

BIOTECHNOLOGY BY MID-CENTURY:

*Assessing current capabilities.
Anticipating tomorrow's leaders.
A 12-country comparison.*

Summary Report

Anne E. Beall, Ph.D. and Robert M. Friedman, Ph.D., *J. Craig Venter Institute, La Jolla, California*

June 2020

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Full report available at <https://www.jcvi.org/Biotech-MidCentury>

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Introduction

“It has become part of the accepted wisdom to say that the twentieth century was the century of physics and the twenty-first century will be the century of biology.”

The esteemed physicist Freeman Dyson, in an essay in the *New York Review of Books* in 2007, wrote: “It has become part of the accepted wisdom to say that the twentieth century was the century of physics and the twenty-first century will be the century of biology.” Cutting-edge biotechnologies, e.g., synthetic biology and genome engineering, offer opportunities to improve our ability to enhance wellness and treat disease, address food insecurity, mitigate climate change, strengthen bio-defense, and as we have seen over recent months, combat future pandemics.

Today, the United States leads the world in biotechnological expertise and innovation. Whether it continues to do so by mid-century will depend on how the biotechnology development environment, i.e., the drivers of innovation, in the United States compares to that of other nations. This report from the JCVI Policy Center attempts to define and semi-quantitatively characterize the factors that may increase or decrease the rate of biotechnology innovation in selected nations around the world. By 2050, we project that the United States’ foremost competitors will be China, followed by India. Continued leadership by the US compared to China seems likely but is by no means assured. Other countries examined within the report include Brazil, Germany, Indonesia, Iran, Israel, Russia, Singapore, South Africa, and South Korea.

Within each of 12 countries, we have assembled and analyzed a series of close to 100 indicators in a wide variety of categories. These include indicators of scientific, technological, policy, and broad societal drivers that enable the development of biotechnology innovation today and in the future. For lack of an existing term, we have coined the word “bio-enterprise” to refer to the entire biotechnology innovation and production system, including the broader science and technology and general societal environment on which it depends.

From these 100 indicators we construct two aggregate scores: 1) Our **bio-enterprise capacity score** is an absolute measure that reflects each country’s capacity, or potential to invent and produce, biotechnology products. 2) Our **bio-enterprise innovation-driver score** is an intensity measure that reflects each country’s capability to grow its bio-enterprise over the next years.

We first evaluate each country’s bio-enterprise capacity and potential for growth as of 2020. We then construct a series of scenarios that project future bio-enterprise capacity in these 12 nations under varying degrees of governmental policy attention or neglect.

This summary report distills the highlights of our research. The full 200-page report includes four sections: 1) an overview of methods, including the choice of indicators, methods used to aggregate the indicators into sector-wide and comprehensive scores for 2020, and projections of country capabilities to 2050; 2) a high-level comparison of the 12 countries, as of 2020 and projected to 2050; 3) four-page summaries for each of the 12 countries; and 4) eight-page detailed datasheets for each of the 12 countries displaying the 100 indicators that form the basis of our analyses.

We have coined the word “bio-enterprise” to refer to the entire biotechnology innovation and production system, including the broader science and technology and general societal environment on which it depends.

Countries analyzed in this report

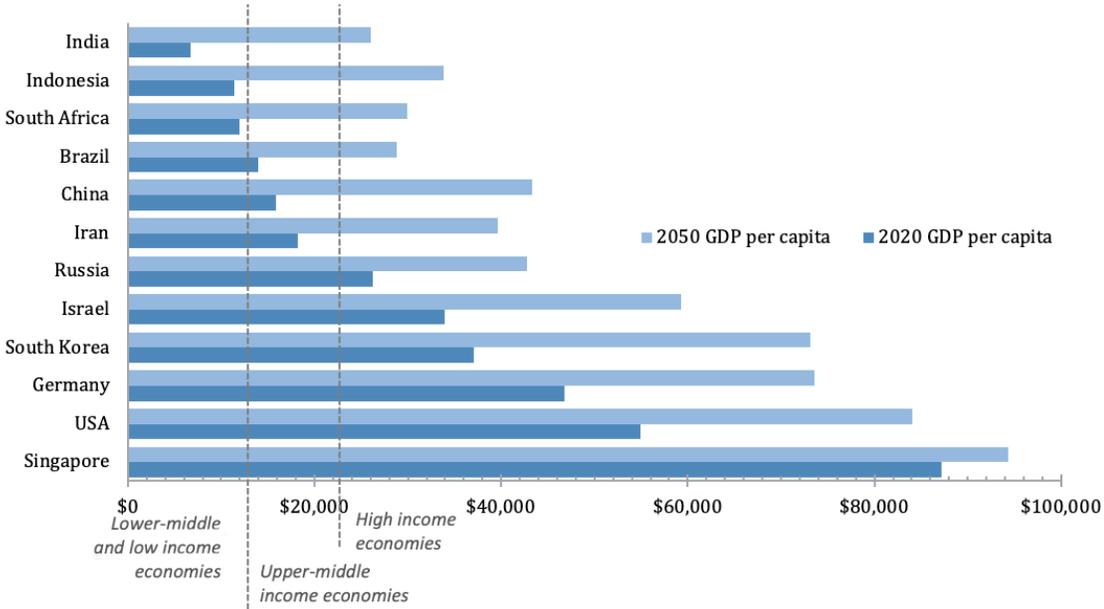
The 12 countries examined in this report include, the United States, China, Germany, South Korea, Singapore, Israel, India, Brazil, South Africa, Indonesia, Russia and Iran.

The 12 countries examined in this report include, first, the **United States** and **China**, the world's two largest economies and biotechnology leaders, on an absolute basis, today. In addition, we include four high-income countries (using the World Bank classification scheme): **Germany**, **South Korea**, **Singapore**, and **Israel**. All four are biotechnology leaders from a different perspective, not in absolute capacity, but the intensity of their biotech sectors. Four of our countries are large, rapidly expanding economies with active biotechnology sectors: **India**, **Brazil**, **South Africa**, and **Indonesia**. Finally, we include two US adversaries: **Russia** and **Iran**. The latter six are all middle-income countries today.

Figure 1 displays current (2020) and projected (2050) GDP/capita for each of our 12 countries. Seven of our 12 countries, China among them, are middle-income countries today. By 2050, all are forecast to increase their GDP/capita to a level that would be considered high-income today. Increasing total economic productivity, as well as increasing per capita productivity, are important factors for understanding the potential growth of the bio-enterprises of these countries by 2050.

Seven of our 12 countries are among the 10 largest economies, as measured by GDP, in the world today; 6 of 12 are forecast to be among the largest in 2050. Together the economies of these countries contribute about two-thirds of global GDP both today and perhaps an even greater share in 2050. Half our countries are also quite populous. Six of our 12 countries are among the top 10 most populous countries today.

Figure 1: Current GDP/capita and projected GDP/capita, constant USD, purchasing power parity. 2050 estimates are an average of World Bank and PricewaterhouseCoopers economic projections, Wittgenstein Center of population projections.



Together the economies of these 12 countries contribute about two-thirds of global GDP today and perhaps an even greater share in 2050. Six of our 12 countries are among the top 10 most populous countries today.

Methods: 2020 Indicators and 2050 Projections

Taking the Measure of the Bio-enterprise in 2020

Throughout this report, we use the term “**bio-enterprise**” to refer to the entire biotechnology innovation and production system, including the scientific and societal environment on which it depends. To help us understand and compare the bio-enterprise within and among each of our 12 countries, we have collected data on approximately 100 indicators in three sectors: the biotechnology sector itself, the broader science and technology sector, and the general societal environment in which they function. We combine these indicators into two high-level bio-enterprise scores: a **bio-enterprise “capacity score”** and a **bio-enterprise “innovation-driver score”**.

Our **bio-enterprise capacity score** is an absolute measure that reflects each country’s capacity, or potential to invent and produce, biotechnology products. Each of the 30 indicators included in this combined score is countable, e.g., number of patents, scientists, and top universities, dollars spent on R&D, etc. The bio-enterprise capacity score includes indicators from three sectors, with greatest weight given to those within the biotechnology sector and diminishing weights to the science and technology sector and general societal sector.

Our **bio-enterprise innovation-driver score** is an intensity measure that reflects each country’s capability to grow its bio-enterprise over the coming de-

acades. Each of the 53 indicators in this combined index are either absolute measures scaled to GDP or some measure of quality that does not depend on country size. Thus, this score includes indicators such as R&D expenditures as a percent of GDP but also includes evaluations of regulatory burden or intellectual property protection. While several of the indicators overlap with those in the capacity score (but scaled to GDP), the emphasis is on more forward-looking or future-oriented indicators.

The Indicators by Sector

Figure 2 is an overview of the categories of indicators we have used to develop our bio-enterprise scores. From the **biotechnology sector** itself, we have included several traditional measures of output, including scientific journal articles related to biotechnology; biotechnology patents; and biotechnology companies in each of four subsectors: biopharma, agricultural biotechnology, “industrial” biotechnology (e.g., production of biofuels, bio-based chemicals, plastics, etc.), and service companies. Ideally, we would have also included a measure of economic output from this sector, but such information is not available. A recent report from the US National Academies of Sciences (NASEM, 2020) recommends collecting such statistics for the United States. The report estimates that the US bioeconomy accounts for about 5 percent of US GDP, about \$1 trillion/year. We could not identify comparable estimates for other countries.

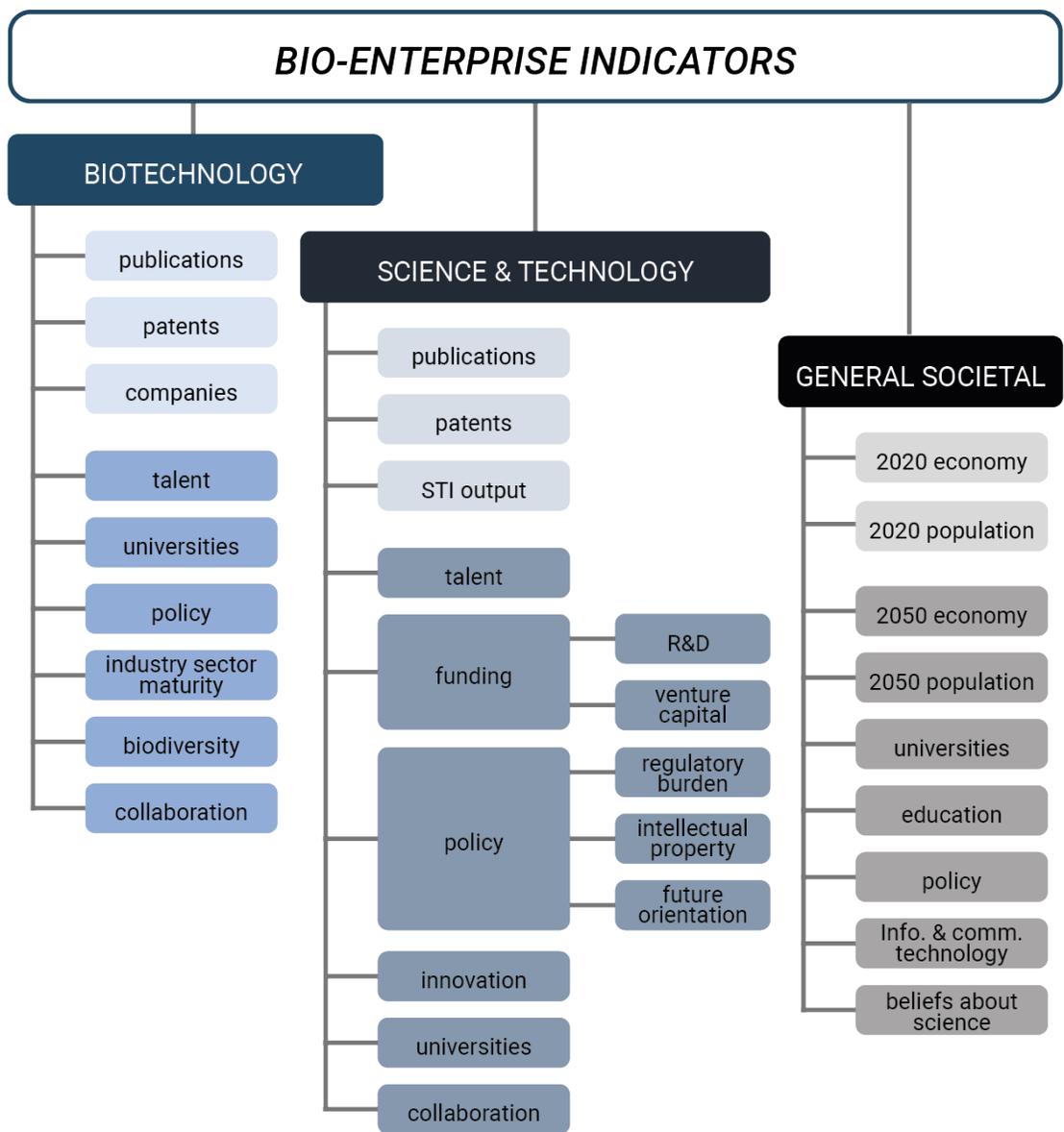
*Our **bio-enterprise capacity score** reflects each country’s potential to invent and produce biotechnology products.*

*Our **bio-enterprise innovation-driver score** reflects each country’s capability to grow its bio-enterprise over the coming decades.*

Indicators particularly important for predicting future success are shown in a darker shade. These include biotechnology and synthetic biology talent, both professionals and students; top universities for biotechnology and life sciences; whether the country has a national biotechnology

policy or plan; measures of the maturity of the biopharma, ag biotech, and industrial biotech subsectors; measures of the knowledge base of each country’s plant and animal biodiversity and genomics, and a measure of international collaboration within the life sciences.

Figure 2: Categories of indicators analyzed in this report. Indicators have been selected from three sectors. Indicators shown in darker shade are those particularly important for predicting future success.



We have collected data on approximately 100 indicators in three sectors: the biotechnology sector itself, the broader science and technology sector, and the general societal environment in which they function.

We constructed a series of simple models that step through time in 10-year intervals, calculating the increase in both bio-enterprise capacity scores and innovation-drivers cores through time.

Indicators from the **science and technology sector** include scientific journal articles in a broad range of advanced technology fields outside of, but relevant to, biotechnology; total patents (all fields); and another study's measure of knowledge and technology outputs (Global Innovation Index, GII, by INSEAD, Cornell, and WIPO). We would have liked to include a measure of economic output from this broad sector, but such information, collected in such a way as to be comparable across our 12 countries, is not available.

Broader science and technology indicators most important to the future success of biotechnology are again shown in a darker shade. These include measures of STEM talent, both recent graduates and researchers; R&D expenditures (all fields of science and engineering) by universities, businesses, and government; venture capital funding; top computer science and engineering universities; regulatory policy; intellectual property policies; a series of aggregate measures related to innovation, acceptance of business risk, and university-industry collaboration from the GII study and the World Economic Forum's Global Competitiveness Report.

General societal indicators include measures of economic output, both GDP and GDP per capita; and population measures, both total population and the ratio of working-age to elderly people. For each of these, we include current data and projections to 2050. Indicators most important to the future success of biotechnology (shown in darker shade) include top-ranked universities; a series of measures related to education of the population and spending on education by government; a measure of "rule of law"; adoption of in-

ternet and communication technologies; and a series of survey results about beliefs about the benefits from science.

Appendix Table 1 includes the complete list of indicators used to construct the **bio-enterprise capacity score** and the arithmetic weightings used to calculate each "within-sector" sub-score. The sector sub-scores are then combined into the bio-enterprise score as a scaled Euclidian distance, with greatest weight given to the biotechnology sector, followed by the science and technology sector, and lowest weighting to the general societal indicators.

Appendix Table 2 includes the list of these indicators used to construct the **bio-enterprise innovation-driver score** and the arithmetic weightings used to calculate each within-sector score. The bio-enterprise innovation-driver score combines indicators from all three sectors in a manner similar to the capacity score. Data sources for the indicators follow Appendix Table 2.

Methods for Projecting the Relative Growth of the Bio-enterprise by 2050

Once we had estimated country scores for 2020, our next goal was to explore the relative country scores and rankings in the global bio-enterprise by mid-century. Our approach assumes that each country's **future bio-enterprise capacity score** depends on:

- The country's **current bio-enterprise capacity score**.

- The intensity or strength of its **bio-enterprise innovation-driver score**. The higher the innovation-driver score, the faster the growth in capacity.
- Forecast **GDP** growth (i.e., growth in the economy overall). A country's capacity will grow at least at the rate of its forecast GDP growth.
- Forecast growth in the average **productivity of its citizens (GDP/capita)**. Innovation-driver score appears related to GDP/capita; exactly how is unclear, as discussed below.

We constructed a series of simple models that step through time in 10-year intervals, calculating the increase in both **capacity scores** and **innovation-driver scores** through time independently for each of the three sectors, as GDP and GDP/capita increases.

We then combine these sector-specific scores into bio-enterprise scores. In essence, the **bio-enterprise capacity score** represents the size of each country's bio-enterprise at a point in time. The **bio-enterprise innovation-driver score** represents the rate at which it is increasing. Those countries with higher innovation-driver scores will see faster growth in capacity.

We are assuming that global bio-enterprise capacity will grow faster than overall global GDP growth. However, just how much faster is unknown, thus we constructed two growth scenarios to test whether relative scores and rankings were sensitive to this unknown.

For the US, the low-growth scenario assumed about 4%/yr. growth of the sector between 2020 and 2050, i.e., about twice anticipated GDP growth of just under 2%/yr. The high-growth scenario assumed a much rosier picture for the sector: over 5% above GDP growth, for an overall growth of over 7%/yr. These higher growth rates have been forecast by observers who are optimistic that new technology (e.g., CRISPR gene editing, synthetic biology, cheaper sequencing of human genomes) will enable the biotechnology sector to grow far faster than the overall economy. For example, Carlson (2016) estimated that revenues from the biotechnology sector grew at over 10%/yr. between 2005 and 2015.

While the absolute capacity scores are, of course, much greater in the high-growth scenarios than under our low-growth scenarios, the relative patterns of growth among countries remained quite similar. In this summary, we use the results from our high-growth scenarios.

Finally, we observed a striking relationship between our 2020 bio-enterprise innovation-driver scores and the average productivity of a country's citizenry (measured as GDP/capita). All of our countries are forecast to become wealthier through time, but at varying rates. We wanted to incorporate these differences into our models, but because we have data from only one point in time, just how was not clear. Thus, we constructed three different models incorporating plausible alternative explanations. As with our growth scenarios, the relative patterns of growth among countries remained reasonably similar across our three different models.

Each country's future bio-enterprise capacity score depends on: 1) its current capacity score, 2) the strength of its innovation-driver score, and 3) its forecast growth in GDP and GDP/capita.

"What-if" Scenarios

We have developed three policy scenarios, which we call status quo, policy push, and policy drag. Policy decisions within each country can significantly affect innovation drivers and thus the future bio-enterprise.

The high-growth and low-growth scenarios discussed above were developed to examine the effects of modest vs. rapid **global technological advance**, not variations in policy emphasis among countries. To interrogate the effect of policy, we constructed an additional series of policy scenarios to test the sensitivity of our bio-enterprise capacity score to changes in policies or societal emphasis in individual countries. We believe that policy decisions within our 12 countries will have striking influences on their relative standings in the future.

We have developed three policy scenarios, which we call **status quo, policy push, and policy drag**. Our **status-quo** scenario assumes that for any individual country, due to little or no change in the national policy influencing our measures, the strength of its 53 innovation-drivers remains about equal to its value in 2020, increasing only slightly as average productivity (GDP/capita) increases through time. Our **policy-push** scenario posits that a country would like to drive biotechnology development, to help grow its economy and/or become a leader in the field, and therefore alters policy toward aggressive and sustained governmental actions supporting biotechnology growth. Under this scenario, we increase a subset of innovation-drivers amenable to policy intervention through time and calculate the resulting increase in bio-enterprise capacity. Our **policy-drag** scenario assumes that policy attention toward biotechnology wanes, innovation drivers decline, and thus future bio-enterprise capacity drops below the status-quo scenario.

Of course, governmental policy does not impact all of our innovation drivers equally; some are amenable to rapid change, others hardly at all. The last column of Appendix Table 2 includes our estimates of how long it might take to see the full effect of governmental policy change on each of our 53 innovation drivers. For about 20% of our innovation drivers, we believe policy change could have significant effects within a decade. These include such innovation drivers as government regulation, intellectual property protection, and investments in R&D and public education. About another 35% of our innovation drivers might significantly respond to governmental policy change within a 10- to 20-year timeframe. In this category we include such innovation drivers as building a strong scientific talent pool, a mature biotech crop industry, or strengthening the rule of law. We believe that 30 years might be a more reasonable timeframe for change in about another 15% of our innovation drivers, e.g., building strong university and industry technology clusters. The remaining 30% of our innovation-drivers will not respond to policy change quickly or are not impacted by policy changes at all.

In addition, some governments can implement change more quickly than others. We have assumed that authoritarian regimes, if they desire to, can implement policy changes more rapidly than democratic governments. Thus, we allow authoritarian regimes, such as China, Iran, and Russia, to change their innovation drivers scores more rapidly in response to our policy scenarios than such democratic nations as Germany, the US, and South Korea. This applies to both the policy-push and policy-drag scenarios. Rate

adjustments are based on the Economist Intelligence Unit Democracy Index scores.

Just how much an individual innovation driver can increase under the policy-push scenario depends on its score in 2020 and its income category. We assume that our high-income countries, with political will and sufficient resource investment, could achieve “best-in-class” performance for that particular indicator. For example, if it chose to do so, the US could increase its rate of R&D spending (when measured as R&D expenditures relative to GDP) to that of South Korea, the current leader. For indicators for which global data was available, “best-in-class” was set to an average of the top fifth of global nations (to eliminate outliers), or the best of our 12 nations, whichever was higher. Middle-income countries such as

Brazil also increase their scores under the policy-push scenario, but not as much. The maximum score for middle-income countries was set to either the average of the top middle-income score and top high-income score, or the average of the top fifth of global middle-income nations, whichever was higher. This recognizes that middle-income countries will be able to push further toward high-income performance as their economies develop in the coming decades.

Under the policy-drag scenario, we assume individual innovation drivers can drop by 30%, regardless of country income category. Again, as under the policy-push scenario, the rate of decline varies by indicator, with authoritarian regimes declining faster than democratic countries.

Our policy-push scenario posits that a country would like to drive biotechnology development to help grow its economy and/or become a leader in the field.

Our policy-drag scenario assumes that policy attention toward biotechnology wanes and innovation drivers decline.

Results: 2020 and Projections to 2050

Bio-enterprise Capacity and Drivers of Innovation in 2020

Figure 3: 2020 Bio-enterprise capacity score vs GDP (purchasing power parity)

Today, the US and China are the clear bio-enterprise capacity leaders, with the US over 50% larger than China. Germany and India fall into a second tier.

Figure 3 displays our calculated **bio-enterprise capacity scores** in 2020. The bio-enterprise capacity scores (vertical axis) are displayed in relation to each country's GDP (horizontal axis). Because our capacity score is an absolute measure, large countries clearly have an advantage.

Note the different scales between the top and bottom panels. The top panel display all 12 countries; the bottom panel expands a portion of both axes so that the relative positions of smaller countries can be seen more easily.

The US and China are the clear bio-enterprise capacity leaders. And even though the US GDP (measured as purchasing power) is about three-quarters the size of China's (due to China's far larger population), the US' bio-enterprise capacity score is over 50% larger. Germany and India fall into a second tier, with Germany slightly outpacing India, even though Germany's GDP is less than half the size of India's. Brazil, South Korea, and Russia form a third tier, again on an absolute basis, followed by Indonesia and the remaining four smaller countries.*

* Country codes: Brazil – BRA, China – CHN, Germany – DEU, India – IND, Indonesia – IDN, Iran – IRN, Israel – ISR, Russia – RUS, Singapore – SGP, South Africa – ZAF, South Korea – KOR, United States – USA.

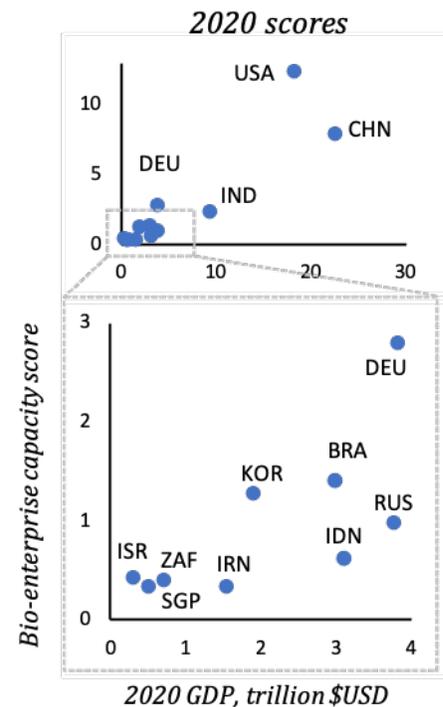
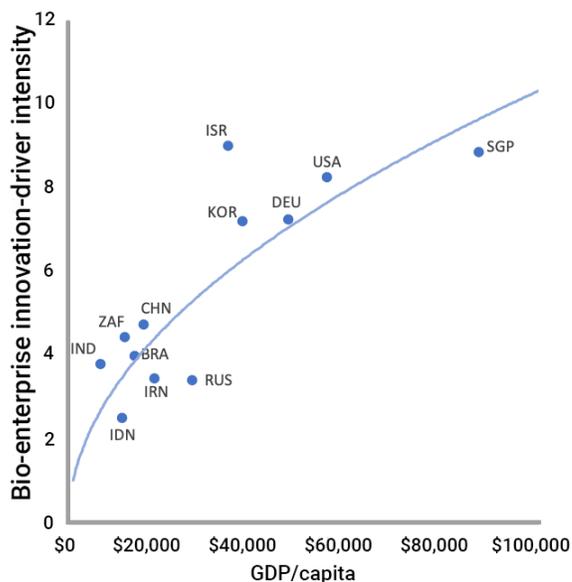


Figure 4 displays our second key measure, each country's **bio-enterprise innovation-driver score** in 2020. Again, this is an intensity measure that reflects each country's capability to grow its bio-enterprise into the future.

One can see a striking relationship between our 2020 bio-enterprise innovation-driver scores and the average productivity of a country's citizenry (measured as GDP/capita), again in 2020. Our 12 countries fall into two tiers. The first tier, with the highest bio-enterprise innovation-driver scores, includes Israel, Singapore, the US, Germany, and South Korea. All five are high income countries.

Figure 4: 2020 Bio-enterprise innovation-driver scores increase with economic productivity (GDP/capita), but at a declining rate.



The second tier of countries are all middle-income countries today. Note that several of these have somewhat higher innovation-driver intensity scores than might be expected simply on the basis of GDP/capita. These include China, South Africa, Brazil, and India. Iran, Russia, and Indonesia have the lowest innovation-driver intensity scores of our 12 countries and are all less than might be expected based on GDP/capita.

Table 1 displays our calculated **bio-enterprise capacity scores** and **bio-enterprise innovation-driver scores** for each of our 12 countries in 2020. The top panel includes the combined bio-enterprise capacity score, as well as the capacity scores for each of its three component sectors. The bottom panel presents innovation driver scores in a similar format. A much deeper understanding of each country’s 2020 bio-enterprise capacity

and drivers of innovation can be gained by examining the eight pages of close to 100 individual indicator scores per country included in Part II of the full report.

Table 1: 2020 Capacity scores and innovation-driver scores, by country. Bio-enterprise score and scores for individual sectors.

Capacity scores:

Combined bio-enterprise score and individual sectors

COUNTRY	Bio-enterprise	biotech	science & tech	general
USA	12.4	9.8	9.4	7.5
CHN	7.9	3.4	8.2	8.4
DEU	2.8	1.8	2.8	1.6
IND	2.3	0.8	1.3	4.0
BRA	1.4	1.2	0.7	1.0
KOR	1.3	0.7	1.5	0.7
RUS	1.0	0.3	1.1	1.1
IDN	0.6	0.4	0.0	1.0
ISR	0.4	0.4	0.3	0.1
ZAF	0.4	0.3	0.4	0.3
SGP	0.3	0.2	0.4	0.1
IRN	0.3	0.1	0.3	0.5

Innovation-driver scores:

Combined bio-enterprise score and individual sectors

COUNTRY	Bio-enterprise	biotech	science & tech	general
ISR	9.0	8.0	7.1	5.0
SGP	8.9	4.9	6.4	7.4
USA	8.3	5.0	6.8	6.0
DEU	7.2	3.9	6.5	5.2
KOR	7.2	4.1	6.3	5.8
CHN	4.7	2.1	4.6	4.2
ZAF	4.4	2.7	3.3	3.6
BRA	4.0	2.5	1.9	2.8
IND	3.8	1.8	2.9	1.9
IRN	3.5	1.7	2.0	3.2
RUS	3.4	1.4	2.7	3.6
IDN	2.5	0.8	1.7	3.0

Five high-income countries—Israel, Singapore, the US, Germany, and South Korea—have the highest bio-enterprise innovation-driver scores.

Bio-enterprise Capacity and Drivers of Innovation Projected to 2050

As discussed previously, our models assume that each country's future **bio-enterprise capacity score** depends on 1) its current **bio-enterprise capacity score**; 2) the intensity or strength of its **bio-enterprise innovation-driver score**; and 3) forecast **GDP** growth (i.e., growth in the economy overall). Each country's future **bio-enterprise innovation-driver score** depends on 1) its current **bio-enterprise innovation-driver score** and 2) forecast growth in the average productivity of its citizens (**GDP/capita**). Our models start in 2020, using the scores calculated from the close to 100 indicators as described and displayed above, then step through time in 10-year intervals until 2050.

Figure 5 displays the scores of both bio-enterprise measures together. In this graph, each country's **bio-enterprise capacity score** (vertical axis) is displayed in relation to its **bio-enterprise innovation-driver score** (horizontal axis). The top panel displays 2020 scores; the bottom panel displays are projections for 2050.

Each graph is divided into four quadrants. The upper-right quadrant of both the 2020 and 2050 graphs includes countries that have both high capacity scores and high innovation-driver scores. In 2020, the US is the only country that falls in this quadrant.

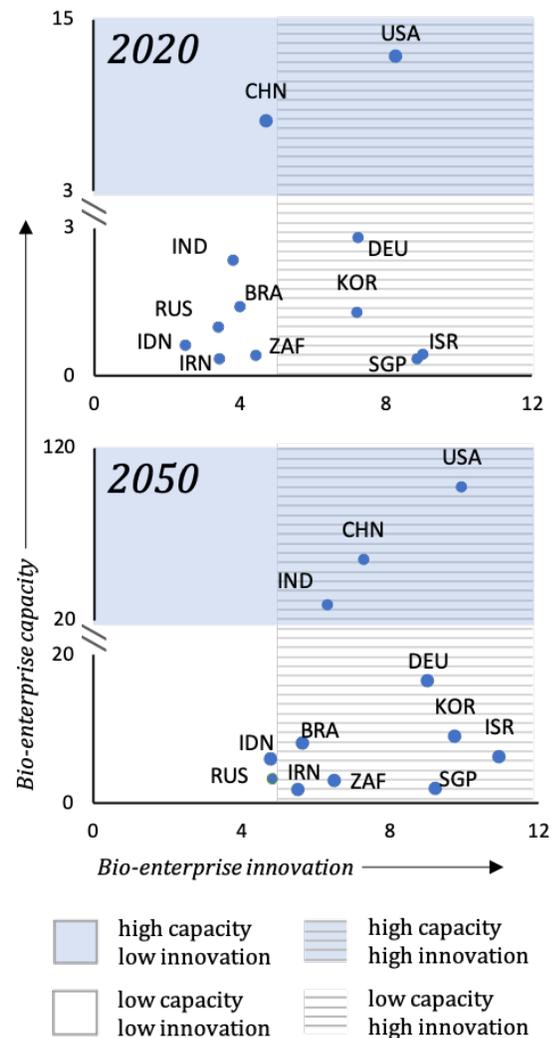
The upper-left quadrant includes countries that have high capacity scores but low innovation-driver scores (below a score of five). China is the only country that falls in this quadrant in 2020.

The graphs in Figure 5 are divided into four quadrants.

The upper-right quadrant of both graphs includes countries that have both high capacity scores and high innovation-driver scores.

In 2020, the US is the only country that falls in this quadrant.

Figure 5: Bio-enterprise capacity score vs. Bio-enterprise innovation-driver score: 2020 and projected 2050 (high-growth, status-quo scenario)



The lower right quadrant includes countries that have high innovation-driver scores, but because of the smaller size of their economies, have lower capacity scores. Germany, South Korea, Israel, and Singapore fall in this quadrant in 2020. These countries, along with the US, are the current drivers of innovation for the global bio-enterprise.

Finally, the lower left quadrant includes countries that have both low capacity scores and low innovation-driver scores. Half of our countries fall into this quadrant in 2020.

The picture in 2050 may be quite a bit different. In the high-capacity, high-innovation-driver quadrant, the US is joined by both China and India. Note that we are using the same threshold for high innovation-driver in 2050 as for 2020. Our dividing line between low and high capacity score increases at an assumed rate of about 6.5%/yr, from a score of 3 in 2020 to a score of 20 in 2050.

Brazil, South Africa, and Iran move into the lower right quadrant, i.e., high innovation-driver scores but still low capacity scores. That said, low capacity in 2050 is relative. We anticipate that, for example, Brazil's capacity in 2050 will exceed that of Germany today. Indonesia and Russia remain in the lower left quadrant, i.e., having both low capacity scores and low innovation-driver scores.

The Importance of National Policy for the Growth of the Bio-enterprise:

As The 2050 projections presented in the graphs above are for our "status-quo" scenario. As discussed in the earlier methods section, we developed three scenarios for this study, which we call **status quo**, **policy push**, and **policy drag**. Our **status-quo** scenario assumes that for any individual country, the bio-enterprise innovation-driver score remains about equal to its value in 2020, increasing only as average productivity (GDP/capita) increases through time, following the relationship shown in Figure 4 above.

However, the positions of these countries, and their positions relative to each other, could change in both capacity and innovation by 2050, depending on the policy pursued by each country over the next three decades. Results for each policy scenario are included in the full report in each of the country's chapters.

Again, our **policy-push** scenario posits that a country would like to become a leader in biotechnology to help grow its economy and intervenes with aggressive and sustained governmental actions. Under this scenario, we increase a subset of innovation-drivers amenable to policy intervention through time and calculate the resulting increase in bio-enterprise capacity. Our **policy-drag** scenario assumes that policy attention wanes, innovation drivers decline, and thus future bio-enterprise capacity drops below the status-quo scenario.

By 2050, we forecast that three countries—the US, China, and India—will have both high capacity and high innovation—driver scores.

Only two will remain in the 'low-low' category: Indonesia and Russia.

Figure 6 displays innovation-driver scores for India under our three policy scenarios.

Figure 7 (next page), shows their impact on future bio-enterprise capacity.

Figure 6 displays the bio-enterprise innovation-driver score for India, between 2020 and 2050, using the 10-year intervals in our projection models. Note the gradual increase in the status-quo scenario, the significant decade-to-decade increases in the policy-push scenario, and decline in the policy-drag scenario. Again, our bio-enterprise driver-innovation score includes over 50 individual indicators; some will respond to governmental intervention within a decade, about half will require a 10 to 30 years to achieve significant change, and quite a few will require even longer. The policy-push and policy-drag scores shown in the figure are calculated using both the magnitude and rates of change for each individual driver. In addition, we assume that authoritarian governments, if they desire to, can implement policy changes more rapidly than democratic governments.

Figure 6: Bio-enterprise innovation-driver score: 2020 through 2050. Status-quo, Policy-push, and Policy-drag scenarios. See text for explanation of scenarios

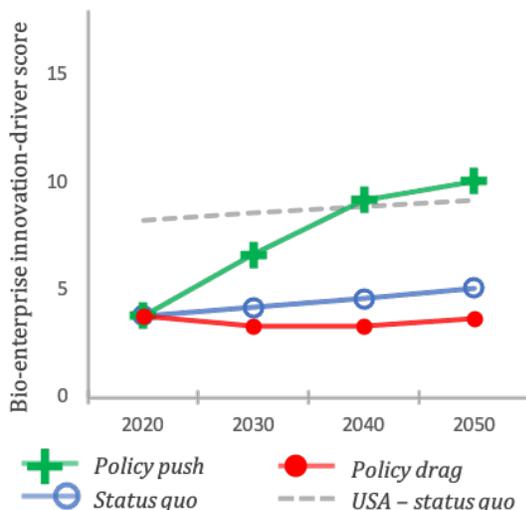
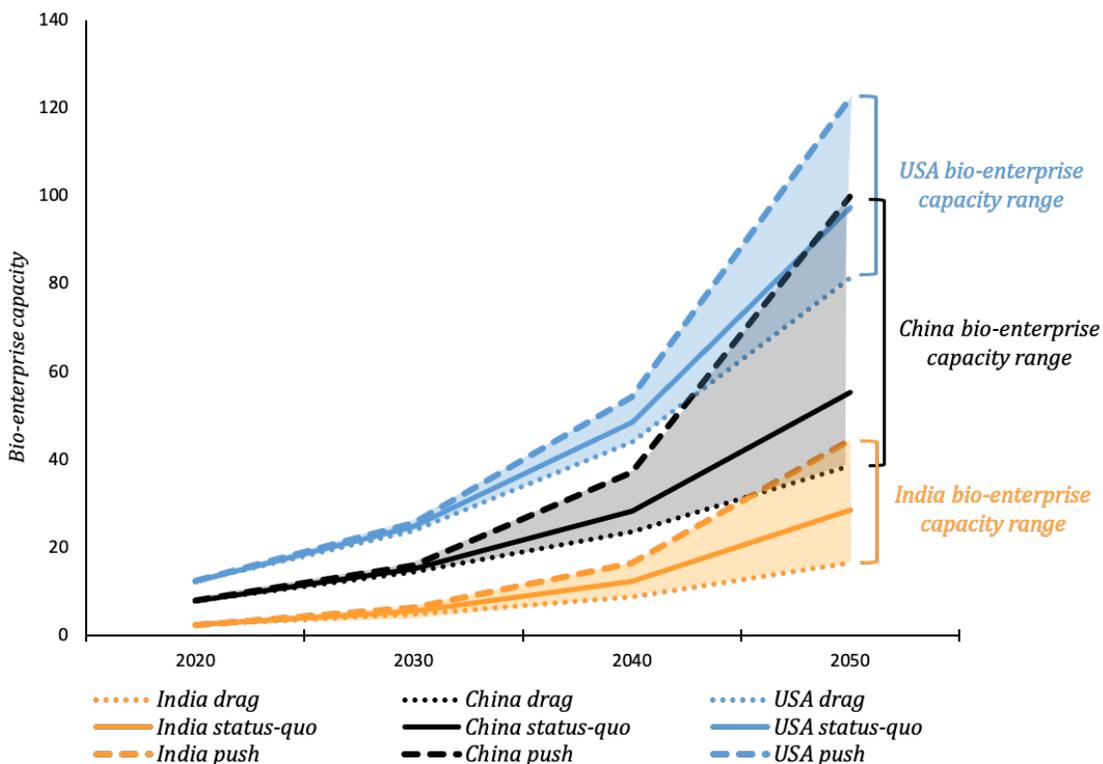


Figure 7 displays the bio-enterprise capacity scores for the US, China, and India, the top three bio-enterprise capacity countries by 2050. The figure displays the results of the status-quo, policy-push, and policy-drag scenarios, between 2020 and 2050 (under our high growth set of scenarios). Figure 5, presented earlier, displayed only the status-quo scenario for 2050. Figure 7 displays the effect that governmental action (or inaction) might have to alter those outcomes.

For example, the status-quo scenario for China projects that by 2050, China's bio-enterprise capacity score will remain behind the US and ahead of India, as it does today. However, with very aggressive and sustained government intervention (policy push), it appears plausible that China could overtake the US, if the US stance towards its bio-enterprise remains about the same as it does today (status quo). If US policy attention wanes (policy drag), the likelihood of China overtaking the US with aggressive policy increases. Similarly, China's bio-enterprise capacity under a policy-drag scenario might drop below India's if India adopts aggressive and sustained policy push.

Figure 7: Bio-enterprise capacity scores for top three nations: United States, China, and India, 2020 through 2050. Status-quo, Policy-push, and Policy-drag scenarios.



By 2050, with aggressive and sustained government intervention by China (policy push), China could overtake the US, if the US stance towards its bio-enterprise remains about the same as it does today (policy status quo).

Table 2 (next page) is a high-level summary of the results of our projections of bio-enterprise capacity and innovation-driver by 2050. The top panel includes our 2050 status-quo capacity estimates for each country, 2050 rank, and change in rank for each country between 2020 and 2050. The last two columns show the change in rank in 2050 if each country were to follow either the policy-push or policy-drag scenarios, compared to all other countries following their status quo. Table 2 (bottom panel) includes our 2050 status-quo bio-enterprise innovation driver scores for each country, 2050 rank, and change in rank for each country from 2050.

the strengths and weaknesses within each of the three component sectors of the bio-enterprise in 2020 and 2) provide additional detail about the results of the three policy scenarios by 2050.

The full report includes four-page summaries for each country that 1) highlight

Table 2: 2050 Bio-enterprise capacity scores and innovation-driver scores, by country. 2050 scores and changes in rank under various scenarios.

Bio-enterprise capacity

COUNTRY	2050 status quo score	2050 status quo rank	Status quo rank Δ 2020	Policy push rank Δ 2050	Policy drag rank Δ 2050
USA	97.4	1	-	-	-
CHN	55.4	2	-	+1	-
IND	28.5	3	+1	-	-
DEU	16.5	4	-1	-	-
KOR	9.0	5	+1	-	-1
BRA	8.0	6	-1	+1	-
ISR	6.2	7	+2	-	-1
IDN	5.9	8	-	+3	-2
RUS	3.3	9	-2	-	-1
ZAF	3.0	10	-	+1	-
SGP	2.0	11	-	-	-1
IRN	1.8	12	-	+3	-

Table 2 is a high-level summary of the results of our projections of bio-enterprise capacity and innovation-driver by 2050.

Bio-enterprise innovation drivers

COUNTRY	2050 status quo score	2050 status quo rank	Status quo rank Δ 2020
ISR	10.9	1	-
USA	10.1	2	+1
KOR	9.7	3	+2
SGP	9.2	4	-2
DEU	9.0	5	-1
CHN	7.4	6	-
ZAF	6.5	7	-
IND	6.4	8	+1
BRA	5.7	9	-1
IRN	5.5	10	-
RUS	4.8	11	-
IDN	4.8	12	-

Appendix Table 1: Indicators used to calculate Bio-enterprise Capacity scores. Weights prioritize the relative influence of each indicator to the health of a country's biotechnology endeavor, with higher scores more influential.*

sector	category	absolute indicators	weights	
biotech	publications	share of top biotech publications	10	
	patents	share of world biotech patents, 2014-2019	10	
	companies	share of world biotech companies	6	
	talent		users of largest genetic sequence database	4
			users of a major genetic engineering tool supplier	4
			participation in international genetic engineering competition	4
			attendance at preeminent synthetic biology conferences	1
			subscribers to a prominent synthetic biology newsletter	1
	universities		share of top biotech universities	4
			share of top biology universities	3
			share of top life sciences universities	3
	industry sector maturity		share of total global biotech crops	3
			share of total global biofuel production	2
		clinical trials of biologics since 2010	5	
biodiversity		well-studied animal and plant species	2	
		non-human sequence entries in largest genetic sequence database	2	
collaboration		life sciences collaboration (Nature Index)	4	
science & technology	publications	share of top high-tech publications	10	
	patents	share of world patents, 2014-2019	10	
	talent		share of world STEM graduates	5
			share of world researchers	5
	funding: R&D	total expenditures on R&D	10	
	universities		share of top computer sciences universities	3
			share of top engineering and technology universities	3
collaboration		share of top international innovation clusters	6	
general societal	economy	current GDP, PPP	10	
	population	current population	4	
	economy	2050 GDP, PPP	10	
	population	2050 population	4	
	universities	share of top universities	6	

* Weighted scores are first calculated for each sector and country. The maximum sector score of the 12 countries is assigned a value of 10 and the remaining countries' sector scores are linearly scaled accordingly. The sector scores are then combined into the bio-enterprise score as a scaled Euclidian distance, i.e., *bioenterprise score* =

$$\sqrt{(\text{biotech score})^2 + 0.5 * (\text{science\&tech score})^2 + 0.25 * (\text{general societal score})^2}$$

Appendix Table 2: Indicators used to calculate Bio-enterprise Innovation-driver scores. Weights prioritize the relative influence of each indicator to the health of a country's biotechnology endeavor, with higher scores being more influential.

sector	category	intensity indicators	weights	rate of change
biotech	talent	users of largest genetic sequence database relative to GDP	4	20 yrs
		users of a major genetic engineering tool supplier relative to GDP	4	20 yrs
		participation in international genetic engineering competition relative to GDP	4	20 yrs
		attendance at preeminent synthetic biology conferences relative to GDP	1	20 yrs
	universities	subscribers to a prominent synthetic biology newsletter relative to GDP	1	20 yrs
		top biotech universities relative to GDP	4	longer
		top biology universities relative to GDP	3	longer
	policy	top life sciences universities relative to GDP	3	longer
		presence of a national biotechnology plan	6	10 yrs
	industry sector maturity	biotech crops relative to total cropland	3	20 yrs
		biotech fuels relative to total liquid fuel production	1	20 yrs
		average annual growth rate in biofuel production, 2006-2016	1	20 yrs
		clinical trials of biologics since 2010 scaled to GDP	2	20 yrs
	biodiversity	innovation in biopharma (Biopharmaceutical Competitiveness Index)	3	20 yrs
well-studied animal and plant species scaled to GDP		2	20 yrs	
collaboration	non-human sequence entries in largest genetic sequence database scaled to GDP	2	20 yrs	
	life sciences collaborations relative to GDP	4	30 yrs	
science & technology	talent	STEM graduates relative to GDP	4	20 yrs
		retention of foreign-educated PhD students	2	20 yrs
		researchers relative to GDP	4	30 yrs
	funding: R&D	total expenditures on R&D relative to GDP	5	20 yrs
		R&D expenditures funded by higher ed. relative to GDP	3	10 yrs
		R&D expenditures funded by government relative to GDP	1	10 yrs
		R&D expenditures funded by business relative to GDP	1	30 yrs
	funding: venture capital	VC availability (Global Competitiveness Report)	3	longer
		VC index (IESE Venture Capital and Private Equity Attractiveness Index)	3	longer
	policy: regulatory burden	lack of burden of government regulation (Global Competitiveness Report)	4	10 yrs
		ease of technology transfer (US Chamber IP Index)	4	10 yrs
	policy: intellectual property	intellectual property protection (Global Competitiveness Report)	3	10 yrs
		patents, related rights, and limitations (US Chamber IP Index)	4	10 yrs
		tax incentives in the creation of IP assets (US Chamber IP Index)	1	10 yrs
	policy: future	future orientation of government (Global Competitiveness Report)	8	30 yrs
		innovation	acceptance of risk in entrepreneurship (Global Competitiveness Report)	3
	human capital and research (Global Innovation Index)		1	20 yrs
	innovation capability (Global Competitiveness Report)		1	30 yrs
	infrastructure (Global Innovation Index)		1	30 yrs
	business sophistication (Global Innovation Index)		1	longer
universities	top computer sciences universities relative to GDP	3	longer	
	top engineering and technology universities relative to GDP	3	longer	
collaboration	state of cluster development (Global Competitiveness Report)	3	30 yrs	
	university-industry collaboration (Global Competitiveness Report)	3	20 yrs	
general societal	economy	2050 GDP per capita	8	longer
		GDP annual growth rate, 2018 to 2050	2	longer
	population	population growth rate, 2018 to 2050	1	longer
		2050 ratio: working age population to young plus elderly population	3	longer
	universities	top universities relative to GDP	6	longer
		education	school life expectancy, primary through tertiary	2
	presence of science education in secondary school		2	10 yrs
	government expenditure on education as percent of GDP		1	10 yrs
	government expenditure on primary education as percent of GDP		1	10 yrs
	policy	rule of law (World Justice Project)	4	20 yrs
		ICT	ICT adoption (WEF Global Competitiveness)	4
	beliefs about science		belief in science as future national benefit	1
		belief in science as increasing jobs	1	longer
belief in science as a personal benefit		1	longer	
trust in science over religion		1	longer	

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