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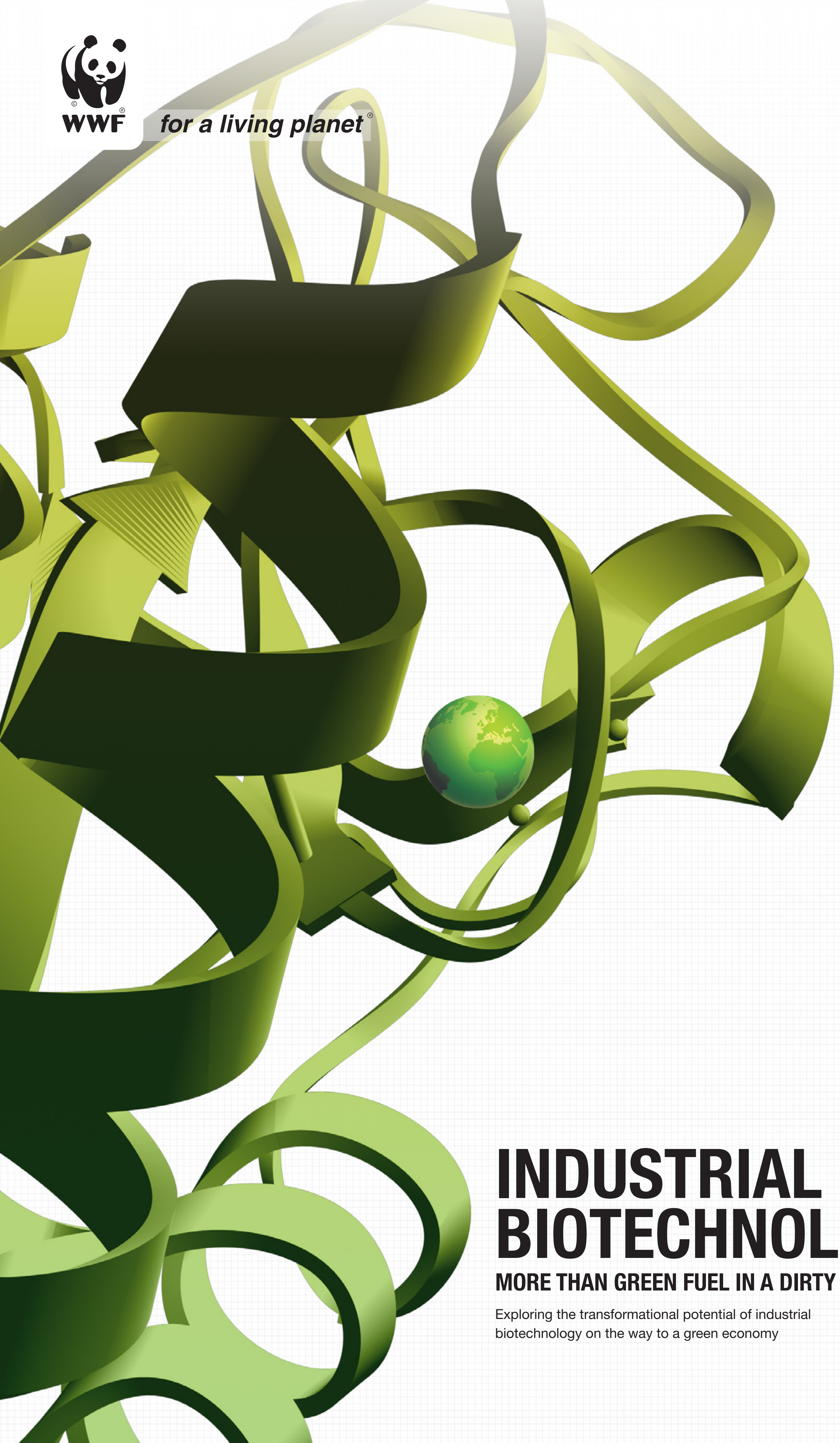
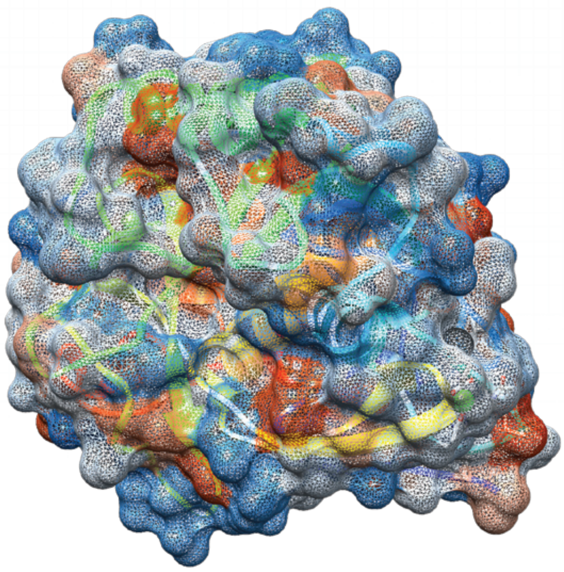


INDUSTRIAL BIOTECHNOLOGY

MORE THAN GREEN FUEL IN A DIRTY ECONOMY?

Exploring the transformational potential of industrial biotechnology on the way to a green economy

CONTENT



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This report can be downloaded at www.wwf.dk

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FOREWORD:

BEYOND INCREMENTAL IMPROVEMENTS

THE CLIMATE CRISIS IS SPINNING OUT OF CONTROL AT THE SAME TIME AS THE WORLD IS FACED WITH A MAJOR DEVELOPMENT CRISIS; BY 2050 THE GLOBAL HUMAN POPULATION WILL HAVE REACHED 9 BILLION. THE MAJORITY OF WHOM WILL LIVE A LIFE OF POVERTY IF WE FAIL TO ALTER OUR CURRENT DEVELOPMENT PATH.

UNTIL NOW, MOST EFFORTS to solve the climate crisis have focused on how to reduce the carbon footprint of our current economic system. However, this approach will not alone lead us onto the right path as it is concerned with eliminating a problem rather than building a new economy.

Efforts to solve the climate crisis must focus simultaneously and speedily on all sectors, all gases in all regions on how to reduce the carbon footprint of our current economic system. However, this approach will not lead us onto the right path if only selective actions are being taken which may focus only on short-term economic benefits and costs.

If we do not radically alter the system and construct a 21st century green economy we are likely to reduce the problem but not solve it entirely.

Furthermore, enhancing the efficiency of the current system will not build an economy capable of providing the jobs and services needed for 9 billion people, within the limits of our planet.

Creating a new economy seems an overwhelming task to most of us and obviously no one knows how a future sustainable economy will look like. However, if we have the courage to rise to this challenge and alter our perspective we will see that certain technologies and sectors have an often overlooked potential to help us take the important steps on the path toward sustainability.

Industrial biotechnology is one such sector. Even though the sector is still in it's infancy, it globally avoids the creation of 33 million tonnes of CO_2 each year through various applications, without taking ethanol use into consideration, whilst globally emitting 2 million tonnes of CO_2.

With this report, WWF sets out to explore the magnitude and nature of this sector in our search for pathways toward a green economy and a sustainable future. The potential is enormous, but the uncertainties and pitfalls are many. The courage, vision and drive of the world's politicians, investors and business leaders will ultimately determine whether we realize this potential.

The path toward a green economy will not be easy, but we must be mindful of where we are likely to end up if we continue on our current path. With this in mind, it is clear that there is no alternative to explore these innovative pathways.

EXECUTIVE SUMMARY

THIS REPORT CONCLUDES that the full climate change mitigation potential of industrial biotechnology ranges between **1 billion and 2.5 billion tCO_2e** per year by 2030, compared with a scenario in which no industrial biotechnology applications are available.[1] This is more than Germany's total reported emissions in 1990.

However, the type of emission cuts we pursue from industrial biotechnology and how we achieve them makes a crucial difference. As with most technologies, the potential to achieve sustainability objectives does not automatically translate into such goals being realized. Industrial biotechnology is no exception.

THE QUESTION IS TO WHAT EXTENT INDUSTRIAL BIOTECHNOLOGY CAN TRANSFORM A FUNDAMENTALLY UNSUSTAINABLE SYSTEM INTO A SUSTAINABLE BIOBASED ECONOMY – OR JUST PROVIDE A STREAK OF GREEN IN A DIRTY SYSTEM.

Some current biotechnology applications reduce emissions but also lead to a high degree of carbon feedback. This is most noticeable when enzymes are used to produce biofuels used to substitute fossil fuels in vehicle engines. Vehicle biofuel can save large quantities of CO_2, but it supports a carbon intensive transport system and further strengthens the social, institutional and cultural dependency on such systems. These reductions are valuable and needed in the short term but risk binding us to future emissions if we don't pursue further transformation of the economic infrastructure. Indeed, the production of biofuel will also lead to some very low-carbon feedback mechanisms in the future as bioethanol know-how and resources have paved the way for the development of biorefinery technology, and which has created the technological foundations for replacing oil-based materials with biobased materials.

The analysis of current technological and market developments within the biotechnology sector identifies opportunities to pursue a path of lower GHG (Greenhouse Gas) emissions over time as illustrated in the figure on the right page. However, it is crucial to ensure that the progression from improved efficiency, to the substitution of oil-based materials, and toward a circular economy where materials are reused, is unhindered.

This report identifies four fundamental dimensions of the contribution of industrial biotechnology: improved efficiency, the substitution of fossil fuels, the substitution of oil-based materials and the creation of a closed loop system with the potential to eliminate waste. As the industry develops and matures there is a possibility that the elimination of oil-based products and closed loop systems will make up the major proportion of the industry's GHG reduction contribution, although all four dimensions will contribute. There are substantial differences not only between the reduction potential of the four dimensions but also the extent of high and low-carbonfeedbacks they create.

The actual impact of industrial biotechnologies on GHG emissions will largely depend upon the overall socio-economic environment and the policy landscape surrounding the dissemination of these technologies. Therefore, for industrial biotechnologies to realize their full GHG emission reduction potential it is paramount that strong public policies and private sector strategies are in place to channel the sector's growth toward low-carbon paths, while avoiding high-carbon lock-ins that are often attractive due to their potential to deliver short term GHG emission reductions.

Such policies and strategies should:

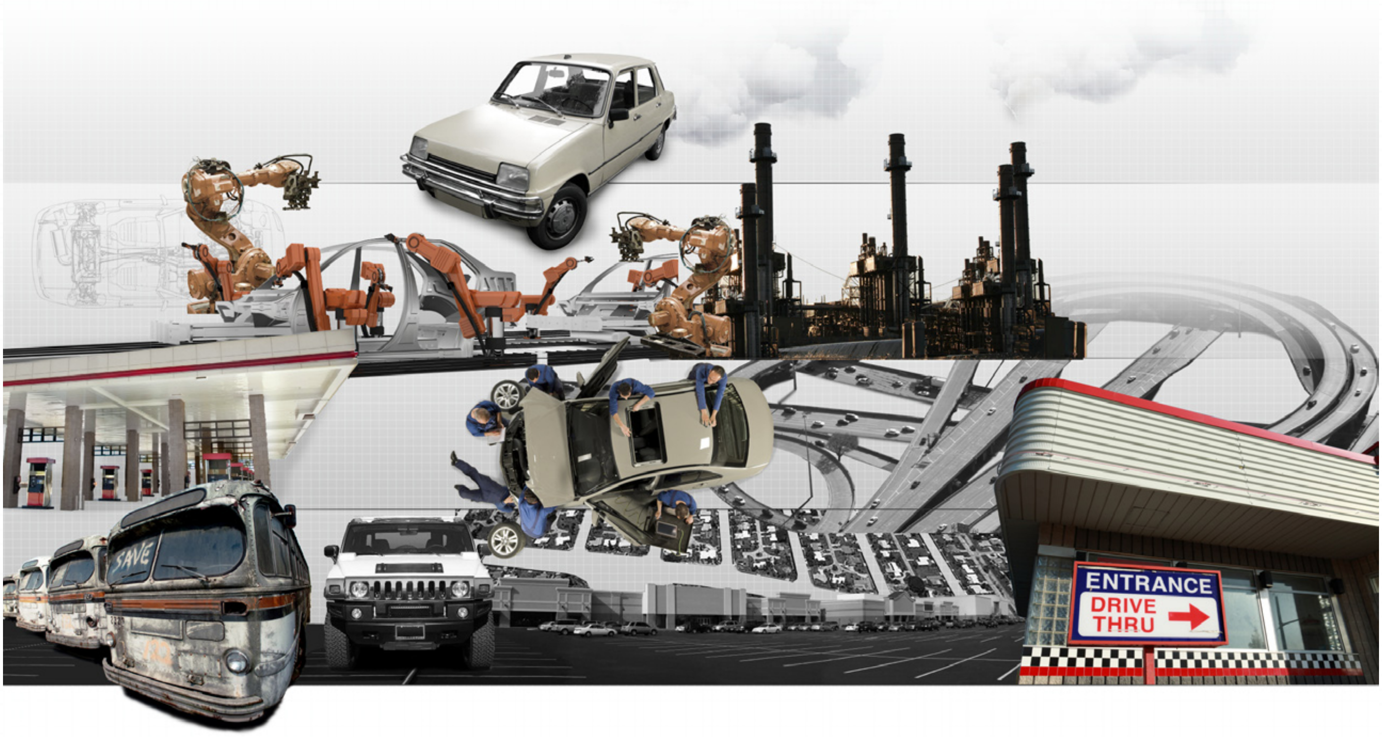
- Support existing and new **efficiency**-enabling solutions to fully capitalize on their short term potential
- Anticipate and nurture the progression towards large scale **biomaterial** and **closed loop** systems
- Ensure that the supply of industrial biotechnology feedstock **land** is managed according to principles of **sustainability**

The industrial biotechnology industry can realize such goals by pursuing strategies such as:

- Scoping existing markets to identify areas where higher GHG emission reductions can be achieved with existing or emerging industrial biotechnology applications
- Developing standards and tools, to be deployed systematically across the industry and for all applications, that document the GHG impacts of industrial biotechnology solutions
- Working with customers and suppliers to develop funding instruments for low-carbonsolutions
- Pursuing R&D and market investments in biobased materials following 'Designed for the Environment' approaches, which include solutions to 'close the loop'
- Working with policy makers to develop policies that support the progression towards large scale biomaterial and closed loop systems
- Supporting the development and implementation of public policies that address the risk of unsustainable land use practices being associated with the production of industrial biotechnology feedstock

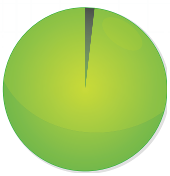
Major crises such as the climate change demand bold approaches. As difficult as it is, we must change the mindset and the practices that got us into this crises to start with. Just improving old technology will not be enough. If we fail to acknowledge and support technologies and sectors as the ones described in this report, we risk reducing the problem at the expense of solving it. Advancing the industrial biotechnology sector into a rapid establishment of a bio refinery infrastructure, able to compete with the petrochemical complex, is a great example of such a bold a crucial approach.

RE-THINKING THE CLIMATE CHANGE CHALLENGE



The figure illustrates the emissions associated with a car journey that originate from petrol stations, car manufacturers, roads, etc. Furthermore, private vehicle transportation systems enable important services, such as shopping malls located on the outskirts of cities, detached from public transportation, which will promote further dependency on private transportation. This is often overlooked when climate change mitigation strategies are made.

WHAT WE REALLY NEED is a shift in focus. We must actually try to solve the climate change issue rather than merely reducing its magnitude; we need to address not only what we must do less of, but also what we should to do more of in order to secure deep GHG emission cuts while simultaneously creating jobs and economic growth.



THE 2% EMISSIONS refers to the emission reductions from more energy efficient production of the products or services

THE 98% POTENTIAL refers to the capacity of the products or services to help other economic actors to reduce their emissions

This might seem in line with current climate change mitigation strategies. However, the fact is that almost all our current mitigation efforts are directed at making the current system more efficient, for example by reducing transportation emissions through improved vehicle efficiency. More efficient vehicles do save large amounts of GHG emissions, but it is important to understand that increasing vehicle efficiency will not provide a truly sustainable transport solution. For example, the supporting infrastructure of a transportation system based on private vehicle transport generates a huge amount of emissions. That is why for instance electrification of all transport modes and based increasingly on renewable power is fundamental part of the transport solution.

Solving the climate crisis by focusing purely on efficiency gains will not ensure the necessary 90% reduction in emissions that is required by 2050, as the original economic infrastructure will remain largely unchanged.

IT IS CRUCIAL THAT THE SHORT-TERM EFFICIENCY FOCUS IS COMPLEMENTED BY STRATEGIES THAT FOCUS ON IDENTIFYING AND BOOSTING SECTORS AND APPLICATIONS THAT HAVE THE POTENTIAL TO TRANSFORM AND FUNDAMENTALLY CHANGE HOW WE MEET OUR SOCIO-ECONOMIC NEEDS.

In order to do this we need to explore alternative systems, rather than merely doing what we already do a little better. We therefore need to begin by identifying how we can eat, live, move and have fun in new and smarter ways.

It is unclear how we will meet the future needs of every human being within the limits of our planet. However, it will require significant innovation and a strong focus on identifying the opportunities for creating value and delivering services with considerably less emissions than today.

In certain sectors, such as industrial biotechnology, ICT (Information and Communication Technology) and the renewable energy sector, the capacity of products to enable other economic actors to reduce their emissions outweigh the emissions they create by between 20 and 30 times. This is often referred to as the 2/98% opportunity inspired by the ICT sector where the sector's own internal emissions amount to only 2% of global emissions but its products and services could play a major role in reducing the remaining 98%.

Despite not having the attention of decision makers, applications from industrial biotechnology already save the world 33 million tonnes of CO_2 whilst emitting only 2 million tonnes per year.

DOING MORE WITH LESS

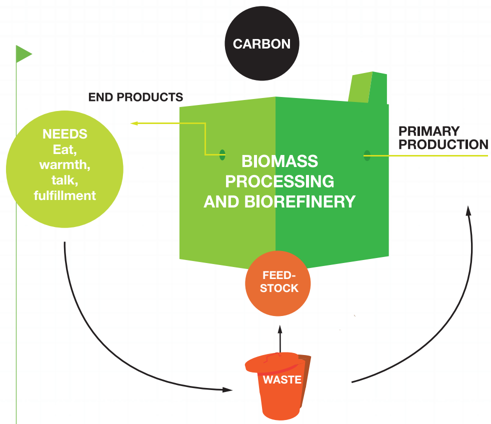
INDUSTRIAL BIOTECHNOLOGY IS THE APPLICATION OF BIOTECHNOLOGY FOR INDUSTRIAL PURPOSES, INCLUDING MANUFACTURING, ALTERNATIVE ENERGY (OR "BIOENERGY"), AND BIOMATERIALS. IT INCLUDES THE PRACTICE OF USING CELLS OR COMPONENTS OF CELLS LIKE ENZYMES TO GENERATE INDUSTRIALLY USEFUL PRODUCTS (EUROPABIO)[2, 3]

THE HYPOTHESIS AND VISION underpinning this report is that sustainable biotechnology solutions, applied in the industrial sector, can provide a vital contribution in the transition from current, unsustainable, economic practices to more sustainable economic systems, that can meet human needs without destroying the natural ecosystems that support life on our planet. To achieve such a transition several critical changes are required, both in mindset and practice, as illustrated by the table below.

Most people are unaware that industrial biotechnology applications are already applied in a broad range of everyday activities. They are for instance used to reduce the time needed to bake bread, to increase the yield in wine, cheese and vegetable oil production and to save heat in laundry washing and textile making. In other words, established biotechnology already allows us to do more with less.

If existing biotechnology solutions were used throughout the food industry today they would save between 114 and 166 million tonnes GHG emissions every year. If existing biotech solutions were used extensively in other traditional industries, such as detergent, textile, and pulp and paper manufacturing, another 52 million tonnes of GHG emissions reductions would be achieved annually.

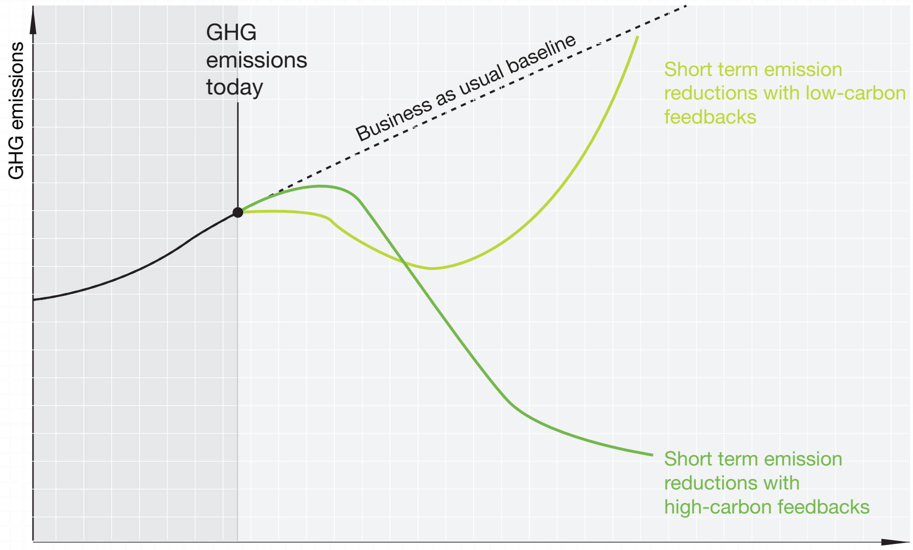
Key dimensions	Unsustainable	Sustainable
Societal/Policy goals	Exponential resource consumption	Growth in well being
Approach to nature	Control over nature	In harmony with nature
Predominant work mode	'Big is better'	'Smart is better'
Focus of business activities	Goods	Services/needs
Energy sources	Fossil fuels	Renewable energy (including biofuels)
Typical Materials	Iron, steel and cement	Biobased materials and digitalization/dematerialization
Predominant chemistry	Energy intensive	Low energy – Biomimicry
Waste production	High waste	No waste



The biobased economy

Output from primary production (agriculture and forestry) is used as feedstock for the production of intermediate and final products and services, which satisfy human needs. Once used, end-products become feedstock for the production of other products, achieving a closed loop.

DOING MORE OF THE RIGHT THINGS



GHG emission pathways with Biotech

INDUSTRIAL BIOTECHNOLOGY IS STILL to mature as an industry and there is no doubt that the efficiency gains that can be made from current applications are only the tip of the iceberg, in terms of emission reductions currently achieved but more significantly in terms of transformational potential.

IN SUMMARY, INDUSTRIAL BIOTECHNOLOGY CAN ENABLE A SHIFT TOWARD A BIOBASED ECONOMY. A BIOBASED ECONOMY IS BASED ON PRODUCTION PARADIGMS THAT RELY ON BIOLOGICAL PROCESSES AND, AS WITH NATURAL ECOSYSTEMS, USE NATURAL INPUTS, EXPEND MINIMUM AMOUNTS OF ENERGY AND DO NOT PRODUCE WASTE AS ALL MATERIALS DISCARDED BY ONE PROCESS ARE INPUTS FOR ANOTHER PROCESS AND ARE REUSED IN THE ECOSYSTEM.

However, the type of emission cuts we pursue from industrial biotechnology and how we achieve them makes a crucial difference. As with most technologies, the potential to achieve sustainability objectives does not automatically translate into such goals being realized. Industrial biotechnology is no exception.

The question is to what extent industrial biotechnology can transform a fundamentally unsustainable system into a sustainable biobased economy – or just provide a streak of green in a dirty system.

Some current biotechnology applications reduce emissions but also lead to a high degree of carbon feedback. These reductions are valuable and needed in the short term but risk binding us to future emissions if we don't pursue further transformation of the economic infrastructure.

Without the right policy context biotech solutions might lead to increased emissions and/or lock us into an infrastructure dependant on liquid hydrocarbons, which would create a "high-carbon feedback". Particularly biotech solutions involving biofuels may contribute to situations where short-term benefits are eroded by rebound effects and perverse incentives that lead to greater long-term emissions.

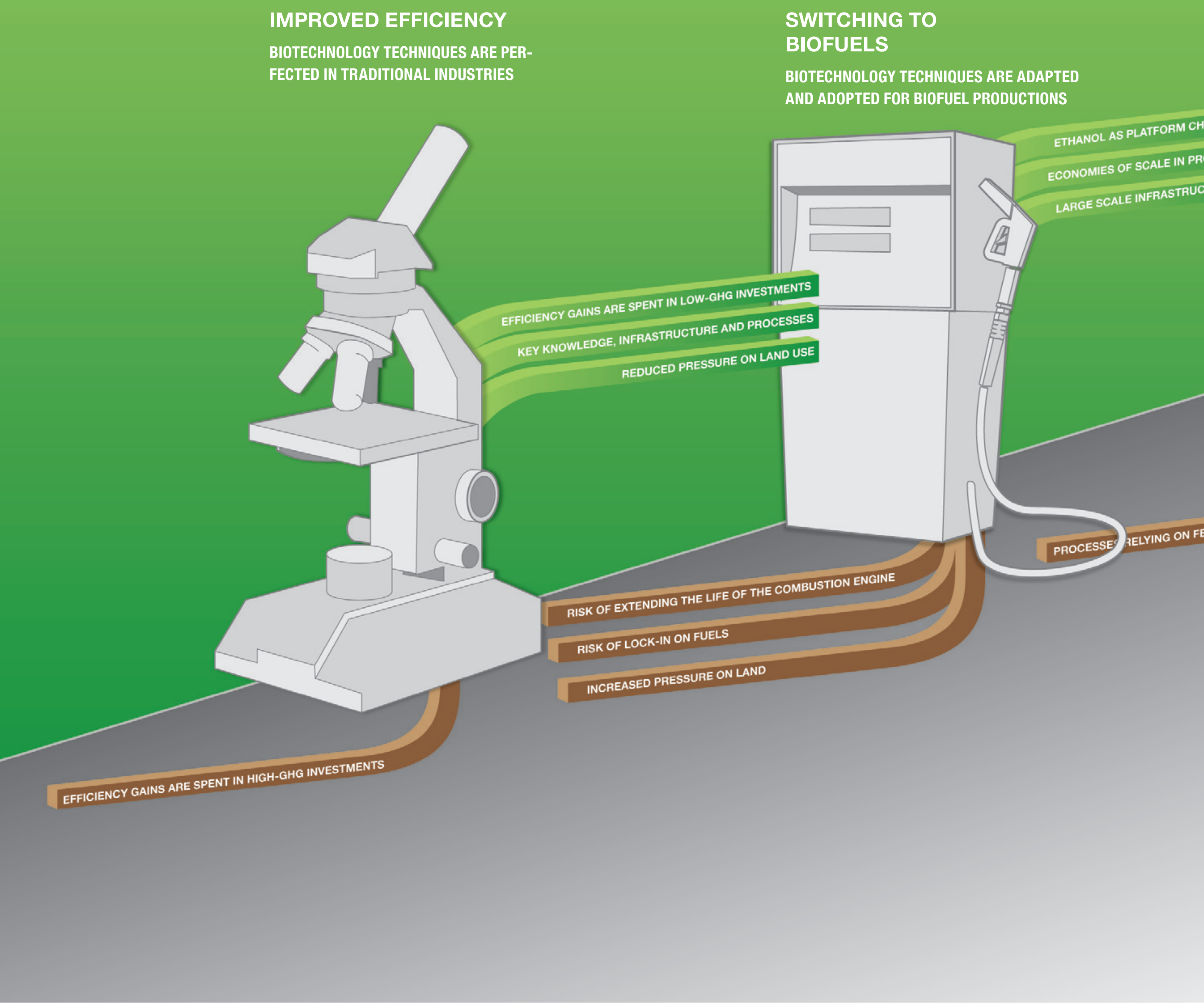
Indeed, the production of biofuel will lead to some very "low-carbon feedback" mechanisms in the future as bioethanol know-how and resources have paved the way for the development of biorefinery technology, and which has created the technological foundations for replacing oil-based materials with biobased materials.

The figure above provides an illustration of these alternative paths.

The analysis of current technological and market developments within the biotechnology sector indicates opportunities to pursue a path of lower GHG emissions over time as illustrated in the figure below. However, it is crucial to ensure the progression from improved efficiency, to the substitution of oil-based materials, and toward a circular economy where materials are reused.

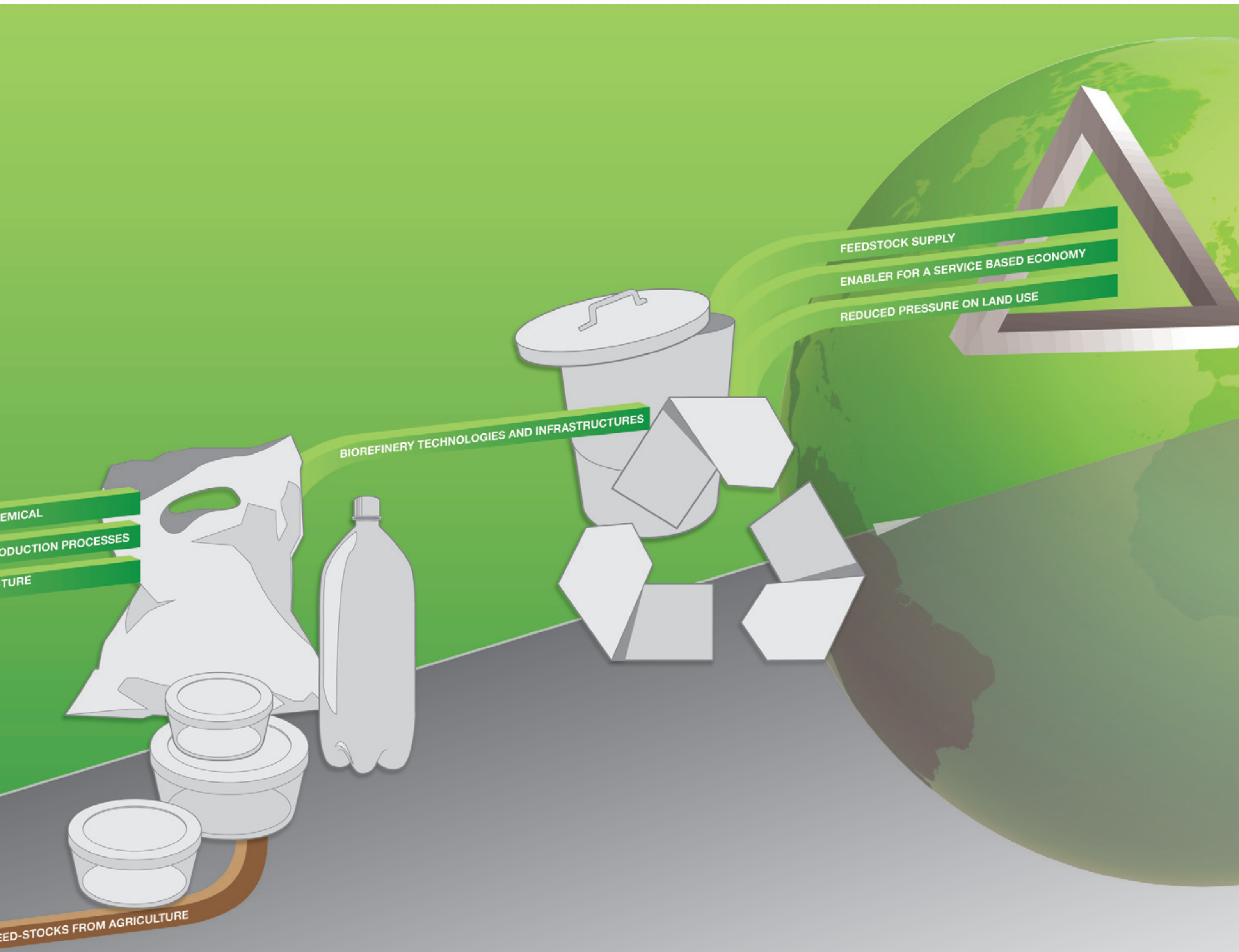
A High-Carbon feedback is a situation that encourages new applications, behavior and institutional structures that result in increased CO_2 emissions. Some biotech applications can support higher emissions over the long-term, even if they contribute toward reduced short term CO_2 emissions. A Low-Carbon feedback is the opposite situation where a biotech application encourages new services, behavior and institutional structures that result in reduced CO_2 emissions over the long-term.

INDUSTRIAL BIOTECHNOLOGIES' PATH TO A LOW-CARBONECONOMY



THE LOW-CARBON PATH DESCRIBED is not inevitable. We need to make it happen through informed investments and policymaking decisions that maximize low-carbon feedbacks and minimize high-carbon feedbacks.

As the figure illustrates, there are four fundamental dimensions of the contribution of industrial biotechnology: improved efficiency, the substitution of fossil fuels, the substitution of oil-based materials and a closed loop system with the potential to eliminate waste. As the industry develops and matures there is a possibility that elimination of oil-based products and closed loop systems will make up the major proportion of the industry's GHG



REPLACING PETROCHEMICALS WITH BIOBASED MATERIALS

BIOFUEL PROVIDE FEEDSTOCK AND CRITICAL INFRASTRUCTURES FOR THE CREATION OF A BROADER SPECTRUM OF BIOBASED MATERIALS

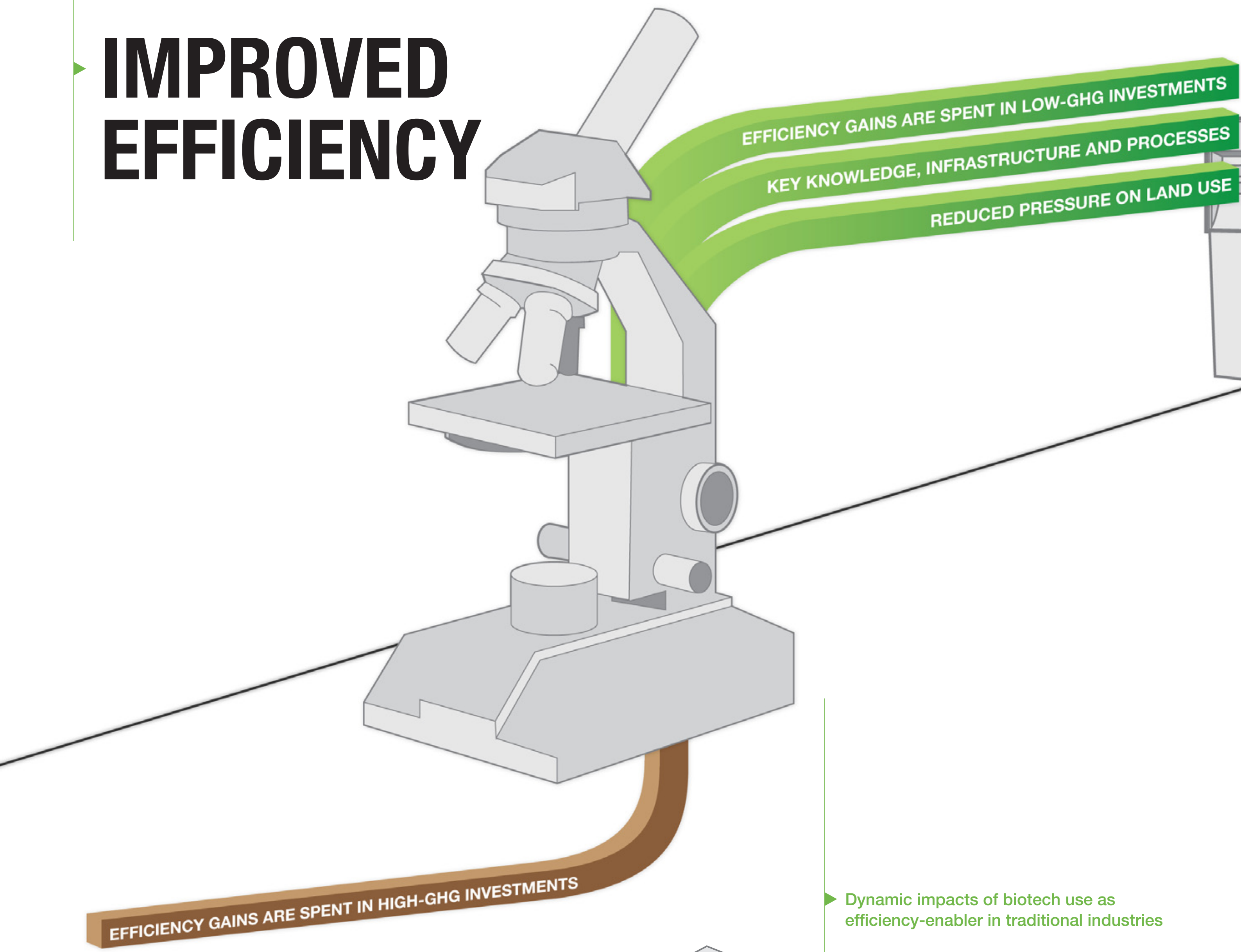
CLOSING THE LOOP

BIOMATERIAL TECHNOLOGIES (BIOREFINERY) ENABLE THE REUSE OF WASTE MATERIALS AS FEEDSTOCK FOR ENERGY AND MATERIALS

reduction contribution, although all four dimensions will contribute. There are substantial differences not only between the reduction potential of the four dimensions but also the extent of high and low-carbonfeedbacks they trigger.

These four dimensions, their content, reduction potential and dynamic effects, are discussed in the following four sections.

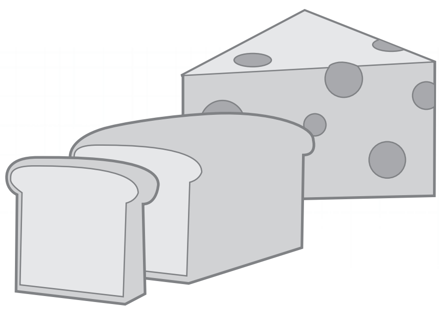
IMPROVED EFFICIENCY



Dynamic impacts of biotech use as efficiency-enabler in traditional industries

NATURAL ORGANISMS OR ENZYMES are currently used in a number of processes within traditional industries, such as in the food industry and other industries that use raw materials derived from living organisms as key production inputs, e.g. pulp and paper, leather and textile industries.

Enzymes and other biological organisms can perform industrial processes with significantly less energy, without the use of aggressive chemicals and with less waste, compared with traditional manufacturing systems. Industrial biotechnology consequently results in a more efficient use of natural resources and reduced energy consumption, either during the production stage when enzymes or yeast are added or indirectly in connected stages along the value chain. In particular, when deployed downstream in value chains,

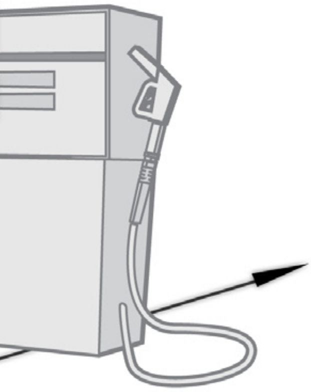


efficiency gains can be multiplied upstream with positive impacts in term of resource usage, GHG emissions and pollution.

Whereas the market penetration of efficiency-enhancing industrial biotechnology solutions varies by type of application, reflecting different degrees of market maturity, overall opportunities for further growth appear significant. Such growth would be accompanied by a corresponding increase in emission reductions enabled by industrial biotechnology applications.

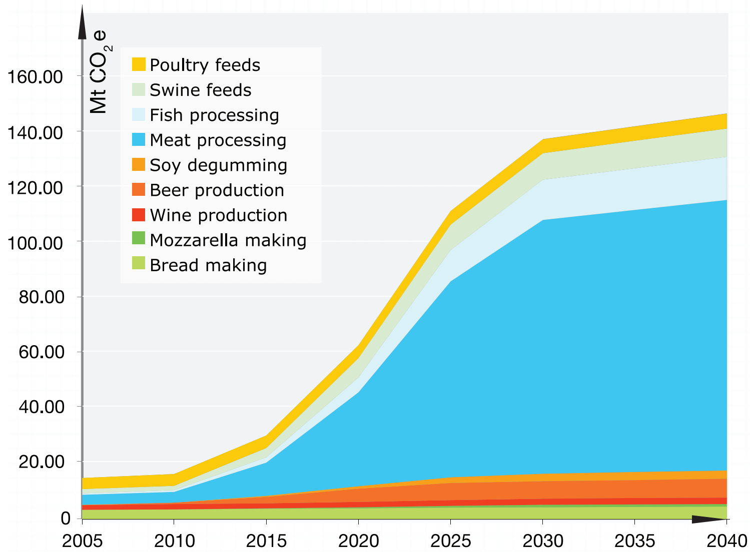
In addition to the potential GHG benefits highlighted above, the deployment of efficiency enhancing biotechnology solutions in food and other traditional industries can potentially have a number of dynamic impacts that lead to low- or high-carbon feedbacks:

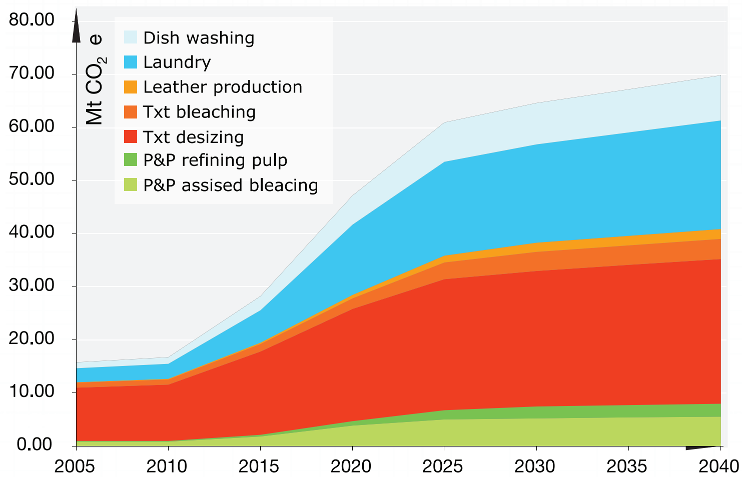
- Increased resources (income for suppliers or consumers) made available by more efficient processes can be invested in activities that further decrease GHG emissions (low-carbon feedback,[4]) or may be spent on products or activities associated with high GHG emissions (high-carbon feedback).[5]
- The ongoing development of biotechnologies for the food and other traditional industries is critical for the development of



knowledge, infrastructure and processes that can be adopted by other sectors, which can subsequently generate significant GHG emission reductions. The development of these biotech applications in the food industry, therefore, produces ‘positive externalities’ that can generate GHG emission reductions in broader sections of the economy (low-carbon feedback).

- Energy efficiency in the food industry and in other industries that use agricultural products as feedstock (e.g. pulp and paper, leather production, textiles production) enables the use of smaller areas of land to deliver the same benefits. Thus, additional land becomes available for other biobased applications that enable reductions in GHG emissions (low-carbon feedback).

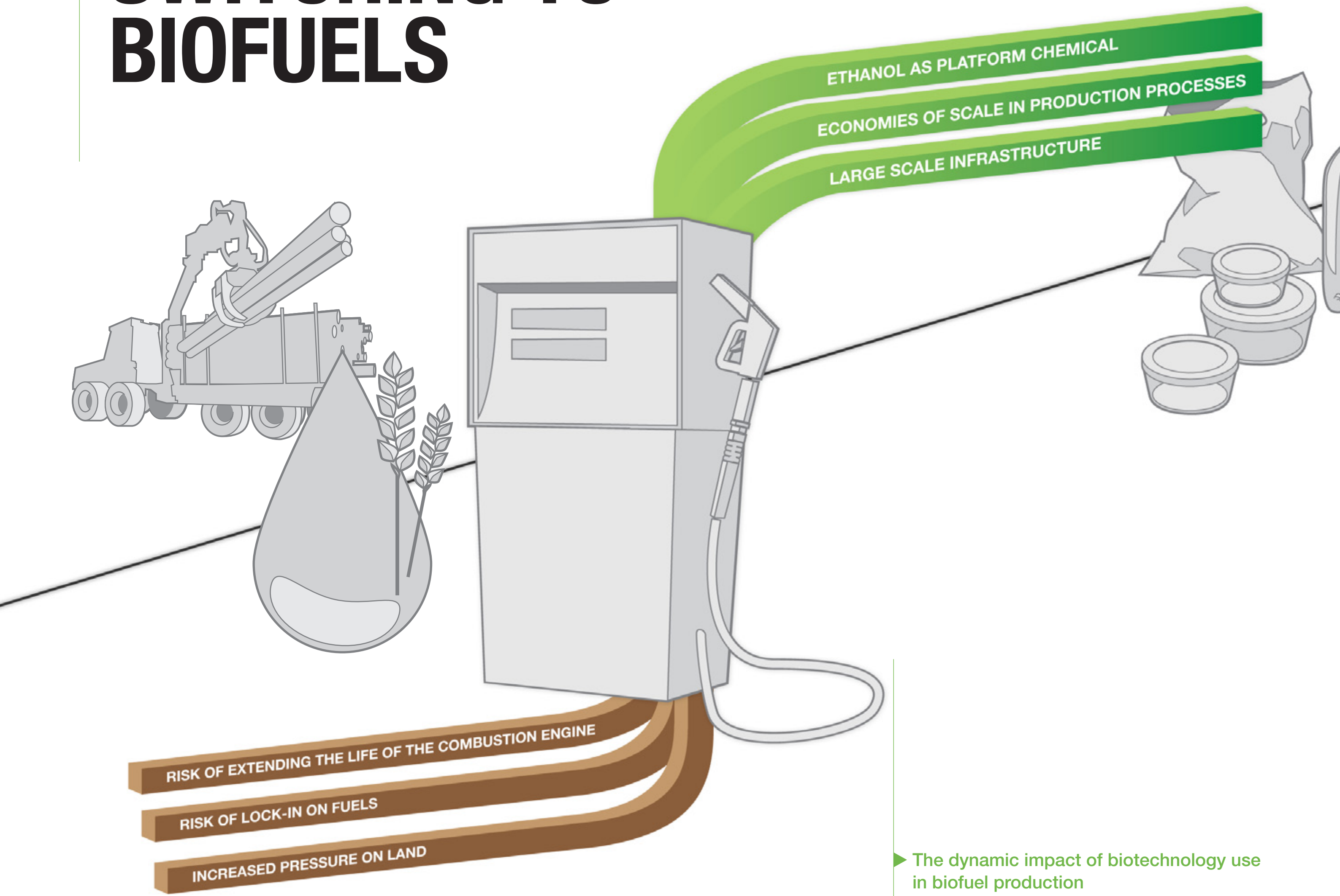




GHG emission reductions achieved by industrial biotechnology in food and traditional industries, assuming industrial biotechnologies reach 100% market penetration by 2030

Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030	Key factors determining the emission reductions
Efficiency improvements in food and traditional industries	• Food industry: up to 139 $MtCO_2$ e • Other traditional industries Up to 65 $MtCO_2$e	• Baseline growth of population and income, and the associated impacts on food and industrial production • Adoption of industrial biotechnology solutions • GHG intensity of baseline industrial processes

SWITCHING TO BIOFUELS



The dynamic impact of biotechnology use in biofuel production

FEEDSTOCK PROCESSING AND FERMENTATION expertise and technologies developed for the food industry were essential in the creation of biotechnology solutions for the processing of agricultural feedstock (or other biological feedstock) into biofuels.

The main use of biotechnology in the biofuel sector today is for bioethanol production. Emerging technologies, currently in R&D or demonstration phases, will also enable the use of biotechnology solutions for the production of biobutanol and biodiesel.[6]

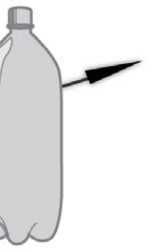
Bioethanol, biodiesel, and biobutanol can provide alternatives to fossil fuels in the transportation sector, particularly for internal combustion engines, and potentially reduce GHG emissions per km travelled.[7]

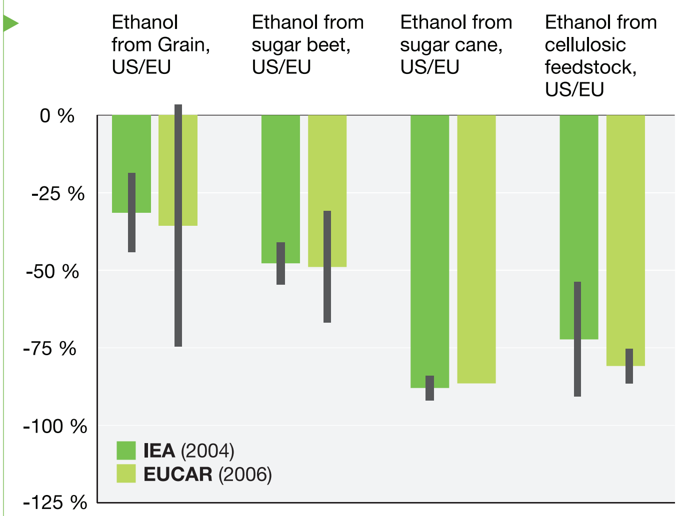
GHG emissions from transportation have steadily increased in recent decades, in both developed and developing countries, and are projected to further increase in the future. Bioethanol and other biofuels could provide a useful instrument to mitigate this increase as they can reduce the amount of GHG emitted per km travelled.

The analysis of alternative scenarios highlights the fact that biofuels have significant potential to deliver emission reductions versus a baseline situation in which no biofuels are present in the market.[8] Whereas biofuel consumption (as % of total fuels) creates a greater effect on emission reductions, a quicker development of second generation biofuels can also play a significant role, almost doubling the emission reductions that can be achieved, given a similar market penetration for biofuels. The rapid adoption of second generation biofuels and their substitution of about 20 % of fuels has the potential to deliver about 1 billion tonnes of emission reductions by 2030. Alternatively, the emission reductions potential would be almost 50 % lower, at 530 MtCO2e, without a rapid introduction of second generation biofuels.[9]

The development of innovative biotechnologies for biofuel production, and fossil fuel substitution, also has the potential to generate a number of dynamic impacts:

- The biotechnology-enabled production of biofuels in large volumes may play a critical role in unlocking economies of scale in the industrial biotechnology field while also stimulating the creation of the essential logistical systems needed to collect the feedstock, distribute the biofuels, or any other





Reduction in the GHG emissions of selected biofuels relative to fossil fuels - average values (bars) and variances (grey lines)[10]

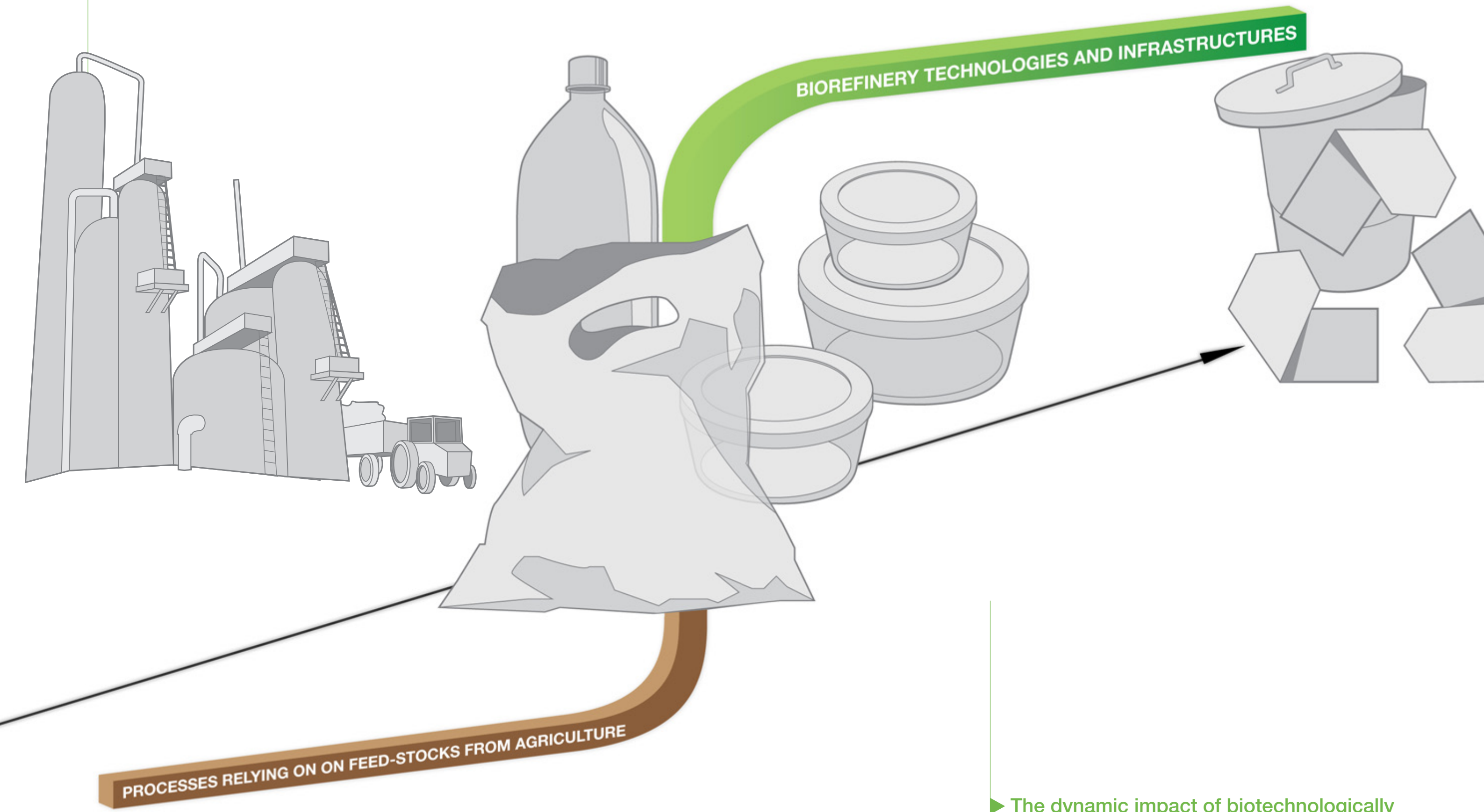
Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030 [11]	Key factors determining the emission reduction
Biofuels	207 to 1,024 $MtCO_2e$	• Price of feedstock • Price of petrol • Technology development • Public policies providing incentives (or disincentives) for biofuel adoption to ensure a sustainable development of the biofuel industry

end-product, and process secondary products generated from biofuel production. These factors are enablers for a wider use of biotechnologies in the creation of a variety of biobased, low-GHG emission compounds, which can replace petrochemical products (low-carbon feedback).

- Ethanol is a platform chemical, which can be used as feedstock for the production of a variety of other compounds. The ability to produce large volumes of bioethanol efficiently is therefore an additional enabler for the biotechnological production of biobased material (low-carbon feedback).
- The switch from fossil fuel to biofuel vehicles may create a false sense of progress, which may lead to complacency and a slower dissemination of more radical innovations, which are needed to dramatically reduce the GHG emissions associated with transportation (high-carbon feedback).
- The strong focus on biofuels, that is typical of current policies, may lead to the creation of highly specialized biotechnology solutions (in terms of feedstock, enzymes, fermentation processes, separation processes, etc.), which are not compatible with the production of other biobased materials and may reduce or delay their adoption (high-carbon feedback).
- As investment resources are finite, heavy investment in biofuels may reduce investment in broad-spectrum-biorefinery projects, which are essential for the production of a large variety of the low-GHG biobased materials (high-carbon feedback).
- Finally, the rising demand for biofuels will lead to an increased demand for feedstock. This will create pressure to devote more land to feedstock production, with the risk of releasing significant quantities of carbon stored in vegetation and soils into the atmosphere (high-carbon feedback).

In general, biofuels can play a vital role to curb short term emissions growth while helping to develop the technologies and infrastructures that can support the establishment of a stronger market for biobased materials. These can in turn have the potential to deliver even greater GHG emission reductions and low-carbon feedback over the long term.

REPLACING PETROCHEMICALS WITH BIOBASED MATERIALS



INCREASING INVESTMENT IN THE biofuel sector, in response to existing incentives, facilitates the construction of the necessary physical infrastructure and associated technologies for the cost-effective collection, utilization and processing of natural feedstock. Advancements in industrial biotechnology, such as the increased productivity and yield of fermentation processes, are simultaneously creating broader opportunities for the production of materials from natural feedstock. The combination of these two factors presents the opportunity to produce a greater variety of biobased materials. In particular, biotechnology processes that are suited to the processing of natural feedstock into the sugars and building blocks necessary for the production of secondary chemicals and end-products.

Upstream processes, such as those targeted by industrial biotechnology, can be energy intensive and use large volumes of oil feedstock. The substitution of petrochemical processes with biobased processes can therefore produce significant benefits in terms of GHG emission reductions. The EU-funded BREW project[12] which was based on independent analysis and expert input from industry representatives, identified a number of biobased materials produced biotechnologically that present opportunities to achieve significant emission reductions, due to their large production volumes and GHG benefit per ton of production (see table to the right).

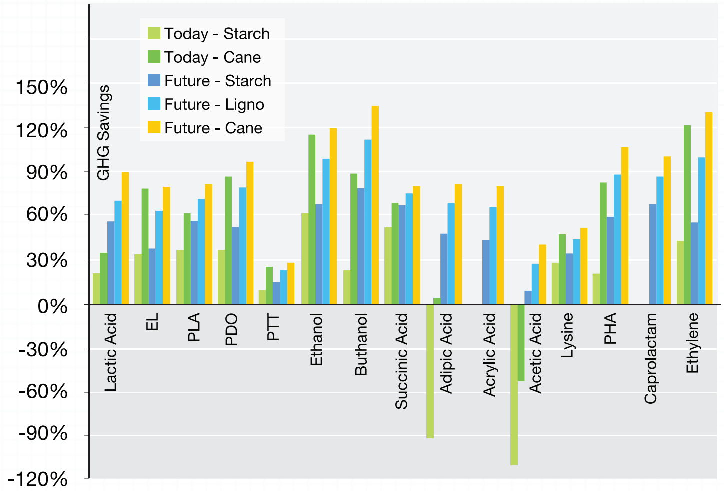
Life cycle analyses of biobased materials produced with industrial biotechnology conclude that significant reductions of both energy consumption and GHG emissions are possible in most cases with current technologies.

Emerging technologies and the ability to utilize a broader set of feedstock can further increase

The dynamic impact of biotechnologically produced biobased materials

Biobased Chemical	Reference Petrochemical
PHA (plyhydroxyalkaonates)	HDPE (high density polyethylene)
PTT (polytrimethylene terephtalate) From 1,3 propanediol	PTT, Nylon 6
PLA (poly lactic acid)	PET (polyethylene terephtalate) PS (polystyrene)
Ethyl lactate	Ethyl lactate
Ethylene	Ethylene
Succinic acid	Maleic anhydride
Adipic acid	Adipic acid
Acetic acid	Acetic acid
n-butanol	n-butanol

Biobased chemicals and their petrochemical reference[13]



The GHG emission savings of biotechnology based products vs. petrochemical equivalent[14]

Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030	Key factors determining the emission reduction
Biobased material production	282 to 668 $MtCO_2e$	• Market developments in the industrial biotechnology as well as in the petrochemical fields (i.e. Feedstock and crude oil prices) • Public sector policies • Private sector proactivity in developing the biobased materials business (vs. concentrating only on biofuels) • The speed of introduction of second generation technologies (able to use lignocellulosic feedstocks)

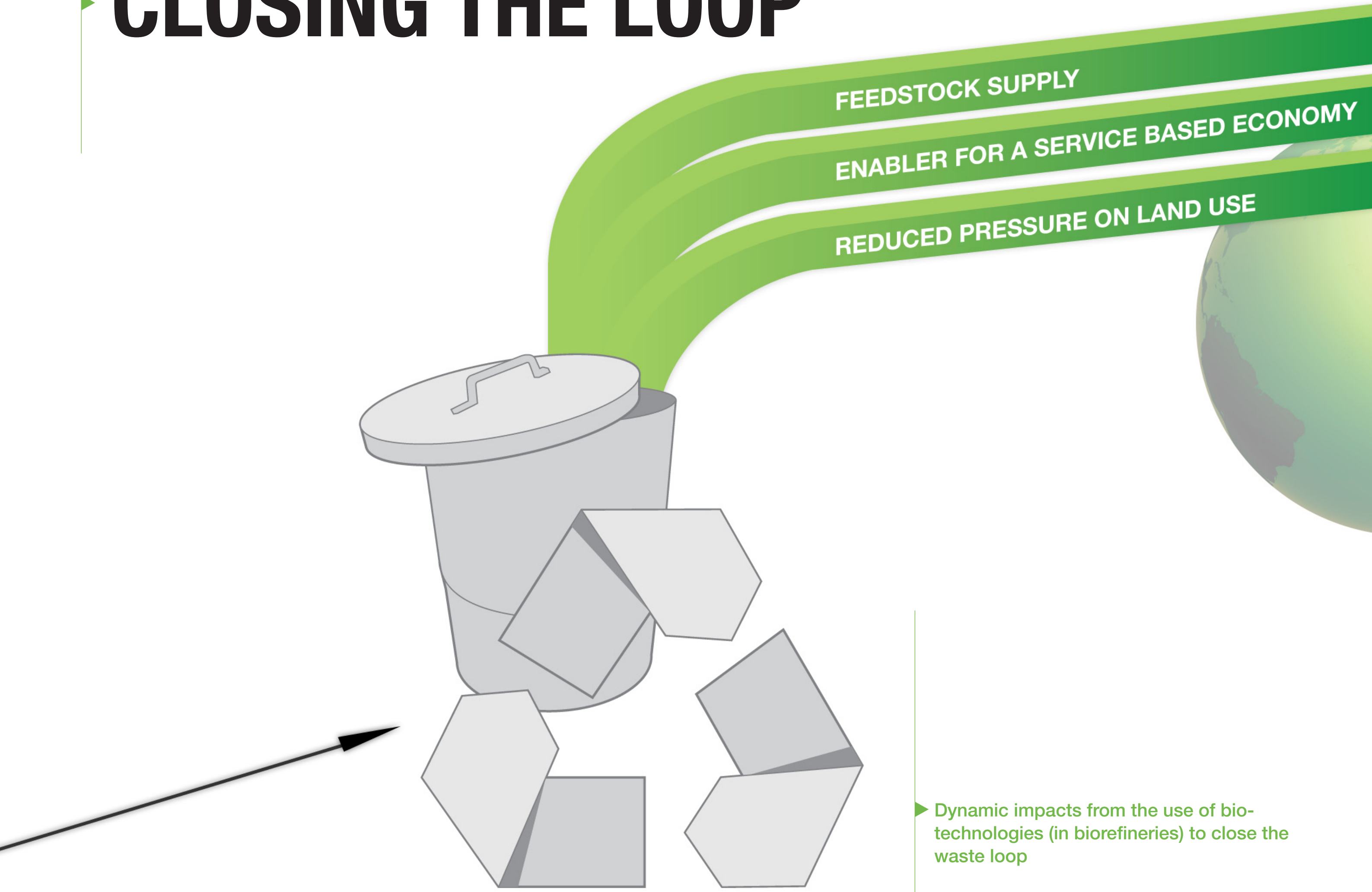
the GHG emission reductions that are achievable. This is illustrated by the figure above, which compares the average GHG savings of industrial biotechnology products with their petrochemical equivalents (see figure above).

The analysis of alternative market and technological development scenarios highlights that significant GHG emission benefits can be achieved by utilizing industrial biotechnologies in the production of biobased materials.[15]

In addition to the potential illustrated above, the creation and dissemination of industrial biotechnology plants creates the conditions to achieve economies of scale and scope, which promote learning and the perfection of relevant biotechnological techniques. When critical mass is achieved, network economies are also possible as the use of a broad variety of natural feedstocks by a significant number of production facilities removes cultural barriers and provides incentives to feedstock suppliers and infrastructure providers to supply their goods and services to industrial biotechnology facilities, while enticing a larger number of end-users to source biobased materials.

- The use of biotechnology in the production of biobased materials can lead to the establishment of a significant number of biorefineries capable of producing a broad range of end products. Such versatile biorefineries can be a critical building block for the creation of production systems that dramatically reduce waste, as all materials produced, used and disposed can re-enter the production cycle (low-carbon feedback).
- However, the construction of versatile biorefineries, able to transform waste into valuable raw materials, is not a necessary outcome of the biotechnological production of biobased materials. Specialized biorefineries, that only use agricultural feedstock, could also emerge if the broader market and policy environment was to direct industrial biotechnology investment in this manner. This may limit the GHG benefits achieved by industrial biotechnology and increase pressure on potential land for feedstock production, with the risk of releasing carbon currently sequestered in natural ecosystems into the atmosphere (high-carbon feedback).

CLOSING THE LOOP



Dynamic impacts from the use of biotechnologies (in biorefineries) to close the waste loop

SIGNIFICANT AMOUNTS OF CARBON are disposed of each day through solid waste and wastewater. IPCC estimate that approximately 900 Mt of such waste was produced worldwide in 2002, and over 33 tonnes of BOD[16]/day were present in industrial wastewaters alone.[17] The carbon present in waste streams constitutes a valuable resource that has the often untapped potential for energy generation, through incineration or biogas extraction from landfills. Methane may be produced when carbon is disposed of in anaerobic environments, which contributes to global warming if released into the atmosphere.[18] Biotechnology solutions currently entering the market or being tested can increase the amount of biogas harvested from digesters and wastewater streams, which increases the amount of biogas that can be extracted for energy generation and improves the business case for companies that use waste to produce energy.

This application of biotechnology to produce biogas provides a useful solution, which can improve the performance (or reduce the negative impact) of existing waste management systems. However, the technique still leads to the emission of biogenic GHG into the atmosphere and requires plants (and land use) to 'close the loop' and recycle the natural carbon as feedstock. Biotechnology solutions, however, have the potential to go one step further by creating a fully closed loop system.

The establishment of a significant number of biorefineries, able to produce a broad range of end products by utilizing a large variety of feedstock, provides the opportunity to transform any biobased material into a valuable feedstock for the production of other biobased materials or biofuels. Biorefineries can therefore 'close the loop' between waste and production, and enable the creation of socio-economic systems that produce significantly less waste, as the organic materials produced, used and disposed of re-enters the production and consumptions cycles through biorefineries.

From a GHG emission perspective closed loops have two potential advantages versus open loops:

- The ability to produce biobased materials generates less GHG emissions. Although, this ability depends on the efficiency of the processes that use agricultural feedstock and waste derived feedstock.
- The creation of growing pools of biobased/renewable carbon that is stored in end-products and is continuously reused in production processes. As additional biobased carbon derived from farming activities is continuously added to this pool, a growing volume of carbon is ultimately stored in end-products.

Closed loop systems that can efficiently create new products from waste materials, could sequester almost 3 billion tons of additional renewable carbon by 2040, according to a 'high growth high penetration' biobased materials scenario.

By creating separate carbon pools that do not rely on agriculture production, closed loop systems:

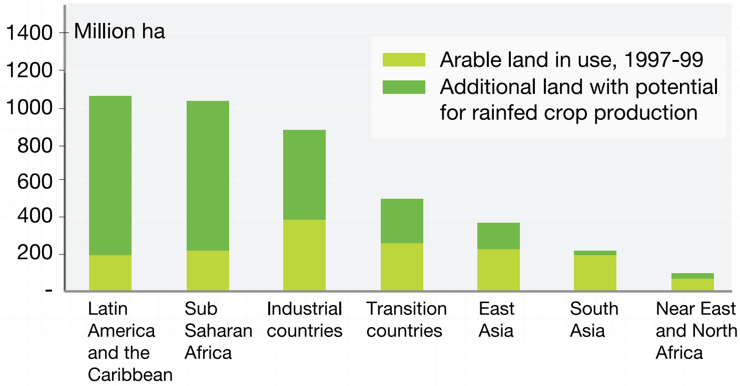
- Reduce pressure on land use and therefore enable a larger production of biotechnology produced biobased materials (low-carbon feedback).
- Perhaps more significantly, the ability to create closed loop systems is an enabler for the creation of new solutions in which the services/benefits delivered by a product, rather than the product itself, are sold to end users. This critical contribution towards a service-based economy may be the most significant low-carbonfeedback attainable through closed loop systems enabled by biotechnology.

Although the data underlying the analyses above are not based on actual biorefinery-enabled-closed-loop-systems, they indicate that closed loop systems have the potential to contribute significantly to the GHG emission reductions attainable through industrial biotechnology solutions. The creation of closed loops should therefore form an integral part of any strategy pursuing GHG emission reductions with industrial biotechnology.

Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030	Key factors determining the emission reduction
Closing the loop	376 to 633 $MtCO_2e$ or renewable carbon stored in materials	• Speed of development of versatile biorefineries • Presence of logistical infrastructure to enable closed loops • Growth of the underlying market for biobased products

LAND USE

Potential for cropland expansion[22]



ANY EFFORT TO ANALYZE THE GHG mitigation potential achieved through industrial biotechnologies need to consider one critical physical constrain; namely land availability. The industrial biotechnology solutions discussed above lead to various impacts on land use, as summarized in the table on opposite page.

The total land use impact on the various industrial biotechnology applications analyzed in this report may therefore vary from between 43 Million Ha to 227 Million Ha, and would require about 195 Million Ha in the most favorable scenario in terms of emission reductions achieved at lower 'land use cost'. Land requirements for biofuel production appear particularly high in both absolute and relative terms.[19] The extreme situation in which all road vehicle fuels are substituted by biofuels would require a land area of approximately 1,100 Million Ha. This can be compared to the total worldwide cropland area of around 1,600 Million Ha.[20]

The sourcing of land for the production of industrial biotechnology feedstock can have a dramatic effect on the net GHG benefit achieved. The conversion of sensitive natural ecosystems, such as tropical rainforests, would generate significant 'carbon debts', deriving from the release of large amounts of carbon stored in vegetation and soil into the atmosphere. Such carbon debt would dramatically reduce the net benefit of industrial biotechnology. Alternatively, the conversion of marginal land may be possible without generating a carbon debt, which would maximize the positive impact of industrial biotechnology.

It is therefore critical that the growth of the industrial biotechnology sector takes place in a socio-economic environment in which the conversion of land for feedstock production does not lead to the release of high volumes of carbon stored in plants and soil, or to other negative environmental or social impacts that may result from unmanaged growth.[21]

In a recent study, the FAO (Food and Agriculture Organization) estimated that an additional 2 billion hectares are considered potentially suitable for rainfed crop production, as illustrated in the figure above.[22] Forest, wetland or other natural land provides valuable environmental functions, including carbon sequestration, water filtration and biodiversity preservation. It is estimated that between 250 and 800 Million Ha of additional agricultural land could be brought into production without encroaching upon areas of high ecological or social value, once forest, protected areas and the land required to meet increased demand for food crops and livestock is excluded. The authors of the FAO study, however, warn that these estimates should be treated with considerable caution.

The creation of strong and effective policies to ensure that land use constraints are adequately taken into consideration is therefore a necessary precondition for the development of an industrial biotechnology sector that can truly contribute toward GHG emission reductions and broader sustainability goals.

Land use impacts of different industrial biotech applications and scenarios[23]

Industrial biotech application	Description of impact on land use	Estimated impact in 2030
Efficiency enhancing applications	Food industry • (small) increase land use to produce efficiency enhancing enzymes • decrease in land use enabled by efficiency gains in various steps of the value chain Other industries • (small) increase land use to produce efficiency enhancing enzymes	Decreased pressure on land use (not quantified)
Applications associated with the switch to biofuels	• Significant impact on land use due to the potentially high production volumes • Decreased impact enabled by second generation biofuels	Land required: • 30 Mln Ha with second generation biofuels rapidly entering the market and biofuel penetration limited to 5% in large emitting countries • 262 Mln Ha with slow introduction of second generation biofuels and policy push for a 20% take up of biofuel in large emitting countries • 179 Mln Ha with rapid introduction of second generation biofuels and 20% take up in large emitting countries • If 100% of fuels used by road vehicles were biofuels: 1,085 Mln Ha
Biotechnologically produced biobased materials	• Significant impact on land use due to the potentially high production volumes • Decreased impact with second generation technologies • Possibility to use biobased materials in closed loop systems (see next raw)	Land required: • Slow growth of reference petrochemical market with fast take up of biobased products: 18 Mln Ha • Fast growth of reference petrochemical market with slow take up of biobased materials: 23 Mln Ha • Fast growth of reference market and rapid take up of biobased materials: 28.2 Mln Ha
Closing the loop	• Decrease impact on land use as biobased materials are continuously reused and create a separate pool of feedstock	Land saved, assuming fast growth and take up in biobased materials: • At the end of its useful lifespan: • a large proportion of biobased products is utilized as feedstock: 12 Mln Ha • a large proportion of biobased products is utilized as feedstock but yields are small: 7 Mln Ha • A small proportion of biobased products is utilized as feedstock but yields are high: 7 Mln Ha

ELEMENTS OF A STRATEGY FOR A BIOBASED ECONOMY

There is great potential to achieve GHG emission reductions with the intelligent use of industrial biotechnologies. Whereas several individual industrial biotechnology solutions can deliver significant GHG emission reductions at present, a greater potential can be realized if the synergies between different industrial biotechnology solutions are pursued, and if low-carbon feedbacks are consequently achieved.

In total, between 1,000 and 2,500 $MtCO_2e$ of emission reductions can potentially be achieved by 2030, compared with a scenario in which no industrial biotechnology applications are available. In comparison, the emissions reported by Germany in 1990 were 1,228 $MtCO_2$.

The actual impact of industrial biotechnologies on GHG emissions will largely depend upon the overall socio-economic environment and the policy landscape surrounding the dissemination of these technologies. Therefore, for industrial biotechnologies to realize their full GHG emission reduction potential it is paramount that strong public policies and private sector strategies are in place to channel the sector's growth toward low-carbon paths, while avoiding high-carbon lock-ins, which are often attractive due to their potential to deliver short term GHG emission reductions.

Such policies and strategies should:

- Support existing and new **efficiency**-enabling solutions to fully capitalize on their short term potential
- Anticipate and nurture the progression towards large scale **biomaterial** and **closed loop** systems
- Ensure that the supply of industrial biotechnology feedstock land is managed according to principles of **sustainability**

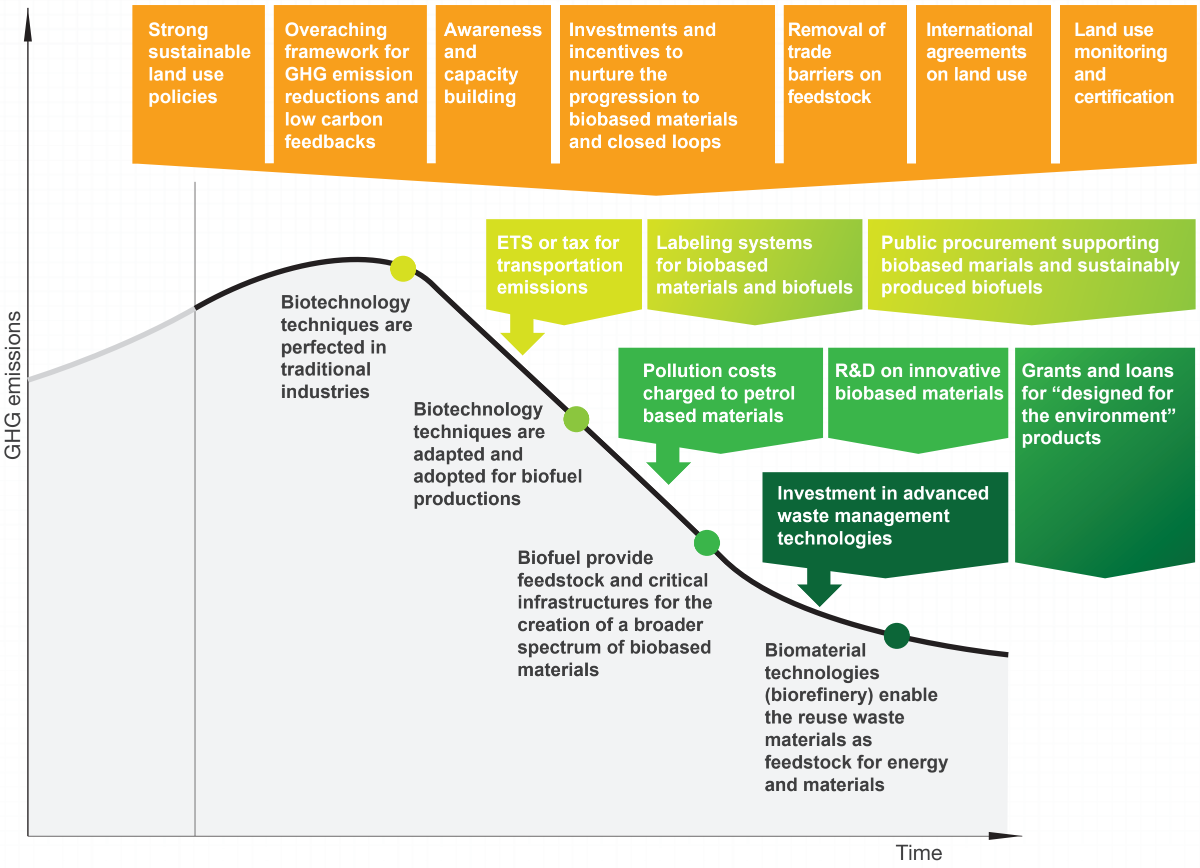
The industrial biotechnology industry can realize such goals by pursuing strategies such as:

- Scoping existing markets to identify areas where higher GHG emission reductions can be achieved with existing or emerging industrial biotechnology applications
- Developing standards and tools, to be deployed systematically across the industry and for all applications, that document the GHG impacts of industrial biotechnology solutions
- Working with customers and suppliers to develop funding instruments for low-carbonsolutions
- Pursuing R&D and market investments in biobased materials following 'Designed for the Environment' approaches, which include solutions to 'close the loop'
- Working with policy makers to develop policies that support the progression towards large scale biomaterial and closed loops systems
- Supporting the development and implementation of public policies that address the risk of unsustainable land use practices being associated with the production of industrial biotechnology feedstock

Policy makers could complement and stimulate private sector activities with specific public policies such as those summarized in the figure on opposite page:

However, the first crucial step is to ensure that the issue is integrated into all relevant policy making decisions with the aim to anticipate the progression of the sector towards biomaterial and closed loop systems through the establishment of biorefinery infrastructure.

Policies for a low GHG path



Governmental intervention can play a significant role in the effort to advance the industrial biotechnology sector down a low-GHG curve. General policies on land use and trade barriers removal as well as more specific policies, related to the different dimensions discussed in the report, are needed to "push" the sector in the right direction.

Industrial biotechnology dimension	Estimated GHG emission reductions vs. baseline 2030	Low-carbon feedback potential
Improved efficiency	Food industry: up to 139 $MtCO_2e$ Other traditional industries: Up to 65 $MtCO_2e$	• Efficiency gains invested in way that further reduce GHG emissions • Key knowledge, infrastructure and processes • Reduced pressure on land use
Switching to biofuels	207 to 1,024 $MtCO_2e$	• Economies of scale in production processes • Large scale infrastructure • Ethanol as platform chemical
Replacing petrochemicals with biobased materials	282 to 668 $MtCO_2e$	• Fully developed and versatile biorefineries
Closing the loop	376 to 633 $MtCO_2e$ or renewable carbon stored in materials	• Feedstock supply for material's production • Reduced pressure on land use • Enabler for the creation of a service-based economy
Total	1,066 to 2,528 $MtCO_2e$	

REFERENCES

1. The GHG emission reductions discussed in this section and in the sections below are based on the review and analyses undertaken in Marco Buttazzoni (2009) GHG emission reductions with industrial biotechnology: assessing the opportunities

2. Industrial biotechnology includes only the use of GMOs in contained environments.

3. Europabio - white biotechnology gateway for a more sustainable future.

4. This may for example be the case of investments in process efficiency, energy efficiency or renewable energy projects

5. This may for example be the case with expenditure on foods with higher GHG footprints, larger vehicles, larger and energy inefficient homes and appliances, etc.

6. Although based on a biological feedstock, currently the production of biodiesel is not based on a biological process as it relies on exterification processes in which alcohol reacts with the feedstock and extracts the oils that are then used for fuel

7. Whereas for some biofuels, e.g. ethanol from sugar cane, the GHG impact is clearly positive, and the degree of variability in the estimates of such impact is relatively low, for other biofuels, namely ethanol from grain, the degree of variability in the estimates is high and the estimated GHG impact, although generally positive, at times can be negative. Finally, with emerging technologies, such as ethanol from cellulosic feedstock, the GHG benefits are clearly positive, but the degree of variability in the estimates is high, reflecting the level of maturity in these technologies and the various feedstocks that are still experimented. The total level of benefit achieved, on a life cycle bases, depends on a number of factors including: type of feedstock used, land productivity, farming practices (more or less intensive in terms of fertilizer use or mechanization), distance travelled by feedstock or fuel, emissions associated to the energy utilized in the transformation processes, production of co-materials and their use. Significant variability affects all the factors driving the overall GHG impact of ethanol production processes. Moreover, when life cycle analyses are performed in practice, data availability and data uncertainty further compound the variance. Most estimates do not take into full account the potential impact of biofuels on land use, thus underestimating the potential risks of biofuels. Consequently, the various analyses that have assessed the GHG impacts and benefits of biofuels have produced a broad range of estimates and should be treated with a degree of caution.

8. Baseline emissions based on projections from IEA/SMP transportation model http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc

9. The market penetration of biofuels in the transportation sector depends on a variety of factors, including feedstock prices, petrol prices, technological development and public policies providing incentives (or disincentives) for biofuel utilization. Public policies have played a critical role in the recent growth in the biofuel markets. Much of the biofuel market growth is driven by supporting policies and measures, which often involve the establishment of some target for biofuel use, typically in terms of percent of biofuel use on total fuel consumption.

10. IPCC 2007, Climate change 2007: Forth Assessment Report, working group 3, chapter 5

11. Assumed maximum biofuel penetration of 20% of total biofuel used in road transport

12. Patel et. al. (2006) The BREW Project: Medium and long term opportunities and risks of biological production of bulk chemicals from renewable resources – the potential for white biotechnology

13. Dornburg V., Hermann B., Patel M. (2008) Scenario projections for future market potentials of biobased bulk chemicals Environmental Science and Technology 2008

14. Hermann, B. G.; Blok, K.; Patel, M. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change. In Environ. Sci. Technol. 2007

15. The market penetration of biobased materials with high potential for GHG emission reductions, and the GHG impact achieved, may vary substantially depending on the market developments and technology dynamics in the industrial biotechnology and petro-chemical fields, which, in turn, may be significantly affected by public sector policies and private sector business and development strategies. Both the growth of the reference market and the speed of introduction of second generation technologies (able to use lignocellulosic feedstocks) play a significant role in affecting the emission reductions achieved

16. Biochemical oxygen demand or BOD is a chemical procedure for determining the rate of uptake of dissolved oxygen by the rate biological organisms in a body of water use up oxygen. It is not an precise quantitative test, although it is widely used as an indication of the quality of water. BOD can be used as a gauge of the effectiveness of wastewater treatment plants.

17. IPCC Fourth assessment report Working Group 3 Chapter 10 waste management

18. The 100 year global warming potential of methane is estimated to be 23 – 25 times greater than for CO_2

19. This may be partially due to the different sources that had to be used for the analysis and to the high degree of uncertainty persisting in literature on land use parameters (especially for more novel applications such as the production of biobased materials biotechnologically)

20. FAO State of food and agriculture 2008, page 60

For biofuels land use estimates are based on the following assumptions for feedstock production per hectare of land.

	2010	2015	2020	2025	2030	2035	2040
Starch based ethanol	1,960	1,960	1,960	1,960	1,960	1,960	1,960
Sugar cane ethanol	4,550	4,550	4,550	4,550	4,550	4,550	4,550
Lignocellulosic ethanol	4,550	4,550	4,550	4,550	4,550	4,550	4,550
FAME biodiesel	1,960	1,960	1,960	1,960	1,960	1,960	1,960
Biotech biodiese	1,960	1,960	1,960	1,960	1,960	1,960	1,960

Biofuels production per ha of land (liters per ha) – based on Rajagopal et al 2007 Review of environmental, economic and policy aspects of biofuels World Bank Policy Research Working Paper N 44 cited by FAO 2008

For biobased materials, where uncertainties are highest and limited sources of information are available, the estimates reported in the table to the right were used as reference.

Land required depending on feedstock used			
	Maize starch long term	Lignocellulosic	Sugar cane
	ha/t	ha/t	ha/t
Acetic acid	0.14	0.06	0.15
Acrylic acid	0.18	0.07	0.18
Adipic acid	0.27	0.11	0.28
Caprolactam	0.33	0.13	0.34
Ethyl lactate	0.16	0.08	0.16
Ethylene	0.45	0.18	0.46
Lysine	0.36	0.15	0.37
Succininc acid	0.13	0.07	0.14
1,3-propanedio	0.22	0.09	0.22
Polyhydroxyalkanoates	0.39	0.16	0.4
Polylactic acid	0.18	0.07	0.18

Land needed for the biotechnological production of biobased materials – Source Patel et al 2006

21. A rapid growth in the demand of feedstock for industrial biotechnology applications can also have a dramatic impact on food markets, farming communities, and biodiversity. Increased demand could lead to price increases in food commodities damaging low-income households, displacement of local farming communities (or competition for limited land) or to the conversion of sensitive areas to industrial biotechnology crops, with significant damages for local ecosystems or biodiversity. For a discussion of some of these topics see FAO State of food and agriculture 2008, section 6 or Madoffe (2009) Africa: Biofuels and neocolonialism http://allafrica.com/stories/200906040880.html accessed June 2009

22. FAO State of food and agriculture 2008

23. Estimates of the land potentially required to produce biofuels and biobased materials biotechnologically are still subject to a significant uncertainty, due to the constant development of new technologies, the broad variety of feedstock, available farming technologies, and differences in land productivity and climate between geographic regions.

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