 to 2020

Global research and innovation, running total per year
Number of research articles and inventions* per year, 1990 to 2020, as running totals



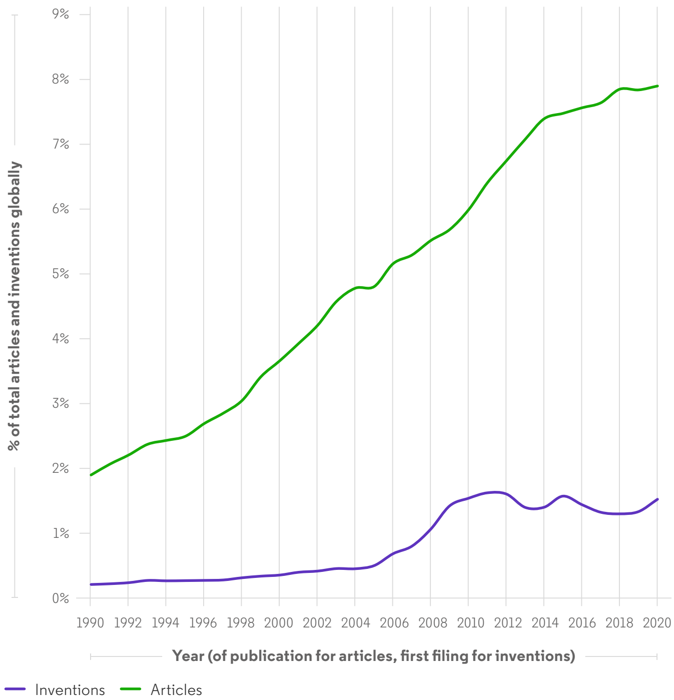
*Excluding utility model patent filings. Source: Web of Science, DWPI

In absolute numbers, and as a proportion of global research, innovation activity in the sustainable energy space is tailing off.

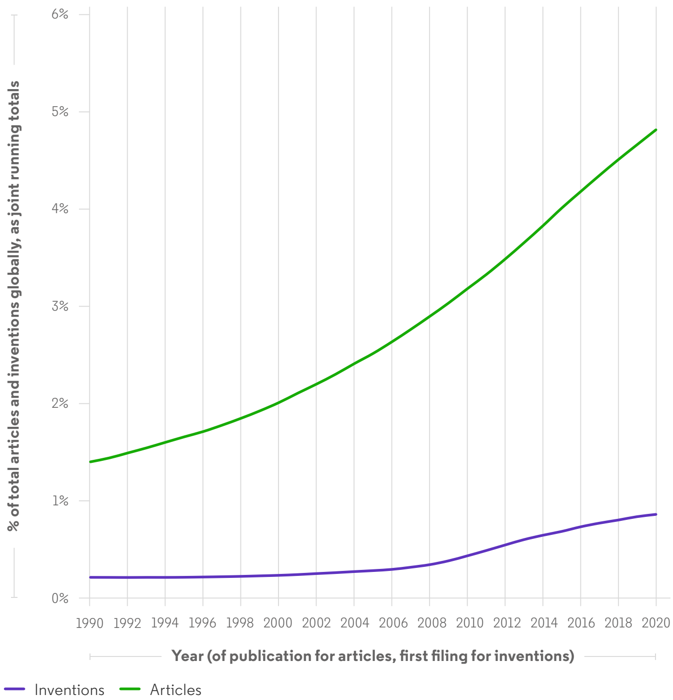
Both foundational and enabling research and direct patent output surrounding sustainable energy appear to show approaches to completed development curves – normally implying they are nearing completion (Figure 2). This finding is based on data normalized for overall increases in scientific journal and patent output increases globally in all subject areas.

Figure 2: Renewable energy research as a share of global research and innovation, 1990 to 2020

Renewable energy research, as share of global research and innovation, per year
Number of renewable energy research articles and inventions* per year, 1990 to 2020, as % of total articles and inventions globally



Renewable energy research, as share of global research and innovation, running total per year
Number of renewable energy research articles and inventions* per year, 1990 to 2020, as % of total articles and inventions globally, as joint running totals



*Excluding utility model patent filings. Source: Web of Science, DWPI

EU Sustainable Finance Taxonomy

In order to deliver on the European Green Deal's policy objectives, the European Commission unveiled an updated sustainable finance strategy. For this study, we used the EU Sustainable Finance Taxonomy, a series of categories put in place so that a definition of what is, and is not, sustainable can be decided. Within this taxonomy, there are eight topics for sustainable power generation which this study focuses on:

- **Solar photovoltaic**
- **Concentrated solar**
- **Wind**
- **Oceanic**
- **Hydroelectric**
- **Geothermal**
- **Bioenergy**
- **Renewable gas or liquid fuels**

Figure 3: Mainland China and U.S. share of national inventions and national scientific articles, 2008 to 2020

United States and Mainland China renewable energy inventions, as share of national inventions per year
Number of renewable energy inventions* per year, 2008 to 2020, as % of total inventions in country/region

United States and Mainland China renewable energy research base, as share of national articles per year
Number of renewable energy scientific articles per year, 2008 to 2020, as % of total articles with first author in country/region

*Excluding utility model patent filings. Source: Web of Science, DWPI

Mainland China leads the way in research and innovation activity for renewable energy sources.

Undercutting this trend is the continued strength and direction of Mainland China research and innovation output for renewable energy. The quantity and quality of the country's scientific research output continues to increase (Figure 3), its patent portfolio strengthening as evidenced by the country consistently improving its inventive strength. However, patent activity for renewable energy in Mainland China is not keeping pace with overall Mainland Chinese patent activity which is accelerating.[9] This supports our finding that research and innovation activity in the sustainable energy space is tailing off.

The U.S., on the other hand, is in decline in real terms with renewable energy patent activity, while its research base in that space is stagnating. We will dive deeper into and compare the capabilities of the G20 nations later in this report.

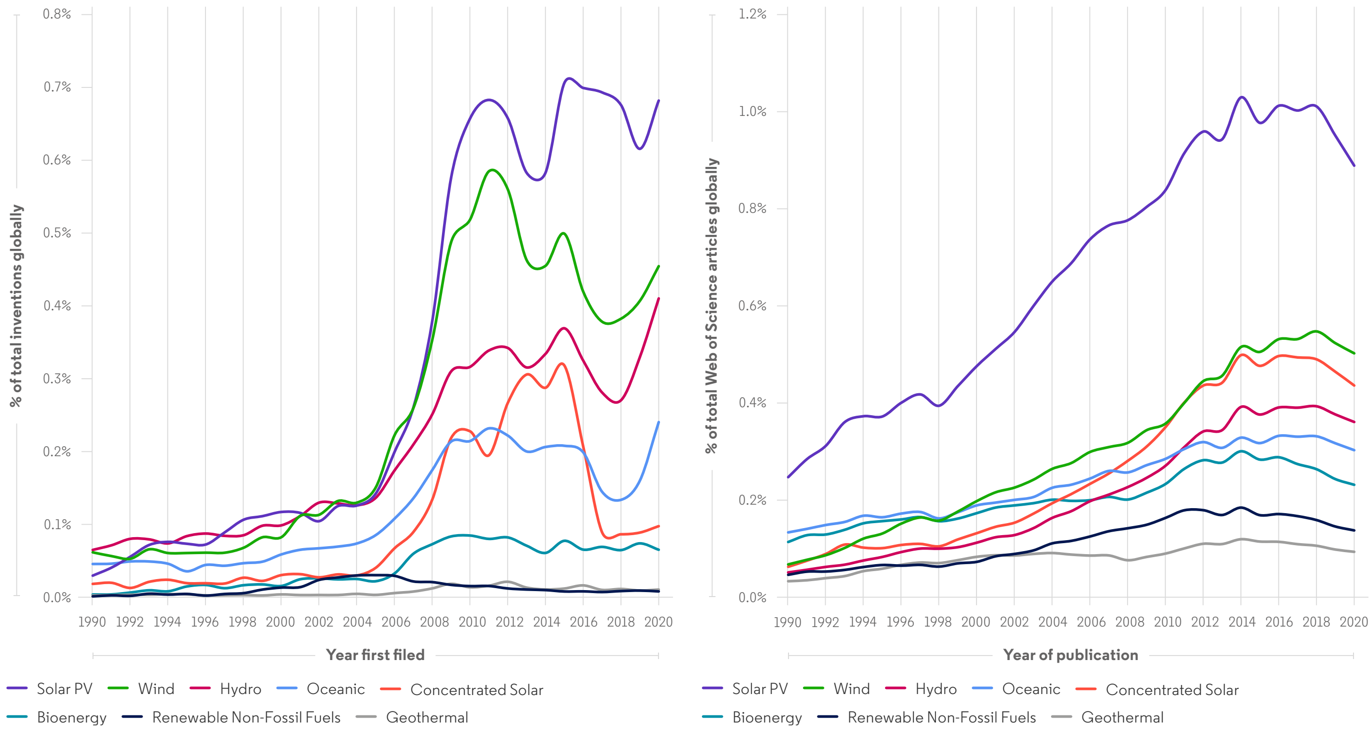
As we scrutinize how activity within the different renewable energy sources is evolving, a more nuanced picture emerges. Research and innovation in the sustainable energy space may be tailing off, but this does not extend equally to all renewable energy sources. When we look at the eight renewable energy sources based on the EU Sustainable Finance taxonomy, we see that photovoltaic solar energy generation is the area of highest focus, followed by wind energy production – in both inventive activity and research foundation (Figure 4). Both demonstrate stagnation in annual research output, indicating development curve completion.

Hydropower presents an interesting conundrum. While its level of research and innovation activity ranks below solar photovoltaic and wind power, hydropower is the biggest renewable energy contributor, double the contribution from all other

Figure 4: Renewable energy inventive activity and research base of supporting scientific articles, 1990 to 2020

Renewable energy inventions, as share of global innovation, by EU Sustainable Finance Taxonomy energy source
Numbers of renewable energy inventions per year, 1990 to 2020, as % of total inventions* globally, by energy category

Renewable energy research base scientific articles, as share of global research, by EU Sustainable Finance Taxonomy energy source
Number of renewable energy supporting articles research base per year, 1990 to 2020, as % of total Web of Science articles glo



*Excluding utility model patent filings. Source: Web of Science, DWPI

48GW

of new hydropower capacity needs to be added every year between 2020 and 2030.

renewables[10] and has a key role to play in the Net Zero Emissions Scenario by the IEA. An average of 48GW of new hydropower capacity needs to be added every year between 2020 and 2030. However, a new consideration in expanding and building new hydropower capacity is the need for stringent sustainability standards – for both current hydropower plants and new projects as experts agree that the climate impact of hydro plants was previously underestimated and must be minimized.[11] In some countries such as the U.S., a challenging licensing and permitting process is expected to limit hydropower growth. Indeed, many existing hydropower plants in the U.S. are approaching re-licensing stage.[12] The IEA believes that "without major policy changes, global hydropower expansion is expected to slow down this decade."[13]

At the other end of the scale, renewable non-fossil fuels, which include green hydrogen, have experienced among the lowest level of inventive and foundational research activity to date. With the EU's recently announced REPowerEU Plan, featuring an additional €200 million investment in developing and implementing clean hydrogen across the union,[14] will actions match ambition and propel green hydrogen to become a more widely adopted renewable energy source?

Without major policy changes, global hydropower expansion is expected to slow down this decade.

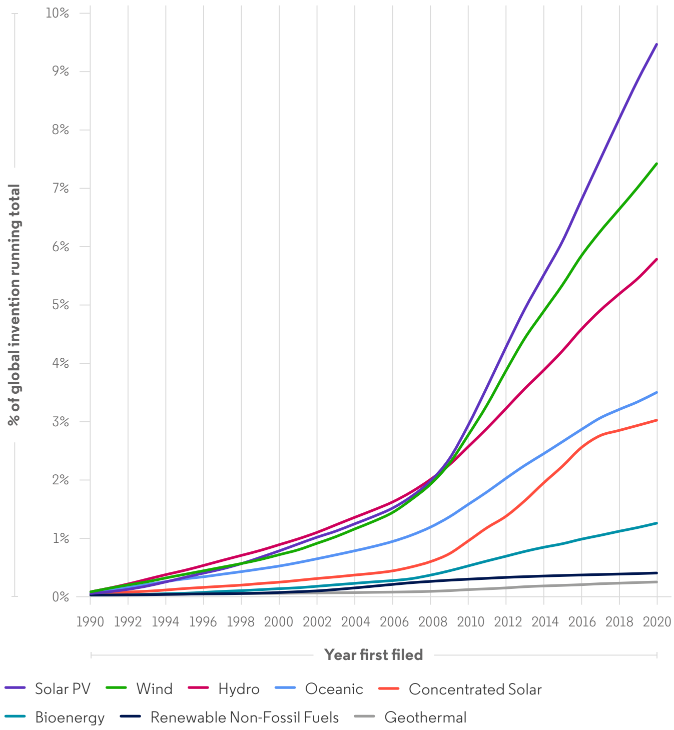
Key findings and trends

Finding: Solar photovoltaic and wind power approaching technical completion; complex issues pertaining to solar voltaic and wind power technologies broadly resolved by the world's scientists

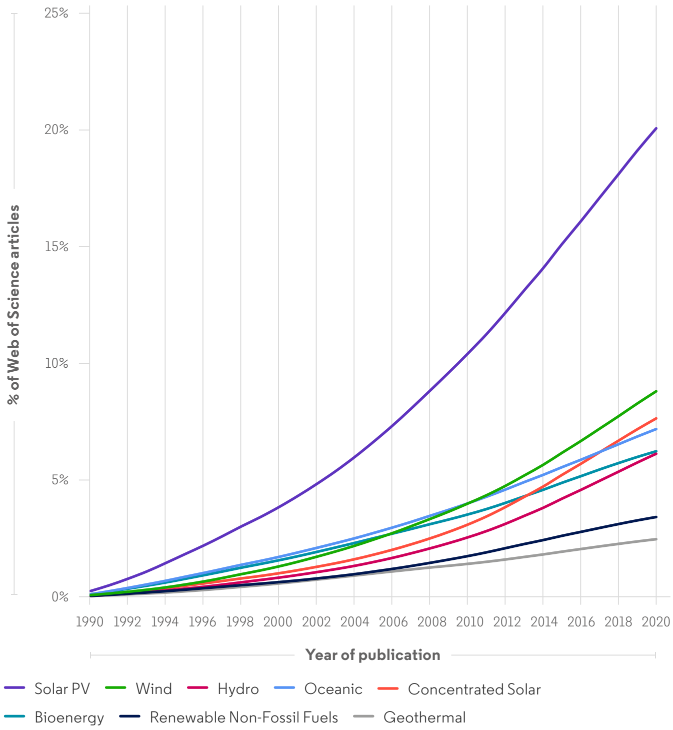
In our study of the research base versus technology output for renewable energy, another notable finding is that the second inflexion point appears to have already occurred in the sustainable energy invention s-curve for solar photovoltaic and wind power, indicating a general movement towards technical completion (Figure 5). This effect is associated with a decoupling of the trend within the supporting research base – one implication being a new development curve has begun in academic research that is yet to be emulated in patent activity.

Figure 5: Renewable energy inventions and supporting scientific articles development curves, as a share of global innovation and as a share of global research, 1990 to 2020

Renewable energy inventions development curves, as share of global innovation, by EU Sustainable Finance Taxonomy energy source
Running total of renewable energy inventions per year, 1990 to 2020, as % of global invention* running total, by energy category



Renewable energy research base scientific articles development curves, as share of global research, by EU Sustainable Finance Taxonomy energy source
Running total of renewable energy supporting articles per year, 1990 to 2020, as % of Web of Science articl



*Excluding utility model patent filings. Source: Web of Science, DWPI

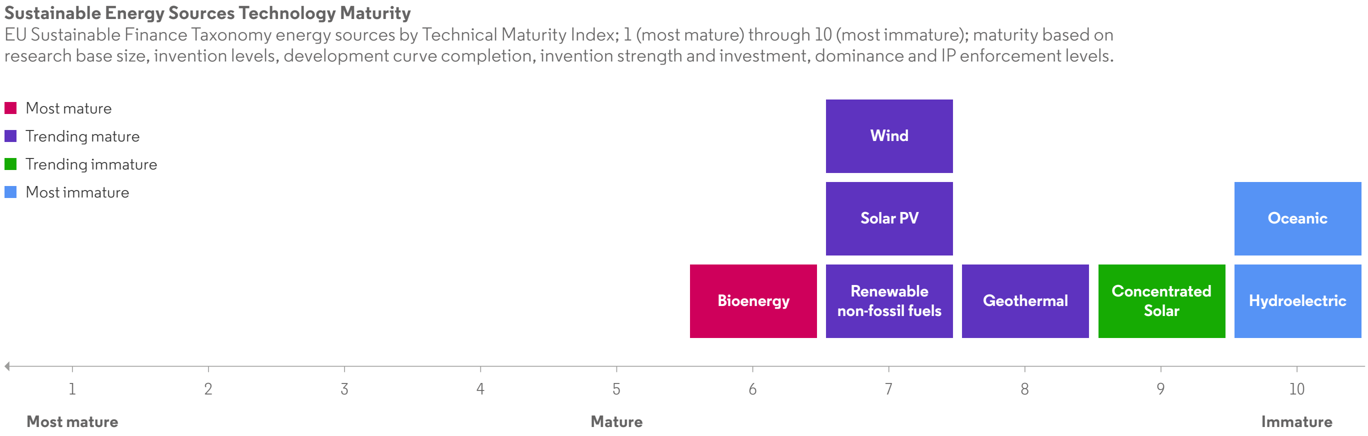
Hydroelectric is the only outlier. Perhaps this should not come as a surprise as hydroelectric is considered 'old' technology compared to the other renewable energy sources. The current method of harnessing hydropower to generate alternating current electricity can be traced back to an alternating current hydropower plant in California in 1893.[15]

In order to better understand the level of maturity within each sustainable energy source, we used data from scientific papers, patents and assertion/contention of patents to map the level of academic research volume to corporate inventive activity and commercialization indicators. The result – a model that indexes technology maturity and reveals the categories of renewable energy sources that have likely reached technology maturity (Figure 6). Our sustainable energy sources technology maturity index supports our thesis that solar photovoltaic, wind, renewable non-fossil fuels and bioenergy are mature technologies.

Oceanic power generation currently falls within the immature scale of the index but is on the cusp of innovation. Oceanic power, with its high energy density, is seen as one of the most promising sustainable energy sources if fully harnessed. For instance, the waves off the U.S coasts could deliver almost two thirds of the country's annual electricity needs.[16]

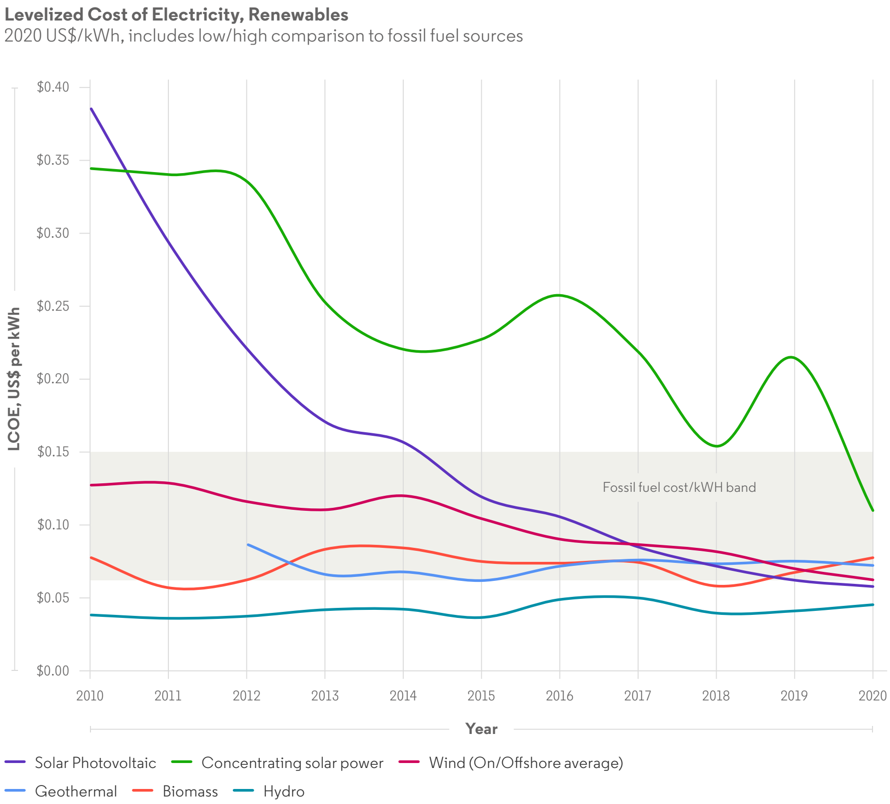
Policy makers are looking to tap into the potential of oceanic power, with several countries introducing policies to encourage greater research and development. For example, the Australian government passed an Offshore Electricity Infrastructure Bill[17] in 2021 to support state and national planning for developing ocean energy projects. The United Kingdom ranks among the leaders in developing oceanic renewable energy, with active projects in England, Wales and Scotland. Wave Energy Scotland for instance, aims to "produce reliable technology which will result in cost effective wave energy generation" and has invested over £48m million and funded 120 contracts since the body was set up in 2014.[18]

Figure 6: A model of sustainable energy sources technology maturity



Source: Web of Science, DWPI, Derwent Patents Citation Index, Darts-ip

Figure 7: Levelized cost of electricity, renewables



Source: IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi

Indeed, while solar photovoltaic and wind have seen the greatest volume of research and inventive activity in the past three decades, activity is tailing off. Coupled with our findings from the technology maturity model, this appears to point to solar photovoltaic and wind approaching development maturity, where the most complex technological issues and challenges have been solved. In fact, the levelized cost of renewable energy is comparable or lower, for some renewable categories, than that of fossil fuel electricity (Figure 7).

Notably, there is a strong correlation between the pace of technical development for sustainable energy sources and the levelized cost of electricity – as the technology approaches maturity, the corresponding drop in the levelized cost of electricity decelerates.

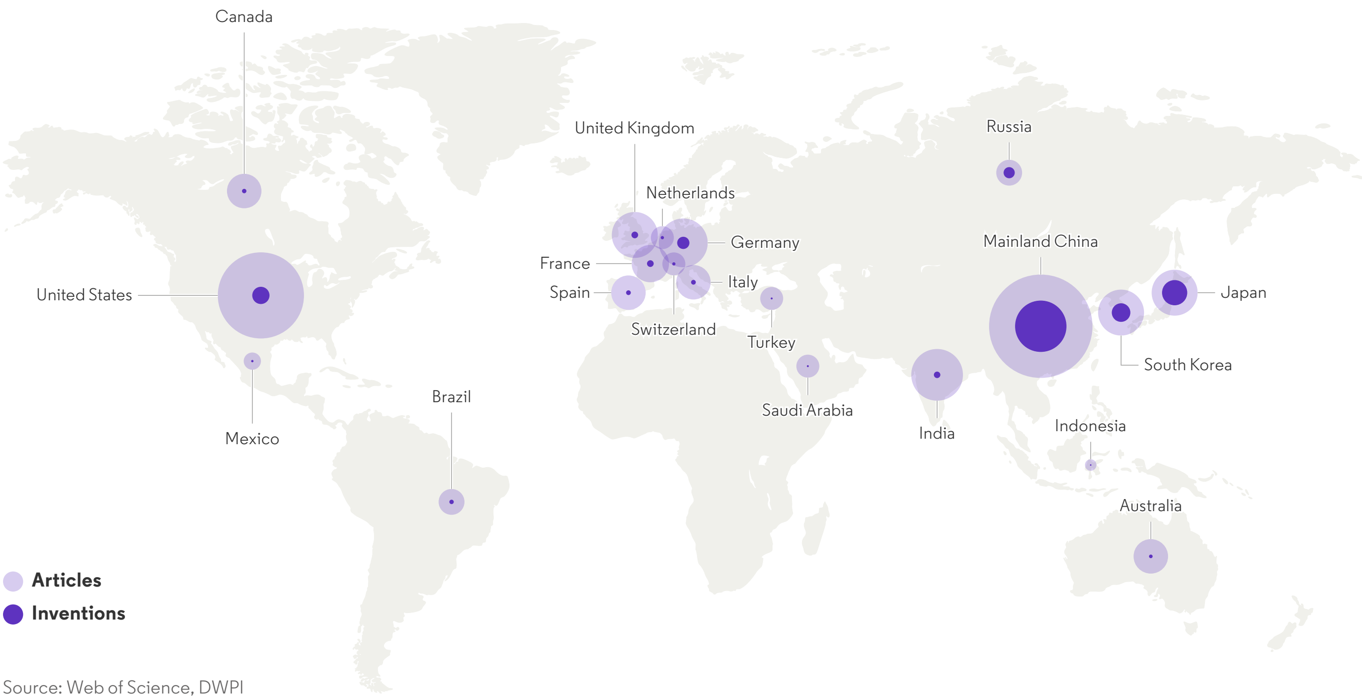
Finding: Mainland China tops global research and innovation output in renewable energy sources; South Korea, Japan and India among nations that see greatest increase in impact rank

Mainland China and the U.S., two powerhouses of research and innovation globally, are closely matched in terms of cumulative scientific research output for renewable energy sources. However, cumulative inventive activity for renewable energy sources in Mainland China far exceeds that of the U.S. (Figure 8).

In terms of both scientific research and innovation impact, the U.S.'s rank has steadily fallen in recent years. While the U.S. numbers among the top five in inventive strength (Figure 10), it does not figure among the top five for articles with the highest citation impact. Indeed, sustainable energy research and innovation activity in the western world, with the exception of Canada, is slowing down.

Figure 8: Cumulative sustainable energy research and innovation among G20 nations, 2008 to 2020

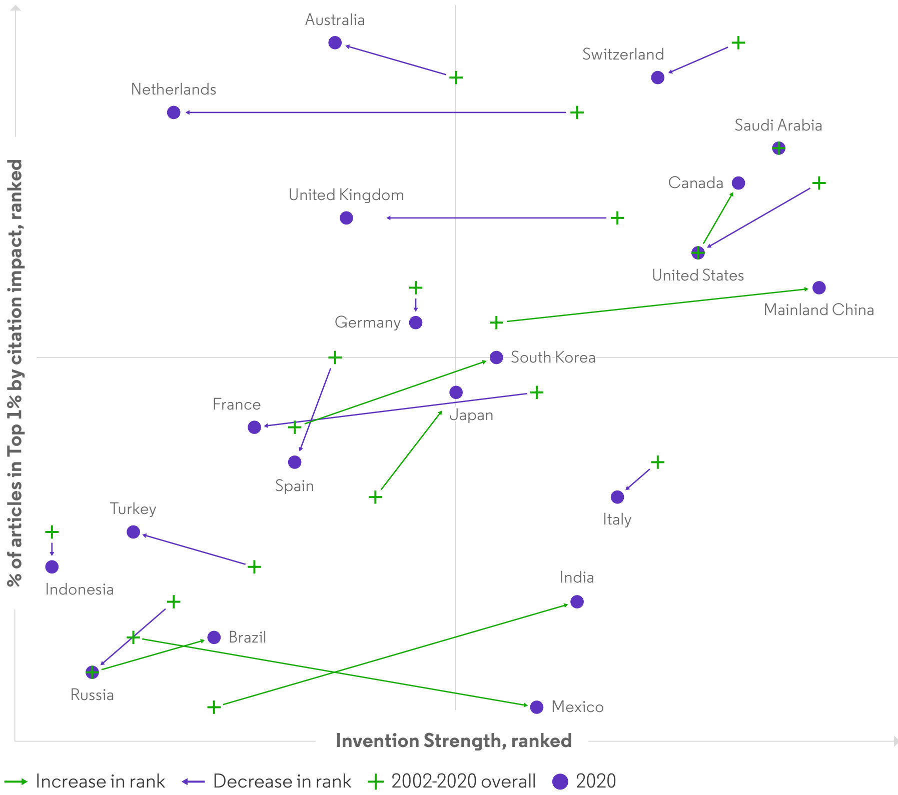
Sustainable energy research and innovation by geography
Geographic source (by inventor residence/country of first filing where residency information unavailable) and article organization location for G20 (plus Spain)



Source: Web of Science, DWPI

Figure 9: Sustainable energy research and innovation impact and quality delta

Sustainable energy research and innovation impact and quality delta
% of articles in Top 1% citation impact (2008+) and average invention strength, both axes ranked 1-20; G20 nations plus Spain, and excluding EU; plus position as of 2020 datasets



Source: Web of Science, DWPI, Derwent Patents Citation Index, Darts-ip

Mainland China, in contrast, continues to leap up the rankings, topping the inventive strength list and boasting the highest increase in the quality of its scientific articles. Mainland China's 14th five-year plan for the energy sector, released in 2021, underscored the importance of delivering larger-scale renewable energy development, with a target of reaching 1,200 gigawatts of renewable energy capacity by 2030. Mainland China's actions match its ambitions – the country added more offshore wind capacity last year than the rest of the world combined in the last five years, pushing the U.K., the previous leader for offshore wind capacity into second place;[19] the country also expects to boost its solar power capacity by up to 90 gigawatts in new capacity in 2022.[20]

Also in Asia, India has made great strides, with the highest increase in inventive strength (Figure 10). 2020 marked a turning point for India's renewable energy sector when bids for solar projects dropped to record lows. In the same year, India awarded more supply contracts for renewable power and more renewable power was delivered to the energy grid, all of which led to renewable energy becoming cheaper and rivalling fossil fuel electricity.[21] More recently, India plans to expand subsidies for domestic solar photovoltaic manufacturers as part of its strategy to reach net zero by 2070.[22]

As a result, solar has become the lowest-cost renewable energy source in India today, falling to INR 1.99 ($0.0269) per kilowatt-hour at the end of 2020.[23] Despite India's efforts to expand its solar capacity, it is falling behind the annual build rate it needs to achieve its target 300 gigawatts of solar capacity by the end of the decade.[24]

Figure 10: Sustainable energy research and innovation impact and quality metrics, G20 nations, 2008 to 2020

Inventions - average invention strength per country/region per year; ranked amongst the top 20 economies (1 - highest strength; 20 - lowest)

Country/Region	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Rank Δ 2008-10
Mainland China	7	**4**	**4**	8	8	10	9	8	8	7	7	7	**1**	+6
United States	**2**	**3**	**1**	**3**	**3**	**3**	**3**	**3**	**2**	**3**	**2**	**2**	**4**	**-2**
India	19	17	18	18	17	18	17	16	15	19	17	15	7	+12
Germany	9	11	11	12	10	12	10	9	10	11	11	14	11	-2
United Kingdom	10	6	7	7	7	7	**5**	**5**	6	8	**4**	**4**	12	-2
South Korea	15	14	15	14	15	14	14	13	12	15	14	16	9	+6
Japan	12	12	12	13	13	11	11	11	11	9	12	13	10	+2
France	8	8	**5**	10	9	**5**	7	10	9	**5**	8	8	15	-7
Italy	14	**1**	**3**	**4**	**4**	**4**	6	**2**	**1**	**4**	**5**	**5**	6	+8
Australia	11	9	9	9	11	8	12	12	**5**	13	13	10	13	-2
Spain	13	13	13	15	14	13	13	14	14	12	15	11	14	-1
Canada	**5**	7	6	6	**1**	9	**2**	**4**	7	6	9	6	**3**	+2
Russia	16	16	16	16	16	16	16	15	16	16	16	18	19	-3
Brazil	18	19	17	19	18	20	15	18	18	17	18	17	16	+2
Saudi Arabia	**3**	-	14	**1**	**2**	**1**	**1**	**1**	**3**	**1**	**1**	**3**	**2**	+1
Turkey	6	**2**	8	**2**	12	17	19	17	19	14	6	19	18	-12
Netherlands	**4**	10	**2**	11	6	**2**	**4**	7	13	10	**3**	12	17	-13
Switzerland	**1**	**5**	10	**5**	**5**	6	8	6	**4**	**2**	10	9	**5**	-4
Mexico	17	18	19	20	19	19	18	19	17	18	19	**1**	8	+9
Indonesia	20	15	20	17	20	15	20	20	20	20	20	20	-	-

Top 5 country /regions 2020
1. Mainland China
2. Saudi Arabia
3. Canada
4. United States
5. Switzerland

Highest perf. Increases
1. India
2. Mexico
3. Italy
4. Mainland China
5. South Korea

1st-5th

Articles - % of articles per country/region within Top 1% highest citation impact; ranked amongst the top 20 economies (1 - highest impact; 20 - lowest)

Country/Region	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Rank Δ 2008-10
Mainland China	16	16	12	13	12	11	11	9	9	9	8	9	8	+8
United States	**3**	**3**	**2**	**3**	**3**	**3**	**3**	**4**	6	**4**	**4**	**4**	7	-4
India	14	20	16	16	19	18	17	18	20	20	18	18	17	-3
Germany	8	6	8	9	8	8	9	7	8	7	9	8	9	-1
United Kingdom	**5**	**5**	**4**	**4**	**4**	**5**	**5**	6	**5**	**5**	6	7	6	-1
South Korea	17	17	15	14	13	13	13	10	11	11	11	10	10	+7
Japan	13	14	14	15	14	15	14	12	14	13	14	12	11	+2
France	9	8	10	12	10	9	12	13	13	10	12	13	12	-3
Italy	11	11	13	11	11	10	15	14	12	14	13	14	14	-3
Australia	**2**	**4**	**5**	**5**	**5**	**4**	6	**5**	**3**	**3**	**3**	**1**	**1**	+1
Spain	10	10	9	8	7	12	10	11	10	12	10	11	13	-3
Canada	6	7	6	7	9	6	8	8	7	8	7	6	5	+1
Russia	12	18	17	20	17	17	16	17	16	19	15	16	19	-7
Brazil	15	12	18	19	18	20	18	15	15	17	17	19	18	-3
Saudi Arabia	7	15	7	**2**	6	7	**1**	**1**	**2**	**1**	**2**	**5**	**4**	+3
Turkey	19	13	19	18	20	16	19	16	19	18	19	17	15	+4
Netherlands	**1**	**2**	**3**	10	**1**	**1**	**4**	**3**	**4**	6	**5**	**3**	**3**	-2
Switzerland	**4**	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	+2
Mexico	18	19	20	17	15	19	20	19	18	15	16	15	20	-2
Indonesia	20	9	11	6	16	14	7	20	17	16	20	20	16	+4

Top 5 country /regions 2020
1. Australia
2. Switzerland
3. Netherlands
4. Saudi Arabia
5. Canada

Highest perf. Increases
1. Mainland China
2. South Korea
3. Turkey
4. Indonesia
5. Saudi Arabia

1st-5th

Source: Web of Science, DWPI

Turning answers into application to accelerate the world's sustainable energy transition

Governments across the world are stepping up their renewable energy initiatives, setting ambitious targets and laying a clear path towards a net zero world. Some countries continue to make big strides forward, while for others, it is a case of a few steps forward followed by a step back.

Through this study, our research and data show that with existing renewable energy sources, the work of the world's scientists is largely complete. Humanity has access to sustainable energy technology that is fairly mature today. It is cheaper to generate electricity by solar or wind power than fossil fuels. Which begs the question – why isn't uptake of renewable electricity more widespread?

Consider the current landscape, where the world is experiencing an energy crisis with soaring gas prices. This has laid bare a fundamental issue with electricity pricing. Consumers are paying one price for electricity regardless of source. Governments are aware of the urgent need for reform in the power market globally, considering for instance, how energy prices could be de-coupled from energy sources such as gas. Greece has taken a step forward, with proposals to create two separate power markets, one for fossil fuel-generated electricity and another for cheaper electricity from renewable energy sources.[25]

De-coupling power prices could help to bridge the gap between technology availability and adoption for renewable energy sources, with consumers seeing and experiencing the full economic benefit of using renewable energy.

Furthermore, the data and analysis demonstrated in this study can be used to shed new light on other issues currently impeding renewable energy uptake – from how grid storage can be engineered for renewable energy power to re-thinking baseload power plants to incorporate renewable energy.

By accelerating renewable energy efforts, nations can take better control of their energy security. Countries with renewable energy infrastructures that substantially address their energy needs will be less vulnerable to volatile or escalating fossil fuel prices.

Policy makers face a watershed moment – taking the answers uncovered by the world's scientists and matching their sustainable energy ambitions with tangible action. What policy makers and the world need is rounded innovation intelligence.

Using a single data source provides only a partial picture of research and innovation. Academic and fundamental research is predominantly covered by scientific literature and journal articles while corporate research is primarily covered by patent activity. Simply stitching together data from two archives of information is not straightforward and requires significant data curation capability and interpretive expertise.

At Clarivate, we are committed to helping the world create, protect and advance innovation.

Our broad range of curated insights – from scientific and academic research to IP intelligence – and deep analytical expertise can help the world make sense of complex issues, such as the state of our world's transition to sustainable energy sources, providing answers for the way forward to a better, sustainable energy-powered future.

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Appendices

1. Choice of taxonomic framework and methodology

An inherent problem within any research and innovation data model is that of definition. Deciding upon how individual research outcome records should be categorized and measured is as varied as the questions that can be directed at the data. For this study, our primary source of technology definition has come from the European Union Sustainable Finance Taxonomy.[26]

The taxonomy, also known as the EU taxonomy for sustainable activities, is a series of categories put in place so that a definition of what is, and is not, sustainable can be decided. The full taxonomy includes several topics surrounding sustainability across such as habitat, environment and climate change.

Within the taxonomy, this study focuses on eight topics for sustainable power generation: solar (both concentrated/thermal and photovoltaic), wind, oceanic, hydroelectric, geothermal, bioenergy and renewable gas or liquid fuels, such as renewable hydrogen.

Emulation in research and innovation data sources

Direct, traditional patent searches were created for each of these eight topics to identify the patented inventions specific to these energy sources; those eight collections were then cross-pollinated into the research base via the activities of patent examiners, where during examination relevant research papers and articles were identified.

Tracking research pathways

Producing a 'seed' collection of background research underpinning the patent activity within the eight energy topics, we then used the citation and bibliographic links around the seed articles to create a wider collection of related peer research articles that reflects the wider scientific and engineering knowledge base supporting the innovation in the sustainable energy space.

Discussion of alternate and further innovation taxonomies

The EU Sustainable Finance Taxonomy extends much further than simply sustainable energy and indeed global invention data are traditionally well categorized into detailed technology, industry and research topics. The technique undertaken in this study is extensible to both the wider sustainable innovation question, i.e., the activities of research organizations and wider economies, as well as to other topics of interest within science and engineering.

2. Further background

For the first time, we harnessed the power of our industry-leading research, patent and patent enforcement data and used the following data sources for this study:

Web of Science: The Web of Science™ is the world's largest publisher-neutral citation index and research intelligence platform. It organizes the world's research information to enable academia, corporations, publishers and governments to accelerate the pace of research. With the Web of Science you can track the evolution of ideas across millions of records linked by billions of citations, all spanning 250+ research disciplines.

Derwent World Patents Index (DWPI): A database built around ideas, DWPI records where and when inventions are patented across 59 patent-issuing authorities. DWPI editors provide English-language summaries that clearly state the invention's intended use, application and novelty – for over 3.5m new inventions every year.

Derwent Patents Citation Index: The Derwent Patents Citation Index focuses on inventions that have been referenced by applicants and examiners in subsequent patent applications. Using the DWPI invention-level structure, the Derwent Patents Citation Index automatically removes double, triple (or more) counting of citation events between the same patented ideas.

Darts-ip: Global IP case data available through Darts-ip provides litigation intelligence that is indexed, available digitally and easily searchable. Darts-ip allows you to easily search over 8.9 million IP cases. Our team of experts collect, read and codify IP case data for trademarks, patents, designs and models, copyrights, domain names and unfair competition to extract unique intelligence and analytics.

With the volumetric increases in general research outcomes, in the form of scientific papers and patents, it is vital that trend information is normalized to wider research and innovation baseline expansion.

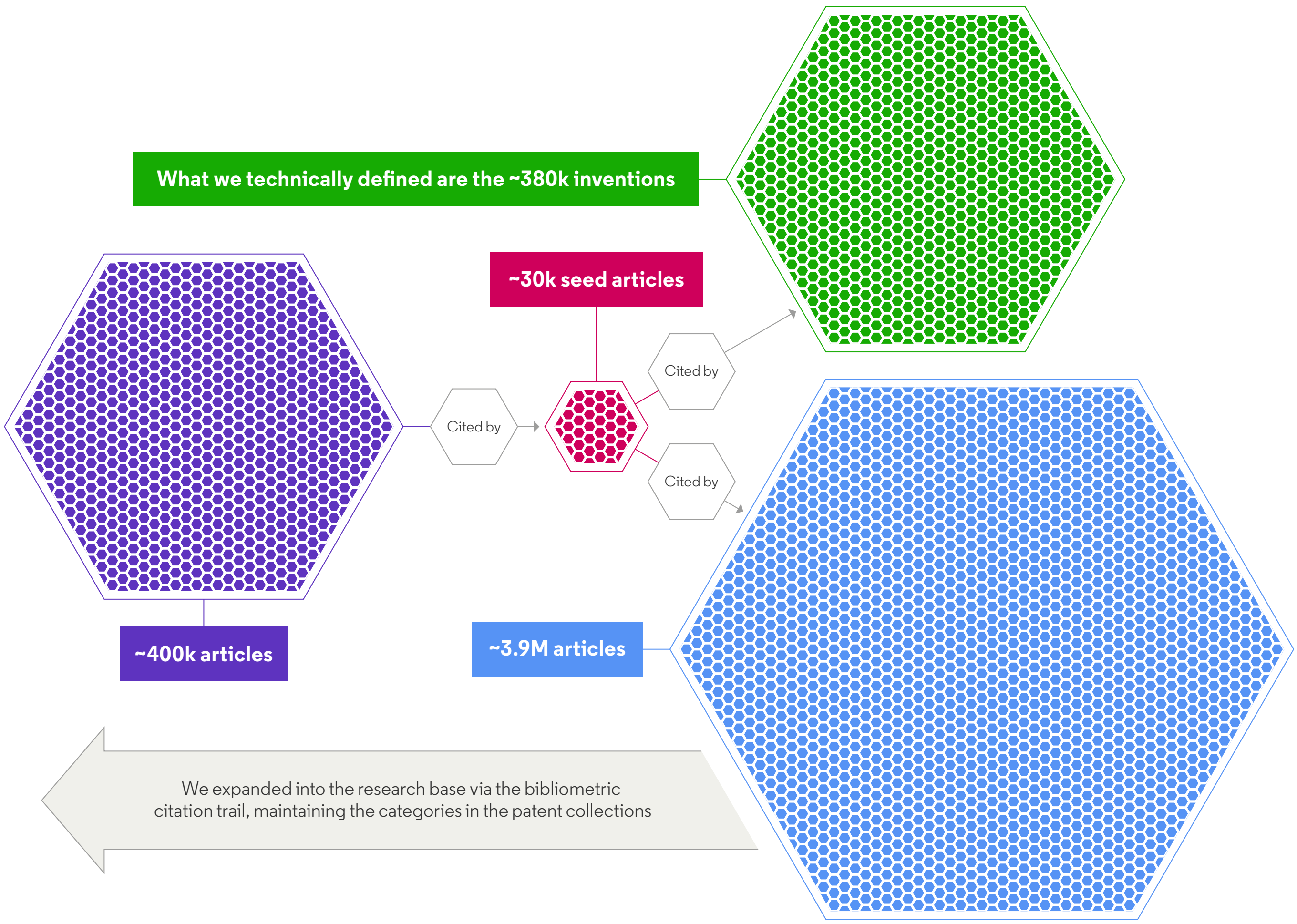
In this study, we use two different data sources to measure basic and applied research. The data source for the measure of basic research is produced as part of the global scientific process, while the data source for applied research provides a specific legal framework for inventions and technology. There is an inherent assumption of the different venues of research outcomes (papers and patents). Scientific articles are part of the verification and rigor of the scientific process – peer review, ethics, basic and fundamental research. Patent information is a measure of more applied research and development, where technology meets commercial pressures and risks, and the opportunity for monetization or competitive advantage.

More fundamental research has no requirement for it to know its potential end use, or indeed have one at all. This creates a need in research and innovation measurement for a more refined collection definition process that differs from more traditional 'patent search' techniques, in that sequester of a scientific research base underpinning the roll-out sustainable energy sources must not rely on researchers being aware of the role of their research in a sustainability setting.

As an example, modern wind turbine technology is heavily reliant on the existence and development of carbon fibre composites at mass scales – the development of which occurred across hundreds of different researchers in both academia and corporations; but they were likely unaware of the potential of these materials to downstream-enable highly efficient wind turbine electricity production.

This study therefore adds a new data collection process reliant on the patent examination process where references to research papers are incorporated in the collection definition and then expanded into a peer group of related, relevant research that forms the 'base' knowledge ecosystem enabling sustainable energy technologies. We then measure this research base and the trends within it, alongside the direct technology development cycles within patented technologies specific to sustainable energy sources.

This creates a research ecosystem of close to 400,000 inventions and a corresponding research base of scientific articles approximately 10 times larger.



Furthermore, the relationship of sources as maturity indicators led to the idea of an 'arrow of time' across different content sources: the basic and fundamental research supported by academic research concentrated in peer-reviewed papers, the more applied/development research within patent activity, and further, the signals of commercial imperative from the assertion or contention implicit in patent litigation and opposition proceedings.

Our experience with our data sources shows a preponderance of activity in scientific articles from government and academic research institutions and within patent activity from corporations – lending a general development and maturity profile of research and innovation from papers to patents to the assertion of those patents. However, it is not a complete model – patented technology can and should be referenced as the relevant research base of further scientific and engineering activity that is then published in academic journals, as this is one of the intended purposes of the public disclosure requirements of the international patent system.

In a general model of technology development cycles, base science and engineering is intended to enable downstream technology applications and therefore basing the model of research and innovation on this maturity axis is used in this report to understand the development cycle as a whole.

The concepts behind the innovation and research metrics for this study recognize that scientific papers, or inventions, are not all the same. Some are highly impactful, influencing or of use to many downstream research pathways. Some are highly strategic inventions for corporations that they wish to protect broadly, with significant investment, while other inventions are rare in their combination of technologies or approaches.

At Clarivate, much of our work involves differentiating individual pieces of research from the wider base of ideas contributed to the modern innovation ecosystem, so that benchmarks are available for decision making. Within scientific journal articles, much of this rests upon Clarivate's heritage in the development of scientific bibliometrics and informatics – using the linkages between papers to understand their relevance and importance compared to the wider field.

For patent information, we go more broadly, leaning once more on the reference links between inventions, but also on the investment levels of the applicant, the novelty of the idea, the economic footprint of the protected idea and the distinctiveness of the invention compared to others – this is known as the Derwent Strength Index which is used for example in our Top 100 Global Innovators report.

In this study, we lean on these indicators and metrics to assess the variation of impact and strength between papers and inventions respectively, across the eight sustainable energy sources.

Our work involves differentiating individual pieces of research from the wider base of ideas contributed to the modern innovation ecosystem.

Furthermore, when assessing trends in research and innovation, we rely on models of evolution of science and engineering that map to how historically research areas have developed. Within research and innovation there are natural patterns of development, similar to product lifecycles (and indeed feeding those cycles), that occur due to the inherent constraints on innovation.

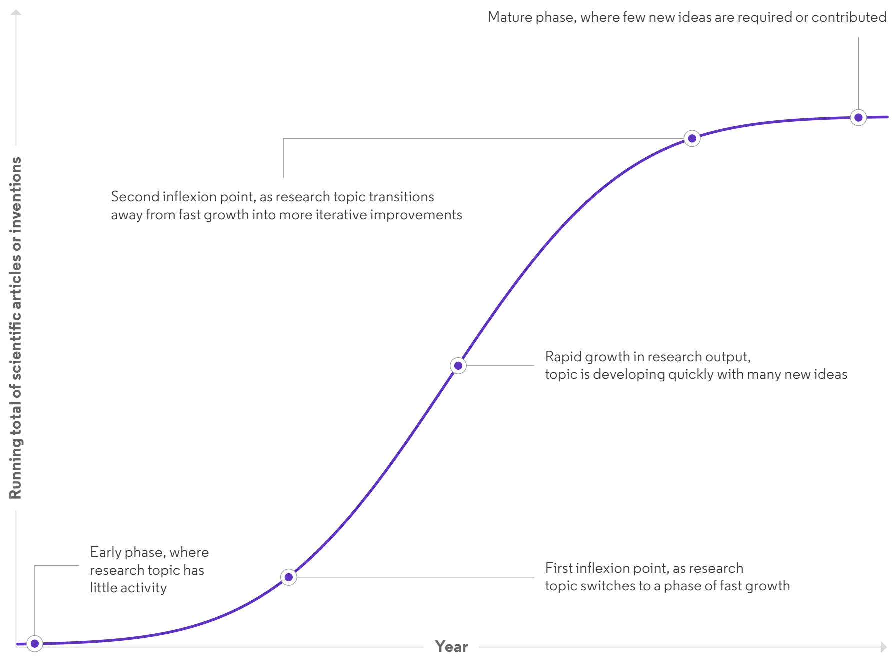
Innovation s-curve theory provides a model for tracking the level of activity over time that is occurring within a particular topic or collection of research data points, and a framework on which maturity and the likely level of future research intensity can be assessed. The s-curve refers to the shape of a running total of research and innovation data points, as they accumulate over time, reflecting the current level the topic has attained to date.

The s-curve theory, when applied to real research fields, provides a template of known future shape of development. Once a research topic passes the first inflexion point, it becomes a known entity with modelling information that provides information on whether the second inflexion point is showing any signs of occurring – the variable being the timing of that event.

The power of this type of innovation model lies in the inherent ability of it to model (and visualize) momentum in innovation ecosystems. Once accelerations and decelerations begin, at scale, they become difficult to stop. With these models, we can review the research and innovation landscape directly within sustainable energy sources inventions, and the earlier curves of the more fundamental research base that supports them.

Figure 11

Distribution of research, innovation s-curve model
Plot of running total of research outcomes (e.g. inventions of scientific articles) as a model over time for a theoretically complete development curve



Source: Web of Science, DWPI

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