AVOIDING GREENHOUSE GAS EMISSIONS
THE ESSENTIAL ROLE OF CHEMICALS

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ENABLING THE FUTURE

Chemistry innovations for a low-carbon society

The ICCA is committed to paving the way toward a more sustainable future. Climate change is a global challenge requiring a wide range of solutions to account for economic, societal, geographical and political differences around the world. This publication showcases a selection of exemplary solutions from the global chemical industry to support the transformation toward a low-carbon society.

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EXECUTIVE SUMMARY

ENABLING THE FUTURE— CHEMISTRY INNOVATIONS FOR A LOW-CARBON SOCIETY

1.

SETTING THE SCENE

The Paris COP21 target of reducing carbon emissions to mitigate climate change poses a challenge to all industries. The chemical industry, currently responsible for some 7% of all industries' greenhouse gas (GHG) emissions,[1] is committed to supporting the transformation toward a low-carbon society. This publication was initiated by the Energy and Climate Change Leadership Group of the International Council of Chemical Associations (ICCA) to demonstrate how the chemical industry can contribute to achieving this low-carbon society.

The landscape of the chemical industry has emerged and evolved dramatically over the last century. Chemistry-based manufacturing typically deals with material conversion processes that require energy. Over the past decades, the major drivers have been resource and energy efficiency, product safety as well as financial performance. It is more recently that the additional driver of sustainable development has gained momentum.

Today's chemical industry possesses profound expertise in transforming innovations into solutions and products that meet market needs. Chemistry-based products cover a vast and highly diverse array of applications, both in mature and developing markets, with great relevance for the low-carbon economy transformation.

2.

PROJECT SCOPE AND IMPLEMENTATION

The process leading to the publication of this report involved the active participation of chemical industry players from the US, Canada, Brazil, Europe and Japan with wide-ranging expertise regarding technologies, raw materials, product applications and markets. Workshops on specific topics were held around the world with representatives from end-user industries. Desktop research and expert interviews were carried out on research and development topics related to carbon emission reduction. Five main sectors were identified in which low-carbon transformations can be achieved: *Power generation and storage, Mobility and transport, Nutrition and agriculture, Building and housing* and *Industry and production*. From an initial 1,000 solutions, a shortlist was created based on expert feedback regarding time to market, market penetration, potential impact on carbon emissions and technological feasibility. The remaining solutions were narrowed down further based on feasibility assessments. This resulted in a final selection of 17 clusters from the five sectors. For each cluster, this report presents at least one exemplary solution from the sponsor companies, including a deep-dive analysis with direct impact quantifications.

3.

MAIN RESULTS

From the initial overall list of 1,000 solutions, 450 generic technologies are identified as enablers of GHG savings where chemicals play a key role. 137 of these generic technologies exhibit a high feasibility rating. This publication showcases individual solutions* from the five sectors and addresses the challenges arising from the low-carbon transformation of each sector. A clarification of the solutions' carbon mitigation potential is provided along with an illustration of their impact on the Sustainable Development Goals (SDGs). The solutions' direct carbon reduction impact by 2050 was estimated based on information from participating companies and from the public domain.
The examples provided in this report lead to an estimated carbon mitigation potential of 5 to 10 $GtCO_2eq$/year by 2050**. Such reduction becomes possible by collaboration with partners among sectors as diverse as *Power generation and storage, Industry and production, Mobility and transport, Nutrition and agriculture* and *Building and housing*. With this far-reaching approach, the chemical industry supports in particular SDG 13: Climate action. It's essential to consider the value chain partners and stakeholders across sectors in implementing the transformations and maximize the impact of the chemical industry's contribution.

Particularly in the *Power generation and storage* and *Mobility and transport* sectors, the carbon reduction potential is achieved through the use of renewable energy from advanced solar cell technology and battery storage systems. Carbon emissions can be further reduced through hydrogen- and ammonia-based energy and mobility concepts that build upon next-generation fuel cell technology.

In the *Nutrition and agriculture* sector, the carbon reduction potential lies primarily in the shrinking of the footprint of livestock farming and animal feed production. The challenge here is to reduce carbon emissions while at the same time feeding a growing global population.

The *Industry and production* sector, including the chemical industry itself, is driven by efforts to improve process efficiency through the advanced catalytic chemical synthesis of large-scale organic and inorganic products. Further options are being explored for replacing fossil fuel feedstock with biomass and biotechnology chemical synthesis.

The challenges of reducing the energy demand of the *Building and housing* sector is closely connected with those of the *Power generation and storage* sector. Improved insulation and solar power generating devices integrated into buildings have the potential to achieve significant carbon emission reductions.

4.

CONCLUSION

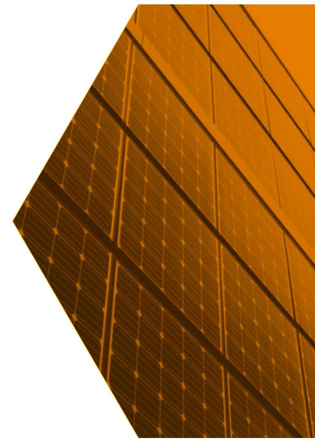
Although climate change is a global problem, there is no one-size-fits-all solution for every region in the world. Differences in economic systems, geographical circumstances, infrastructures, market needs and the level of societal and political acceptance—even among adjacent countries and economies—make it necessary for tailored development trajectories to be designed. Not only must these trajectories include factors such as technological feasibility but also environmental, societal and financial options, and be compatible with the SDGs. In this publication, the chemical industry presents various innovative approaches that take these points into consideration. Mindset changes and political and societal consensus are fundamental prerequisites.

The window of opportunity is closing rapidly when it comes to long-term strategic decisions toward achieving a low-carbon society by 2050. Financial restraints, both in public spending and the chemical industry, limit research and development—which means a clear focus is needed. To commercialize large-scale low-carbon production technologies in mature markets and to make capacities for developing applications and markets financially resilient and economically viable — with each solution having a favorable risk-reward balance — highly reliable political frameworks are indispensable. Those frameworks provide security to committed companies and support the unfolding of the chemical industry's potential toward a low-carbon society.

* The solutions provided in this report are to be considered as individual case studies in terms of their impact potential in the production or use phase. No full life cycle analyses were conducted as part of this project. In many other studies, however, the ICCA includes life cycle analysis, e.g. in the publication 17 case studies. Summaries. Available at https://bit.ly/2ORHMSo

**The projections in the various sectors were not harmonized or prioritized in terms of their energy or resource intensity. The carbon mitigation potential of each solution is shown in megatonnes (Mt).

PREFACE



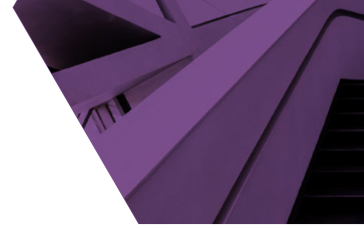
When it comes to climate protection, one thing has become abundantly clear: The world is in need of a far-reaching transformation that pervades all aspects of society. A transformation of this magnitude cannot begin and end with individual policies, specific technical solutions or industries. Nor can it stop at national borders. Instead, a comprehensive transformation is required. It must reach deeply into society—and bring about a fundamental mindset shift for enabling the future.

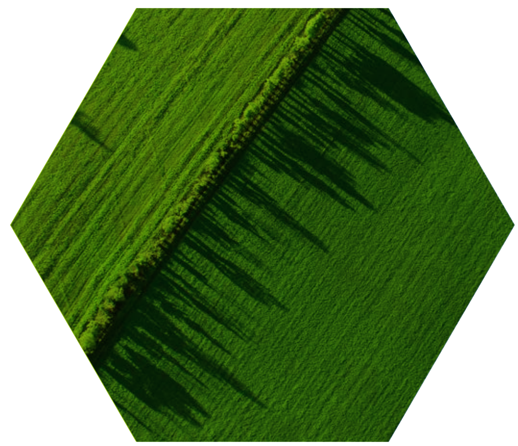
This mindset shift is required of all climate change stakeholders—individuals, societies, companies, industrial sectors, organizations and politicians—as a foundation upon which to engage in multilateral dialogue and build a future together where each stakeholder can offer their specific expertise. A combination of technology, market-based and policy solutions will be necessary to reduce greenhouse gas emissions (GHG) and achieve climate protection goals, such as those of the Paris Agreement. Here, the global chemical industry can play a significant role and be a true enabler. Its technical and innovative potential, both in its own field and through collaborations with other industries, is enormous with regard to facilitating the transition toward a low-carbon society. The task of developing technologies that cut emissions, improve energy efficiency and enable a socially, environmentally and economically sustainable future is highly complex.

The chemical industry's potential can only fully unfold if it is supported by society and the right political frameworks. To this effect, higher awareness of technical innovation must be raised within society and among all stakeholders is needed. Time is short and moving forward effectively will only become possible if we join forces—for the sake of our planet and future generations.

The global chemical industry is fully committed to supporting the transition toward a low-carbon society; it is also keen to include stakeholders in a joint effort to bring about the right framework conditions for the necessary innovations to be made. For this transition to occur, solutions must be socially, ecologically and economically viable—and sensible, too. In other words, these solutions must achieve significant carbon emission reductions along the entire value chain and be socially acceptable while simultaneously offering genuine commercial potential. For such solutions to bear fruit, many of them require years of intense and stringent research and development efforts and management. This involves major economic risks that companies cannot be expected to shoulder unless planning security and the respective political frameworks are in place.

So far, many published reports have used the concept of avoided emissions to show the chemical industry's contri-





bution to carbon emission reductions along the entire value chain. We've created this publication to demonstrate the clear intention of the chemical industry to contribute its vast expertise to making the world sustainable for the long term.

It is our conviction that by showcasing the potentials and trends set by the chemical industry, we can paint an insightful overall picture of the significant role of our industry in paving the way toward a more sustainable future.

Calvin M. Dooley
ICCA Council Secretary

Nobuyuki Kawashima
Chairman ICCA Energy and Climate Change Leadership Group

ENABLING THE FUTURE

The special Intergovernmental Panel on Climate Change (IPCC) report issued in October 2018 on the impacts of global warming has served as the latest wake-up call: It's another striking reminder that when it comes to climate change, a business-as-usual approach is no longer an option.[1] However, envisaging exactly how to mitigate climate change—one of the most pressing issues of our time—to change things for the better is not a simple task.

Climate change is a global challenge that requires long-term commitment and action by every segment of society to crack open the status quo and create room for new ways of thinking and acting that ideally lead to long-term positive change. The United Nations' COP21 agreement and Sustainable Development Goals (SDGs) have served as important stepping stones. For them to succeed, an alignment of all involved parties—society, policy makers and the industrial sector—is paramount.

As a global industrial sector, the chemical industry is intent on rising to this challenge and leveraging the power of chemistry for the benefit of future generations. The ambition of the International Council of Chemical Associations (ICCA) is to play a leading role in the transformation of society along the complete value chain. We want to help limit global warming by creating innovative climate-friendly and energy-efficient solutions—both for our own processes and for many other sectors' solutions through chemical products. This includes sectors as diverse as energy, nutrition, construction, industry and mobility. With this far-reaching approach, the chemical industry supports in particular SDG 13: Climate action.

As the worldwide voice of the chemical industry, the ICCA and its members are committed to pushing this agenda. We're aware that the chemical industry is a resource- and energy-intensive industry. And we also realize that we're a significant enabler for other sectors to become more sustainable in the course of transformation.

This publication aims to showcase the present and future contributions of the chemical industry toward a low-carbon society—and to demonstrate the future-forward expertise it can bring to the task.

PARTNERSHIPS AND LONG-TERM THINKING

Complex questions require multilayered responses, and solutions must be geared toward achieving the greatest impact within the right overall framework. Broad-scale implementation takes more than just proven technology and a sound business case. Increasingly, the challenges and opportunities that lie ahead will necessitate large-scale transformations of entire sectors, as solutions can no longer be implemented in isolation: Collaborations among governments, industry players and other stakeholders will be key. As we see it, overcoming technical challenges is but one part of what we face—a combination of new technologies, the right policies, financial basis and widespread societal acceptance will be essential for reducing greenhouse gas (GHG) emissions and achieving the necessary climate protection goals as needed.

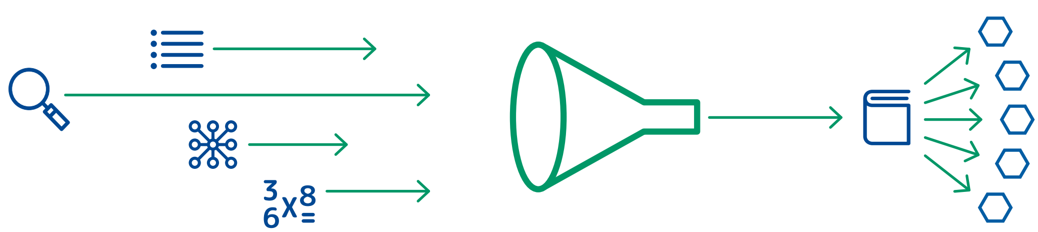
Due to different social, economic and cultural circumstances, the global problem of climate change frequently requires regional approaches. It's just as essential to think up and down the complete value chain and across sectors to implement the transformations needed and maximize the impact of what the chemical industry can do.

With this publication, we seek to demonstrate both the great potential and the dedication of the global chemical industry to advancing the cause of our planet. In the past, the chemical industry focused on its operational and technological performance. Today, we're prepared to take it to the next level and rise to the challenges of our time—to enable the future we want.

...

THE SELECTION PROCESS—CHOOSING 17 CONCISE SOLUTIONS OUT OF 1,000

The report you're looking at right now is the result of an intense journey. The objective of the ICCA and its project team, including experts from the sustainability consultancy fors and KPMG, was to create a bold and valuable publication. One that would provide relevant, easy-to-understand information for policy makers and the interested public about the chemical industry's contribution to bringing about a low-carbon society. The solutions presented in this publication should not, however, be considered exhaustive. They're a collection of examples demonstrating the power of chemistry to bring about cross-sectorial change.



RESEARCH

Step one in our journey toward this report was to identify the right technological solutions: KPMG supported desktop research on publicly available reports, chemical company sources and interviews with research and development experts from ICCA member companies as well as KPMG Sustainability Services contacts from around the world. This resulted in a longlist of over 1,000 relevant solutions, which were then filtered for those offering a deployment time extending beyond 2030 and a significant global greenhouse gas (GHG) reduction impact. The remaining 450 or so solutions were narrowed down further based on feasibility assessments carried out by our in-house experts. This resulted in a list of 137 solutions (see pages 14/15).

CLUSTERING

Based on the research, 17 technology clusters were created based on their related technological areas and carbon impact. The clusters were linked to relevant sectors: *Power generation and storage*, *Industry and production*, *Mobility and transport*, *Building and housing* as well as *Nutrition and agriculture*—and these have served as a structure for this publication. The selection and clustering criteria included the necessary research and development efforts, infrastructure and technological systems readiness, socio-political acceptability, time horizon and, most importantly, climate change mitigation and overall impact in terms of the UN Sustainable Development Goals (SDGs).

WORKSHOPS AND SHORTLISTING

To validate our findings, we engaged experts from fors, a strategic sustainability consultancy, to carry out dialogue events with external stakeholders along the value chain. This included companies from the chemical industry itself as well as suppliers, customers, regulatory and financial experts, experts from think tanks, academic institutions and NGOs.

Throughout 2018, KPMG conducted interviews and fors held workshops in Tokyo, Berlin, São Paulo and Pittsburgh focusing on specific sectors. They were set up as a framework to enable the in-depth assessment of the proposed solutions and to gain insight into opportunities, obstacles and necessities along the path toward a low-carbon economy.

Between 15 and 25 high-level representatives participated in each workshop, addressing two sectors each to make the results comparable. In a pre-workshop survey, participants had estimated the chemical industry's contribution to global carbon emission reductions by 2030 and 2050. In addition, they were asked to share their opinion on political, economic, technological or societal challenges.

The workshop discussions often brought to light regional opportunities and challenges. While the results demonstrated a clear consensus regarding the urgency of counteracting climate change and the necessary mechanisms, views regarding specific aspects varied among participants due to differing underlying mindsets and assumptions (see pages 12/13).

QUANTIFICATION

The process resulted in 17 concise solutions proposed by chemical companies to represent application areas and technology clusters with a substantial impact on a carbon-neutral society. By defining a set of performance metrics, we quantified the GHG impact of the solutions showcased in this report. This well-founded process involved a number of experts and scientific sources. Yet, due to the extent of the time horizon, quantification must be based on assumptions and projections in many places. Nevertheless, the selected solutions offer valuable insights into potential carbon emission reductions thanks to the chemical industry.

THE POWER OF CHEMISTRY IN AN EXEMPLARY FASHION

This publication is but the tip of the iceberg of a far-reaching task embraced by the global chemical industry: to create technological solutions that can help bring about the crucial changes our planet requires. It sets out to provide an impression of the types of changes that are possible through the power of chemistry. To be clear, the 17 solutions outlined in this report are not an exhaustive selection—and not all solutions are viable or appropriate for all world regions, sectors, companies and processes. We present them merely as current examples to illustrate the potential of the chemical industry for mitigating climate change in collaboration with other sectors.

INCLUDING THE COMPLETE VALUE CHAIN

Throughout the process, we remained focused on considering the complete value chain so as to accurately assess and quantify contributions. For this purpose, we again called upon a wide range of external stakeholders and experts from the areas of research and industry, along with NGOs. Because of its importance for bringing about meaningful change, each of the solutions outlined in the following also contains a schematic representation of its impact along the value chain:

RAW MATERIALS

Resources are limited. Seeking out alternative sources that bind or process carbon can make a significant contribution to mitigating climate change.

CHEMICAL OPERATIONS

Within chemical operations, core aspects for carbon reduction and sinks include efficiency and renewable energies. Efficient processes help to reduce energy consumption, while the use of alternative energy carriers can mitigate emissions. To exploit this potential, new solutions for chemical operations are needed, and these may also lead to new business models.

CUSTOMER OPERATIONS

The chemical industry supplies materials or product components to their customers, i.e. industry down the value chain, and their processing causes carbon emissions. Energy efficiency and the generation and use of renewable energies are key to mitigating these emissions. Alternative products all the way to whole new business models can be part of the solution, combining economic and ecological advantages.

END USERS

The minimization of carbon emissions must also play a central role in product use—and therefore already be included at the product development stage. New and alternative products may also meet the needs of customers.

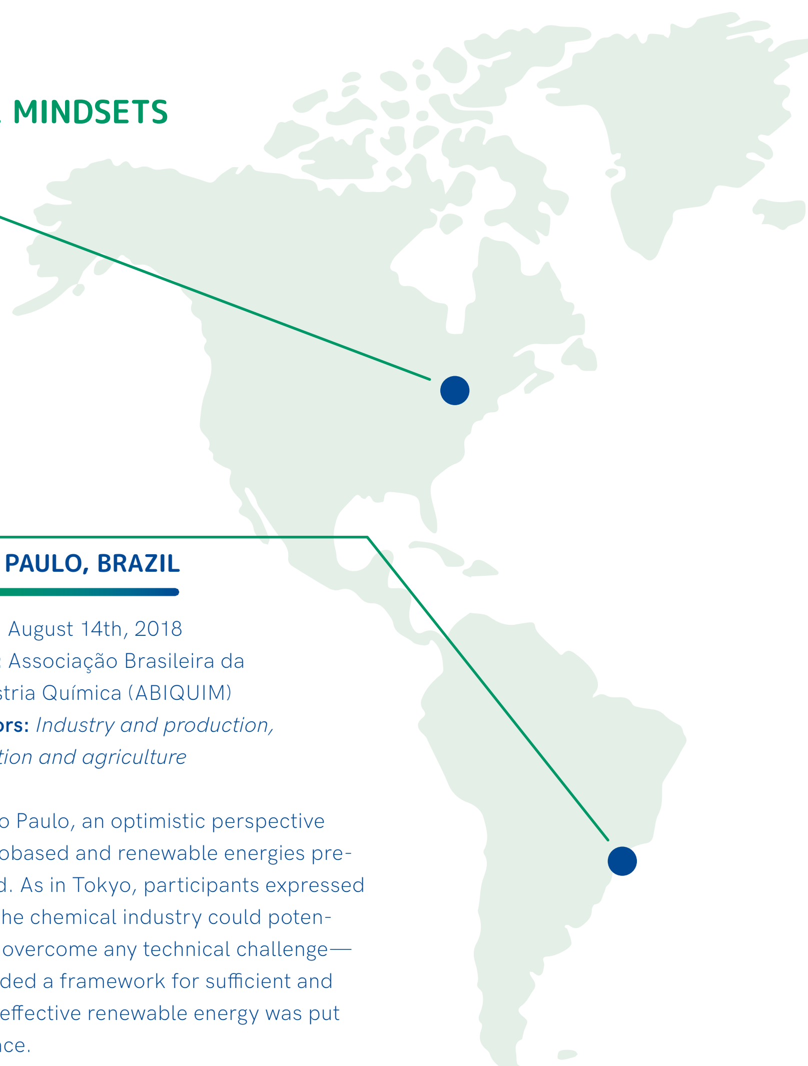
END OF LIFE

At the end of its life cycle, when a product is broken or no longer needed, it can be recycled. The components contained can replace primary materials and thus prevent carbon emissions. This requires recycling technologies ideally based on carbon-neutral energy that enable a closed cycle.

A GLOBAL SENSE OF URGENCY

Various stakeholders’ perspectives and mindsets were integrated into the evaluation process for the proposed solutions in this publication, especially during the four workshops: What soon emerged was a global sense of urgency and a clear commitment to taking action about climate change. A scientifically based online survey of participants revealed their expectation that climate change would affect their respective nations, sectors and companies very strongly (an average of 4.3 points out of 5). They also displayed a low degree of confidence in societies’ current preparedness for these changes (2 out of 5 points on average).

WIDE DIFFERENCES IN REGIONAL MINDSETS



PITTSBURGH, PENNSYLVANIA, USA

Date: September 11th, 2018
Host: American Chemistry Council (ACC)
Sectors: *Building and housing, Mobility and transport*

Participants in Pittsburgh painted a multi-faceted picture of substantial differences on the local level, including varying approaches to climate change, a vibrant start-up culture and a wide range of different perspectives regarding the future of renewable energies.

SÃO PAULO, BRAZIL

Date: August 14th, 2018
Host: Associação Brasileira da Indústria Química (ABIQUIM)
Sectors: *Industry and production, Nutrition and agriculture*

In São Paulo, an optimistic perspective on biobased and renewable energies prevailed. As in Tokyo, participants expressed that the chemical industry could potentially overcome any technical challenge—provided a framework for sufficient and cost-effective renewable energy was put in place.

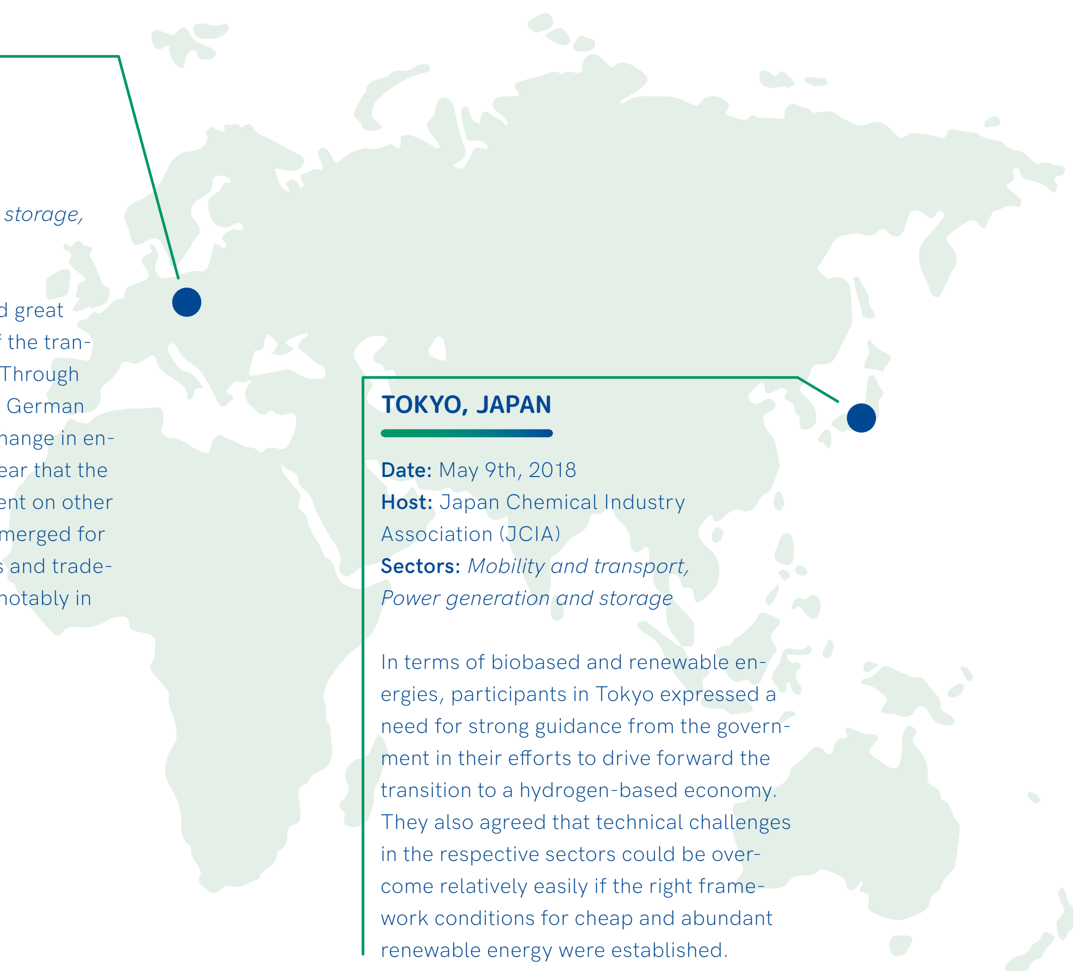
ONE CLIMATE—DIVERSE POLICIES

The workshops demonstrated that approaches to the global phenomenon of climate change will follow diverse regional patterns reflecting culturally, geographically and politically varied mindsets. For instance, Brazil's story of change will be based on the nation's natural resources—an approach that will not work in Japan.

There was consensus that necessary investments were the biggest obstacle to meeting the challenges of climate change, and that these investments would require sound and reliable political frameworks. The views on technological leaps differed substantially among participants. However, all agreed that the chemical industry was technologically ready to deliver the right solutions in concert with society's movement toward the use of more renewable energy. As the chemical industry's interests are strongly aligned with the support of renewable energies, policy makers will increasingly be able to draw on support from the chemical industry. Even so, societal acceptance of the solutions remains essential and will involve varying degrees of challenge by region.

The workshops also showed that well-informed professionals tend to have a high level of initial motivation to bring about change. In organizations, however, too much focus on potential risks and challenges may thwart this drive. Policy makers will therefore have to promote an opportunity-driven attitude and promote a perspective of a favorable climate future for their region.

Putting to work solutions with a potentially high beneficial impact is a complex undertaking that requires regional initiatives and must occur along the entire value chain. While the chemical industry is in a good position when it comes to technological solutions, the planning and construction of the relevant chemical facilities typically takes time. Reliable medium and long-term climate policy as well as clear indications for the development of future business cases will prove decisive success factors if companies are to invest in climate solutions.



BERLIN, GERMANY

Date: September 18th, 2018
Host: Evonik Industries AG
Sectors: *Power generation and storage, Nutrition and agriculture*

In Berlin, participants displayed great awareness of the complexity of the transition to a low-carbon society: Through Germany's experience with the German "Energiewende," a structural change in energy systems, it has become clear that the energy sector is highly dependent on other sectors. A broad perspective emerged for the necessity of connectedness and trade-offs between all sectors, most notably in the areas of power and food.

TOKYO, JAPAN

Date: May 9th, 2018
Host: Japan Chemical Industry Association (JCIA)
Sectors: *Mobility and transport, Power generation and storage*

In terms of biobased and renewable energies, participants in Tokyo expressed a need for strong guidance from the government in their efforts to drive forward the transition to a hydrogen-based economy. They also agreed that technical challenges in the respective sectors could be overcome relatively easily if the right framework conditions for cheap and abundant renewable energy were established.

Solutions enabling the future—Shortlist

For this publication, over 1,000 relevant solutions were reviewed and filtered by their expected deployment rate/date, feasibility and estimated impact on global GHG reduction. This desktop research resulted in 137 solutions, out of which 17 exemplary solutions were selected to represent different clusters. This selection is presented here.

17 clusters | 137 solutions | 5 sectors

ALTERNATIVE ENERGY GENERATION

- Advanced mooring materials
- p. 58 | **Building-integrated photovoltaics (BIPV)**
- Composite tidal turbines
- Fusion energy
- Lead-free perovskite solar cells
- Methanol economy
- Organic photovoltaics
- Perovskite tandem solar cells
- Quantum dot solar cells
- Roll-to-roll solar
- Solar ponds
- Superhydrophobic coatings for wind turbines
- p. 22 | **Water-stable perovskite solar cells (PSCs)**

BATTERIES

- Graphene-based supercapacitors
- p. 46 | **Lithium-ion battery development**
- Metal-air batteries
- p. 18 | **Sodium-based batteries**
- Solid state batteries

BIODEGRADABLE PRODUCTS

- Biobased degradable plastics from non-edible plants or sugar
- Edible packaging

BIODIVERSITY AND LAND USE

- Grazing land, cropland, restoration supported by chemical products
- Instinct technology
- Microbial fertilizer

BIOFUELS

- Alternative fuels for shipping
- Bioethanol/biomethanol/biomethane
- Biofuels for aircrafts

BIOMASS AS FEEDSTOCK

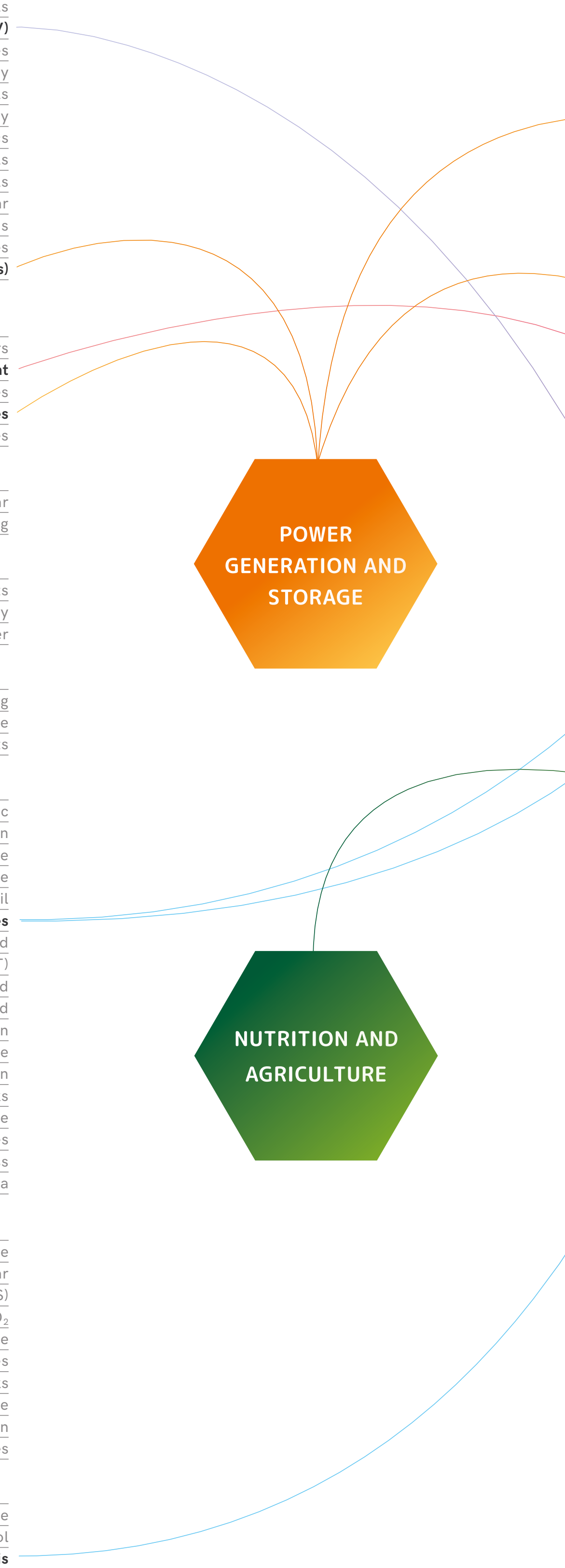
- Algae-based plastic
- Aromatics from lignin
- Biobased PHA from sugar beet waste
- Biobased plastics from agave waste
- Biobased plastics from renewable isoalkane oil
- p. 34/36 | **Biobased plastics from renewable resources**
- Biobased polymers from itaconic acid
- Biobased polyethylene terephthalate (PET)
- Biobased succinic acid
- Biomass to liquid
- Bionylon
- Bioplastics from lignin waste
- Glycerol utilization
- Improved biofuel feedstocks
- Micro algae
- Soybean-based polyolefin composites
- Switchgrass
- Wood-based diesel and naphtha

CARBON CAPTURE AND STORAGE (CCS)

- Ambient air capture
- Biochar
- Bioenergy-combined carbon capture (BECCS)
- Enzymes capture CO_2
- Geothermal power with direct carbon capture
- Hybrid membranes
- Metal organic frameworks
- Microporous copper silicate for carbon capture
- Mineral sequestration
- Nano sponges

CARBON CAPTURE AND UTILIZATION (CCU)

- Acrylic acid derivatives from CO_2 and ethylene
- Air to methanol
- p. 28 | **Artificial photosynthesis**
- Artificial trees
- Carbon dioxide to mono ethylene glycol
- CCU plastics: air carbon
- Electrochemical reduction of carbon dioxide to ethylene
- Geothermal renewable methanol plant
- Hydrogenation of carbon dioxide into formaldehyde
- Membranes for thermochemical reduction of CO_2
- Scalable CO_2-to-oxygenate production
- Steel manufacturing symbiosis



ENERGY EFFICIENCY

- (P)-OLED
- **Aerogel insulation** | p. 56
- Air sealing
- Bundled external thermal insulation
- Bundled lighting
- Cool roofs
- Double glazing using sodium carbonate
- Efficient building envelopes
- External thermal insulation composite systems (ETICS)
- Fuel-efficient tires
- High-temperature superconducting transmission cables
- Insulation concrete forms
- Laser diode lighting
- LED
- Phase change materials
- Structural insulated panels (SIP)

ENERGY STORAGE SOLUTIONS

- **Ammonia as carrier of hydrogen energy** | p. 24
- H_2-absorbed materials
- PCP/MOFs for energy storage
- Toluene for hydrogen storage

FUEL CELLS

- Direct carbon fuel cells
- Generating electricity from waste water
- Hydrogen home refueling
- **Anion Exchange Membrane Fuel Cells (AEMFCs)** | p. 48
- New fuel cell catalyst
- Solid oxide fuel cells (SOFC)

HYDROGEN PRODUCTION

- Biohydrogen
- Biosynthetic water splitting
- Hydrogen from biogas
- Hydrogen fuel cells for aircraft
- **Hydrogen production process** | p. 20/40
- Photocatalytic water splitting
- Photoelectrochemical water splitting
- Steam reforming with carbon capture

LIGHTWEIGHT MATERIALS

- Advanced composite materials
- Carbon fiber
- Cellulose nanofibers
- **Lightweight plastics** | p. 44
- Metal and resin integration

LOW-CARBON HANDPRINT PRODUCTS

- **Amino acid-enriched animal feed** | p. 52
- Amino acids in aquaculture
- Cultured meat
- DL-methionine as feed additives for broiler production
- Effective packaging—multilayer polyethylene packaging film
- Efficient packaging to reduce food losses
- Ethanol to olefins
- Low-carbon cement
- Low-temperature detergents
- Methanol to olefins

NEW CATALYTIC PROCESSES

- **BTX from ethanol** | p. 30
- Direct methane conversion
- HPPO process for propylene oxide
- Olefin production via catalytic naphtha cracking

PROCESS EFFICIENCY

- Advanced control and optimization
- Advanced heat integration
- Ionic liquids for biomass processing
- **Low-temperature/-pressure ammonia synthesis** | p. 32
- Mechanochemical synthesis
- Reduced flaring
- Urease inhibitors

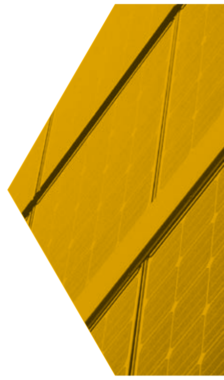
WASTE TO CHEMICALS

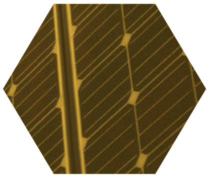
- Alkaline solid waste for carbon mineralization and utilization
- Biofuel from coffee waste
- Carbon black from used tires
- **Chemical recycling of waste plastic** | p. 38
- Municipal solid waste (esp. residue derived fuel) to urea
- Palm oil waste utilization
- PVC recycling
- Residual waste to methanol
- Waste coffee grinds to biodiesel
- Waste polyolefins to fuel or chemicals

POWER GENERATION AND STORAGE

Facilitating the generation and storage of renewable energy

Power generation and storage technologies are vital for the successful transition to a new energy mix and low-carbon economy. The chemical industry has a major role to play when it comes to enabling energy storage solutions—from ammonia utilization and hydrogen storage to the production of hydrogen from biogas, steam reforming and water-splitting technologies. In addition, the chemical industry can contribute to alternative energy generation through perovskite solar cells, advanced mooring materials and superhydrophobic coatings for wind turbines as well as building-integrated photovoltaics and many other solutions.





PAVING THE WAY FOR A NEW GENERATION OF BATTERIES

Batteries are a form of energy storage whose primary benefit is the provision of a stable energy supply. Advanced materials and chemicals are required to create compact and efficient batteries that will facilitate the broad use of renewable electricity on a global scale. It is the size and capacity of batteries that limit the growth of many electric products. Improved, more efficient and more economical batteries will be necessary if a viable transition to renewable electricity is to occur. The chemical industry plays a substantial role in paving the way toward this new generation of batteries.

Selected solution

RESEARCH ON SODIUM-ION BATTERIES (SIBS)

Toward lighter, cheaper and more readily available batteries

Power storage technology witnessed a breakthrough with the commercialization of lithium-ion (Li-ion) batteries, now widely used for portable electronic devices or electric vehicles. Yet, key resources used in Li-ion batteries are unevenly distributed, and this can affect supply chains and costs.[1] Moreover, Li-ion isn't ideally suited for stationary applications—which will be an important field given the projected growth rates of renewable energy for 2050.

Research in this field began over 40 years ago, most notably in sodium-sulfur systems. Sodium is now attracting renewed attention as it can enable large-scale power storage, primarily in the form of sodium-ion batteries (SIBs). Naturally abundant and cheaper than lithium, sodium appears to be an attractive alternative for assembling large-scale electrochemical energy storage solutions to balance peak production and frequency of renewable energies.[2] SIBs resemble Li-ion batteries in terms of their components, electrical storage mechanism and intercalation chemistry. Initial experiments have also shown similar performance characteristics, with energy densities even exceeding LFP-LTO or LFP-C.[3] Additionally, certain varieties can be discharged more deeply than Li-ion batteries without material damage, enabling a more efficient use of materials. Moreover, sodium does not form an alloy with aluminum, thereby allowing the traditional copper current collector to be replaced with this cost-effective component.

Thanks to continued insights from Li-ion technology research, some progress on material development has already been achieved in SIBs.[4] Yet, to move toward commercialization, research is being carried out on the matching of the anode, cathode and electrolyte properties of electrodes and other components.[5] There is also increasing attention on two emerging energy storage systems: safer, lower-cost Na-aqueous batteries and sodium-air

($Na\text{-}O_2$) batteries, which meet the need for high-energy density storage devices.[6]

Compared to current Li-ion batteries, SIBs tend to be at the lower end of the spectrum regarding GHG emissions, resource utilization, toxicity, acidification and eutrophication. For SIBs to become a meaningful contributor on a daily basis, their performance must continue to improve. Furthermore, better scale-up and cost-competitiveness compared to Li-ion batteries and other battery systems, such as flow batteries, must be achieved. For the most part, research into these sodium-based systems currently remains at the lab and early prototype stage.

Challenges

TECHNICAL

- Similar challenges as for the Li-ion battery system, e.g. electrolyte stability over a wide range of conditions and a high voltage (knowledge and technology transfer); special focus on charge/discharge performance reducing aging effect on capacity, safety in construction and handling)
- Search for anode with appropriate, robust sodium storage properties, a large reversible capacity and high structural stability
- High reactivity of metallic sodium with organic electrolyte solvents and dendrite formation during sodium metal deposition
- Gradual capacity fade, likely due to structure changes induced during sodium insertion and extraction[7]

FINANCIAL

- Early stages of commercialization face challenges in new product introduction and scale-up

REGULATORY

- Regulatory considerations and safety matters resembling those of other batteries (e.g. Li-ion for non-aqueous systems, lead acid for aqueous systems)
- Market entry and commercialization to be supported by recycling/circular economy approach

Impact on SDGs

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

The development of SIBs would contribute to enhancing energy efficiency and access to affordable, reliable and sustainable energy (SDG 7) as well as fostering the development of an affordable, resilient and sustainable infrastructure (SDG 9).

Carbon mitigation potential

80 $MtCO_2eq$/year by 2050

Avoided emissions through the use of SIBs

ASSUMPTIONS[8]

- Scope assigned to battery production for power storage in stationary and mobile applications
- Savings based on the benefits of the new SIB systems as opposed to Li-ion battery systems
- Scenario with a projection of around 4,600 GWh/year global battery production capacity and an annual growth rate of about 5%
- Selected scenario assigning 50% of the new capacity to be installed by 2050 to SIB technology
- 20% fewer GHG emissions through SIB production (140 tCO_2eq/MWh) as opposed to Li-ion batteries (175 tCO_2eq/MWh)

INDIRECT IMPACT

The International Renewable Energy Agency (IRENA) has quantified the renewable share of electricity generation as 85% (2018), making the impact of electric vehicles in the future even more significant. The lifetime of SIBs is expected to be longer than that of Li-ion batteries. Thus they would need to be replaced less often, which could have an extended impact on production emissions. In terms of renewable electricity generation, batteries will play a key role in buffering the intermittent supply of electricity from wind and solar.

Hydrogen production

HYDROGEN AS A LONG-TERM GREEN REPLACEMENT FOR FOSSIL FUELS

Hydrogen is one of the most abundant elements on earth and is used in large quantities by the chemical industry as a reactant. It is also touted as a potential large-scale replacement for fossil fuels. If produced with renewable electricity (water electrolysis or methane pyrolysis), it is a carbon-free energy carrier. Hydrogen is rarely found in its pure form and is typically produced from fossil fuels through energy-intensive processes. For hydrogen production to become truly carbon-neutral, these processes must employ renewable energy.

Selected solution

BASF RESEARCH ON CARBON-NEUTRAL HYDROGEN PRODUCTION

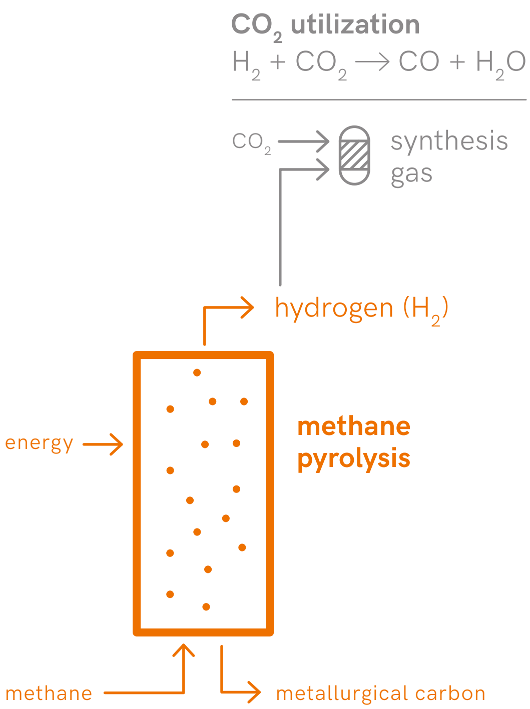
Producing hydrogen from methane pyrolysis

Today, around half of the world's hydrogen is produced through methane steam reforming, partial oxidation of hydrocarbons or coal gasification. These processes emit large amounts of CO_2. Options for reducing the carbon footprint of hydrogen production include biomass gasification, electrolysis of water based on renewable electricity and carbon capture and storage (CCS), a somewhat controversial technology due to a lack of societal acceptance in different regions.[9]

With funding from the German government, BASF and its subsidiary hte GmbH have formed a consortium with several research and development partners to create a more environmentally friendly technology for producing hydrogen.[10] Through the pyrolytic decomposition of the natural gas methane under high temperatures (>1,000 °C), hydrogen and solid carbon atoms can be directly split from one another at a ratio of 1:3. This comparatively energy-efficient process could also be combined with the catalytic reaction of hydrogen with CO_2 to form synthesis gas through reverse water-gas shift (rWGS). The process makes use of immediate waste heat recycling.

This technology enables hydrogen to then be used as feedstock for chemicals and fuel components, while the resulting by-product CO_2, once brought into solid form, can be used in steel, coke or aluminum production. Methane pyrolysis has the potential to achieve more than 50% cradle-to-gate reduction in GHG emissions as compared to conventional steam methane reforming (SMR) and coke making processes while creating the same output of hydrogen, carbon and heat at competitive costs.[11]

The consortium's research is contributing to the development of new reactor concepts, new catalysts and a chemical engineering process development that could serve as a blueprint for future process designs. Research is currently at the lab stage. Methane pyrolysis could lead to industrial-scale carbon-neutral hydrogen production, provided a good energy integration of the pyrolysis reactor can be achieved and a strong collaboration between the chemical industry and the metallurgical sector established.



Source: BASF

Challenges

TECHNICAL

- Lowering energy requirements to compete with steam reforming and meeting energy demands fully based on renewable energies
- Generation and formulation of a solid carbon product from carbon dust for the coke and steel industry
- Process integration of pyrolysis and CO_2 activation

FINANCIAL

- Solid carbon utilization crucial for process economics
- Business decision for methane pyrolysis requires regional data, sound process cost estimates, a certain metallurgical carbon market size and successful feasibility testing

Impact on SDGs

This technology enables hydrogen production at a lower cost and with a reduced carbon footprint. It thereby contributes to affordable and clean energy (SDG 7) as well as a resilient infrastructure and sustainable industrialization (SDG 9) through the co-production of solid carbon for steel and coke. The technology also contributes to improving the management of chemicals and waste throughout their life cycle (SDG 12).

Carbon mitigation potential

110 $MtCO_2eq$/year by 2050

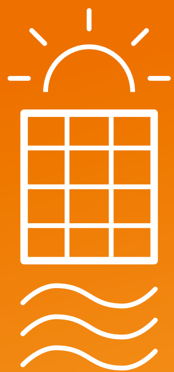
Potential for reducing GHG emissions through hydrogen production via methane pyrolysis

ASSUMPTIONS [12]

- Carbon mitigation impact attributable to the energy sector, i.e. generating hydrogen as fuel and, in the chemical industry, introducing methane pyrolysis as a replacement for conventional SMR
- Hydrogen demand by 2050 close to 108 Mt/year (according to projections from 2017 at 56 Mt/year)
- Scenario based on 24% deployment rate of overall capacity for hydrogen production for new methane pyrolysis replacing a variety of technologies (not just SMR)
- Conventional electricity mix for energy supply
- 50% reduction of specific GHG emissions per tonne of hydrogen (4.4 tCO_2eq/tH_2) vs. SMR (8.9 tCO_2eq/tH_2)

INDIRECT IMPACT

Evaluating the full carbon mitigation potential of methane pyrolysis compared to SMR must take into account the broader value chain beyond carbon emissions attributable to other sectors, including the feedstock being used (natural gas, biogas), the energy required (e.g. electricity from renewables), the quality of the hydrogen produced, the utilization of by-products (solid carbon, CO_2 for CCU), the scale of production, the application and the required infrastructure.



Alternative energy generation

FACILITATING THE GENERATION OF ALTERNATIVE ENERGIES

The need for alternative, renewable energy is growing rapidly. The rise of solar, tidal and wind power technologies and the desire to reduce emissions from energy production are putting great demands on the chemical industry. This also gives the chemical industry an opportunity to develop the right materials for overcoming any technological challenges in this field. A variety of materials and compounds are currently being explored, and will necessarily create considerable demand for raw materials and chemicals if adopted. Moreover, the chemical industry's role in end-of-life considerations will also grow.

Selected solution

THE FUTURE OF SOLAR CELLS

Perovskites for efficient low-cost photovoltaics

The chemical industry is researching and developing new types of materials to make solar cells more efficient. In this area, perovskite solar cells (PSCs) are considered a highly promising solar energy technology under development. Perovskites are a class of minerals with a specific structure displaying a myriad of interesting properties such as superconductivity, magnetoresistance and symmetry of the material. Their distinctive crystal structure, enabled by the chemical components of methylammonium lead trihalide, makes them perfect for efficient, low-cost photovoltaics.

PSCs include a perovskite-structured compound, usually a hybrid organic-inorganic lead or tin halide-based material, as its light-absorbing active layer. The cells can absorb a large portion of the visible solar spectrum, thereby leading to a relatively high yield.[13] Under lab conditions, an efficiency of over 22% has been achieved,[14] exceeding the average efficiency of traditional silicon photovoltaics of around 18%.[15] The other major advantages of PSCs include their relatively low production costs, flexibility and lighter weight.

As the most investigated type of PSC material is methylammonium lead trihalide, this type of technology still struggles with major stability issues, which prevent it from being commercialized. The material is moisture-sensitive and degrades in regular outdoor conditions. This adversely impacts performance as well as lifetime and, more importantly, can lead to toxic pollution of lead iodide from the cells.[16] This is also why research and development efforts are not only aimed at improving the efficiency of the technology, but also at increasing its water-repellence through encapsulation of the material. Further alternatives, such as lead-free caesium gold iodine, are also being explored regarding a replacement of the lead in the material to counter the pollution impact.

One possible application of PSCs lies in combining them with traditional silicon solar cell technology. A combined cell installation of this kind has achieved an efficiency of 28% under lab conditions.[17] This combination could leverage the widespread use and existing capacity of mainstream solar cells, which make up around 90% of the photovoltaics market share.

General PSCs are currently in the pilot phase and water-stable PSCs at the lab stage. As soon as a solution for the stability issues is found, PSCs could potentially take green solar electricity to a new level in terms of efficiency, flexibility and production costs.

Challenges

TECHNICAL

- Improving the currently limited chemical stability of PSCs due to their sensitivity to humid conditions, replacement of lead by non-toxic components

FINANCIAL

- Scaling up the dimensions might require additional material costs for PSCs if the same performance is to be reached, which might offset the benefit of the low production costs

SOCIETAL

- Health and environmental risks due to toxicity risks associated with the methylammonium lead trihalide technology. This can lead to the release of toxic PbI_2 in humid conditions—research on its environmental impact is therefore increasingly relevant

Impact on SDGs

The flexibility and low production costs enable improved access to energy (SDG 7). As a clean technology, it can be used in a decentralized manner, thereby also contributing to more sustainable cities and settlements (SDG 11).

Carbon mitigation potential

3,400 $MtCO_2eq$/year by 2050

Potential GHG emission reduction of water-stable PSCs

ASSUMPTIONS [18]

- Carbon mitigation impact attributable to the energy sector, i.e. power generation based on renewable energy using solar cells vs. non-renewable power
- Entire GHG reduction in power sector close to 8,800 Mt/CO_2eq/year
- 43% of GHG reduction for power generation contributed to increased solar PVC capacity
- Assuming 90% market penetration of PSC technology in PV market by 2050 and assuming use of tandem technology of silicon-based cells with additional perovskite elements

INDIRECT IMPACT

The production of PSCs is an energy-intensive process and the energy required may be fuel-based, potentially implying significant GHG emissions. These emissions could amount to an estimated 50–300 gCO_2/kWh, depending on the lifetime and type of cell. PSC lifetime currently remains a challenge. Due to the technology's stability issues, PSCs need to be replaced regularly, which, in turn, requires that they be produced in larger quantities.

Energy storage solutions

MANAGING POWER SUPPLIES THROUGH ENERGY STORAGE

Ever since electricity was discovered, effective methods have been sought for storing and generating electricity on demand. Energy can take many different forms such as radiation, nuclear and thermal energy, kinetic and potential energy, chemical and electrical energy. To make electricity available on demand, energy must be converted into a storable form, for short- and long-term use. For this, the chemical industry is developing a wide array of technological approaches: Metal organic frameworks (MOFs) for example, a new class of nano porous material, have great potential in capturing and re-using gases such as CO_2 or hydrogen.[19] Another approach is the transportation of hydrogen in the form of ammonia. The goal is to create a more resilient energy infrastructure and bring cost savings to utility providers and consumers.

Selected solution

SIP "ENERGY CARRIER" DEVELOPMENT PROGRAM

Hydrogen storage and transportation through ammonia[20]

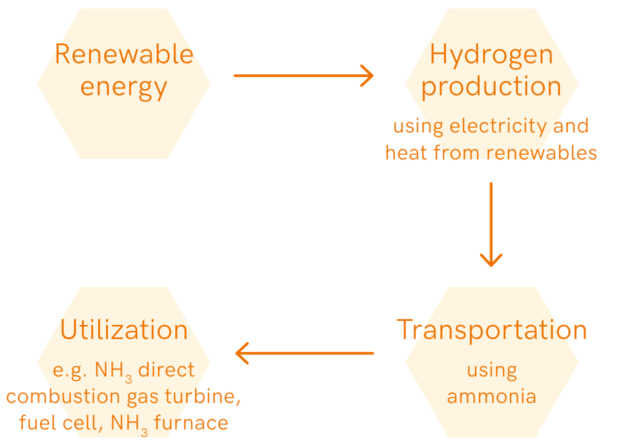
A carbon-free fuel, hydrogen offers great potential for various fields of application. It can be produced from water via electrolysis using renewable energy or by reforming or gasifying fossil fuels in liquid form or as an organic hybrid. Yet, it is the transportation process that raises cost challenges due to hydrogen's low density and the necessary energy input for dehydrogenation.

The Cross Ministerial Innovation Promotion Program (SIP) *Energy Carriers*—sponsored by the Japanese government's Cabinet Office and with Sumitomo Chemical leading the program as Deputy Program Director—offers a solution to this challenge: hydrogen transported in the form of ammonia. Carbon-free ammonia, i.e. ammonia produced with no carbon footprint, can be produced from natural gas-based processes if combined with carbon capture and storage (CCS) or from hydrogen produced with renewable energy. Ammonia has a volumetric hydrogen density that is 1.5 times higher than that of liquefied hydrogen and can therefore be transported in existing chains, making it cost-effective.

The research has identified conditions in which ammonia can be used directly—without emitting pollutant nitrogen oxides (NO_x)—for gas turbine combustion, coal-fired boilers or for fuel cells as a carbon-free fuel. This paves the way for using ammonia without extracting hydrogen from it, thereby greatly reducing the cost of ammonia as a hydrogen energy carrier. These technologies have successfully passed a number of application tests and are approaching commercialization.

Further research is focusing on the development of an ammonia synthesis process from hydrogen under low temperature and pressure conditions by developing catalysts. Additional research is looking at large-dimension gas turbines for power generation that utilize ammonia as a hydrogen carrier. Meanwhile, micro-gas turbines of 300 kW size using solely ammonia as fuel, coal-ammonia mixed combustion boilers and medium-sized gas turbines using 20% ammonia are in the making. SIP *Energy Carriers* expects them to be introduced to the market in 2020 (micro-gas turbines) and around 2025 (coal-ammonia mixed combustion boilers and medium-sized gas turbines).

Additionally, more efficient cracking technologies for hydrogen stations based on ammonia as the hydrogen source are being developed.



Challenges

TECHNICAL

- No major technical challenges regarding coal-ammonia mixed combustion boilers and medium-sized gas turbines
- Long-term control of NO_x in large gas turbines
- Due to ammonia toxicity, use of ammonia limited to areas where experts for handling ammonia are available, such as power generation

FINANCIAL

- A market needs to be created for carbon-free ammonia at an affordable price for potential users

SOCIETAL

- Increasing public acceptance of ammonia use in power generation needed

REGULATORY

- Some regulatory rationalization will be required, e.g. in countries where ammonia is categorized as a flammable substance

Impact on SDGs

The production of ammonia could foster the development of the hydrogen economy, and therefore contribute to reliable and sustainable energy (SDG 7).

Carbon mitigation potential

65 $MtCO_2eq$/year by 2050

Potential GHG emission reduction by deploying ammonia as a hydrogen carrier in power plants

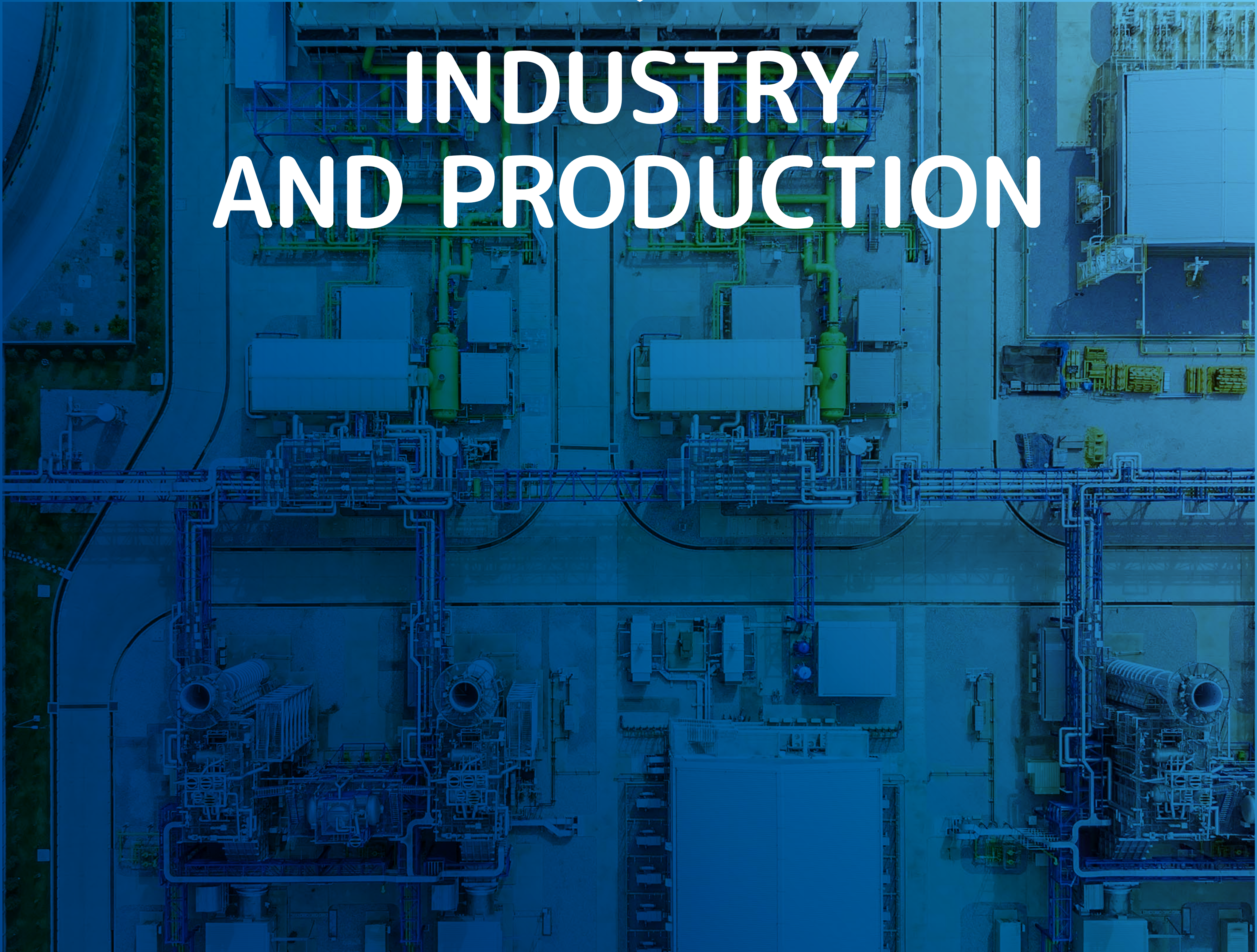
ASSUMPTIONS [21]

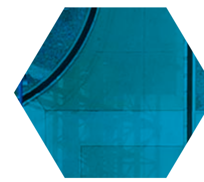
- GHG savings from partial replacement of coal and natural gas with ammonia as a carbon-free hydrogen carrier for combustion, thus direct GHG emission reduction at power plants
- Total electricity consumption forecast for 2050: 149,309 PJ/year
- Share of natural gas: 16,200 PJ/year (~10%); share of coal: 1,620 PJ/year (~1%)
- Equivalent GHG emissions of around 280 $MtCO_2eq$/year and 47 $MtCO_2eq$/year
- Based on a 10% global deployment rate for ammonia technology with partial (20%) replacement of fossil fuels and related GHG emissions
- Ammonia as a hydrogen carrier produced to be carbon-neutral either through the use of fossil resources combined with CCS or from renewable energies/new synthesis processes

INDIRECT IMPACT

The production of ammonia can take place through hydrogen by reforming fossil fuels or through hydrogen synthesis using electricity and heat. For the first option, emissions from fossil fuels could be captured and stored to produce carbon-free ammonia. For the second option, carbon-free ammonia could be produced by using electricity and heat from renewable resources.

INDUSTRY AND PRODUCTION





Optimizing the chemical industry´s processes

The *Industry and production* sector is responsible for 36% of global final energy consumption and 24% of total carbon emissions among other relevant emissions and impacts.[1] With a proactive move, this sector can clearly expect to bring about considerable improvement in resource efficiency as well as energy management systems and practices through technological innovation and better process design. As part of this development, the chemical industry has an important role to play as a solution provider and enabler. It has the innovative power to contribute to solving a wide range of technical problems along the value chain.

Carbon capture and utilization (CCU)

RECYCLING CARBON EMISSIONS INTO CHEMICAL FEEDSTOCK

Carbon emissions have the potential to be used as raw materials for the production of various products including bio-oils, specialty chemicals, polymers and fuels. If low-cost energy from renewable sources can be used, products based on carbon capture and utilization (CCU) technology may replace those based on fossil fuels. While carbon capture and storage (CCS) primarily binds carbon as CO_2 from industrial off-streams and the atmosphere, CCU delays or prevents CO_2 from being released. This includes the utilization of CO_2 as a by-product of chemical production. But to enable CCU, large amounts of renewable energy at a competitive price are needed.[2]

Selected solution

RHETICUS PROJECT BY EVONIK AND SIEMENS

Chemicals made from water, renewable energy and CO_2

The Rheticus project is aimed at creating an environmentally friendly process for producing specialty chemicals with the help of CO_2, water and electricity from renewable sources. The process is a technological adaptation of the basic principles of photosynthesis, nature's way of transforming light into chemical energy.

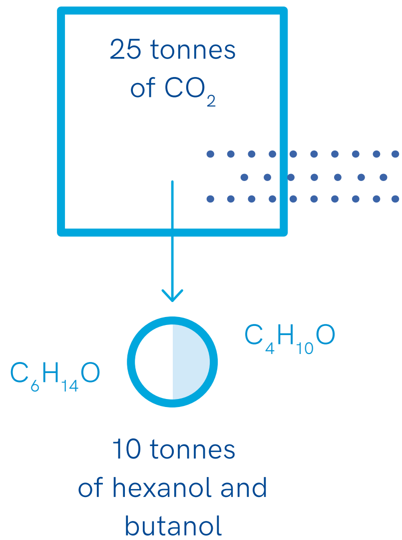
Evonik and Siemens are tackling the crucial question of how volatile renewable energy can be meaningfully used and intelligently stored. Their approach involves two different types of wild Clostridia bacteria that naturally synthesize chemicals by metabolizing hydrogen and carbon monoxide as their energy source. Thanks to the various sources of off-gases and product streams in chemical plants, for example, CO_2 is available in copious amounts and can be converted into carbon monoxide by means of electrolyzers and renewably energy. Hydrogen can also be produced through electrolysis.

The bacteria naturally produce butanol and hexanol, two types of alcohol serving as raw materials for, among other things, specialty polymers, water-based paints and dietary supplements.[3]

Rheticus illustrates the powerful potential of "sector coupling" to advance energy storage options and stabilize the electricity grid. Some 20 Evonik and Siemens employees are working to transfer Rheticus from the lab to a technical test plant on a 25-tonne scale. The first test plant is expected to go live in 2023.

The German Federal Ministry of Education and Research is supporting Rheticus with €2.8 million, with the two industrial groups investing roughly the same amount each.

POSSIBLE TRANSFORMATION IN A TECHNICAL TEST PLANT



Impact on SDGs

The use of CO_2 to produce chemicals instead of other resources could make a considerable contribution to responsible consumption and production (SDG 12).

Challenges

TECHNICAL

- Smart combination and coupling of hydrogen production through a process of electrolysis and biotechnological fermentation

FINANCIAL

- High research and development costs for possible target molecules
- High CAPEX for the running of production plants on a relevant (industrial) scale

REGULATORY

- In production, cheap electricity from renewable sources without additional tax grid fees, etc.
- Patent lifetime of over 20 years as research and development has already exceeded 10 years and first significant commercial application may take another 10 years or more

Carbon mitigation potential

25 $MtCO_2eq$/year by 2050

Potential GHG emission reduction through "artificial photosynthesis"

ASSUMPTIONS [4]

- GHG savings from industry sector for the production of compounds based on CCU, i.e. producing chemicals from water, renewable energy and CO_2
- Scenario with n-butanol as reference case, extrapolated to three additional compounds and 2050 projection of 11 Mt/year conventional production
- Deployment rate of CCU by applied artificial photosynthesis: 10%
- All process energy including hydrogen must be produced with zero GHG emissions
- GHG savings of artificial photosynthesis vs. conventional n-butanol process 3.5 tCO_2eq/t n-butanol
- Carbon credit for CCU 2.5 tCO_2/t n-butanol

INDIRECT IMPACT

Replacing conventionally produced butanol and other chemical compounds would also influence the current petrochemical value chain. This is not accounted for in the quantification.

New catalytic processes

CLEANER, GREENER AND MORE EFFICIENT

Among industrial sectors, the chemical and petrochemical industries are by far the largest consumers of energy, accounting for roughly 7% of global greenhouse gas emissions.[5] Around 90% of chemical processes use catalysts for efficient production. Catalysts are substances that speed up chemical reactions, yet are not consumed in the chemical reaction. Some catalysts are required for the initial chemical reaction itself. Catalysts can help keep energy usage and costs down. Today, the chemical industry is working to develop new, longer-lasting catalytic processes to ensure cleaner, more sustainable and more efficient industrial processes.

Selected solution

NEW CATALYSTS FOR MORE SUSTAINABLE BTX AROMATICS

Deriving chemical building blocks from biobased feedstock

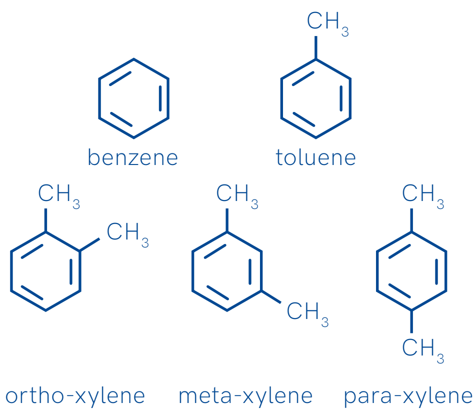
In the petrochemical industries, BTX aromatics play an important role. BTX stands for the three aromatic hydrocarbons benzene, toluene and xylene. They are standard building blocks for a wide range of chemical products, including polymers. BTX aromatics are also used in consumer products like solvents, paints, polish, agricultural products, detergents and pharmaceuticals. The global demand has increased rapidly over recent years, and is expected to continue to do so in the future.[6]

BTX aromatics are derived from crude oil, typically through the catalytic reforming of naphtha in steam crackers. This is part of the established refinery process to produce gasoline. BTX production is energy-intensive with high greenhouse gas emissions both in the production process and upstream.[7]

For this reason, scientists are researching catalysts using biobased ethanol as a renewable feedstock for BTX. The goal is to make the production of BTX less dependent on crude oil and to establish value creation through greener chemistry. Ongoing research and development have already tested different catalysts and achieved a conversion rate of 97% of ethanol to aromatics (vol-%).[8] The research is currently at lab stage.

This alternative BTX production process has the potential to reduce carbon emissions as compared to a conventional process, yet a more significant carbon emission reduction can be achieved upstream through the use of biobased feedstock. For these emission reductions to be achieved, it is imperative that the ethanol be produced from biomass such as sugarcane. For the successful long-term commercialization of a solution to occur, a steady supply of biobased ethanol and the right infrastructure must exist to support it.

BTX AROMATICS



Challenges

TECHNICAL

- Developing catalysts that can provide a significant and durable yield from ethanol so as to compete with conventional BTX production

FINANCIAL

- Improving the efficiency of bioethanol feedstock production as compared with conventional production
- Processes must be improved to ensure competitiveness regarding aromatics from naphtha

SOCIETAL

- Growing concern about the amount of arable land required for a high-volume, biobased chemical feedstock infrastructure and potential competition with food production

Impact on SDGs

When biomass is used as feedstock for producing BTX, this contributes to improving the sustainability of the production of chemicals (SDG 12). Yet, the use of sugars and other biomass for biobased chemicals such as ethanol raises societal concerns regarding land use and food availability (SDG 2).

Carbon mitigation potential

8 $MtCO_2eq$/year by 2050

Savings thanks to the generation of BTX from new catalytic processes instead of conventional oil-based technology

ASSUMPTIONS [9]

- Growth of BTX production 2023 to 2050: 90 Mt (based on foreseeable growth rate from 2017 to 2023)
- Total BTX production in 2050: 244 Mt/year
- Assumption: 10 % penetration rate of the new technology for total BTX capacity in 2050 (≙ 27% share of new installed capacity)
- 75% fewer GHG emissions from ethanol process (0.1 tCO_2eq/t BTX) than from oil-based technology (0.43 tCO_2eq/t BTX)

INDIRECT IMPACT

Based on renewable raw materials and short-cyclic atmospheric CO_2, the use of bioethanol has negative carbon emissions (~3.5 tCO_2 savings/t of product). The production process of the final feedstock creates emissions similar to that of sugarcane to bioethanol and crude oil to naphtha. New factories will have to be built for using BTX technologies, thereby necessitating materials transportation that may offset the technology´s emission mitigation potential.

Process efficiency

MITIGATING THE ENVIRONMENTAL EFFECTS OF INDUSTRIAL PROCESSES

Making industrial processes more efficient can significantly contribute to reducing their impact on the environment. This can be achieved by using fewer resources, speeding up processes or emitting fewer greenhouse gases. The chemical industry plays a key role in providing chemicals that enable such efficiency increases in various sectors, e.g. housing (insulation) or mobility (lightweight materials). The chemical industry itself benefits greatly from enhancing its own processes and thus reduces the impact of industrial processes on the environment.

Selected solution

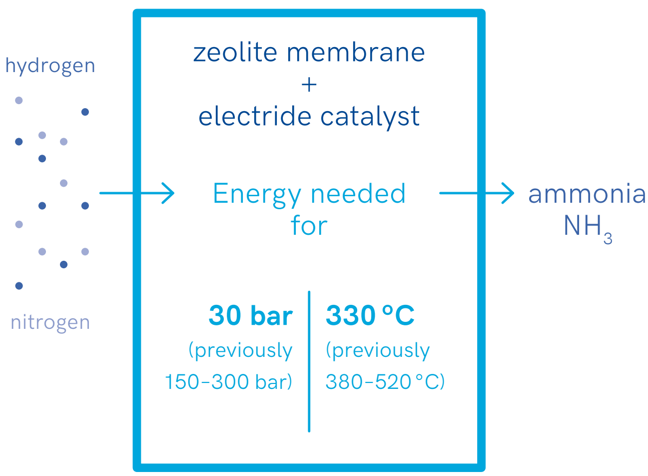
INNOVATIVE AMMONIA PRODUCTION BY MITSUBISHI CHEMICAL

A new membrane technology to replace Haber-Bosch

Ammonia is one of the most important chemicals in the world and the largest energy consumer and carbon producer among all chemicals. Based on global figures from 2010, ammonia production of some 150,000 kt consumed around 2.6 EJ of energy and contributed 340 $MtCO_2eq$.[10] It is most commonly used in agricultural fertilizer, chemicals having amide and nitrile as functional groups and in the selective catalytic reduction (SCR) of nitrogen oxides emitted by automobiles. Most of the worldwide production plants use the conventional Haber-Bosch process, based on more than a century of history. The conventional process combines hydrogen (usually produced from natural gas by steam reforming and a successive water shift reaction that produces hydrogen and releases CO_2 as a by-product) with nitrogen. Both react over an iron-based catalyst in a process requiring very severe reaction conditions, such as high temperature (380–520 °C) and high pressure (150–300 bar). Ammonia is typically produced in locations where natural gas fields can be commercialized. This conventional method is very capital- and energy-intensive, and only viable in large-scale centralized plants.[11] Therefore, the conventional Haber-Bosch process requires the economic viability of large-scale high-pressure production systems.

Mitsubishi Chemical is working to change the energy intensity of ammonia production. At the core of its technology is a new zeolite membrane that can effectively separate ammonia from a mixture of nitrogen, hydrogen and ammonia. In addition, Mitsubishi is working on the development of a new intermetallic electride catalyst in collaboration with Prof. Hideo Hosono from the Tokyo Institute of Technology. The effect of these two components is a rapid separation process that removes the ammonia from the reaction system. This prevents the reaction from reversing and allows for appropriate reaction rates at much lower pressures of around 30 bar and lower temperatures of around 330 °C. The technology increases the one pass yield of ammonia by breaking through the thermodynamic equilibrium. This results in the very small recycling rate of unreacted nitrogen and hydrogen. As a result, a considerable reduction of both initial investment and operation expenditure can be expected. The catalyst is currently at the lab stage and the membrane at the pilot stage.

Reactive separation



Challenges

TECHNICAL

- Long trial operation period under specific conditions needed for developing a new catalyst
- As fertilizers containing ammonium nitrate also release the GHG nitrous oxide, it is important to use it sparingly and in a targeted fashion

FINANCIAL

- Due to many existing old plants with little or no depreciation, financial incentives would be required for investment in the new technology

REGULATORY

- Differences between regulations regarding ammonia production and use in different countries

Impact on SDGs

Ammonia is the main feedstock for fertilizer production. As the solution would make fertilizer considerably cheaper, it could also make a significant contribution to reducing hunger (SDG 2).

Carbon mitigation potential

40 $MtCO_2eq$/year by 2050

Avoided emissions from low-temperature and low-pressure ammonia synthesis

ASSUMPTIONS [12]

- Carbon mitigation impact attributable to emissions from ammonia production processes
- Growth of ammonia production from 2018 to 2050: 139 Mt/year (based on foreseeable growth rate from 2019 to 2023)
- Total projected ammonia production in 2050: 309 Mt/year
- 10% penetration rate of the new technology for total ammonia capacity in 2050
- Scenario with substantial new technology capacity for ammonia in 2050: 31 Mt/year (≙ 22% share of newly installed capacity)
- 80% fewer GHG emissions for low-temperature and low-pressure ammonia process (0.3 tCO_2eq/t ammonia) than from Haber-Bosch process technology (1.6 tCO_2eq/t ammonia).

INDIRECT IMPACT

No significant further impacts on GHG emissions in the value chain have been identified. The direct impact includes the emissions from production. No difference is expected in the end-of-life.

Biomass as feedstock

DERIVING FUELS AND PLASTICS FROM BIOLOGICAL MATERIALS

Biomass feedstocks are plant materials from which fuels and plastics can be derived—for instance ethanol, butanol, biodiesel, polypropylene. Such feedstocks include corn starch, sugarcane and crop residues. These organisms obtain carbon directly from the CO_2 in the atmosphere and are therefore considered carbon-neutral, or in some cases, even carbon-negative. Multiple technologies are under development to make use of biomass on a large scale. The processes of "biorefining" differ from traditional petrochemical refining. The chemical industry plays a central role in addressing the challenges of biomass processing as a means to create such fuels and plastics on a commercial scale. In the following, we present two different solutions from this area to demonstrate the weight and diversity of biomass utilization in the chemical industry.

Selected solution

1

BIOMASS-BASED POLYMER PRODUCTION BY BRASKEM

Bioplastics derived from sugarcane

Biomass feedstock can be used in polymer production. It serves as a source for the carbon atoms in the polymeric chain, in place of traditional feedstocks such as naphtha from oil or ethane from natural gas. A highly suitable source of these carbon atoms is sugar, as well as the ethanol obtained through its fermentation, derived from sugarcane cultivated in Brazil.

It is through this process that Braskem has developed a polyethylene (PE) and ethylene-vinyl acetate copolymer (EVA). The ethanol is dehydrated and transformed into green ethylene, which is then turned into polyethylene or EVA at polymerization plants.

Together with Haldor Topsoe, Braskem is also working to pioneer monoethylene glycol (MEG) from sugar. MEG is a key component of polyethylene terephthalate (PET) resin used in textiles and packaging. Conventional MEG production from biomass involves several steps, whereas the Braskem process only requires two steps. Thus, MEG can be produced at a single industrial unit, bringing down investment costs while boosting productivity. This makes it competitive with production from fossil feedstock naphtha.[13]

PE, EVA and MEG are chemically identical to their fossil counterparts and can therefore be used in the same economic sectors, including retail, home care, agriculture, packaging, industry, cosmetics and hygiene.

As stable molecules, polymeric chains can keep carbon locked for hundreds of years, unless combustion ends their life. If these chains are made from biomass and the

products they make up are recycled, polymeric chains can effectively act as carbon sinks. The use of these biobased feedstocks can greatly reduce the carbon footprint of polymers if combined with recycling as a circular economy approach.

PE and EVA have already reached the commercial stage. Other families of polymers as well as other types of chemical building blocks and MEG production process are currently under development.

Challenges

TECHNICAL

- The development of new biochemical and bioengineering processes
- Validation of technology with different raw materials such as sucrose, dextrose and second-generation sugars[14]

FINANCIAL

- Higher production costs mainly due to raw material costs
- Small production scale compared to their fossil counterparts and no valuable co-product from ethanol cracking, therefore higher costs than its fossil counterpart

SOCIETAL

- Agriculture more exposed to social, environmental and labor risks, strong supply chain management needed

REGULATORY

- Currently no benefits for using biobased polymers
- Support through regulatory strategies and incentives for the commercialization of sugarcane-based chemical building blocks and polymers needed

Impact on SDGs

When biomass is used as feedstock for polymers, this contributes to making the production of chemicals more sustainable (SDG 12). However, the use of sugars for biobased chemicals may raise societal concerns regarding land use and food availability (SDG 2). While this conflict might arise in land-constrained countries, less densely populated countries with significant amounts of available land, such as Brazil, offer favorable conditions for implementing this solution.

Carbon mitigation potential

270 $MtCO_2eq$/year by 2050

Potential GHG emission reduction through building blocks for polymers made from biomass feedstock

ASSUMPTIONS [15]

- GHG savings from industrial sector, especially the production of building blocks for polymers such as MEG, PE and EVA
- Growth scenarios for rising demand: CAGR of between 4 and 6%
- Deployment rate scenario of biomass-based processes for building blocks: 10%
- Capacity projection for biomass-based MEG (26 Mt/year), PE (34 Mt/year), EVA (4 Mt/year)
- Total specific GHG emissions savings (i.e. 3.1 tCO_2eq/t MEG, 5 tCO_2eq/t PE, 5.3 tCO_2eq/t EVA) of biobased building blocks vs. conventional naphtha technology, including credit for biogenic carbon

INDIRECT IMPACT

No significant further impacts on GHG emissions in the value chain have been identified.

2

BIOBASED POLYPROPYLENE PRODUCTION BY MITSUI CHEMICALS

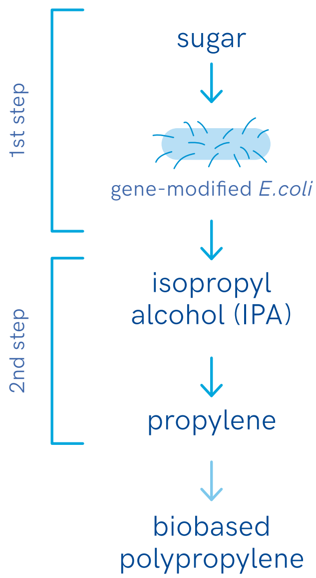
Producing plastics through biomass fermentation

Polypropylene (PP) is one of the most common plastics with 56 Mt produced each year. It is primarily made from fossil resources such as naphtha. Up until now, the commercial production of PP from biomass has not been a feasible option.

A new technology developed by Mitsui Chemicals is making PP production from biomass a realistic option. Mitsui has found a way of using biomass to produce PP as feedstock. This new technology is based on Mitsui's development of a unique strain of the Escherichia coli bacteria (E.coli) through gene recombination technology. The metabolic pathways of the special strain of E.coli has been modified to increase the gene expression of specific enzymes. Non-modified E.coli bacteria do not produce isopropyl alcohol (IPA). This gene-modified E.coli catalyzes IPA synthesis reactions by such enzymes and produces IPA selectively from glucose and sucrose, which is produced from biomass.

The production process comprises two steps. First, IPA is produced biochemically from biomass such as sugarcane, sorghum and cellulose sugar through the gene-modified microbe. Second, propylene is produced by conventional dehydration of the IPA. These steps enable PP production by the polymerization of this biomass-based propylene. The key step is the fermentation, through which sugar is converted to IPA. In this process, the gene-modified E.coli is inoculated to the nutrient medium in the fermentation reactor and cultured under ideal conditions. The first step has already been proven on a pilot scale. The propylene production process still needs to be optimized to enhance overall production efficiency.

The results of a life cycle assessment of PP production by this process has shown significant net carbon reduction as compared to conventional PP production: The replacement of 1 t of conventional PP by bio-PP enables mitigation of 4.2 t of carbon emissions. The technological feasibility of the fermentation process has been proven on a pilot scale. The entire production process of propylene on a pilot scale is to be proven by 2024.



Challenges

TECHNICAL

- Further development to establish robust commercial feasibility on a large scale for (i) biotechnological process from biomass to IPA and (ii) dehydration to propylene with (iii) confirmation of GHG savings compared with conventional naphtha-based technologies
- Establishing an integrated system where biomass is efficiently used and generation/utilization of fuel-based electricity and heat are coordinated

FINANCIAL

- Rendering biobased PP cost-competitive as compared to conventional PP produced from fossil resources

SOCIETAL

- Enhancing public recognition of the value created from biobased materials from a social perspective, which plays no role commercially

REGULATORY

- Encouraging the replacement of conventional PP with biobased PP via a public procurement system

Impact on SDGs

By using biomass as feedstock for producing PP, this solution contributes to improving the sustainability of chemical production, which is connected with sustainable consumption and production patterns (SDG 12). Yet, the use of biomass as feedstock still raises concerns regarding land use and food availability (SDG 2).

Carbon mitigation potential

100 $MtCO_2eq$/year by 2050

Avoided emissions with biobased PP production

ASSUMPTIONS [16]

- Carbon mitigation impact attributable to emissions from propylene production based on biomass, including carbon credit for biomass
- 100 Mt/year, annual demand of PP forecast for 2050, representing an annual growth of around 1%
- Scenario with 24 Mt capacity of biomass-based PP and 24% deployment rate
- Bio-PP process with scope biomass cultivation to PP providing GHG savings of about 1 tCO_2eq/t PP vs. conventional naphtha technology
- Additional carbon credit for biogenic carbon by using biomass adds another 3 tCO_2eq/t PP as GHG-saving potential

INDIRECT IMPACT

No further indirect impact is expected along the value chain as the final product is identical to conventional PP.

Waste to chemicals

CHEMICAL RECYCLING OF WASTE

Used materials and even waste streams can be processed back into chemicals by recycling and processing. This is an important step toward the circular economy. It can be achieved through, among other methods, gasification, cracking and pyrolysis. This can save resources and energy while reducing disposal needs and greenhouse gas emissions compared to incineration. Numerous waste streams, from biomass materials to waste plastics, are under investigation for use in raw material supply. The benefit of this concept lies in using materials that would otherwise be disposed of. Its core challenges are the current lack of suitable industrial solutions at scale and cost-effectiveness to efficiently process such materials and to meet the high quality standards required for chemical building blocks.

Selected solution

ASR LIQUEFACTION TECHNOLOGY BY MITSUI CHEMICALS

Converting automotive plastic waste into recycled oil for plastics

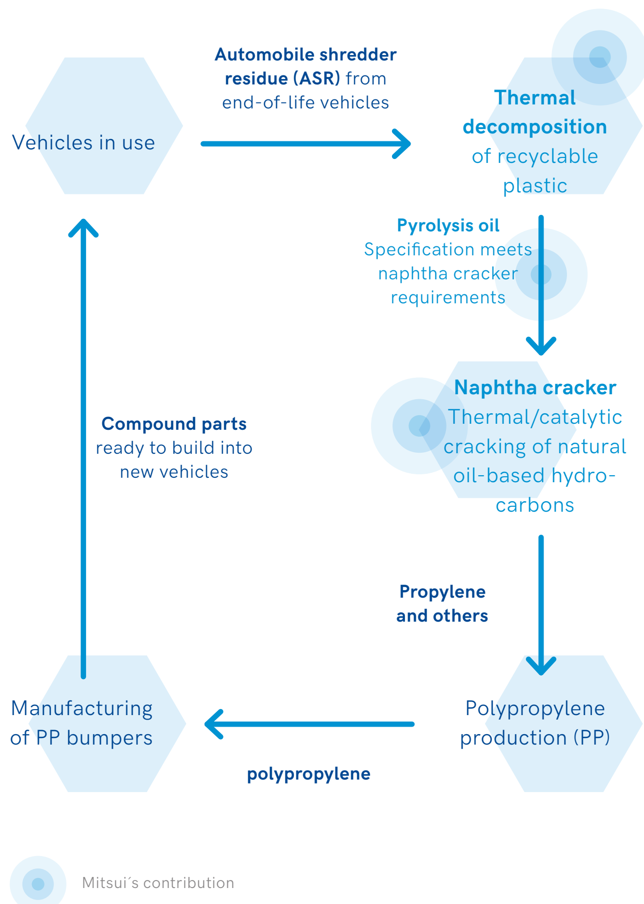
In Japan, approximately 600,000 tonnes of automobile shredder residue (ASR) are generated annually from end-of-life vehicles. Today, while most ASR is thermally recovered as fuel substitutes, it can also be effectively recovered as feedstock for commodity plastics production. Mitsui Chemicals, Inc. (MCI) and a Japanese automobile manufacturer have been developing a pyrolysis-based liquefaction technology converting ASR into recycled oil.

ASR contains metals, multiple plastics and fillers. The new technology enables the separation and decomposition of recyclable materials based on a thermal decomposition process with a focus on separating polypropylene (PP). Thanks to its purification technology, the resultant oil is equivalent to the quality of the original raw chemical material (naphtha equivalents of carbon no. 10 or less). It is then fed through naphtha crackers to produce raw material for commodity plastics such as PP to be used e.g. in plastic car parts. Thanks to this process, waste can be diverted from landfills to feedstock and fossil resources can be saved.

This technology can considerably contribute to reducing carbon emissions by establishing a closed-loop chemical recycling of plastics in automotive sectors.

Currently, MCI is analyzing the plastic components of various ASR samples and carrying out separation and recovery processes of recyclable materials on a lab scale. A proposal is being developed for the liquefication technology process flow and a pilot plant.

FLOW OF RECYCLING AUTOMOBILE WASTE PLASTIC



Impact on SDGs

The process of manufacturing plastics from recycled waste plastics contributes to the sustainable management and efficient use of resources (circular economy approach), as well as improved waste management (SDG 12).

Carbon mitigation potential

<1 $MtCO_2eq$/year by 2050

Potential GHG emission reduction from ASR waste plastic to oil instead of crude oil

ASSUMPTIONS [18]

- ASR as source of oil used as co-feedstock for naphtha crackers
- Annual volume of ASR produced globally in 2050, based on 56 million demolished vehicles: 6.56 Mt/year
- Scenario with 10% deployment rate for technology providing 0.2 Mt PP per year
- Lower GHG emissions of ASR oil production route (0.13 tCO_2eq/t PP) vs. crude oil-based feedstock (0.5t tCO_2eq/t PP), provided renewable energy is used

INDIRECT IMPACT

No significant further impacts on GHG emissions in the value chain have been identified.

Challenges

TECHNICAL

- Process design and establishment of commercial-scale liquefaction technologies for various types of ASR
- Suitability (in terms of quality) of recycled oil for existing naphtha crackers
- Overall environmental feasibility with a focus on GHG emissions

FINANCIAL

- Economic feasibility

REGULATORY

- Legal frameworks encouraging chemical recycling of waste[17]

Hydrogen production

REPLACING FOSSIL FUELS WITH HYDROGEN AS A CARBON-FREE ENERGY CARRIER

Hydrogen offers significant potential as a carbon-free energy carrier. It could also replace commonly used fuels as it possesses the highest specific energy density of any fuel used for oxidation processes. In the chemical industry, hydrogen is primarily used in a range of essential production processes. The greater part of global hydrogen is generated from natural gas through steam reforming technology. This technology, however, causes a significant amount of carbon emissions. Alternative hydrogen production can be achieved through water electrolysis and biogas processing, and these processes do not generate any emissions. Efforts to make hydrogen production fully carbon-neutral are underway. Industrial-scale production volumes could enable long-term stability and efficiency in the manufacturing of hydrogen-powered fuel cells and herald a transition to a hydrogen-based economy.

Selected solution

POLYMERIC SEPARATION MEMBRANE BY TORAY INDUSTRIES

High-purity hydrogen production for powering fuel cells

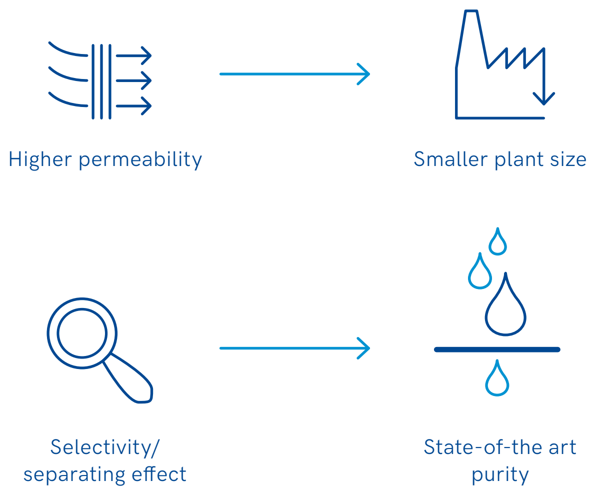
By 2030, global hydrogen production is expected to increase to 300 million tonnes from its current output of 60 million tonnes. Membrane separation can play a crucial role in this development as an efficient and energy-saving purification method. Toray Industries has developed an extremely hydrogen-permeable polymeric separation membrane for hydrogen production. It enables the high level of purity necessary when selectively separating hydrogen from a gas mixture.

The membrane separation process typically requires high temperatures and high pressure. The porous substrate that makes up the separation membrane must be capable of resisting heat and pressure in order to achieve the necessary superior separation properties of hydrogen permeability and selectiveness. In addition, it is extremely important for the pore size in the functional separation layer to be precisely controllable.

Toray Industries has researched new material membranes. Its membrane's porous substrate design combines heat-resistant polymeric materials and separation membrane technology. This enables the phase separation rate of polymers with a high glass transition temperature. In this way, gas permeability is preserved while heat and pressure resistance are significantly improved.[19] Thanks to interfacial polycondensation technology based on reverse osmosis, Toray's membrane offers precisely controlled pore diameter, suitable for the selective permeation of hydrogen molecules. This hydrogen permeability level exceeds existing solutions tenfold.

The technology is currently in the lab phase. Once it reaches the large-scale production stage, it could facilitate the use of hydrogen, thereby accelerating a shift toward a hydrogen-based, and therefore low-carbon, economy.

ADVANTAGES COMPARED TO EXISTING SOLUTIONS



Impact on SDGs

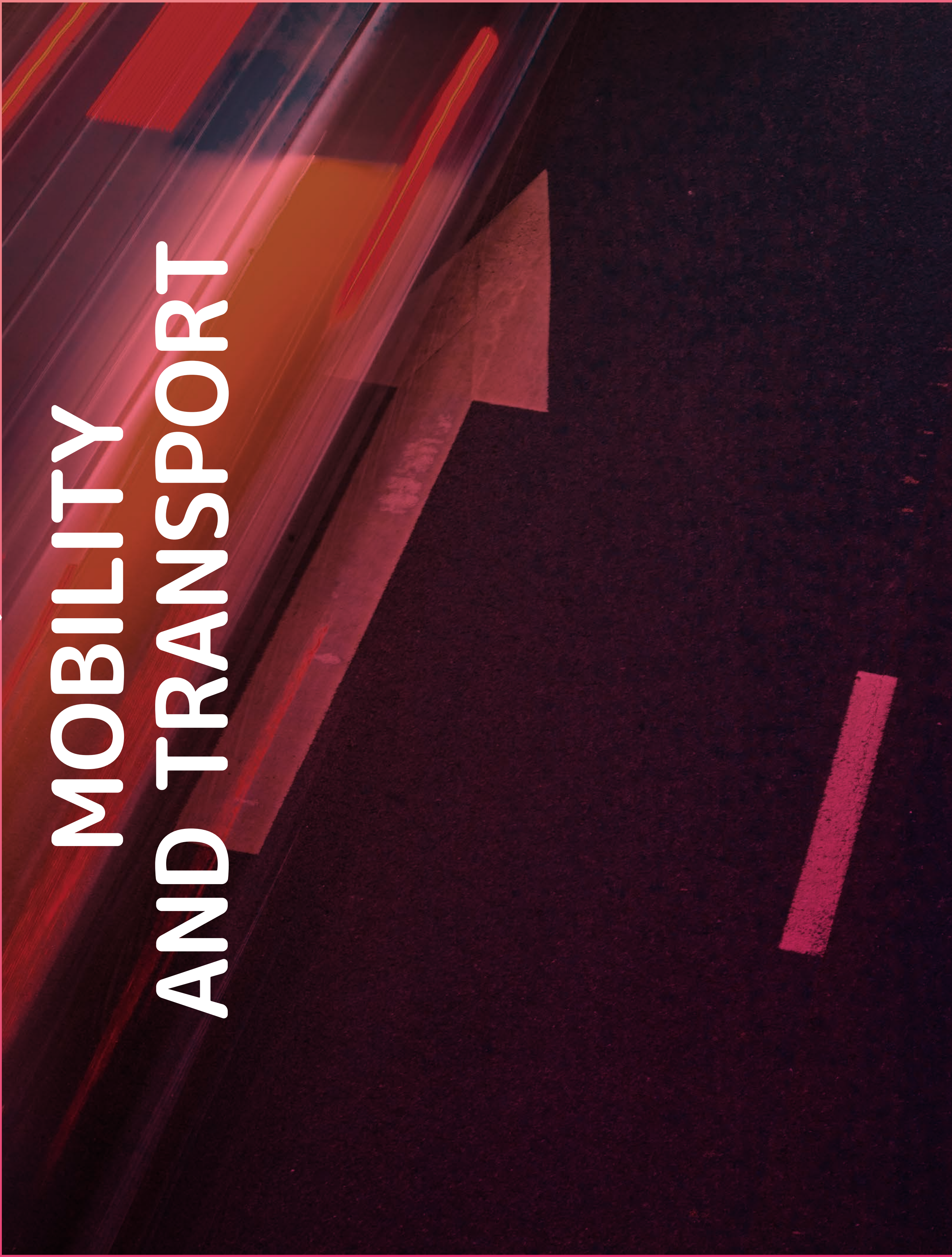
By facilitating the transition to a hydrogen-based economy, this solution could also contribute to improving (renewable) energy access (SDG 7), reducing resource consumption (SDG 12) and building sustainable cities and communities based on hydrogen-fueled transport systems (SDG 11).

Challenges

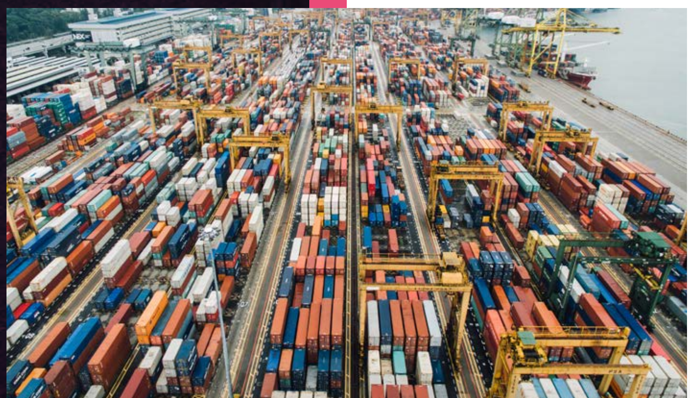
No major challenges were identified.

Carbon mitigation potential

No data available.



MOBILITY AND TRANSPORT



Shrinking the mobility and transport footprint

With 23% of all energy-related carbon emissions caused by global transport,[1] this area has great potential when it comes to low-carbon solutions. Attempts to reduce the harmful impact of mobility and transport by road, rail, air and sea are already underway and the chemical industry plays a key role in this effort. It can contribute to reducing transport-related energy consumption and GHG emissions by, for instance, developing lighter materials for fuel efficiency and better solutions for e-mobility batteries and fuel cells. Technical challenges are inherent to all these areas. With its research and development expertise, the chemical industry is ideally placed to contribute to the revolutionizing of global mobility and transport.

Lightweight materials

LIGHTWEIGHT MATERIALS FOR FUEL EFFICIENCY

Transport is responsible for 23% of global energy-related carbon emissions.[2] The concept of using lightweight materials in the transport sector to improve fuel efficiency is known as "lightweighting." This concept is already well established in the aviation sector—not limited to the use of high-strength aluminum but also used in engineering polymers and high-tech foams. The automotive sector has already started to apply similar technologies replacing traditional steel components to achieve a relevant transformation: A 10% reduction in vehicle weight can result in fuel savings of 6-8%. To unlock further potentials, the biggest challenge involved is the development of lightweight materials with high-performance structural and safety features—and at a competitive price. To achieve this, the chemical industry's contribution is vital.

Selected solution

BASF HIGH-TECH FOAMS FOR LIGHTER CAR PARTS

Lightweighting in the automotive industry

One lightweighting solution already established in the automotive industry is a polyurethane (PU) foam used, for instance, inside car seats and bumpers, energy absorbers within the car´s metal framework as well as special sealings and adhesives for the windshield and coating. An active supplier of advanced PU foams for instrument panels, BASF has developed a new generation of semi-rigid systems whose structure and air-permeable composition enable significant weight reduction and flexibility. Its robust, fine-cell structure makes it potentially suitable for use in components with a cross-sectional thickness of less than 5 mm. With a foam density of about 120 g/L, the foam weight can be reduced by up to 30%, depending on the component geometry, resulting in very light and thin elements.[3] This way weight reduction can be achieved in the relevant parts containing the foam, mostly in the interior of the car, reducing the overall weight of the vehicle by a small percentage.

BASF has also designed an innovative foam system made with castor oil as a renewable raw material. This bio-based foam can be used to produce complex components with strong adhesive and lightweight properties. Its production has an improved environmental impact and carbon footprint, also thanks to its low foam density. BASF chose to use castor oil as a non-food, renewable compound for the product. This biobased PU does not differ from conventional PU in terms of its material properties and is not biodegradable. These semi-rigid foam systems are already widely used in dashboard manufacturing, and BASF continues to work on further enhancing this product portfolio.

Challenges

TECHNICAL

- Formulation of renewable PU raw materials for semi-rigid foams for instrument panels that meet industry standards

FINANCIAL

- Overall system price is above industry average due to the price of the raw materials used

REGULATORY

- Regulations for lower car emissions

Impact on SDGs

PU foam can contribute to more sustainable transport systems (SDG 11) as well as a more sustainable and efficient use of natural resources (SDG 12).

Carbon mitigation potential

<1 $MtCO_2eq$/year by 2050

Emissions prevented through light-weight foams for vehicle dashboards

ASSUMPTIONS [4]

- Carbon mitigation impact attributed to the transport sector, i.e. reduced vehicle weight resulting in lower tailpipe emissions during vehicle use
- Scenario with 564 million internal combustion vehicles (ICE) by 2050
- Lightweight materials application close to 50% of ICE vehicles
- Thereof 10% of applications made of lightweight foams in dashboard
- Vehicle weight reduction enabled by advanced foams close to 0.16%
- Standard assumption of 7% fuel and tailpipe reduction by 10% weight reduction
- Reference scenario based on tailpipe emissions from ICE vehicle: 3 tCO_2eq/year
- The displayed solution is an example of an array of lightweighting solutions that could provide more mitigated CO_2 emissions.

INDIRECT IMPACT

No significant further impacts on GHG emissions in the value chain have been identified.

Batteries

IMPROVING BATTERY SIZE AND CAPACITY

The number of newly registered electric cars is set to dramatically rise over the next decade. Until now, the size, capacity and performance of batteries have been the limiting factor for the growth of many electric products, most prominently battery electric vehicles (BEVs) and stationary electricity storage. Improved, more efficient and more economical batteries will be required if the transition away from fossil fuels to renewable electricity is to occur. Many forms of renewable energy, most importantly solar and wind, are intermittent, making them critically dependent on large-scale energy storage to ensure a stable supply. Compact and efficient batteries require both advanced materials and chemicals. These will need to be supplied by the chemical industry on a global scale to enable mass production for the long term.

Selected solution

SOLVAY SOLUTIONS FOR ENHANCED LI-ION BATTERIES

Improved performance, longevity and safety for e-mobility

In battery production, the three most critical aspects are performance, lifetime and security. To make BEVs as attractive as gasoline cars for consumers and to unleash the full potential of BEVs, factors such as mileage range, safety, charging, aging and purchase cost will have to be significantly improved. Innovations in these areas are crucial to their success and competitiveness with gasoline vehicles—and could have a significant impact on GHG emissions.

First developed in the 1990s, Lithium-ion (Li-ion) batteries tend to be used because of their low maintenance, safety of use and high energy content as compared to lead-based batteries. Li-ion batteries show great promise as a power source, especially for BEVs. Technical limitations, however, prevent Li-ion batteries from reaching their maximum theoretical energy density, thereby impacting the BEVs' range and charging time.

Solvay is developing specialty polymers to optimize the lifetime and performance of Li-ion batteries, in an effort to achieve high energy density at an affordable cost and with maximum safety. Solutions being developed include LiFSI salt for electrolytes, electrode binder material and a separator coating, additive F1EC, water-based production technology to eliminate the use of a toxic solvent during production, a polymer-based gel and solid electrolytes. These products contribute to lifetime extension, energy density, safety and thermal performance at low and high temperatures.

In the long term, solutions under development also include polymer-based and solid inorganic electrolytes enabling long-range use and intrinsically stable and safe batteries, free of flammable compounds and with increased energy densities.

Challenges

TECHNICAL

- Design and manufacturability of BEV batteries (battery management system, mechanical engineering, thermal management); recycling of Li-ion batteries
- Supply chain management (sourcing materials and lead times)
- Manufacturing flexibility (prototypes and small volumes with rapid scalability)[5]
- Recycling of Li-ion batteries

FINANCIAL

- Cost efficiency at a large scale and practical limits of energy density (while the cost per kWh should be ~US$100/kWh if a battery is to allow a BEV to be cost-competitive with a gasoline car; it is currently >US$200/kWh)[6]

SOCIETAL

- Social and environmental challenges related to lithium mining as fundamental elements of the value chain

REGULATORY

- Regulations regarding Li-ion batteries (e.g. regarding recycling); quality/safety standards

Impact on SDGs

By improving charging properties, energy density and safety, Li-ion batteries can enhance energy efficiency and provide access to affordable, reliable and sustainable energy (SDG 7) while also contributing to the growth of e-mobility and the development of a sustainable transport system (SDG 11). Even so, improvement is still needed when it comes to batteries' consumption of natural resources and management of chemical waste (SDG 12).

Carbon mitigation potential

1,700 $MtCO_2eq$/year by 2050

Avoided emissions thanks to Li-ion batteries in BEVs

ASSUMPTIONS [7]

- Carbon mitigation impact attributed to the transport sector, i.e. BEVs reducing vehicle tailpipe emissions during vehicle use
- Scenario with 579 million BEVs by 2050
- Reference scenario based on tailpipe emissions from ICE vehicle: 3 tCO_2eq/year (45 tCO_2eq/270,000 km in 15 years for overall mix of weighted tailpipe emissions from personal light duty vehicle with various internal combustion engines (ICE))

INDIRECT IMPACT

An indirect impact exists on emissions from other sectors with the biggest impact in the area of battery production, along with fuel production, electricity generation, vehicle production and disposal. Power generation mix and waste management practices play an important role. Depending on the model or country, according to KPMG (2019) the carbon footprint advantage of BEVs will only arise at around 250,000 km or more driven. However, other sources indicate that the electricity mix that the car uses over the entire BEV life cycle is more important: The current European generation mix will enable BEVs to deliver GHG emission savings of about 30% as compared with gasoline ICE vehicles.

Fuel cells

BETTER PERFORMANCE, LOWER EMISSIONS

Fuel cells are electrochemical devices that convert the chemical energy in fuels into electricity via an electrochemical reaction, typically involving hydrogen and oxygen (from the air). Besides hydrogen and oxygen, research has also considered advanced fuel cell technologies based on methanol, thus providing access to renewable feedstock. The widespread adoption of fuel cells has the potential to significantly enable the transition toward a low-carbon future. The electrochemical process is up to three times more efficient than fuel combustion and generates fewer harmful emissions as by-products. Yet, for the moment, most fuel cell varieties are still in the research phase. The production of the cells requires highly sophisticated materials and precise manufacturing. This means that the chemical industry has an important role to play in advancing the development of fuel cells.

Selected solution

ANION EXCHANGE MEMBRANE FUEL CELLS (AEMFCS)

Lower-cost fuel cells for long-term commercialization

A large variety of fuel cells exists. They differ in terms of operating temperature, catalyst and hydrogen content depending on the carrier: There are polymer electrolyte membrane or proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs).[8] Each one has different applications such as stationary power generation, mobile electronics and vehicles.[9]

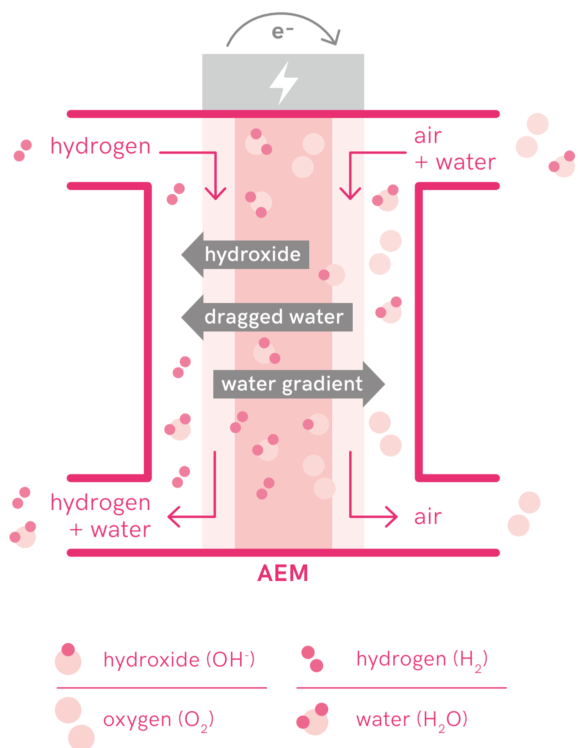
The market penetration of hydrogen fuel cells within the transportation sector is currently limited, mostly due to cost pressures related to low production volumes and the need for expensive platinum group metals (PGMs) in the electro-catalysts. Durability is another important challenge and is related to load cycling and rapidly changing operating conditions.[10] Research and development in this field is in full swing.

Attention is growing around AEMFCs. While similar to PEMFCs in their technical design, their main difference lies in their solid membranes—alkaline for AEMFCs and acidic for PEMCFs. This basic pH cell environment in AEMFCs results in an enhanced oxygen reduction reaction (ORR) enabling better cell stability and lower material costs.

Over the last decade, multiple factors have enabled continuous improvement of the cells' performance: new polymer chemistries, highly active PtRu hydrogen oxidation reaction (HOR) catalysts and improved water management for hydrating the membrane.[11]

The technology of AEMFCs is still under development and has not yet reached the maturity of the PEMFC technology. Research is still needed to achieve cost-effective and commercially viable AEMFCs with long-term chemical and physical stability.

FUNCTIONALITY OF AEMFCS



Source: Dekel, D. (2018) Review of cell performance in anion exchange membrane fuel cells

Challenges

TECHNICAL

- General: improvement of performance stability;[12] development of PGM-free highly-efficient catalysts; new, cheaper materials for higher power density; new catalysts to reduce platinum loading; new manufacturing techniques for the consistent manufacture of solid oxide fuel cells or the cheaper production of nafion; clean hydrogen production and storage; refueling infrastructure
- Mobility-specific: application space—unlikely to find widespread use in light duty vehicles, probably best to focus on heavy duty trucks, motor drives, boats and trains (niche)

FINANCIAL

- Cost competitiveness with battery electric vehicles (BEVs)

SOCIETAL

- Safe handling of hydrogen in public places, such as parking garages
- Civil disruption due to large-scale (CapEx) investment, e.g., in upgrading gas networks

Impact on SDGs

7 AFFORDABLE AND CLEAN ENERGY | 11 SUSTAINABLE CITIES AND COMMUNITIES | 12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Improvement in fuel cell-based mobility has the potential to enhance energy efficiency and access to affordable, reliable and sustainable energy (SDG 7). It can also contribute to the expansion of e-mobility and sustainable transport systems (SDG 11). Moreover, the reduction of PGM use enables improved consumption of natural resources (SDG 12).

Carbon mitigation potential

950 $MtCO_2eq$/year by 2050

Emissions prevented through AEMs for advanced fuel cells in FCVs.

ASSUMPTIONS [13]

- Carbon mitigation impact attributed to the transport sector, i.e. FCVs reducing vehicle tailpipe emissions from ICE during vehicle use
- Scenario with 300 million FCVs by 2050
- Reference scenario based on tailpipe emissions from internal combustion vehicles: 3.2 tCO_2eq/year
- 47 tCO_2eq/300,000 km in 15 years for overall mix of weighted tailpipe emissions from personal light duty vehicles, buses and trucks with various ICEs
- AEM considered strong enabler for fuel-cell technology in vehicles, thus 100% deployment rate

INDIRECT IMPACT

The indirect impact arises from emissions from other sectors, including fuel and hydrogen production, vehicle and fuel-cell production as well as vehicle disposal. Due to the varying influence of these factors on hydrogen production (feedstock mix, technology, carbon capture and storage utilization) and vehicle features, estimates vary between 15 and 125 gCO_2/km. According to the International Energy Agency (IEA), global fuel cell electric vehicles could account for an emissions reduction of almost 1 $GtCO_2$ per year by 2050.

NUTRITION AND AGRICULTURE

Helping to rise to the nutrition challenge of a growing world population

The agriculture, forestry and other land use sector (AFOLU) is responsible for almost 25% of anthropogenic GHG emissions (reference year 2010).[1] The majority of these stem from deforestation as well as livestock, soil and nutrient management. With the global nutrition challenge of feeding a growing world population, this sector has come into the spotlight of the target to limit global warming. The chemical industry is instrumental to meeting the nutritional needs of humans and animals and making nutrition and agriculture more sustainable. Chemical technologies in this area include those affecting the nitrogen cycle, e.g. through lower carbon-emitting fertilizers, animal feed additives as well as enabling carbon storage in ecosystems through ecosystem restoration and enhancement approaches.

Low-carbon handprint products

OPTIMIZING THE CARBON HANDPRINT OF PRODUCTS AND SERVICES

The production of animal protein to feed the growing world population is putting global food production systems and the planet under immense pressure. Livestock farming is responsible for 14% of all anthropogenic GHG emissions (reference year 2008).[2] New and more efficient farming practices are therefore being developed, fostering carbon sequestration through improved pasture management and better integration of livestock in the circular bio-economy.[3] There's also growing demand from consumers for food and other agricultural products with a lower environmental impact. One way to measure the climate change mitigation potential is the so-called carbon handprint.[4]

Selected solution

EVONIK NUTRITION & CARE ANIMAL FEED SOLUTIONS

Amino acid-enriched animal feed

Animal feed production is one of the largest sources of emissions in meat production. Conventional feed contains large amounts of plant-based proteins from corn, soybean and other crops requiring intensive farming. Evonik has developed amino acid-enriched animal feed that requires fewer plant-based proteins, more efficiently meets the nutritional needs of animals and improves the carbon effects of meat production.

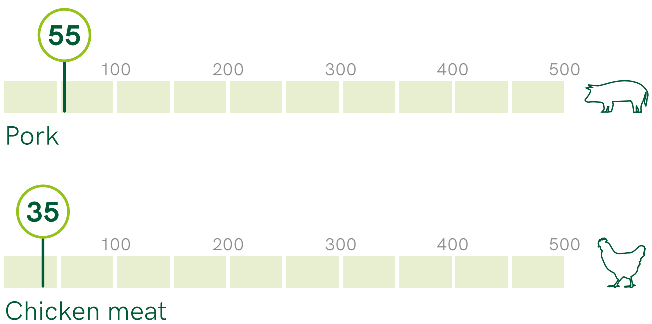
Amino acids are the building blocks of protein. They ensure metabolic reactions and other vital functions. Ten essential amino acids are unable to be synthesized directly by animals (or humans), and need to be ingested in specific proportions to ensure healthy nutrition. When used in advanced feed formulations, these amino acids reduce the overall quantity of feed required.

Evonik's crystalline amino acid feed additives are produced through chemical synthesis or biotechnological fermentation,[5] such as from corn sugar, to include the first five limiting amino acids DL-Methionine, L-Lysine, L-Threonine, L-Tryptophan and L-Valine. They are most widely used in broiler and pig meat production.

Amino acid-enriched feed enables a reduction of the crude protein content in feed. This also lowers the amount of GHG nitrous oxide (N_2O) in animal excretions. Due to amino acid-enriched feed requiring fewer raw feed materials, arable land can be freed up, resulting in an improved GHG impact related to land use, crop production and transport. ISO- and TÜV-certified life cycle analyses of Evonik amino acid-enriched animal feed have proven a significant and positive effect on livestock production with regard to GHG emissions.

Evonik produces the five most important essential amino acids on a full industrial scale. It collaborates with the Specialty Feed Ingredients Sustainability (SFIS) project and the International Feed Industry Federation (IFIF) along the complete value chain. It also works with independent specialists from the world of academia to further reduce crude protein in feed by improving feed formulations.[6]

GLOBAL EMISSION INTENSITIES BY COMMODITY



kgCO$_2$eq/kg protein^{-1}

Source: FAO (2019) http://www.fao.org/gleam/results/en

Challenges

TECHNICAL

- Improving livestock production efficiency by increasing the inclusion rate of further limiting amino acids

FINANCIAL

- Sustainability performance must be increased combined with enhanced animal welfare through improved efficiency in large-scale units

SOCIETAL

- Increasing consumer awareness about sustainable, healthy nutrition and food production
- Enabling consumers to make better choices and accept the higher costs of more sustainable animal nutrition, welfare and health

REGULATORY

- Adjustment of national and international dietary recommendations
- Regulations regarding livestock operations, e.g. introducing nitrogen thresholds for manure
- Maximum content of crude protein in feed, etc.

Impact on SDGs

The use of amino acids in animal feed lowers the need for raw feed materials, such as soybeans, thereby improving land use and, subsequently, the impact of crop production, transportation and animal excretion (SDG 12). It also results in decreased GHG emissions from livestock farming and water pollution. In this way, it contributes to improving access to safe, nutritious and sufficient food, increased agricultural productivity (SDG 2) as well as the conservation, restoration and sustainable use of terrestrial ecosystems (SDG 15).

Carbon mitigation potential

1,680 MtCO$_2$eq/year by 2050

Avoided emissions from amino acid-enriched pork and poultry feed production

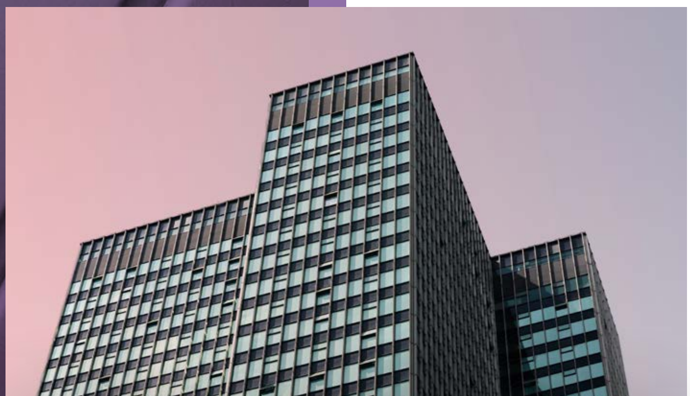
ASSUMPTIONS [7]

- Global annual consumption of pork increasing from 119 Mt in 2017 to 171 Mt by 2050 (around 1% annual growth)
- Global annual consumption of poultry meat increasing from 121 Mt in 2017 to 174 Mt by 2050 (around 1% annual growth)
- Amino acids as supplementation for pork and poultry feed to offset relevant protein in feed, i.e. 53% (pork) and 44% (poultry)
- Scenario with a projection of 100% deployment rate for amino acid feed supplementation
- Significant GHG savings due to increased feed, i.e. amino acid efficiency vs. soy feed and rapeseed protein source (tCO$_2$eq/t amino acid)
- Quantified CO$_2$ savings based on current technological status of feed production, including the conversion ratio, the current source of proteins for meat and the associated land use change effects of these proteins.

INDIRECT IMPACT

No significant further impacts on GHG emissions in the value chain have been identified.

BUILDING AND HOUSING



Energy efficiency and alternative energy are key

As the global population and economy expand, energy-efficient building and housing will have to contribute substantial GHG emissions savings to enable the transition to a low-carbon future. Globally, buildings consume over one-third of all energy and carbon emissions. Insulation can play a significant role in reducing heat and cooling requirements. To this end, the chemical industry is developing new materials and researching new generations of thermal control and lighting systems. Another important aspect of building and housing is the need for alternative energy generation. Technological advances in solar photovoltaics, tidal energy and wind power offer great opportunities for the chemical industry to overcome technological challenges in this field.

Energy efficiency

SHRINKING THE CARBON FOOTPRINT OF ENERGY USE

As the world's population is growing, efficient energy use is becoming ever more essential for a low-carbon future. According to estimates, the energy intensity of global buildings needs to improve by some 30% by 2030 (as compared to 2015), if the transition to the low-carbon society is to be achieved. With the buildings sector growing by about 2.3% per year, energy efficiency improvements are proving even more important.[1] New materials are being developed by the chemical industry to meet these needs, and the next generation of heating, cooling and lighting systems is currently being researched in laboratories. Heating and cooling alone account for a significant proportion of global energy use. Any efficiency gains, therefore, positively impact the carbon footprint of energy use.

Selected solution

BASF HIGH-PERFORMANCE AEROGEL INSULATION

Insulation solutions for energy-efficient buildings

BASF develops high-performance thermal insulation solutions for buildings, with new and very slim aerogel-based insulation materials. Aerogels are porous lightweight solids. They are derived from gels by replacing the liquid component with air. The result is a highly porous solid material with low thermal conductivity. These high-performance products are especially effective in exterior and interior thermal insulation systems. Moreover, they can be inserted between carbon concrete and reinforced concrete walls, and also directly integrated into the production of precast concrete elements. This makes them useful for a wide range of applications in construction and refurbishment including roof, floor or facade insulation for tailored climate management.

These extra-thin materials provide better insulating results than conventional alternatives and reduce energy consumption by preventing thermal bridges. The heavy-duty polyurethane-based (PU) aerogel insulation panel consists of 90% air and has an open-porous structure, making it both robust and water vapor-diffusive. Due to the small pore size, heat transfer is drastically reduced—making use of the Knudsen effect, i.e. providing significantly better insulation properties than conventional materials. The panels are up to half the width of conventional insulation, enabling both space savings and high-performance insulation (thermal conductivity: ~18 mW/m*K).[2] The inorganic aerogel material is based entirely on mineral raw materials, with much lower thermal conductivity (<19 mW/m*K) than conventional mineral insulation materials.[3] It's also non-combustible in euro class A2-s1, d0 and has water-repellent characteristics. The production of the materials occurs through a so-called sol-gel process followed by supercritical drying with CO_2 as a processing agent. The

CO_2 is fully recovered after every cycle. Hence, there are no direct carbon emissions from the process.

The easy processing of the materials makes them an efficient alternative that provides increased insulation with a minimal environmental impact.[4] The inorganic aerogel-based solution is fully commercialized and the PU-based aerogel insulation panel is currently in the pre-marketing stage.

Challenges

TECHNICAL

- New process technologies and pilot plants required for production of such innovative aerogel materials
- Separating the (non-aging) materials from other construction components for re-use

FINANCIAL

- New production plants require considerable capital investments and risk-taking

Impact on SDGs

Innovative building insulation improves living comfort while generating significant energy savings, thereby improving access to affordable and future-resilient housing (SDG 11) and increasing energy efficiency (SDG 7).

Carbon mitigation potential

30 $MtCO_2eq$/year by 2050

Potential GHG emission reduction through new materials for building insulation

ASSUMPTIONS [5]

- Carbon mitigation impact attributed to the *Building and housing* sector (i.e. reducing energy consumption through improved insulation of building envelope during use phase)
- Assumption based on IEA 2 °C scenario for energy reduction in *Building and housing* sector
- Projection of GHG emission reduction by 2050 around 525 $MtCO_2eq$/year
- 55% potential share to be achieved through improved insulation technologies
- Scenario with 10% market share for advanced insulation materials

INDIRECT IMPACT

The solutions enable the retrofitting of insulation material in existing walls. This could lead to higher energy savings from the building envelope as the existing stock can be insulated more easily. It may also extend the lifetime of the existing stock because buildings can meet efficiency requirements, leading to fewer emissions from new construction and demolition. There are also significant emissions related to the production and end-of-life phase of aerogels. When the lifetime of a building is short or when emission savings (achieved through renewable energy used for the thermal demand) are limited, other insulation materials may be more advisable.

Alternative energy generation

POWERING BUILDINGS WITH GREEN ENERGY

When it comes to energy management and generation for commercial and residential buildings, the demand for highly efficient solutions is growing rapidly. Heating and cooling alone account for half of the EU's energy consumption, which means any efficiency improvements can have a significant impact. The chemical industry is developing technological innovations to help overcome challenges associated with insulation, temperature and climate control, as well as heating and cooling devices in building and construction. Smart technologies for building-integrated alternative energy generation are also under development, and a variety of elements and compounds are currently being explored. Furthermore, the large-scale production of new and innovative materials will require efficient and reliable manufacturing systems, and the chemical industry will also be involved in the respective end-of-life considerations.

Selected solution

BUILDING-INTEGRATED PHOTOVOLTAICS (BIPV)

Turning buildings into power stations

BIPV is one of the growing trends in solar renewable energy generation in the construction sector. It directly transforms a building's envelope from an energy consumer to a renewable energy producer—a mini-power station of sorts. Photovoltaic (PV) devices can substitute conventional architectural components such as the roof, walls, glazing, cladding, shading devices, parapets and balconies. Its approach is particularly suited to commercial buildings with large roofs and surfaces. In addition to enabling on-site energy generation, these elements provide weather protection, thermal insulation, noise protection and daylight modulation.

BIPV has been a niche market since the late 1970s. Recently, as PV technology itself has progressed and its price decreased, it has attracted growing interest. It currently holds a 2% market share of the overall PV market but shows potential for growth, which could enable the zero-energy building target to be reached.[6] BIPV also provides material savings and lowers resource utilization. Off-grid renewable energy generation that is provided on-site keeps electricity costs from accruing, while also optimizing the infrastructure of energy supply and demand.[7]

A BIPV system is composed of an array of interconnected solar cells, usually based on inorganic semiconductors such as silicon and inorganic nanocrystalline salts. The most widely used PV, based on crystalline silicon technology, provides an efficiency of 15 to 20% under lab conditions, but its performance decreases when exposed to high temperatures or in the shade. Thin-film solar cells are less efficient but perform better under variable lighting conditions.[8] They can be used as a transparent solar coating laminated onto windows, absorbing and converting non-visible light into electricity while blocking infrared radiation. The potential exists, therefore, for these cells to turn traditional windows into energy-efficient electricity-generating elements. They are also lighter in weight and offer greater flexibility than their rigid c-Si counterparts.

Research and development are being intensified with the goal of increasing system efficiency, replacing costly crystalline silicon-based systems,[9] improving thin-film PV cells and enhancing architectural aspects (e.g. colored PV).[10]

Challenges

TECHNICAL

- Improving the efficiency and lifetime of BIPV products to increase return on investment[11]
- Price competitiveness with conventional solar-based panel systems (building-added PV)[12]

SOCIETAL

- Lack of communication/information about the advantages of BIPV, leading to low acceptance from the construction sector and end users

REGULATORY

- No uniform approach to the promotion of BIPV

Impact on SDGs

BIPV provides on-site renewable energy while limiting the use of resources and decreasing energy costs. It contributes to the development of an affordable, reliable and sustainable energy system (SDG 7) and sustainable housing and cities (SDG 11) while improving natural resource management (SDG 12). As cross-sector collaboration is required for its development, it also contributes to partnerships (SDG 17).

Carbon mitigation potential

430 $MtCO_2eq$/year by 2050

Potential GHG emission reduction through BIPV

ASSUMPTIONS [13]

- Carbon mitigation impact attributed to the *Building and housing* sector (i.e. producing electricity with solar cells integrated into the building envelope during use phase)
- Total greenhouse gas reduction from buildings estimated to be the total greenhouse gas reduction from the power sector (8.8 Gt) times the relative electricity consumption from buildings (43%)
- 43% of GHG reduction from power sector attributed to increased use of solar PV
- Scenario of market penetration with BIPV amounting to 26% of installed PV-cell capacity by 2050

INDIRECT IMPACT

Although the emissions related to the use of PV cells is zero, emissions arise from the production and end-of-life phase of PV systems. There are upstream emissions from raw material extraction, production and manufacture of the system and components as well as downstream emissions associated with system/plant decommissioning and disposal. When the entire life cycle is included, carbon emissions from PV systems per kWh are generally similar to other renewables and nuclear energy and much lower than fossil-fuel technologies.

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