Making sense of the bioeconomy

Promises, challenges and opportunities in a developing market

Robin Francis, Chandler Hatton, Enguerran Ripert, Philip Webster

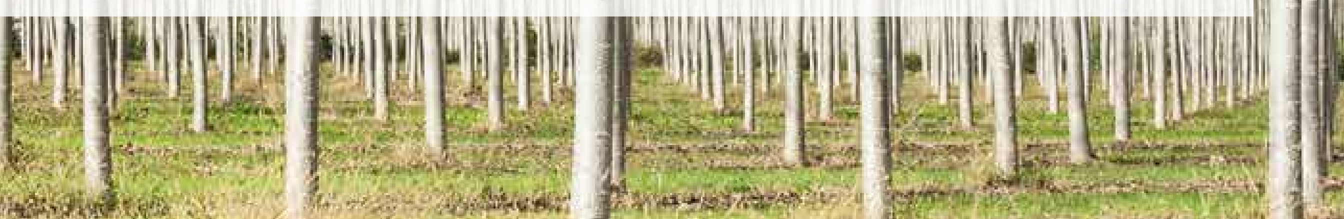
Many companies, both large and small, view fuels and chemicals derived from bio-based feedstocks as a potential source of sustainable growth. Yet in practice, breakthroughs have been hard to achieve and the number of large-scale commercial successes are few. In this article the authors examine the promise of the "bioeconomy", the challenges faced in bringing bio-based products to market, how these challenges can be overcome, and how companies can spot which opportunities may be attractive for them.

Fuels and chemicals produced from bio-based feedstocks, such as waste wood and agricultural co-products, offer incredible potential. They can help to reduce demand for non-renewable fossil hydrocarbons such as oil and gas. They are completely renewable, often help to reduce atmospheric carbon emissions, can improve national fuel security and can play a key role in the emerging concept of a "circular economy", helping to minimize the consumption of non-renewable materials (Table 1)[1].

From a business perspective, using and manufacturing bio-based products can present a completely disruptive approach to conventional fuels and chemicals. They offer opportunities for new entrants to disrupt existing markets, and for incumbents to defend their businesses against emerging threats. Some bio-based materials are produced from low-value or waste materials whose potential is under-exploited, providing an opportunity to create completely new market niches. This creates opportunities for agricultural commodity companies to derive new materials from crop co-products, for food companies to find ways to repurpose waste materials, and for chemical companies to create entirely new product lines.

Yet despite this promise, the sector's development has historically been disappointing. In particular, segments such as "second-generation" biofuels (Box 1) have been – at least to date – a perpetual "jam tomorrow" story – perennially on the cusp of materializing as a major market, but never quite breaking through. The environment today is even more challenging for many bio-based products due to four main hurdles:

[1] An economy that relies on renewable resources to produce food, energy, products and services, and that maximizes recycling while minimizing consumption and waste



Picture by scalatore1959/123RF

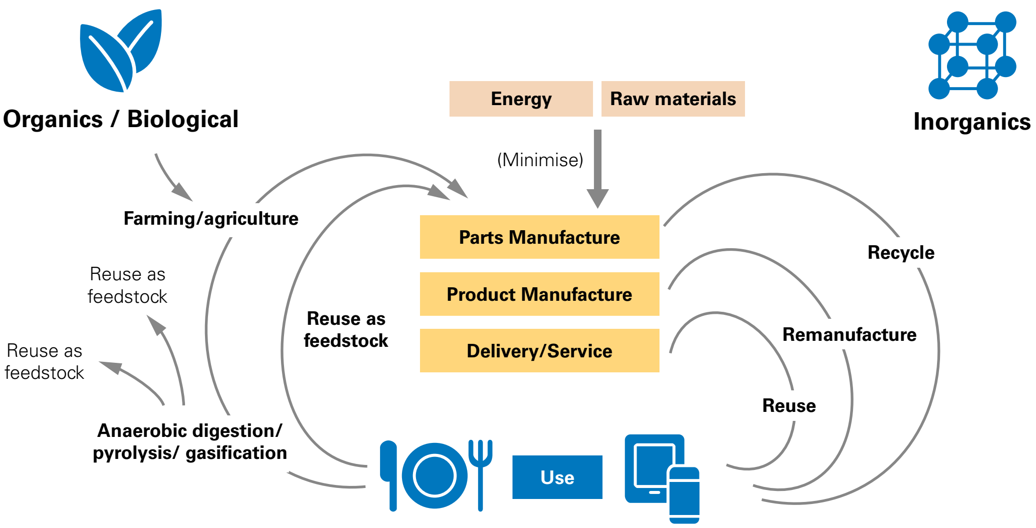


Table 1 **Biomaterials in the circular economy**

Source: Adapted from: Braunart & McDonough and Cradle to Cradle (C2C)

- **Environmental and ethical concerns:** Some bio-based products are produced from arable food crops such as wheat and palm oil. This causes indirect land use change, especially in Latin America and Asia-Pacific, as forests are cleared to create more farmland. There are accompanying ethical concerns over whether growing crops for use as fuels and chemicals should be prioritized over food.

- **Inconsistent and unpredictable regulation:** Bio-based products are sometimes more expensive to produce than fossil alternatives. They may also require substantial upfront investment in putting supply chains and processing equipment in place. In some cases, mandates or penalties to favor their uptake are necessary – and where business cases are built on legislation, an abrupt change can prove disastrous. The European Commission and several national governments have been unable to provide long-term support for bio-based materials, which has resulted in the collapse of some industries, notably the "first-generation" biodiesel industry in Germany during 2008.

- **Technology and supply chain development:** Bio-based feedstocks are often variable in composition with relatively low calorific value. Processing them into high-energy-density fuels and pure chemicals is therefore difficult and expensive. Many technology approaches have floundered due to poor reliability, difficulties in maintaining product quality, high costs and problems in ensuring a consistent supply of raw materials.

- **Costs relative to bulk tradable commodities:** Bulk bio-based products which are intended to directly compete with those derived from oil and gas are strongly affected by fluctuating oil and gas prices. Those derived from arable crops are also influenced by fluctuating prices due to changes in supply and demand across global markets and poor harvests caused by adverse weather conditions, for example. Recent falls in the price of oil and gas, and as a consequence, the products derived from them, have exacerbated the issue.

Despite these issues, under the right set of circumstances, some businesses have managed to balance the complex interplay between feedstock prices, regulation, processing costs and end-market values to achieve success in the bioeconomy. Some are making healthy profits. For example, Coca-Cola is now using bio-based polyethylene terephthalate (PET) in many of its drinks bottles, while DuPont has successfully commercialized its bio-based fiber, Sorona®, in carpets and apparel. The fashion brand G-Star Raw is using Lyocell, a man-made natural fiber of cellulose extracted from eucalyptus wood pulp, in many of its products.

What have these companies done differently? In this article, we set out a framework for finding the right opportunities and making sense of the bioeconomy.

Finding the right opportunities

Our work with food, chemicals and industrial biotechnology companies over the last decade has revealed that there are three basic approaches which a company can take in the bioeconomy: the valorization of low-cost feedstocks, finding advantageous process

Box 1: Producing "second-generation" transport biofuels in Northern Europe

"Second-generation" biofuels – those produced using non-edible feedstocks such as waste wood, crop co-products and other non-edible biomass, rather than "first-generation" food crops – have been the holy grail of the bio-based products industry for decades. Key to their attractiveness is their lack of competition with food crops, and potential for higher yields within a given land area.

However, commercial production poses significant challenges due to difficulties in obtaining large quantities of high-quality feedstock at viable prices, as well as controlling and managing the technological complexity of producing consistent, finished products. Even with high oil prices, in many cases the business case was marginal, and many manufacturers such as Range Fuels and KiOR bankrupted themselves when attempting to initiate commercial-scale manufacturing. In a world of oil at $40 per barrel, the commercial case is extremely difficult to make, and market mechanisms such as mandates and long-term projections of increasing oil prices are not sufficient conditions for commercial success.

However, if oil prices are higher (>$60 per barrel) and where regulation, feedstock availability and technological advancement are in alignment, a favorable business case can be made – providing that organizations are prepared to wait for longer than average to see a return on their investment. Our work with an energy company in Northern Europe established that second-generation biofuels can be economically viable if the following combination of regulatory, infrastructure and technology attributes are true:

- Availability and accessibility of cheap feedstocks: Demand for pulp and paper products is declining, reducing demand for wood in Northern Europe. The forestry industry is increasing in Eastern Europe, and increasing volumes are certified as sustainable. Prices are being driven down in some regions, irrespective of changes in subsidy level.
- Longer-range regulatory stability at the national level: Governments in Scandinavia have substantial reserves of biomass along with a desire to promote energy independence and boost longer-term economic competitiveness. They have sought to exceed Europe-wide targets and mandates for second-generation biofuel production. This gives investors the longer-term certainty that Europe-wide regulatory schemes (which are uncertain beyond 2020) currently lack.
- A superior and proven technology approach: Plasma gasification – the use of a plasma torch to convert organic matter directly to synthetic gas – has been used for many years to destroy hazardous waste, but can also be used to convert heterogeneous and poor-quality biomass into consistent fuels and chemicals. The latest technologies – when supported by regulation – can be cost-comparable with fossil fuels. The use of highly automated wood-harvesting approaches, together with carefully managed forest resources, can further improve technoeconomics.

technology routes, and producing high value products that cannot be made by other means (Table 2). Each approach must be underpinned, to varying degrees, by four main drivers: regulation, infrastructure and logistics, technologies and markets. This combination of approaches and drivers can be used to help position an organization within the bioeconomy.

1. Valorization of low-cost feedstocks

The first of these approaches involves using the abundant availability of cheap bio-based feedstocks. It can provide a powerful driver for commercial success when seeking to generate bulk, lower-value finished products. The most well-known example of this is the development of the market for sugarcane-derived bioethanol in Brazil during the 1970s, when high oil and low sugar prices created a substantial market for biofuels, which subsequently tailed off as oil prices fell and subsidies declined in the early 1980s.

		Approach		
Drivers		**Valorization of low-cost feedstocks** Conversion of low-, zero- or negative-value feedstocks to higher-value products	**Advantageous process routes** Cost-effective routes to bio-based chemicals and polymers	**Production of high-value products** Routes to high-value products which cannot be made by other means
Regulations	■ Favorable & stable regulatory environment supporting bio-based products or feedstock use			
Infrastructure & logistics	■ Infrastructure for collection of feedstocks ■ Effective transport of feedstocks & products			
Technology	■ Efficient, clean, reliable, and low -cost conversion technologies			
Customer & markets	■ Strongly growing/developed market ■ Customer or brand owner desire for bio-based products			
		Examples: Decentralized biogas from forestry waste; municipal waste conversion; food-waste conversion	Examples: Platform chemicals such as succinic acid, adipic acid and polylactic acid	Examples: Astaxanthin from microalgae; alternative high-value sweeteners, dietary supplements

Table 2 **Identifying opportunities in the bioeconomy – a framework for analysis** *Source: Arthur D. Little*

Box 2: Generating decentralized biogas in the developing world

The global production of agricultural waste is the thermal equivalent of 25% of the global production of oil[2]. Many agricultural co-products and wastes in the developing world are not used effectively, and the decomposition of agricultural waste in fields contributes to greenhouse gas emissions and the contamination of ground and surface water. Open burning practices, which are common in developing countries, generate atmospheric carbon emissions, and rapid urbanization has brought challenges for the disposal of municipal solid waste and sewage.

Low-value feedstocks derived from waste streams in the developing world present a number of challenges. Their varied and seasonal availability, combined with inconsistent quality, poor energy density and high moisture content can make them difficult to process[3]. Transport infrastructure and logistics for feedstocks are often entirely missing, and feedstocks are typically distributed over a wide geographic area.

Businesses in sub-Saharan Africa and South East Asia have overcome these challenges by establishing a market for decentralized biogas[4]. This involves setting up small decentralized processing plants close to sources of waste, such as livestock farms, urban agglomerations and agricultural processing facilities. The plants use anaerobic digestion tanks to ferment waste materials and produce methane which can be used locally for cooking, heating, and even power generation. The effluent slurry from the anaerobic digestion can be used locally as a high-value organic fertilizer, and the technology is generally well proven.

Very careful siting of distributed plants has helped to eliminate the issues of feedstock transport, although this also means that anaerobic digestion plants are smaller, using lower process temperatures and increased digestion time. The effective use of regulation, notably tradable carbon emission rights, to discount the sale of digesters to farmers, and incentives such as the Clean Development Mechanism can help to reduce up-front costs. This is an example of how small businesses have created value from a bio-based feedstock that was previously under-utilized, while using regulation as an enabler.

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[2] The International Environmental Technology Centre's "Policy Brief on Waste Agricultural Biomass", United Nations Environment Programme, 2013.

[3] The Feedstock Logistics Interagency Working Group's "Biofuel Feedstock Logistics: recommendations for research and commercialization", the United States Biomass Research and Development Board, 2011.

[4] Biogas results from the anaerobic digestion of organic feedstock. Common feedstocks include manure from livestock, sewage sludge, farmyard waste and by-products from crops.

An increasingly important source of low-cost feedstocks is waste biomass. Biomass wastes can include anything from food wastes, to crop co-products, sewage or unsorted municipal solid waste from households. These wastes can have zero or even negative value, and may represent a disposal problem. In some cases value can be extracted before materials are further disposed of or recycled. The use of a technology called anaerobic digestion in the developing world (Box 2) illustrates how companies have adopted a novel approach to using waste to create value for local communities.

2. Development of more efficient process routes

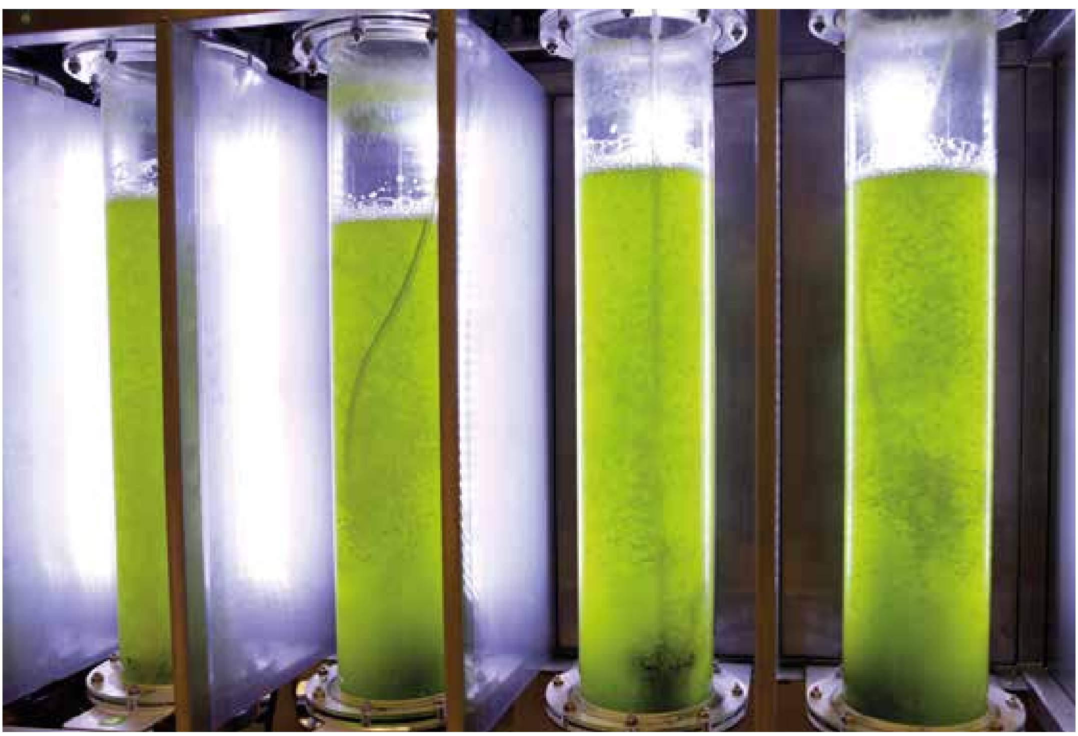
In some cases bio-based products can compete head-on with hydrocarbon equivalents. Often this is because they are produced using simpler process technology which substitutes the often complex and circuitous routes used to produce petrochemicals. For example, Argent Energy, a Scottish biofuels company, has produced biodiesel fuel from waste cooking oil for many years using an extremely simple process of transesterification as a means of conversion, while many apparel companies are now using well-understood mechanical and chemical processes to extract bamboo fiber for use in clothing.

Some organizations are using novel catalysts and smaller, lower-capex installations to product platform chemicals as precursors for finished products. Novel catalysis is being used to produce bio-based adipic and glucaric acid by the catalysts company Johnson Matthey and a technology developer, Rennovia, for a range of applications in plastics, fibers and detergents.

Often, industrial biotechnology – the use of enzymes and microbes to produce products – can be used to process bio-based feedstocks to create completely novel process routes to existing products. The chemicals company DuPont has found that production of its sustainably sourced 1.3-propanediol, a polymer used in adhesives and coatings, consumes up to 40% less energy than its fossil equivalent, providing a powerful cost driver for the process.

As mentioned, Coca-Cola is now using bio-based polyethylene terephthalate (PET) in many of its plastic bottles, and has collaborated extensively with technology providers such as Avantium, Virent and Gevo to enable this. Other consumer products companies have also explored the use of bio-PET in their products, including Heinz, Proctor & Gamble, and Nike.

For the majority, the use of industrial biotechnology to synthesize chemicals and polymers is still in its early stages, and competition from conventional routes remains fierce, especially in an era of low oil prices. Penetrating supply chains can also be a challenge. For example, a joint venture between Royal DSM and Roquette Frères focused on polyurethanes has struggled to penetrate well-developed markets and supply chains. To mitigate this issue, many are seeking to use chemically identical "drop-in" replacements to help to penetrate existing markets.



Picture by Phloxii/dreamstime

Table 3 **A photobioreactor, used to synthesize high-value end products**

3. Production of high-value products

Some chemicals and materials are either difficult or expensive to synthesize, or incredibly rare in nature. One such example is astaxanthin, a chemical found in microalgae and increasingly scarce marine organisms, which is both a dietary antioxidant and a valuable food additive which gives farmed salmon the pink color that is appealing to consumers. Businesses worldwide have sought to synthesize astaxanthin by farming microalgae on an industrial scale, to extract astaxanthin and other valuable compounds such as omega 3 fatty acids, often by growing them in complex photo-bioreactors (Table 3).

Where novel routes offer the potential to produce high-value bio-based products that cannot be produced practically via other methods, a commercial case can be made, even if the feedstock or the process technology is expensive. Cargill and its partner, Evolva, are due to achieve this soon with their EverSweet product, a novel natural sweetener (Box 3).

Box 3: Synthesizing natural sweeteners to meet consumer demand in North America

Higher-value opportunities in the bioeconomy are often driven by a need to find a more economically viable alternative to a chemical, material or food product which is in demand by consumers, but is expensive to produce. One such example is the growing demand for alternatives to sugar. Artificial sweeteners have been available for decades, but cost- and health- conscious consumers are increasingly seeking natural alternatives. Novel crops such as the South American plant Stevia rebaudiana are increasingly becoming sources of naturally derived and low-calorie sweeteners, although the stevia extracts are often associated with a bitter aftertaste, and those which are more "sugar-like" are prohibitively expensive. As a result, companies such as Cargill are developing new approaches to synthesize stevia extracts with a more rounded, sugar-like flavor in recombinant baker's yeast. This brings the advantages of a high-yield, lower-cost source of natural sweetener, which meets demand from a growing market and uses new technology to drive down cost.

Balancing the drivers

Each of the three approaches shown in Table 2 offers a great starting point for a foray into the bioeconomy. However, the four main drivers influencing the sector must also be carefully evaluated and balanced. No business case in the bioeconomy should be founded on just one of them. Table 4 shows how these drivers are applied to second-generation biofuels (Box 1). Here, commercial viability is predicated by the combination of a low-cost, widely abundant feedstock, a government prepared to subsidize the cost of the feedstock, a process technology with advantages over competitors, and a regulatory regime which is supportive of high-cost biofuels.

Driver 1: A positive and long-regulatory environment

In many cases, regulation plays a significant part in driving the value proposition of bio-based materials, and many opportunities have failed because the regulatory environment has not been long

Drivers	Approach	**Valorization of low-cost feedstocks** Conversion of low-, zero- or negative-value feedstocks to higher-value products	**Second-generation biofuels via plasma gasification in Scandinavia** **Advantageous process routes** Cost-effective bio-based routes to conventional chemicals and polymers	**Production of high-value products** Routes to high-value products which cannot be made by other means
Regulations	■ Favorable & stable regulatory environment supporting bio-based products or feedstock use		Incentives for feedstock use and mandates for second generation biofuel production (positive driver)	
Infrastructure & logistics	■ Infrastructure for collection of feedstocks ■ Effective transport of feedstocks & products		Well developed forestry industry (positive driver) Competition for forest feedstocks (potential risk)	
Technology	■ Efficient, clean, reliable, and low-cost conversion technologies		Efficient and well understood process (positive driver) Competing technologies (potential risk)	
Customer & markets	■ Strongly growing/developed market ■ Customer or brand-owner desire for bio-based products		Demand from transport fuels sector for "drop in" replacements to meet mandates (positive driver)	

Positive driver | Potential risk

Table 4 **Identifying opportunities in the bioeconomy – balancing the drivers**

Source: Arthur D. Little

term or consistent enough. The example of second-generation biofuels in Northern Europe (Box 1) highlights a promising potential business case founded on a longer-range regulatory view. This will create sufficiently favorable conditions to give investors confidence to make the required capital and infrastructure investments needed to create a self-sustaining biofuels market. In some cases, markets are being created through procurement mandates for "green" products, such as the US government's "BioPreferred" program.

Generally speaking, those measures which seek to stimulate the creation of new industries rather than penalize existing ones are more favorable, and no business case should be founded on the basis of subsidy alone. That said, so long as companies are cognizant of the risks, regulatory-enabled opportunities should not be ignored since they can be substantial and make the difference between a successful and unsuccessful venture.

Driver 2: Favorable infrastructure and logistics for raw materials and finished products

Bio-based feedstocks used for bulk products such as biofuels are typically obtained from a wide geographical area, and transport infrastructure is frequently lacking since, in many cases, the material has not been collected for this purpose before. This is particularly the case for initiatives using wastes, which by their nature are usually produced from scattered user bases.

Attractive opportunities will enable the collection of suitable-quality feedstocks at a sufficient scale by either achieving a level of mobility which allows the process to be taken to the feedstock, or by leveraging existing infrastructure (e.g. waste collection facilities, or the pulp and paper supply chain) to aggregate and quickly sort materials into relatively pure streams for further processing.

Driver 3: Creating a step change in technology performance

Technology is a critical enabler of the bioeconomy, in terms of having the flexibility to convert heterogeneous, poor-quality materials into higher-value products; offering more efficient process routes compared to those used with conventional products; or providing a route to a high-value product that cannot be achieved conventionally. The necessary technologies to enable this include:

- **Conversion technologies** that enable the conversion of raw materials into finished products and demonstrate sufficiently low operating costs, quality, flexibility and yield

- **Supporting process technologies** which enable core conversion technologies, such as gas clean-up, separation and pre-treatment technologies

- **Enabling technologies at point of use** which help a finished bio-based product to be used in the marketplace, including flex-fuel cars, new methods of molding bio-based polymers, and engine-control technologies capable of handling blends of bio-based fuels and their oil-based counterparts

Technology development is the only item that can be directly controlled by project developers and investors, making this a key enabler to the bioeconomy concept. It also requires consideration of all elements within the supply chain, both in terms of raw materials and finished products.

Driver 4: Customers and markets

For a bio-based product to be attractive, clear market demand must either exist today, or hold strong potential for creation and growth in the future. In addition, demand from customers and consumers – and from the brand owners such as food or automotive companies which supply them with products – must also be taken into consideration. Often a desire for added functionality outweighs the demand for a "green" product – though in some cases, a premium can be charged for sustainable materials and chemicals, as is the case with high-margin products such as apparel or packaging associated with premium ready-meals. However, in the vast majority of cases, demand is greater for a product which is a direct "drop-in" replacement, or which is cost comparable or cheaper than a conventional alternative.

This is because familiarity and ease of use are of great importance, and bio-based products must work in ways that are familiar to both consumers and brand owners. Any bio-based products that necessitate substantial changes in behavior or usage patterns from the outset will likely fail. From the perspective of brand owners, a "drop-in" replacement in terms of quality and product performance is important to ensure that existing supply and distribution channels are not disrupted.

Finally, where a "green premium" is possible, it is important to ensure that bio-based products are genuinely sustainable to avoid claims of "greenwashing". This is complicated to achieve in terms of both transparency and legality – and the plethora of accreditation schemes that have sprung up have confused many brand owners and consumers. Some companies have communicated to consumers through simpler messaging around "natural" products, underpinned by adequate transparency to validate any claims.

Aligning the stars

The challenges involved in the development of bio-based products are significant, but by picking an appropriate approach and balancing the different drivers described in Table 2, some organizations have managed to pick winners. The following principles can help with this:

Embrace the principles of a circular economy. Extended utilization, reuse and recycling are the buzz-words of today, in which essentially, nothing goes to waste. From the perspective of the bioeconomy, this is a key principle, particularly from the perspective of sourcing renewable feedstocks, and in finding uses for co-products from a production process to enhance the economic case for an investment.

Identify the risks as well as opportunities. The four main drivers can be used to identify opportunities, but they can often generate a huge range of options, particularly when looking for routes to new chemical intermediates, which offer virtually limitless possibilities. A risk-based approach can be used to eliminate opportunities quickly on the basis of regulatory uncertainty, slow-growing markets, and logistical barriers in certain geographies, as shown for second-generation biofuels in Table 4.

Look for opportunities to disrupt the market. The scenarios we describe above are not mutually exclusive, and it is possible to move to mid- or even high-value products from low-value feedstocks. One such example is gas fermentation – the use of microbes to convert flue gases from factories into hydrocarbon products – which could potentially completely disrupt conventional gas-scrubbing markets.

Avoid being wooed by bold claims about radical new technologies. New approaches for converting bio-based feedstocks into products emerge on an almost-daily basis, and it is worth bearing in mind that many approaches have been available for several decades. Instead, those organizations with considerable experience in process technology and an understanding of its limitations make for sensible partners.

Maintain a focus on profitability at scale. Development companies can become overly focused on creating new technologies, and may lose sight of the fact that bio-based products must be cost competitive. This is particularly important for manufacturing at scale, and considerations around scale-up of both processing technology and supply chains need to be considered from the outset.

Proactively develop multidisciplinary partnerships. The vast majority of organizations that are developing attractive offerings in the bioeconomy are doing so through partnerships, notably between technology developers, large and established chemicals players, and end users. This is because it involves a degree of convergence between many sectors, including forestry and agriculture, chemical engineering, product design and consumer insight.

Don't expect results immediately. Given the state of the market today, many investments will take a long time to mature as supply chains and markets evolve and regulation becomes more stable. Therefore, there is a need to manage the expectations of investors, and a need to work closely with governments in the early stages of activity to ensure that stable markets and supply chains are appropriately supported.

With these factors in mind, and taking into account the four main drivers of regulation, infrastructure and supply chain, customers and markets and technology, there is strong potential for businesses to successfully make sense of the bioeconomy.

Insight for the Executive

The bioeconomy is one of the most challenging sectors in which to find commercial success. Huge sums of money from investors, government and industry have been invested to try and create an industry which creates sustainable products from renewable materials. Yet many have suffered from major setbacks and financial losses through failed ventures, often just as initiatives approach commercial scale. An approach of focusing on winners is central to success.

Executives tasked with making decisions on how best to proceed with bio-based products must initially understand where they currently stand in terms of seeking to valorize low-value feedstocks, create high-value products, or develop effective process technologies, which allow bio-based products to be competitive against hydrocarbon alternatives. They must then weigh up the benefits and risks associated with four main drivers:

- Finding pockets of stability in an uncertain regulatory environment which seeks to promote bio-based products in favor of hydrocarbon alternatives

- Finding a process technology which is simpler or more effective than that already on the market today

Picture by lianem/123RF

- The availability of supply chains and infrastructure, to obtain bio-based raw materials at the right price and quality

- Clear demand from consumers and brand owners for a product which is more sustainable, or cost effective, or brings added functional value

Picking winners requires focus, persistence and a greater appetite for risk than is found in many other industries, together with a recognition that pioneers in this sector must focus as much on creating new markets as they do in addressing existing ones. Key to achieving success within the bioeconomy is effective partnership, both up and down the supply chain, and with technology providers, together with the realization that every co-product, side-stream and output from the process must be valorized in line with the principles of a circular economy. Following these principles will help leaders and fast followers in this sector succeed.

Robin Francis
is a Principal at Arthur D. Little's London office and is a member of the Technology & Innovation Management Practice.

Chandler Hatton
is a Manager at Arthur D. Little's Amsterdam office and is a member of the Technology & Innovation Management Practice.

Enguerran Ripert
is a Manager in the London office of Arthur D. Little and is a member of the Energy Practice.

Philip Webster
is a Principal in the London office of Arthur D. Little and is a member of the Technology & Innovation Management Practice.