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CONSENSUS PAPER

PLASMA PROCESSES AND POLYMERS

The future for plasma science and technology

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The application of gas discharge plasmas has assumed an important place in many manufacturing processes. Plasma methods contribute significantly to the economic prosperity of industrialized societies. However, plasma is mainly an enabling method and therefore its role remains often hidden. Hence the success of plasma technologies is described for different examples and commercial areas. From these examples and emerging applications, the potential of plasma technologies is discussed. Economic trends are anticipated together with research needs. The community of plasma scientists strongly believes that more exciting advances will continue to foster innovations and discoveries in the first decades of the 21st century, if research and education will be properly funded and sustained by public bodies and industrial investors.

KEYWORDS

economic potential and impact, plasma technology, research needs, societal challenges, trends and directions

1 | INTRODUCTION

Solids can change to liquids and eventually gases with an increase of the internal energy. If still more energy is provided, the number of collisions between individual constituents and their energy increases further, promoting ionization and dissociation processes. The resulting gaseous "fourth state of matter" is comprised of reactive species, ie, excited molecules and atoms, radicals, positive ions as well as negative species (ions and, mostly, electrons) in a neutral background gas. Irving Langmuir coined for this special mixture the term "plasma" in 1928.[1] Most of the visible matter in the universe is in fact in a plasma state, such as the interior of stars and interstellar matter. Apart from these naturally occurring plasmas, to which one might add lightning and flames, plasmas can be man-made and are exploited in a wide range of applications including surface modifications, environmental remediation, and increasingly also biotechnologies and medicine, to name a few.

Popular association with plasma technology is often limited to high-temperature plasmas used for controlling and harvesting energy from nuclear fusion processes. However, more mundane applications of plasma technologies are already widespread and have shaped everyday lives comprehensively and ubiquitously.[2] Some of these developments, eg, plasma television sets, have caught consumer attention, but in many products, the contributions of plasma processing steps remain hidden, and their vital role is not obvious (cf. Figure 1). For instance, about one third of the steps involved in manufacturing of microelectronic circuits and microprocessors are plasma-based.[3] Fluorescent lighting tubes and energy-saving light bulbs rely heavily on plasma processes.[4] Although the advent of light emitting diodes (LEDs) is changing the field of lighting technology, plasma processes still play an important role in the fabrication of these devices.[5] Plasma surface modification processes to provide and enhance properties and functionalities of materials are common and cover a range from the preparation of plastics for printing, to the improvement of optical properties of reading glasses.[3,6,7] Plasma can further provide successful means for the decomposition of chemical pollutants and harmful microorganisms in air and water.[8,9] The generation of ozone as a disinfecting agent is probably the oldest commercially viable application of a plasma technology since it was first described by Siemens in 1857,[10] and is still in use today. Many more areas of application of plasma technologies can be added to this list and it is one of the objectives of this review to present several additional examples and highlight their economic and societal impact.

The success of all these applications is only possible by utilizing the unique properties and interaction mechanisms that are provided by plasma. Technological exploited plasmas are almost exclusively generated in gas discharges, meaning that energy is provided to an operating gas by an applied electric field with the goal to partially dissociate and partially ionize molecules and atoms. The result is a mixture of mostly neutral but in part excited and reactive species in addition to charged particles, in particular including free electrons.[11] The mix of species and its properties are determined by the operating conditions, such as foremost supplied gas, gas pressure, and characteristic of the electrical excitation scheme. The actual kinetic energy that different species acquire in the plasma is important in many applications, especially for the interaction with materials but also liquids and biological matter. Strongly correlated is the chemistry or the potential for chemical reactions of plasma constituents. Especially electrons and their kinetics play an important role which participate in different ionization-, activation-, and excitation processes and can by themselves induce unique characteristics and secondary mechanisms, such as for example ultraviolet (UV) and vacuum ultraviolet (VUV) light emission.[12] The latter is of course important for the development of light sources but also for surface treatments. Accordingly plasmas are often generated at much reduce pressure of less than 1 mTorr (ie, 0.0013 mbar) from noble gases, such as in particular argon, especially for semiconductor manufacturing.[13,14] Electrical energy is provided primarily capacitively coupled, inductively coupled or from glow discharges.[15,16] More recent developments strive for the generation of plasmas at atmospheric pressure, preferable with ambient air as working gas if this is possible with respect to the intended application.[17] In many cases are dielectric barrier discharges (DBDs) the method of choice for creating a plasma. In this case, at least one of the electrodes is covered by an insulator and oscillating high voltages are sustaining the plasma.[18,19] Corona discharges constitute another type of plasma that is in particular interesting for applications in water.[20] An unwanted transition into an arc discharge is in this case prevented by the application of short high voltage pulses of nano- or microseconds. Conversely, arc discharges, which sustain rather high currents at low voltages in comparison, are of interest for arc welding and plasma cutting.[21,22] In many specific industrial applications are characteristics of different discharge configurations also exploited simultaneously. Electrodes for the generation of corona discharges covered with insulators and dielectric barrier discharges operated with pulsed high voltages. In some cases basic approaches are also engineered into apparently new plasma configurations. For example are many plasma jets that are currently investigated for medical applications based on dielectric barrier discharges.[23] Microplasmas in particular, ie, plasmas with at least one critical plasma dimension below 1 mm, become increasingly relevant for many areas of application. Microplasmas can be operated stably at atmospheric pressure with much less effort than larger plasma sources.[24,25] Furthermore, they can be excited

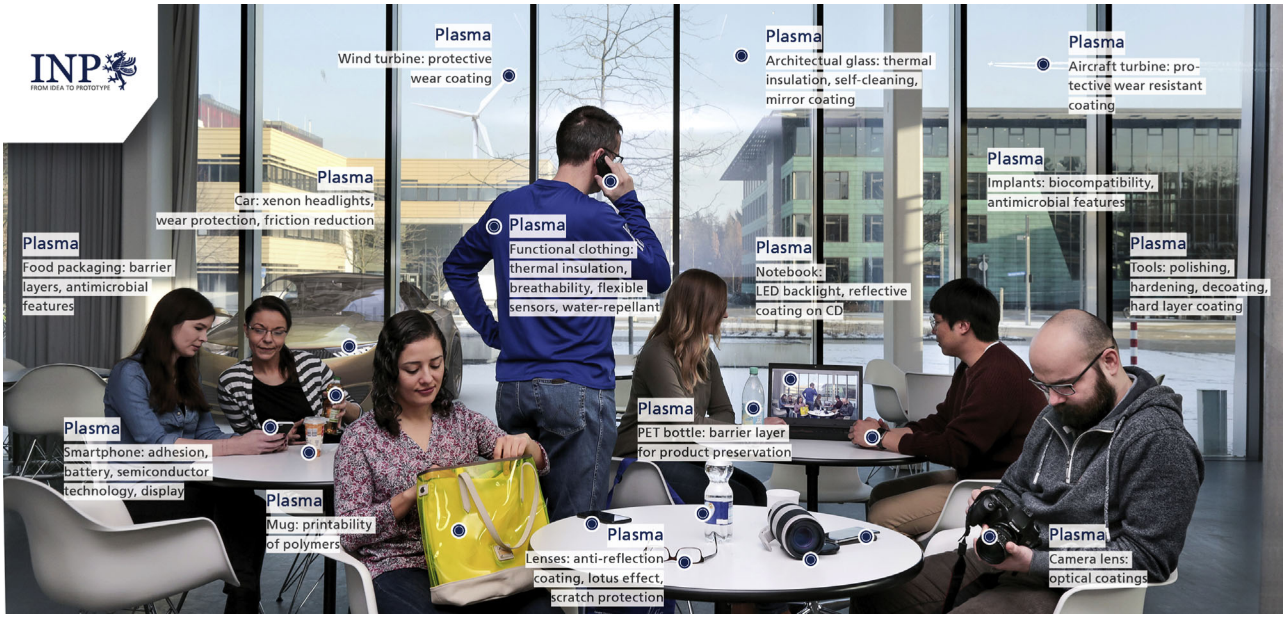


FIGURE 1 Plasma technologies have a crucial, although often hidden, role in manufacturing processes. Many products and services that depend on plasma treatments are ubiquitous in modern societies. Integrated Circuits for computers and cells phones are only possible with plasma processing. Surface treatments and modifications of plastics and textiles improve printing, dyeing, adhesion, and biocompatibility properties, as well as either increase or decrease wettability. Other characteristics that can be afforded are antimicrobial, self-cleaning, scratch-resistant, and even self-repairing properties. Understanding of plasma processes is further crucial for welding and metal cutting technologies and the development of components for power distribution systems. Novel energy generation and storage systems, such as fuel cells, batteries, and supercapacitors, rely on plasma manufacturing. Of increasing interest is the possibility for the plasma-synthesis of new nano-materials. Power savings for lighting is directly correlated to plasma innovations. Activation and hardening of metal and other surfaces minimizes friction and abrasion and hence affords, together with plasma-assisted combustion, higher energy efficiencies for cars and for aircraft engines. Plasma thrusters and actuators provide completely new approaches for propulsion and maneuverability of planes and spacecraft. Plasmas have successfully demonstrated an efficient cleaning of exhaust gases from nitrogen and sulfur oxides. The generation of ozone by plasma is already an undisputed standard method for air and water purification and further developments offer a potential solution to address also emerging pollutants. Thermal plasmas in particular are also already an alternative for the processing of hazardous waste, eg, dioxin contaminated or nuclear waste. The possibility for an effective inactivation of microorganisms by non-thermal plasmas has further promoted increasing interest for the disinfection of heat-sensible materials, including human tissue. Successful novel therapies for chronic wounds have been developed that are now introduced in hospitals. Moreover, findings that plasma can also instigate more subtle biological responses are currently studied for other medical applications, most prominently for their effect on cancer cells, but also applications in agriculture

by direct current (dc) as well as pulsed dc and alternating current (ac) sources over a wide range of frequencies, and arrays of individual sources can be operated in parallel without individual ballasting.[25,26]

It is the general ambition of plasma technologies to control electrical setting and operation parameters of a plasma with respect to different needs and purposes. These could be geared towards complex reaction chemistries in the bulk of the plasma itself or at the interfaces of deliberately exposed surfaces and materials. One parameter that is of special interest for the operation of a plasma is the temperature which is generally referring to the kinetic energy of molecules, atoms and ions. For gas discharge plasmas, especially dielectric barrier discharges and corona discharges, it is possible to keep this temperature rather low and even close to room temperature while electrons assume much higher kinetic energies that are described by a separate, much higher, electron temperature. These non-thermal (or more general non-equilibrium) plasmas are interesting especially for the treatment of sensitive materials, such as textiles, fresh produce, and even body tissues, eg, skin.[12] Conversely, arc discharges as they are exploited for example for arc welding technologies are rather hot, respectively thermal plasmas, ie, with temperatures that are for all species at least locally in thermodynamic equilibrium (LTE).

Much of the progress, especially in the fields of plasma-assisted and plasma-enabled surface modification, is related to the exploitation of fundamental knowledge that was created in microelectronics and photovoltaics in the 1970s and 1980s. Etching (microlithography-aided ablation) and plasma enhanced chemical vapor deposition (PECVD) of thin films created new technological surfaces and continue to provide new possibilities to this day. Lithographic etching processes of silicon, silicon oxide, and other materials are still at the core of the fabrication of VLSI (very large scale integration) integrated circuits in microelectronics – which are now perhaps better referred to it as nanoelectronics. The number of components on a single chip has increased enormously over time, largely due to the increased spatial resolution of plasma processes, and paved the way to smaller and ever more powerful computers and devices. PECVD processes provide the majority of photovoltaic coatings and other layers for solar cells for highly efficient energy conversion of sun light.

Committed international research is steadily expanding the understanding of plasma processes and their potential applications.[27–29] The success of Plasma Science and Technology in advanced applications is clearly related to a significant and sustained investment in basic and applied plasma research worldwide to develop strategic applications, but also through the introduction of courses and new degree programs in many universities focusing on the fundamentals and applications of Plasma Science and Technology. The basic knowledge generated through dedicated investments by public bodies and companies has further encouraged novel approaches also in other strategic fields, such as automotive, textile, aerospace, and even entertainment. In the meantime, the respective applications are no longer limited only to surface treatments and modifications. Besides advanced materials, other high impact areas include lighting, environmental remediation and protection, improvements in biomedical materials, health care and medical therapies, applications in agriculture and for biomass conversion, energy generation and transfer, plasma thrusters, plasma assisted combustion, and advanced display technologies.

Given the flexibility and potential of plasma technologies, considerable research efforts have been expended towards many different application areas. Notable almost all of these developments are contributing to engineering solutions that address important societal challenges, as defined for example by the US National Academy of Engineering in its Grand Challenges for Engineering or by the European Commission in the Framework Programme for Research and Innovation.[30,31] Plasma technologies are already instrumental in the production of photovoltaic cells, fuel cells, and other components for green energy generation, storage, and distribution.[32–35] As such, their contribution to secure clean and efficient energy, but also towards clean transportation systems, is continuously increasing. The significance of plasma processes towards solutions to mitigate environmental hazards and related processes that contribute to man-made climate change is gaining concurrently. Plasma technologies already allow to treat exhaust gas streams and wastewater, and thus directly contribute to environmental protection[8,9,36]; by improving manufacturing processes, they further indirectly support protecting natural resources and conserving raw materials. New materials, eg, textiles, available through plasma exposure, assist these efforts in addition to having an impact on consumer health and well-being. More recent success in the application of non-thermal plasmas in medicine, agriculture, and food technology now also opens up possibilities in areas where plasma technologies have not been present so far.[37,38]

Since plasma technologies are primarily enabling technologies, it is difficult to assess their direct economic impact to a product or manufacturing method. Plasma technologies offer unrivaled advantages, especially when high quality manufacturing is required or environmentally benign processes are needed. Accordingly, plasma technologies are developed and are preferentially employed in highly industrialized countries with economies thriving on high-value products. In 2004, the German Federal Ministry of Education and Research studied the significance of plasma technologies for the German economy.[39] It was reported that 45 000-60 000 people are directly working on building and maintaining plasma technologies. Far more, up to half a million employees were working in manufacturing chains that require a plasma treatment step along the production line. In 2004, this amounted to 6-7% of all jobs in the German economy or a contribution to the GDP of almost 160 billion[1] Euros. Similar estimates and shares can certainly be assumed for other highly industrialized countries in Europe, in Asia, the Americas, and for Australia. For a growth of the German GDP by 28% from 2004 to 2014, it is safe to assume that the contribution of plasma technologies has proportionally increased.

Developments are currently primarily driven by applications for cold plasma methods. Their economic potential was evaluated in a recent Market Research Report, predicting a commercial volume of 2.91 billion USD by 2021.[40] The largest market is currently in Europe but considerable growth potential is found around the world, however, limitations in the commercialization of new ideas need to be overcome.

A group of leading experts on plasma technologies met in 2015 and 2016 in Greifswald, Germany, for two Workshops on the “Future in Plasma Science.” The goal of the meetings was assessing current status and future perspectives for development and application of plasma technologies. Basic research needs and directions for investigations that are needed to further enhance the economic significance and contribution of plasma technologies in key areas were identified. Important general recommendations and conclusions relevant for decision makers in politics and industry were deduced, accordingly. Key areas of interest that were identified with existing and future potential for plasma technologies are Energy & Power, Optic & Glass, Medicine & Hygiene, Aerospace & Automotive, Plastics & Textiles, and Environment & Biotechnologies.

This paper is the immediate outcome of the workshops and of the initiated discussion. For the different fields identified, selected examples of considerable technological, environmental, societal, and economic impact of plasma technologies are presented. The potential and benefit of plasmas for the respective areas is highlighted with emphasis on current needs, research challenges, and emerging applications. Concurrently, for each of the topics that were discussed during the workshops individual "white papers" were compiled that present more details especially on trends and the different research questions in the respective areas. Four of them have already been published on "the future of plasma science for optics and glass,"[41] "the future of plasma science and technology in plastics and textiles,"[42] "the future of plasma science in environment, for gas conversion and agriculture,"[43] and "plasma for medicine and hygiene."[44]

2 | FIELDS OF APPLICATION FOR PLASMA TECHNOLOGIES

The fabrication of semiconductor devices and respective integrated circuits would not be possible without plasma technologies. As such is the economic value and wealth that is based on microelectronics and information technologies directly and indirectly based on ongoing improvements especially of plasma etching, plasma deposition, and plasma bonding techniques. In the meantime features of only a few nanometers can be etched over a depth of more than 1 μm and film depositions controlled in the range of Angstroms.[15,45,46] Respective plasma methods have been continuously developed on a larger scale since the 1970s[47] and since then has the average price for a single transistor (on an integrated circuit chip) dropped by a factor of about 100 000 000. Concurrently, computers and other microelectronic devices have become readily available and functions and services that can be provided as a result are one of the most important economic driving forces of our generation. According to the 2015 Factbook of the U.S. Semiconductor Industry, the US currently dominates about 50% of the global semiconductor market. However, other countries, such as in particular China, are catching up fast. Semiconductor sales worldwide have increased from 102 billion USD in 1994 to 336 billion USD in 2014 with a predicted ongoing growth of about 10% annually.[48] The U.S. Bureau of Labor Statistics estimated for 2015 close to a quarter million jobs for the semiconductor industry with each of these jobs indirectly supporting 4.9 more jobs in other parts of the US economy.[49] The majority of semiconductor sales demand is driven by consumer products, mostly communication devices but also other "smart" systems, eg, automotive assistants. Important associated key drivers of economic growth are also networking and information technologies which are only available through the successful commercialization of semiconductor technologies since 1977.[50] The respective stock market value of companies, such as Apple or Amazon, is prominent example of the wealth that was generated by 2018 ultimately also by the success of plasma technologies.

Plasma processing techniques in semiconductor manufacturing are generally operated at low pressure. The R&D expenditures in this industry are with 18.4% with respect to sales still higher than in any other key technology industrial sector.[51] The impact of progress in microelectronics is notably also important for advancements in the automotive sector which is in general a sector where also other developments benefit from developments of plasma applications. The workshops in Greifswald in 2015 and 2016 have focused primarily on these other topics while developments in semiconductor fabrications were generally omitted or addressed only implicitly. In the following sections the role of plasma technologies and their impact on the development of selected representative application areas is described. Where possible, the economic impact resulting from the utilization of plasma methods is explained in detail. Different areas benefit from of the unique properties and characteristics of plasmas, thus leveraging the same approach for different objectives. This is particularly true for coating technologies and methods for surface modification, which affect a broad and very diverse range of applications.

2.1 | Energy and power

Plasma phenomena play a key role in high-voltage arrangements and accordingly for components of power distribution systems.[52,53] Corresponding fundamental research on thermal plasmas, and in particular high-current arcs and their interaction with the walls of containments, has enabled considerably improvements of circuit breaker techniques. Plasma-based fabrication techniques are likewise crucial for the development of novel energy storage and generation systems such as membranes for fuel cells or photovoltaic semiconductor elements.[33,54] By exploiting chemical reactions, especially involving non-thermal plasmas, it is possible to increase efficiencies and reduce CO_2-emissions of fossil fuel plants.[55] Plasmas are directly and indirectly also responsible for significant energy savings through the replacement of conventional incandescent light bulbs by energy saving lamps and Light Emitting Diodes (LEDs).[3]

2.1.1 | Success stories and market shares

Switching of currents at high and medium voltages is generally associated with an arc occurring when closing or breaking a circuit connection. In comparison to solid state devices, the respective arc-switches and −breakers are still superior in ensuring a true galvanic separation. The global market size for circuit breakers (air, vacuum, oil, SF_6, and others) was estimated in 2015 with revenue of more than 6 billion USD for medium and high voltage applications, notably with vacuum technologies accounting for more than half of this amount. Increasing demand is expected to promote growth of the vacuum circuit breaker industry of about 9%. For the high voltage circuit breaker market in general, an increase of at least 6% is expected by 2024.[56,57] Growth is driven by numerous electrification programs around the world. China, India, and several Arabic countries have announced investments for the development of their electrical grids of several billion USD. Replacement and renewal of power distribution and delivery systems in USA and Europe is another significant driver. Especially important are investments in new technologies, such as high voltage DC (HVDC) transmission and grid integration of renewable energies.

Welding is still the most important technique to join metals and more recently also used on thermoplastics. Among the different welding technologies, especially gas metal arc welding and gas tungsten arc welding depend on an understanding of associated plasma mechanisms which is needed in some cases also for laser welding. In 2015 the global market for welding products reached 23 billion USD and is expected to exceed 31 billion USD in 2021.[58] Growth is driven by changing demands and regulations that often address challenges arising from new materials and environmental concerns but also by improved manufacturing processes. To a large extend this includes further development and implementation of automated processes. Accordingly, the global market for robotic welding accessories is predicted to grow from 1.9 in 2015 to 2.8 billion USD in 2021. Concurrent with this growth is an ongoing need for research in welding technologies, including laser and arc welding, to exploit the inherent potential of these technologies.

2.1.2 | Established potential

The reduction of development costs due to the extensive use of simulations for the development of gas and vacuum breakers as well as similar efforts in the pursuit of a better understanding of welding technologies is directly benefiting manufacturers (cf. Figure 2). In addition, continuous further development and increasing sophistication of models and simulation methods for switching arcs and current breaking devices have initiated and supported corresponding progress also in related areas.[59] Another example of established plasma technologies in the energy and power area is the use of thermal arcs in energy intensive industrial processes, ie, for metallurgy, metalworking, and recycling. For example are electric arc furnaces established for producing steel and other metals for many decades.[60] Thermal arcs are also applied as a non-combustion technology for metal recycling. In addition, thermal plasma torches are in use for for clean melting, remelting and smelting. Welding with use of thermal plasma is still the dominant joining technology for metalsworking.[61,62] This includes gas metal arc welding, tungsten inert gas arc welding, plasma arc welding, and arc-laser hybrid welding.[63,64] In some instances pure laser welding is accompanied by a laser-induced plasma. For some specific applications, such as the cutting of thick steel pates by means of a hot plasma torch (plasma cutting), eg, thick steel plate cutting, there is to date no real alternative to the plasma-based methods.[22] Accordingly, considerable efforts are expanded on the improvement of all these technologies to meet changing demands.[65] This includes in particular treatment of new materials for lightweight production, developments that are supporting increased automation, higher process stabilities, and efficiencies, as well as minimizing emissions.

Light sources for general lighting and specific lighting applications that are based on thermal and non-thermal plasmas represent another example that has entered the consumer mass market. Today, more than 19% of the total electricity consumption is used for artificial lighting, however, with a decreasing tendency in part due to the progress in plasma technologies.[66,67] Lighting in general was dominated by plasma sources until the beginning of the 21st century. Fluorescent lamps, with light generation based on a plasma, are still dominant in commercial lighting and have an increasing share in residential lighting. High-intensity discharge lamps are well established in outdoor and industrial lighting, whereas incandescent lamps, with their much lower efficiency and shorter lifetime, and also halogen lamps are still used mostly in residential lighting. Plasma light sources are responsible for an overall considerable increase in energy efficiency and reduction of overall energy consumption for lighting in the last 20 years. The fast growing replacement of all other types of light sources by LEDs will further enhance these trends.[5,68]

2.1.3 | Unique solutions

One of the most important trends initiated by plasma technology in the area of energy and power applications is without doubt the transformation of the power generation and distribution system. This is happening especially in Europe with countries such as Germany and Denmark leading the way. Germany is committed to phase out nuclear power and significantly reduce the use of fossil fuels. Denmark is a world leader in wind energy generation. In the USA, which lacks a cohesive energy policy at the federal level, populous states, such as California, New York, Massachusetts, and Texas, have enacted or are committed to progressive energy efficiency and carbon emission reduction programs. The rapid growth of decentralized renewable energy sources and intermittent interruptions of power feeds require a transition, as well as an expansion, of the power distribution grid. When

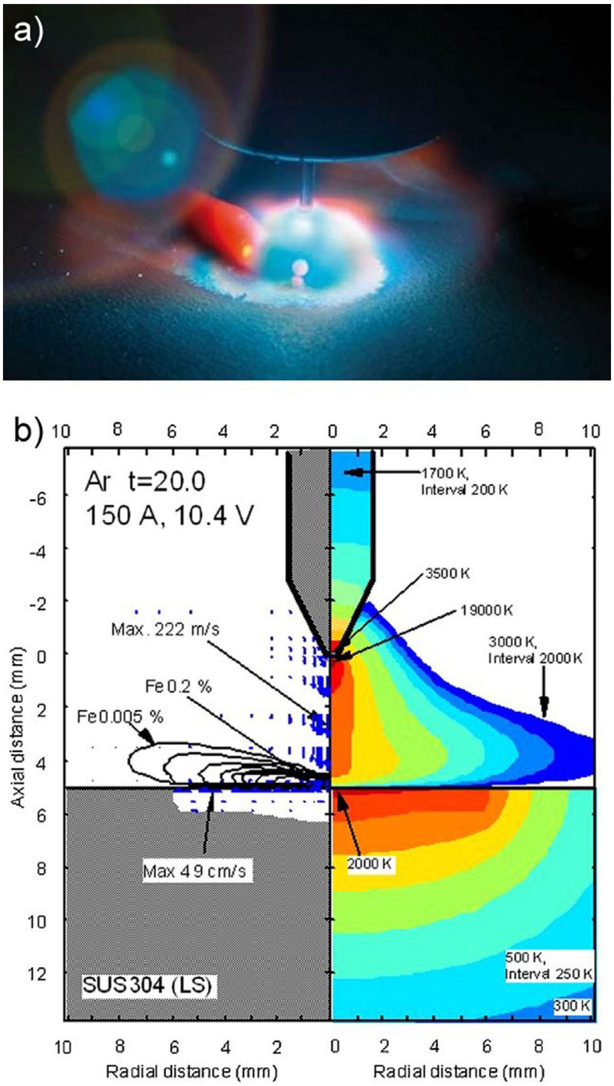


FIGURE 2 a) Composite photograph of a gas metal arc welding process, where the torch nozzle and wire can be seen in the upper part. Beside the bell-shaped arc under the end of the wire, the weld pool (in red) and a droplet (white) can be well identified (G. Goett, Leibniz Institute for Plasma Science and Technology, Greifswald Germany, private communication). b) Iron vapor concentrations, temperature distribution and velocity vectors in a tungsten inert gas (argon) welding arc after 20 s of operation.[65]

electrical power has to be transferred over larger distances, the transmission at higher voltages and higher frequencies and the use of high-voltage direct current transmission becomes more efficient than conventional approaches. Accordingly, gas and vacuum circuit breakers will remain dominant technologies compared to power electronic solutions because of their ability to also handle very high currents. Expanding their performance for higher voltages and extending their lifetime as well as reducing size and maintenance intervals are of increasing importance. A corresponding aspect is the growing significance of discharge phenomena in high-voltage insulation systems (eg, cables). A better control of discharge phenomena can help improving the operational reliability and prolonging the lifetime of insulations. The upward number of wind turbines and new overhead transmission lines together with progressive development of general air traffic results further in the need of improved lightning protection. Lightning constitutes a high-current thermal plasma. The study of genesis, together with temporal and spatial development, of lightning strokes, their impact on materials, eg, aircraft and wind turbines, is crucial to improve protection systems.[69]

As part of the transition of the power generation and power distribution system, more efficient devices for energy storage and generation and the use of *renewable energy sources* are under steady development. Hydrogen technology and other options for power-to-gas as well as for power-to-liquid transformations are being pursued and accompanied by new methods for direct electrical power storage and biomass conversion. Plasma technology can support these developments in different ways. Processes, such as plasma enhanced chemical vapor deposition (PECVD) and plasma enhanced atomic layer deposition (PEALD), physical vapor deposition (PVD), and high-power impulse magnetron sputtering (HiPIMS) offer considerable potential for the generation and functionalization of new materials, in particular nanostructured materials.[16,70] For the cross-sectional significance of these methods and respective applications, a more detailed description of plasma methods for surface modification, functionalization, and material synthesis is given in the section on the treatment of plastics & textiles. Catalytically active, photoactive (eg, hydrogenated amorphous silicon, a-Si:H) and electroactive materials with extremely enlarged surfaces that can be manufactured by plasma methods and in addition deposited on specific membranes, play a key role in fuel cells, electrolysis systems and batteries.[71,72] Moreover, the same methods can provide new solutions for example for solar water splitting, gas reforming, and supercapacitors[73–75] and are also used in the fabrication of thin-film and organic solar cells. Another approach is offered by exploiting specific pathways of non-equilibrium chemical reactions for reforming processes, especially for processing of waste and biomass and the generation of syngas.[76–78] Thermal and non-thermal plasma volume processes are quite flexible in the use of electrical excess energy, can be easily scaled up and can use synergetic effects in conjunction with catalytic processes. They can help reduce the use of rare materials in comparison with conventional catalytic processes. Electrodeless processes, like microwave plasmas can also be designed for the treatment of corrosive substances.[79]

Therefore, the study of lightning and its genesis, i.e. temporal and spatial development, as well as the impact of lightning strokes on materials, e.g. of aircrafts and wind turbines, is crucial to improve protection systems.

In addition to the trend to move towards renewable energy sources, the conservation of energy and resources remains an associated important task. Therefore, the role of plasma technology as a cross-sectional technology in the broad field of energy production has to be mentioned. The use of plasmas in conjunction with other technologies for thin-film coatings and other modifications of surfaces supports light-weight production, the use of composite materials, thermal isolation, friction reduction, erosion protection, and, therefore, also the increase of the lifetime and life cycle assessment. As a last example with respect to the conservation of resources, we point to the importance of plasma technology for recycling and waste treatment. Current trends are the increasing demand for the recycling of high-value materials and the energy generation from waste, the increased demand for waste processing, in particular of hazardous waste as well as the rising amount of nuclear waste in view of the abandonment of nuclear power plants.[80] Plasma technology, eg, based on thermal plasmas, can support the required developments utilizing specific features such as its high energy density and high quench rates at low gas flow rates, use as a heat source with sharp interfaces and steep thermal gradients that can be controlled independently of chemistry and high throughput even for compact reactors.

2.1.4 | Emerging applications

A number of unique solutions provided by plasma methods were already described as trends. Some of them could still be considered emerging applications that benefit significantly from ongoing research and development. One example is the need of improved concepts for DC current breaking in the HVDC transmission as well as for switches and other components of local DC networks. Photovoltaic installations, for example, also require respective studies of DC switching arcs and their interaction with electrodes and walls.[52] Another example is the plasma-based waste and biomass conversion as well as gas reforming, where plasma technologies have to be developed to be more efficient and economical. This also applies towards the use of plasma processes for the production of new materials, for hydrogen technologies, energy conversion and storage, where efficiency increases and upscaling are required in addition to providing unique material properties. As a last example, the role of plasma technology for light-weight production, including *generative processes,* should be pointed out.[81] Here, improved processes for the plasma coating or plasma spraying of protective layers, plasma hardening, nitriding, and polishing as well as plasma activation of surfaces eg, for joining different materials represent a huge potential. For the significance of these technologies and applications in the automotive and aerospace industry they are discussed in more detail in the respective section. The use of gas metal arc welding for *additive manufacturing* is already an example for a new efficient and resource-saving technology.

2.1.5 | Research needs

Especially the emerging applications discussed above require more specific research. In spite of the many decades studying thermal plasmas and their physics, a number of physical processes are not understood in sufficient detail or cannot be properly described quantitatively. Major general question are the plasma behavior out of the local thermodynamic equilibrium (LTE) and the mechanisms of interaction with materials. For example is the arc attachment in contact with molten (metallic) surfaces a key issue for energetic processes and can currently not be described quantitatively in sufficient detail nor experimentally determined.[21,82] Furthermore, the interaction of arcs with dielectric materials needs to be understood quantitatively in terms of the relevant elementary processes. Also the non-equilibrium characteristics of transient discharges (eg, vanishing of arcs or breakdown) requires also more research. Investigation of plasma-surface interaction, including the detailed molecular plasma chemistry, remains likewise an unresolved key issue in the applications of non-thermal plasma processing of surfaces and new materials.[53,83] In particular, the treatment of nanostructured materials requires the coupling with nanoscience and addressing multiscale problems in energy, space, and time. Finally a stagnation in determining atomic and molecular data, must be pointed out, which has to be overcome with a certain urgency to enable progress in plasma physics. The data is needed in particular for the modeling of non-LTE plasmas, plasma chemistry, and for plasma diagnostics.

2.1.6 | Outlook

Plasma technologies can contribute to the solution of current problems in the transition of the energy distribution system, improve technologies for the exploitation of renewable energies, conserve valuable resources, improve material and energy consumption, and reduce hazardous emissions in production processes. It also remains a key technology in the metal industry. Moreover novel plasma manufacturing methods promote advances for the synthesis of new materials for production and storage devices that can be utilized for renewable energy production and storage, in particular for hydrogen and power-to-gas technologies.

2.2 | Optics and glass

The treatment and modification of glass and optical materials or elements in general has been a rapidly growing area of research for more than two decades, with solutions that have been readily accepted by industry.[84–86] Fast adoption of some processes was initially motivated by the success of low-pressure (LP) plasma technologies in microelectronics.[3] Similar objectives and further possibilities soon encouraged the application of plasma treatment methods for the modification of a wide range of materials and surfaces. The opportunity to afford multifunctional coatings has since enabled novel devices and applications.[87–89] Correspondingly, intricate modifications enable the development of optical components with unique features. In addition to providing precise and small micro- and nanostructures, reasons for modifications are improving abrasion, erosion, hardness, scratch-resistance, adhesion, and other mechanical and functional properties. Several characteristics are often pursued simultaneously. The goals of plasma technologies are not limited to the treatment of glass, but are also applied to plastics. Need arises especially from the increased use of panels and optical components. Pertinent examples are found in fiber optic communication, photovoltaic or touch panel displays. These examples point to the main objective of plasma modifications in this respect, which is the change of optical properties, such as reflective and refractive index, but also transmission properties. Where high deposition rates and high quality of coatings are required, eg, uniformity and few defects, plasma is the method of choice for optical filters and mirrors, where high precision is required.

2.2.1 | Success stories and market shares

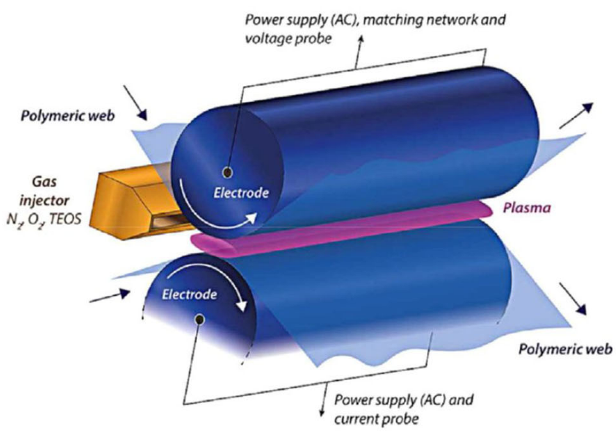
Among the different techniques that are available for the treatment of glass and optics, the most widely used method is plasma enhanced chemical vapor deposition (PECVD) and plasma assisted chemical vapor deposition (PACVD).[16,90] More than 70% of the global flat glass production, especially architectural glass, windshields, and precision optics, are given an antireflective coating. This alone represents a market value of several billion US-dollars per year. In addition, plasma coatings achieve accuracy for a desired index of refraction within 0.001% or even better at acceptable deposition rates (about 10 nm/s). PECVD in particular has been of interest for coatings of panels and optics made from plastics. Inherent advantages with respect to adhesion properties suggest PECVD as method of choice when compared with wet chemical or mechanical treatments or exposure to flames or UV radiation. A prominent example is the coating of ophthalmic lenses. About 90% of all these lenses are made of plastic and roughly 80 million pairs of these glasses are sold each year in the United States alone. In addition to antireflective characteristics, these coatings have to afford excellent adhesion properties with respect to different thermal expansion coefficients for the coating and the underlying material. Simultaneously, high scratch resistance needs to be provided. Many of these coatings provide additional functionalities, such as an immediate adaption to changing lighting situations. In addition, plasma processes have successfully been used and studied for photo- and optoelectronic devices, including low-cost photovoltaic cells, smart windows, sensors, displays, but in particular for waveguides, filters, and other components crucial for photonic applications. An important example is the plasma-assisted growth of semiconductors for light emitting devices (LED). According to different reports, the photonics market has been valued between 450 and 700 billion USD for 2015 and 2016, respectively.[91,92] Annual growth rates of 7-8% are estimated until 2020. Vacuum vapor deposition process that are in many cases relying on plasma mechanisms are expected to be the fastest growing segment in this area, with annual growth rates of 15%.[92]

2.2.2 | Established potential

The potential of plasma processing technologies for optics and glass can be summarized from the aforementioned success stories. Plasma processes and especially PECVD techniques can deliver the same results that are offered by competing methods, eg, chemical vapor deposition, and at the same time provide novel and additional functionalities. Since plasma processes are often operated at low temperatures in comparison with other deposition techniques, they lend themselves especially for the treatment of temperature-sensitive materials (cf. Figure 3). Arguably, one of the most interesting features that can be provided by plasmas is the possibility to provide multilayered coatings with a continuous, ie, graded, transition between different layers that can be achieved by changing process parameters such as delivered power and composition of the working gas. Depending on the underlying surface and the desired coating, interactions between surface and plasma can be tailored to fit process requirements and boundary conditions. A unique strength of plasma coating techniques is the fact that the characteristics can be changed with the growth of the film, and allows coatings to be fabricated with changing composition and microstructure. Furthermore, it is possible to introduce specific chemical groups or nanoparticles into the coatings that provide other functionalities. These can be exploited for biomedical applications or sensing characteristics, thus allowing the coating and hence the optics to respond to light, electrical or other signals, and hence provide the coating with sensing capabilities. Consequently plasma methods are of increasing interest for the manufacturing of smart materials, such as touch screens and energy-harvesting window panels.[93–95] At the same time, coatings can be produced with additional properties, eg, with high scratch resistance being the most popular for optics. In this case, films and coatings generally benefit from high packing densities and are environmentally very stable. Other desired features are antimicrobial and self-cleaning characteristics or the possibility for self-repairing, ie, resealing of films. When compared with more traditional deposition techniques, foremost other vacuum-based techniques, plasma processes are known for much higher deposition rates that are not limited to flat surfaces, but can in principle be used on substrates of any shape and size.[96,97] Penetration into narrow crevices is another particular advantage of plasma methods, which is therefore a much sought-after manufacturing solution for microelectromechanical systems (MEMS) and nano-electro mechanical systems (NEMS).[98,99]

2.2.3 | Unique solutions

The success of PECVD-processes is based on the inherent advantages offered by the plasma. The gaseous media used for modifications can be tightly controlled and mixed, including injection of specific precursors into the background gas, which are mostly noble gases.[16,90] The ionization in a plasma provides a unique way for controlling the energy and impact of ions with surfaces and, consequently, the surface chemistries thus achieving subtle process control at economical treatment times. This renders plasma treatments a competitive method for cleaning, etching, and microstructuring for a variety of applications, with the plasma tuned towards the specific objective. Electron distribution functions can be directly affected by the way electrical energy is dissipated in the plasma. More energetic electrons create distinct chemistries through dissociation, ionization, and energetic de-excitation processes (generating UV and VUV emissions). A related unique strength of plasma surface processes is the therefore the possibility to deposit high quality functional coatings, especially with distinct optical properties. Instead of providing only layers with different indices of refraction, it is, in fact, possible to provide optics with coatings with a graded index of refraction, which facilitates the fabrication of precise optical filters and lenses. The absence of sharp changes in the index of refraction can further be used to suppress harmonics and associated losses in fiber optic communication components. Furthermore, grated coatings are generally less susceptible to thermal and mechanical stress. In fact, this characteristic can be exploited further to provide multi-functional coatings that have, for example, simultaneously sensing abilities and antibacterial properties.



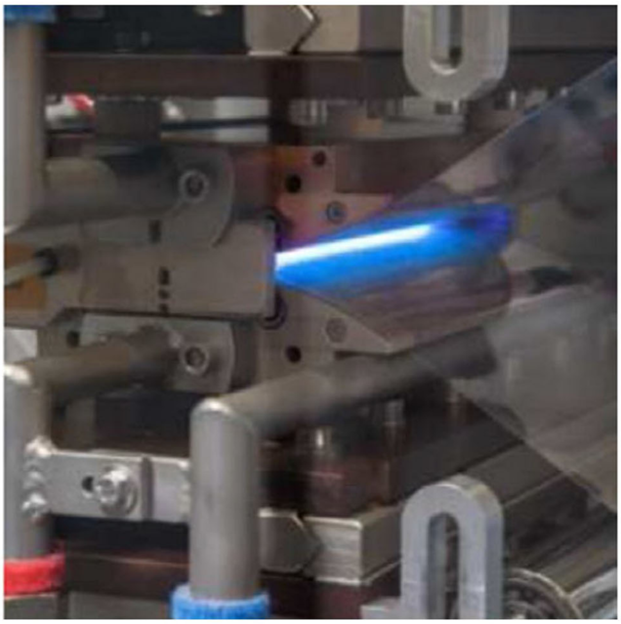


FIGURE 3 Deposition of high quality moisture barrier films on foils by treatment with a dielectric barrier discharge at atmospheric pressure.[54] Plasma technologies can change surface properties and provide coatings for different purposes, eg, with antimicrobial properties or for improving adhesion and printing characteristics.

2.2.4 | Emerging applications

One of the most attractive applications taking advantage of the unique aspects of plasma is the development of new coating materials or materials with new properties.[54,100] The complex, but controllable plasma chemistry has already been exploited for nano-material generation, eg, graphene or gold nanoparticles, often providing either higher quality or higher yields, or both compared to competing technologies. New material compositions are required for smart window products and building-integrated photovoltaic systems.[101] It is expected that windows will become an active and interactive part of building systems by providing energy, climate, information and entertainment, security, and lightning. So-called smart windows or switchable windows altering light transmission properties (from translucent to transparent when voltage, light, or heat is applied) will allow designing future climate-adaptive building shells.[102,103] Another field with great potential in optics is the use of plasma as an optical element itself with the goal of replacing conventional lenses and mirrors.[104] Tunable reflectivity or transmission by adjusting electron densities permit the development of adaptive lenses and mirrors for electromagnetic radiation with frequencies from the visible to the terahertz range and, in particular, for radiation and beams of high intensity.[105,106] Plasma mirrors and plasma lenses can be tuned by changing operating and plasma parameters, accordingly. The control of the plasma as an optical element can readily be used for other applications, such as mixers and filters, for example for emerging terahertz applications. In principle, changes can be made on rather short time scales. Unlike more traditional optical components, plasma elements do not suffer the risk of damage or loss of performance, especially for intense radiation, eg, from pulsed lasers. Plasma might thus also offer features that cannot be achieved by any other means, such as a negative index of refraction.[107–109] This would allow not only a variety of new focusing configurations, but also enabling new applications in communications, sensing, and imaging (super lensing, near-field imaging and amplification, cavity super-resonance, highly selective frequency filters, focusing and expanding devices).[110,111] The use of plasma elements in optical communications certainly requires further development in the miniaturization of appropriate plasma sources, and operation at atmospheric pressures.[112,113]

2.2.5 | Research needs

Although plasma technologies for optical coatings are already being used commercially, their potential is not exhausted yet. Pushing developments on high quality coating and manufacturing processes forward requires dedicated further basic research efforts. This includes the possibility for developing methods for achieving tight control of gas-mixtures, gaseous species and their ionization, and excitation. Deposition of tailored coatings will require a detailed control and understanding of all process parameters and their interdependency. These challenges need to be addressed experimentally, ideally providing insitu diagnostics and monitoring and controlling of plasma parameters and deposition, and advanced modelling and simulation efforts to achieve a better understanding of the plasma chemical processes. The latter should again include all species that are involved and, in particular, also the surface chemistry. These fundamental studies need to be complemented by improving plasma sources with the goal to attain more stability and reliability for increasing treatment area and treatment speeds, respectively.

2.2.6 | Outlook

Continued progress and emerging applications will guarantee an ongoing interest in the further developments of plasma coating and processing methods. Respective challenges and newest developments in the area of optics and glass are described in more detail in a recent "white paper on the future of plasma science for optics and glass."[41] Since a major limitation of current procedures is the need for operation at reduced pressures, major breakthroughs in the development of atmospheric-pressure procedures that are providing the same quality and characteristics as low pressure methods are highly desirable and are currently driving major research efforts. Even without this achievement, plasma-based processes are already competing successfully with wet chemical ones for surface activation and cleaning, and hold the promise to become the gold standard. Understanding of plasma parameters and plasma-surface interactions will eventually allow comprehensive control and on-demand manufacturing. Compared with conventional techniques, plasma technologies are generally less toxic and produce less waste, in particular less chemically hazardous residues. A further advantage is that plasma processes are in most cases inherently dry. This ultimately translates into considerable cost reductions. Further developments and improvements, especially for MEMS/NEMS and fiber optics are particularly promising.[114–116] The rising demand for optical elements compatible with intense lasers, terahertz, and other radiation technologies are another promising field, where plasma devices could assume roles as filters and mirrors that can currently not satisfactorily provided by conventional means.

2.3 | Aerospace and automotive

The application of plasma technologies in the aerospace and automotive industry may not be obvious. However, especially these industries explicitly benefit from new technologies, such as for welding, new energy storage solutions and surface treatments, as they are discussed in the sections on "energy and power," "optics and glass," and "plastics and textiles." Plasma technologies can also be used in particular to prepare superior varnishes or harder but light-weight turbine blades.[117–121] An especially important plasma technology in this respect is plasma spraying. Materials, usually powders, that are injected into a hot thermal plasma stream are heated or molten and then sprayed onto a surface.[122] Another plasma method of increasing commercial interest is plasma electrolytic polishing which can provide very smooth, high-gloss surfaces with excellent corrosion resistance.[123] Of course, planes and cars also benefit increasingly from microelectronic devices and therefore implicitly from manufacturing processes that are relying on plasma methods. These include new semiconductor power electronic components and energy systems, for example membranes for fuel cells,[33,124] as well as anti-corrosion and hard PECVD coatings. Plasma technologies are currently also studied to improve combustion processes and hence energy efficiency of motors.[125–127] Future breakthroughs using plasmas are also anticipated for airborne and space-based applications. Plasma actuators are expected to reduce drag and, therefore, fuel consumption, and plasma thruster have received much interest for novel propulsion concepts for satellites or even spacecraft.[128–131]

2.3.1 | Success stories

Manufacturing processes for different, often novel materials, and especially joining these materials with sufficient strength by either welding or gluing is a key challenge for modern automotive and aerospace industries.[132–134] In recent years, plasmas have also significantly changed lighting for cars. Halogen and high intensity discharge lamps are generating light from plasma and are now state of-the art.[135] Furthermore, plasma processes are also an indispensable step in the manufacturing of light emitting diodes (LEDs) that are currently replacing many lamps including headlamps.[136,137]

Functional coatings for automobiles feature improved corrosion resistance, decreased friction in combustion engines and other mechanically stressed parts, higher heat resistance, and coatings of catalytic materials for exhaust gas treatment.[138–141] The same advantages are exploited in the aerospace industry where plasma treatments can in addition provide anti-icing coatings and possibly reduce radar cross sections for military aircraft.[142,143] Turbine blades can be hardened or coated with heat-resistant ceramics and in addition provided with reduced friction and erosion, therefore achieving continuous progress with respect to efficiency and life time.[144,145]

2.3.2 | Market shares

Given the broad and versatile possibilities of plasma methods, it is rather difficult to assess the direct economic impact of plasma technologies for the automotive and aerospace industry. In many cases, component suppliers and subcontractors use plasmas in the manufacturing chain. Forecasts predict robust and significant growth in both aerospace and automotive industry that will depend on steady progress and development of new technologies, including plasma processes, eg, for batteries and fuel cells. A study by McKinsey for the automotive industry predicts that "technology-driven trends will reinforce and accelerate one another."[146] Overall, a growth from 3.5 in 2016 to 6.7 billion USD by 2030 is expected. A steady annual growth of 4-7% is also predicted for the aerospace industry by a report presented by kpmg.[147] Demand is in particular driven by rapidly growing air travel business in Asia and the Middle East. Accordingly, aircraft production is expected to go up. A report by Deloitte shows a jump in profits for aircraft manufacturers from 31.9 to 38.4 billion USD from 2014 to 2015.[148] Since defense spending and growth is not included in these numbers, the total market share is actually even higher. If, by a very conservative estimate, only 5% of the respective profits are attributed to the use of plasma methods, about 1.77 billion USD are generated by plasma manufacturing techniques, demonstrating both need and potential for this technology.

2.3.3 | Established potential

In addition to welding, established applications for the automotive and aerospace industry are generally assisting methods that are used for surface preparation and modification.[118,119] Recently, new materials, eg, aluminum alloys, carbon fibers, and composites are introduced more widely. Joining parts together or with other materials usually requires pre-treatment of surfaces, eg, by an organic solvent. Plasma treatments offer an alternative, especially for materials that could be eroded by solvents, as well as for enhancing the fiber-matrix adhesion in composite materials.[149,150] Non-thermal plasmas, in particular, offer the advantage to initiate non-equilibrium chemical reactions, which typically allow high chemical reactivity without increasing gas or surface temperatures. Conversely, using thermal plasmas, one can use both chemical reactivity and thermal effects such as melting of materials and enhanced diffusion. Controlling plasma operating parameters allows changing surface morphologies, structures, and properties (eg, wettability). Future applications are expected to utilize high selectivity depending on materials, and the possibility to provide several functionalities simultaneously. Where plasma technologies are competing with conventional chemical treatment methods, plasmas generally produce less or no toxic substances or residual additives. The chemical reactivity of plasma is further particularly suitable to enhance combustion processes and exhaust gas treatments.

2.3.4 | Unique solutions

For many applications, plasma technologies are currently competing with mechanical or wet-chemical treatments, and shortcomings of the conventional approaches drive the search for alternatives with plasma. Some products and characteristics can only be achieved with plasma processes. Computer, sensor, communication, and lighting systems rely on semiconductors that are fabricated based on plasma methods. Another much wider area for the use of plasma is material modification. Plasma-polishing, for example, has proved to attain smooth surfaces for complex shapes that cannot be achieved by mechanical procedures.[151] Likewise, plasma-spraying can provide tailored surface coatings and structures.[122] Both methods are interesting also for sharpening, shaping, and hardening tools needed for metal machining in general. Mostly used as a dry process, plasmas are successfully in use for the pre-treatment of different materials with the goal to clean and improve the hydrophilicity of surfaces before adhesives are applied. The same pretreatment advantages also apply to improvements of paint jobs or, more generally, for coatings with superior and unique characteristics. Some coating materials, such as diamond-like carbon (DLC), which is especially sought-after to reduce friction in gear-boxes and other parts that move relative to one another, can only be deposited by a plasma process.[152] In a broader sense, plasma-manufacturing techniques are this way contributing to noise reduction systems for wheels and engines, including anti-vibration and vibration-reduction technologies. Competitive functional coatings are also needed for other purposes. Self-cleaning, smudge-, or water-repelling surfaces, for example for interior furnishing or windshields, can be fabricated by supplying micro-structures, enhance hydrophobicity, or even introduce nanoparticles.

2.3.5 | Emerging applications

Plasma methods play a key role in the development of new materials, modification of materials, and joining of materials by adhesives or welding technologies. Synthesis of nanomaterials and plasma-modification of polymers are promising methods for components needed in the design of fuel cells, hydrogen storage device, novel batteries, and other energy storage technologies, including supercapacitors and solar energy systems.[153] Simultaneously, plasma methods contribute to the development of lightweight materials such as carbon-based or fiber reinforced materials, and of smart materials such as those having self-healing properties.

Plasma technologies have also been extensively studied to remove nitrogen (NO_x) and sulfur oxides (SO_x) from exhaust gases.[154,155] Such technologies combined with catalysts may be introduced into automobiles and environmentally friendly aircraft engines in the future. Plasmas might also facilitate and improve combustion of fuels in internal combustion engines directly.[127] Highly reactive chemical species can enhance oxidation mechanisms, resulting in higher efficiencies and more complete fuel conversion. In addition, plasma-assisted combustion processes can ensure a more homogeneous and complete fuel burn. For aircraft engines, this could translate into higher thrust. Spacecraft and satellites may in the future use completely different and more powerful propulsion systems that are based on plasma characteristics and allow deep space missions.[156–158] High-altitude and high-velocity flight has further raised the interest in using plasmas for maneuverability by plasma actuators.[129,159–162] For the same reason, plasma is exploited to keep airflows attached to wings (cf. Figure 4). Surface structures and coatings by plasma and generated directly at critical edges are also an interesting stealth technology, absorbing or dispersing radar signals.

2.3.6 | Research needs

The automotive and aerospace industries have the common goal to manufacture highest quality products that excel in reliability and safety. Accordingly, materials and manufacturing techniques as well as any final system component have to adhere to this standard. This also applies to any plasma device or method used. Therefore, an overall goal of research efforts is a better control of plasmas that meet the technological needs and high quality control standards in these industries. Therefore, extensive research is also needed for new and enhanced plasma diagnostics, for example of plasmas used in combustion. Concurrently, our understanding of mechanisms in complex environments and conditions, eg, at high altitudes, needs to be improved. Since such environments and conditions are unfortunately not readily accessible to experiments, highly accurate modeling and simulation of plasmas, including chemical reactions and modeling of

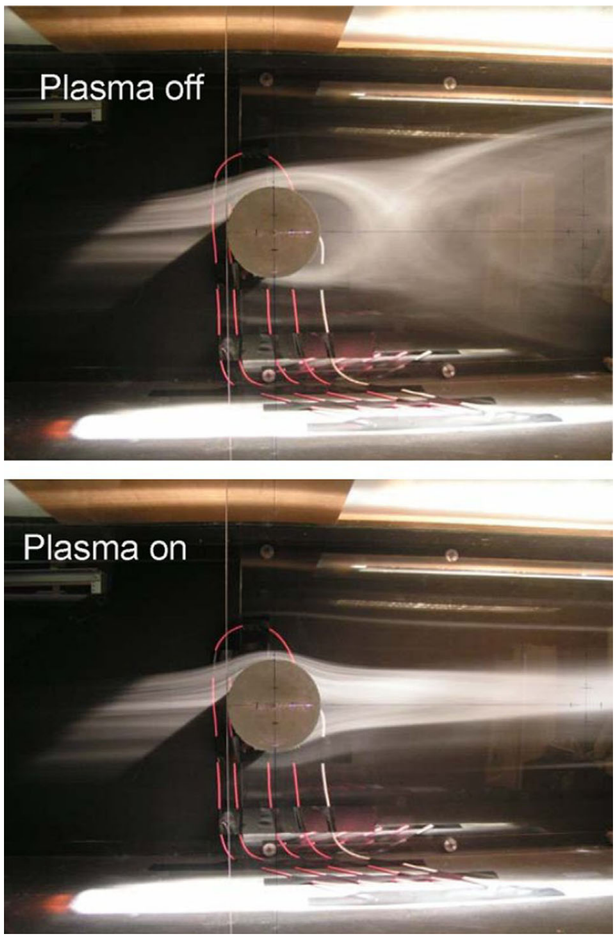


FIGURE 4 Smoke visualization of the flow control by a dielectric barrier discharge plasma actuator around a cylindrical cross section.[163] The actuator is built into the surface of the cylinder. With the "plasma on" the flow does not detach from the surface resulting in a far less turbulent flow around the body, which can be exploited in aircraft to improve fuel efficiency and noise reduction

plasma-surface interactions is instrumental. Many challenges for surface and material modifications and material synthesis by plasmas are shared with other application areas. Accordingly, progress for a better understanding of related technologies, eg, PVD and PEVCD, can be transferred and simultaneously benefit other fields. Most applications operate at higher pressures than typical low-pressure plasmas and, therefore, in particular the development of atmospheric-pressure plasma (APP) sources needs to be expanded. APPs are expected to significantly reduce investment and maintenance costs. However, at atmospheric conditions in ambient air, plasma chemistry and physics are very different from the well-studied low-pressure noble gas plasmas, and much more research is still needed for APPs to provide the same results and qualities as low-pressure plasma processes.

2.3.7 | Outlook

As motor vehicles, aircraft, and spacecraft continue to advance, more and more challenging requirements for surface control, flow control, and pollution control will arise. Plasma scientists and engineers will pay closer attention to the needs in the automotive and aerospace industries as plasma technologies may provide unique solutions to such challenges that competing technologies may not be able to offer.

2.4 | Plastics and textiles

Plasmas are successfully used for processing natural fibers, such as wool or cotton (cf. Figure 5).[164,165] With the dry plasma treatment, preferably at atmospheric pressure, impurities can be removed and the water absorption of fibers promoted. Accordingly, scourability and dyeability of fabrics are improved while the need for water and chemicals is reduced.[166,167] However, many modern textiles are made from polymers or at least include polymer fibers. Polymer materials often have bulk properties superior to conventional materials such as high strength-to-weight ratio, high resistance to corrosion, and are often relatively inexpensive to produce. Consequently, they are used in a wide variety of commercial applications as plastics and textiles. It is very rare that a polymer material with desirable bulk properties also possesses the surface characteristics required for certain specific applications. For this reason, surface modification and functionalization is often essential in processing plastics and textiles to control both bulk and surface properties. Accordingly, the ability to perform controlled surface engineering of polymers is of considerable scientific and commercial importance.[168–170]

2.4.1 | Success stories and market shares

There are many known methods for treating polymer surfaces to control their properties, including flame treatments, wet chemical processing, chemical oxidation including supercritical fluids, photochemical, and e-beam treatment in the presence of specific gases and chemical species, or combinations of these processes. Typically, these techniques are energy-intensive, costly and ecologically questionable. In addition, they are often associated with side effects on polymer structure or bulk properties. Plasma surface treatments in comparison presents a “green” alternative, which is an environmentally benign, workplace-safe and cost-effective method for re-engineering a polymer's surface at atomic level.[6,171,172] The most unique advantage of plasma treatment is fast processing, affecting only about 10 nm of the top surface layer, which is however sufficient for subsequent processing steps.[173–175]

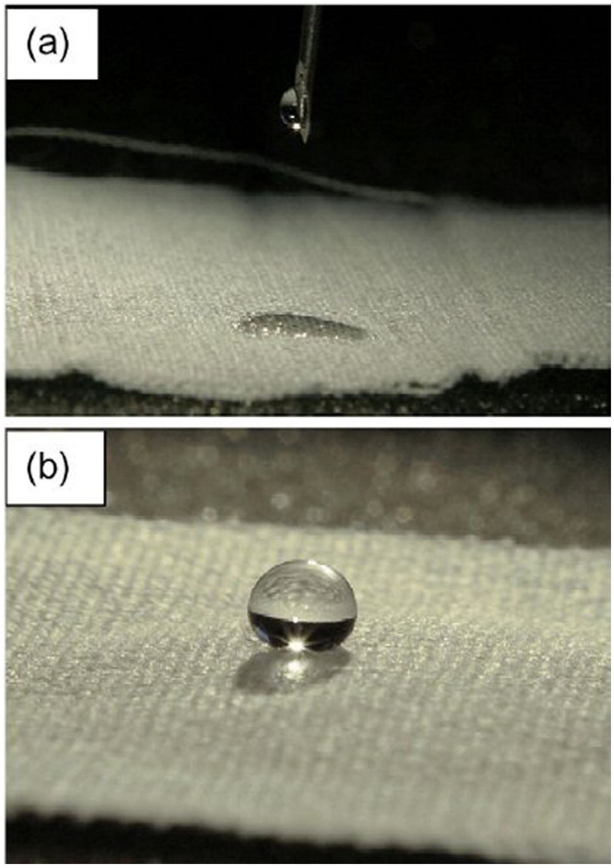


FIGURE 5 a) Cotton fabric is prone to readily soak up water. b) The treatment in a plasma-process (here in addition to heating) affords the fabric with hydrophilic properties.[177] The treatment of fabrics and textiles is an increasingly more important application for plasma processes. In addition to changes in hydrophobicity other characteristics, such as antimicrobial properties, can be provided

Plasma processing of plastic and textile polymers, which is based on cold plasma surface treatments for functionalization, etching, and deposition, is one of the major areas of plasma technology. The clean technology market facilitating cold plasma is expected to grow at a lucrative CAGD of 16.2% from 2016 to 2021, to reach 2.91 billion USD by 2021 from

1.38 in 2016.[40] This growth is associated in particular with plastic and textiles processing, where plasma has proved to provide a cost-effective and ecologically benign replacement for wet chemical processing technologies. Implementations are found predominantly for packaging, processing of renewable polymer materials, and textiles – including papers, flexible optoelectronics as well as polymers for biomedical applications.

With plasma as enabling technology for printing, dying, deposition, etc., plasma-processed polymers and products are already common in daily life. Prominent example is the functionalization of polymer bags (ie, shopping bags) that enables the adhesion of printing dyes to otherwise hydrophobic surface, with the result of stable and colorful prints. In the automotive industry in particular, plasma surface treatments are an established method to improve adhesion between different materials. For examples is Adria Mobil® as one of the leading European manufacturers of caravans and motorhomes relying on plasma pre-treatment for the connection of walls and ceilings. Other manufacturers are using plasma treatments for similar challenges, however, in most cases these are proprietary technologies. Some better-publicized applications are the achieved improved adhesion of rubber caskets for windshields used by the Ford Motor Company or color-coating of propylene handles for household appliances by Bosch-Siemens Hausgeräte (BSH). Plasma technology can further enable and expand the bonding capabilities of thermoplastic polyurethane (TPU) with other thermo-plastics in multicomponent injection molding, eg, for the BASF-product Elastogran.[176]

Another successful application is the LP PECVD deposition of very thin gas barrier coatings of silica-like and DLC composition on polymers utilized in food packaging, for prolonging the shelf life of liquid and solid food. These state of the art process are nowadays run at high speed on roll-to-roll web coaters more than 2 m wide, at web speed of several tens to several hundreds of meters per minute.

2.4.2 | Established potential

Low-pressure plasma technologies are now routinely used for surface treatments for a wide scale of materials, mainly for high-end applications. Conversely, atmospheric pressure treatments have found a stable place mostly for low-cost products. Respective methods can provide a surface treatment for engineered plastics with the required quality standards in terms of homogeneity, process stability, and flexibility. The industrial-scale equipment and the basic process-scheme are commercially available and very often require only minor adjustments for the engineered surface treatment. An exception is the plasma treatment of the inner surface of porous polymer fabrics materials, where the size of the pores is considerably smaller than the Debye length in typical low-pressure plasmas.[164] In such conditions, plasma is not generated inside the pores, and the activation of the inner surfaces must rely solely on the diffusion of reactive particles. The use of low-pressure plasmas for large scale industrial surface treatment of low-cost commodity plastics used in a wide range of high volume products, such as films for packaging, textiles, beverage, and trash containers, etc. has often been ruled out. Major obstacle are especially constrains imposed by the need for low pressure or vacuum environments to sustain the plasma. However, more easily applicable atmospheric pressure plasmas are already filling in the need.

2.4.3 | Unique solutions

Many types of plasma jets at atmospheric pressure[171,178] which are industrially used for "small area" local treatment of three-dimensional polymer workpieces are not practical for large area processing of polymer films and fabrics. The only standard atmospheric-pressure plasma technique routinely used for ambient air surface activation of polymer surfaces is based on filamentary volume dielectric barrier discharges (DBD), often marketed as "coronas" or "industrial corona" treaters. These are extensively used for improving the surface energy of plastics from almost six decades. A typical device consists of two metal electrodes, in which at least one, usually a grounded metal roll, is coated with a dielectric layer. The gap between the electrodes, where the plasma is generated, is in the order of several millimeters, and the alternating (up to 50 kHz) applied voltage has amplitude about 20 kV. Such ambient air plasma is generated through a succession of plasma filaments (streamers), lasting several nanoseconds, and randomly distributed in space and time. The streamers are some 100 μm in diameter and are separated from each other. While this treatment is generally effective, since it is not uniform on a sub-millimeter scale, it makes the film surface rough, and the effect of a corona discharge treatment on the film surface may degrade with time. Accordingly, the corona discharge treatment is generally only acceptable if it can be done along with the coating, which in a number of applications may not be practical. Moreover, substrates thicker than some 0.5 mm usually do not respond well to the corona treatment, often resulting in undesired treatment of the backside of the film that may cause the film layers to stick together.

2.4.4 | Emerging applications

As a consequence of the limitations of low pressure plasmas for the industrial treatment of commodity plastics and fabrics, there has been a strong desire to move away from low-pressure plasma technologies, that need expensive and limited volume vacuum equipment, towards atmospheric pressure approaches, preferably using ambient air as the cheapest and consequently the commonest plasma gas. The use of open-air plasmas, or other low-cost gases as CO_2 and water vapors at atmospheric pressure, eliminates the need for expensive and cumbersome vacuum chambers and specialty gases, but, as discussed below, it vastly complicates the plasma physics and chemistry involved, and limits the chemical composition of the product surfaces. This is the reason for which large-scale industrial applications of such plasma are still rather limited for polymer surface treatments. For almost three decades, examples of corona surface activation of textiles have been entering the literature.[179–181] However, as discussed in detail by Černák et al., it is apparent that the corona treatment is not practical or economical for textile industry.[174] As alternative atmospheric-pressure plasma devices, based on the so-called Atmospheric-Pressure Glow Discharges (APGDs) generating homogeneous plasmas have already been designed and developed. APGDs sources are often claimed to be able to work with any gas, but practically applicable examples have been shown only for helium and occasionally argon, or their mixtures with other gases. This is because acceptable plasma uniformity can only be achieved with these costly noble gases, which is limiting the potential economy and operational advantages of the atmospheric-pressure treatments.

A novel approach in the field is the so-called diffuse coplanar surface barrier discharge (DCSBD) generating a visually diffuse high-density "cold" plasma in atmospheric-pressure air at a high plasma power density of about 100 W/cm^3, designed for in-line plasma activation of fabrics at speeds on the order of 100 m/min.[174,182] This is to the best of our knowledge the highest plasma treatment speed among the plasma sources hitherto tested for textile surface treatment applications. It is well suited also for treating surfaces of flat polymer desks and films, where it has the potential of replacing the conventional corona treatment.[172] Nevertheless, the DCSBD is yet a relative unknown technology, and its real commercial breakthrough is still missing.

2.4.5 | Research needs

The above mentioned limitations are due to the principal disadvantage of the "industrial corona" treaters, that is they produce a relatively low density of active species ($OH^•$, $O^•$etc.) at the treated surface because most of such species are produced inside the narrow streamer channels and are rapidly lost by recombination. Thus, the homogeneity of plasma is crucial for the efficiency and permanency of the polymer surface treatment, since the local densities of charged species near the surface can differ by a factor of thousand between homogeneous and filamentary streamer plasmas.[183,184] The ongoing research on large scale industrial applications of APGDs illustrates the need for innovative, simple, and easy to service techniques, such as corona treatments, but with more control, greater uniformity, and higher efficiency. Some large-scale machines are now already operating with nitrogen, resulting in reasonable costs.[185] Process cost efficiency is driving the demand to produce large areas of dense and diffuse atmospheric pressure plasmas in low-cost processing gases, preferably in open air.[177,186] The latest developments in gas discharge and plasma physics have opened up a way to create such plasmas.[175,180,187–189] Nevertheless, not all of the plasma sources discussed in the technical literature have proven practical or economical for real industrial applications, and none has enjoyed real commercial success. Apparently, this is because many of such plasma sources were developed as spin-offs of existing technologies.[179,190,191] Since they were usually not developed specifically for large-area polymer films and textile treatment, such plasma sources are not completely optimized for applications in which they are used.

2.4.6 | Outlook

Plasma processes are already an indispensable part for a vast range of plastics manufacturing applications and will become even more ubiquitous in use in the foreseeable future. The capabilities of plasma treatments and the enhancement they can provide to the plastics, such as abrasion resistance, chemical stability (or sensitivity), anti-fouling properties, and biocompatibility for biomedical materials, or as part of the process for the development of "smart" textiles, will grow and the market for them will expand. A dedicated "white paper on the future of plasma science and technology in plastics and textiles" highlights and describes existing efforts and frontiers for the respective applications of non-equilibrium plasmas in more detail.[42] The use of plasma techniques to enable biodegradable polymers to achieve the properties need for wide-scale use will be of increasing importance. The need to treat large areas of plastics and textiles at very high speed will demand the development of improved and novel plasma systems, in particular at atmospheric pressure.

2.5 | Environment

Plasma technology is already playing a vital role in combating air and water pollution. The method to generate ozone by a dielectric barrier discharge (DBD) that was first described by Werner von Siemens in 1857 is in the meantime a standard method for water purification.[36,192] Pollutants in exhaust gas streams are also already frequently abated in filtrations systems that employ plasma (cf. Figure 6). Plasma filters are now available to eliminate odors especially in kitchens.[193] Many more current and emerging environmental challenges could be addressed by the continuing development of

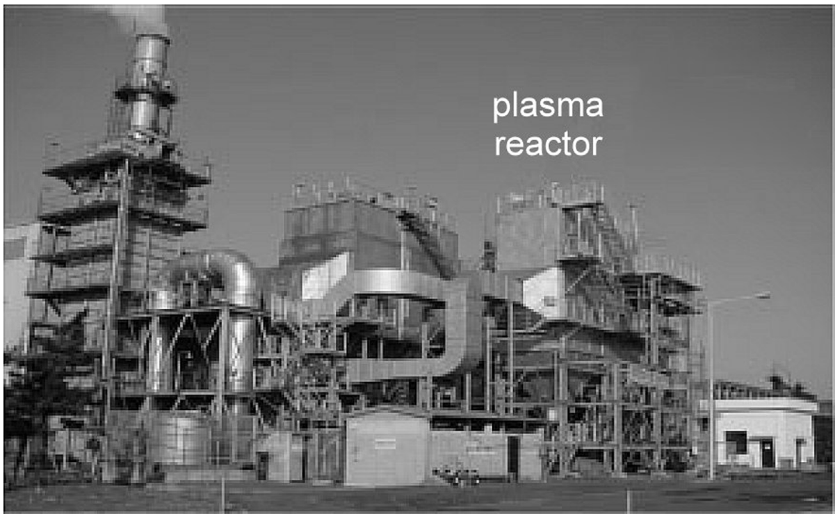


FIGURE 6 Large scale (50 000 Nm^3/h) plasma-reactor for removal of NO_x, SO_x and dust in the flue gas emissions of an industrial incinerator.[9] The unique reaction chemistry that is provided especially by non-thermal plasmas provides efficient means for the oxidation and degradation of even stable chemical compounds and also microorganisms

respective plasma technologies. These main aspects and the potential of non-thermal plasmas for environmental remediation and production are summarized in a recent "white paper on the future of plasma science in environment, for gas conversion and agriculture."[43] The capability to initiate and control chemical reactions that led to pollution abatement is a key property of plasma, and the development of efficient electrical power supplies for plasma generation and improved plasma diagnostics have facilitated several key commercial successes that demonstrate the potential for use in other applications.

2.5.1 | Success stories and market shares

The application of plasma processes for environmental purposes began with the invention of the DBD ozone generator by von Siemens in the middle of the 19th century.[18] Since that time, the scientific understanding of the plasma state and the engineering ability to produce and control plasma have allowed for the utilization of ozone for the treatment of drinking water, of industrial wastewater, of polluted air, and for the bleaching of pulp in paper processing, to name a few of the many applications of this technology.[9,124,194–197] For example, in 2014 the global market for equipment to generate ozone was over 700 million USD with a 7% annual growth rate expected in the next 5 years. Ozone applications for water and air treatment had a market share over 550 million USD and 177 million USD, respectively, in 2014. The application of ozone is the basis for a range of modern water treatment technologies, termed Advanced Oxidation Processes (AOPs). These processes utilize highly reactive oxidative chemical species to degrade organic contaminants in water. Ozone coupled with UV light and/or with hydrogen peroxide is particularly effective in removing trace contaminants from water that are not usually removed or degraded in conventional water treatment biological processes.[198,199] The generation of UV light by plasma discharges has been successfully commercialized for such applications as antimicrobial treatment of gases and liquids as well as for UV based water cleaning.[200] The global UV disinfection market has the potential to reach 2.8 billion USD by 2020 and water treatment accounts for 60% of the UV market with other areas including air treatment and surface disinfection.

Electrostatic precipitators (ESPs), developed in 1906 by Frederick Cottrell to remove sulfuric acid fumes from a gas stream, utilizes high voltage electrodes to charge small particles in a gas stream and to collect these charged species on electrode surfaces, thereby preventing them from being into the atmosphere.[201] Modern electrostatic precipitators not only can produce plasma, but are also combined with plasma processes to initiate chemical reactions that can lead to the removal of chemical contaminants, such as sulfur and nitrogen oxides, often found in exhaust gas from large combustion sources like power plants.[202,203] The world market for new ESPs is 7.6 billion USD and the market for repair and service of existing ESPs is 8.4 billion USD. China alone installed 50 000 MW of new precipitators for electric power plants in 2014. There is an extensive need for such technology in the industrialization of India and China where coal power plants are still heavily used and where fine particulate matter from combustion leads to millions of deaths a year from lung cancer and other respiratory diseases. Other air cleaners using plasma processes are currently marketed extensively in Asia by Sharp and Panasonic, and millions of small units for indoor air cleaning in homes and offices are sold each year.

2.5.2 | Established potential

The key areas of application of plasma processes include gas pollution treatment, water pollution treatment, and synthesis of useful chemical compounds by processes with reduced environmental impact. Gas treatment by plasma processes includes devices tailored to decompose and remove odor compounds from industrial emissions as well as indoor air.[204–207] Pilot and full scale plants have been built to remove nitrogen and sulfur oxides as well as other compounds such as dioxin, from a wide range of combustion processes.[124,208–210] The field of plasma assisted combustion promises to improve combustion efficiency in many types of engines and power sources which will lead to lower emissions of waste gases.[125,211]

The synthesis of chemical species by plasma, as demonstrated by ozone generation and plasma processes in microelectronics industry, may be very efficient and can be considered as green chemical processes where the impact on the environment can be reduced. Example species that have been synthesized by plasma processes in the lab and in pilot scale include: nitrogen based compounds from air such as nitrates and nitrites, hydrogen peroxide from water, synthesis gas from various gas streams including natural gas, methanol from methane, hydrogen from water or hydrocarbons, carbon based compounds from carbon dioxide, and other value added compounds from hydrocarbon feed streams. Although not yet commercialized, the application of plasma to these very important processes has a very high economic and societal potential.

Plasma processes can be classified into thermal and non-thermal processes. Many of the applications mentioned above are non-thermal processes, where the energy of the plasma is directed to the free electrons rather than to heating the entire gas stream.[24,212] Thermal plasma (eg, plasma arcs) are more energy intensive and reach much higher overall temperature. Accordingly, thermal plasmas have been successfully commercialized for the treatment of highly concentration wastes, including solid and hazardous waste.[76,213] An associated challenge is the recycling and treatment of waste. Current trends are the increasing demand for the recycling of high-value materials and the energy generation from waste, the increased demand for waste processing, in particular of hazardous waste as well as the rising amount of nuclear waste in view of the abandonment of nuclear power plants.[80] Plasma technology, eg, based on thermal plasmas, can support the required developments utilizing specific features such as its high energy density and high quench rates at low gas flow rates, use as a heat source with sharp interfaces and steep thermal gradients that can be controlled independently of chemistry, and high throughput even for compact reactors.

2.5.3 | Unique solutions

The unique features of plasma chemical reactors include the capability of on-demand production of reactive species and various chemical products with off-the-shelf electrical components. Minimal chemical addition is required. Plasma reactors produce very reactive short-lived chemical species that can not generally be stored, but which are produced on-demand and typically in very high local concentration.[214,215] Plasma reactors can be constructed over a wide range of size scales from small portable home units (eg, indoor air cleaners) to large scale industrial processes (eg, electrostatic precipitators), thus serving markets from consumers to industrial scales. The non-thermal plasma processes mentioned above may be most efficient for removal of low concentration pollutants from gases and liquids, and they may also be suitable for treatment of sensitive goods and surfaces (eg, foods and medical devices) for microbial inactivation.[215–217] For this purpose, plasma may be particularly effective since such organisms do not seem to exhibit or acquire resistance to plasma treatment. Water treatment with plasma has potential to degrade recalcitrant emerging contaminants such as antibiotics, estrogen disrupters, and other personal care products that are found in very low concentrations in drinking water supplies, and it may be particularly effective at degrading surface active compounds that preferentially accumulate at gas-liquid interfaces.[20,218–220] Further, recent laboratory studies suggest that the development of commercial advanced ozone generators with much higher efficiencies is possible.[221–223]

2.5.4 | Emerging applications

In addition to the processes mentioned above other important areas under development include using plasma with adsorbents (eg, activated carbon regeneration) and combining plasma with heterogeneous catalysts (for air and water treatment and chemical synthesis).[224,225] This way it will be possible to increase efficiencies and application range of current technologies. Likewise possible is the combination with other established and emerging technologies, such as integrating plasma directly in filters for not only retaining but also for the direct and simultaneous degradation of compounds. In this respect, a rather new approach is to use plasma chemistries for the conversion of substances to either bind them, eg, CO_2, or to store the energy that is provided by the plasma in specific compounds.

2.5.5 | Research needs

In order to realize the potential of plasma processes in the applications cited above, the major research needs include:

developing our understanding of the coupling of the plasma physics with the plasma initiated chemistry, analysis of the plasma interactions with solid interfaces as in plasma-catalysis and with liquid interfaces as in water treatment, and expanding the understanding of the mechanisms by which microbes such as bacteria are inactivated by plasma.[28,226,227] This is a topic that is studied in particular also with respect to "medicine and hygiene" as discussed in the respective section in this report. Plasma properties such as plasma gas temperature, density, and energy of the free electrons in the plasma need to be carefully measured and related to the resulting chemistry, including radiation chemistry induced by ultraviolet emission. Further research on plasma chemical similarity and factors that control reactor scalability is particularly important to expand the size range of process scales that can be addressed with plasma–chemical systems. Analysis of the efficiencies, including energy and chemical, the formation of side-products from various chemical reactions, and development of means to enhance chemical selectivity are other areas that need research and development. Technical and economic comparison with existing processes (eg, in water treatment the other advanced oxidation methods) are needed to assess the commercialization potential of plasma processes.[228–230]

2.5.6 | Outlook

Plasma-chemical processes already play a vital role in the world economy such as utilization in ozone generation, UV light generation, electrostatic precipitators, and the billion dollar market in microelectronics processing. These applications coupled with the unique features of plasma, including scalability, electrical control, and minimization of environmental impact suggest that plasma has a key role to play in solving many of our other environmental problems from air and water pollution control to chemical synthesis of important compounds. Investment in research to address these challenges will provide significant societal and economic returns.

2.6 | Medicine and hygiene

The possibility to generate and exploit plasma of rather low temperature at atmospheric pressure in air has led to rapidly developing applications not only for treatment of inanimate matter, but also for exposures of living cells and tissues. An obvious immediate use is the inactivation of harmful microorganisms located on temperature-sensitive surfaces. The high antimicrobial efficacy of plasma has already been shown for low-pressure plasma which, however, requires putting objects in a vacuum system and is thus of limited practical use.[231,232] Fast and significant microbial inactivation kinetics have in the meantime also been demonstrated for atmospheric-pressure plasma devices, such as dielectric barrier discharges (DBDs) and a variety of plasma jet configurations.[233,234] The opportunity to apply these sources also on human tissue, such as skin and teeth, has been readily embraced for potential medical therapies, eg, to reduce the bacterial load in wounds or in dental treatments.[235–237] For some of these applications, only the transient chemistry provided by the plasma is needed and the plasma does not even have to interact directly with the treated object. The discovery that plasma can further affect cellular functions in more subtle ways is now being investigated in the context of the stimulation of cell responses and in cancer therapies.[238,239] Altogether these efforts are commonly described as plasma medicine.[240–242] Encouraged by the success for selected medical therapies, it is not surprising that plasma is also applied towards fruits, vegetables and plants in general.[243,244] The primary goal is again decontamination to improve shelf life and food safety. However, it is also possible to affect more physiological processes in plant cells, which raises immediate interest for different agricultural applications and for crop processing.[38,245–247]

PECVD and plasma treatment of biomedical materials to optimize their interaction with biological tissues is another field where non-thermal plasmas have raised academic and industrial interest for decades. Interesting properties, such as cell compatibility,[248] non-fouling features,[249] tunable hydrophobic/philic and acid/base surface character,[250,251] drug release,[252] and bacterial resistance,[253,254] can be achieved on prostheses and biomedical devices.

2.6.1 | Success stories and market shares

The use of plasma for medical applications and on living matter or cells, respectively, is rather new in comparison with other technological exploitations of plasmas. Accordingly, implementation and utilization of respective methods is not yet widespread or common. One of the first plasma systems that was introduced into a production line on a larger scale was a low-pressure sterilization unit developed by Groninger & Co. GmbH together with Ruhr University Bochum.[255,256] With this system, tubs with syringes wrapped in a Tyvek®-wrap are successfully sterilized upon delivery to prevent recontamination before being filled. The throughput achieved was already comparable with electron beam sterilization units. Distinct advantages, such as system-weight, no need for toxic chemicals (eg, ethylene oxide), and little or no degradation of materials, suggested the approach also for other pharmaceutical packaging and filling needs. Another sterilization unit that already includes a plasma generated in part with hydrogen peroxide is the STERRAD®–system marketed by Johnson & Johnson Medical. For some time, plasmas have also been used in surgical procedures for the removal of tissue or precision cutting. ArthroCare® claimed the removal of collagen, especially in joints, by a brush-like device in saline solution[257] and the PEAK® plasma blade is used primarily for soft tissue dissection.[258] Both methods use the disruptive potential of a rather hot, although localized, plasma for tissue ablation. The currently most common application of a plasma in medicine is the coagulation of tissue using argon as operating gas. Argon plasma coagulation offers the major advantage of a non-contact treatment with a coagulation depth of only a few millimeters. Most importantly, the plasma can be generated and delivered endoscopically.[259,260] The mode of action for non-thermal plasmas that are now studied for wound healing and other conditions in dermatology is very different in comparison. Some of these devices received approval as medical devices only recently, eg, Adtec®, PlasmaDerm®, and kINPen® MED.[261–263] The primarily anticipated application of these systems is the treatment of chronic wounds (cf. Figure 7). Non-thermal plasmas have been especially successful for the treatment of patients with long-lasting ulcered legs that in many cases could not be healed by conventional means, eg, antiseptics. Currently, treatment times between 6 months and 6 years are needed with standard methods if patients can be healed at all. Accordingly, the economic impact of more effective and faster therapies for chronic wounds is considerable. Since mostly elderly patients are affected, the number of incidents is expected to increase with a steadily aging population. Currently, 2 million patients in Germany suffer from chronic wounds, which amounts to 8 billion Euros annually in health care costs.[264] On a global scale, this corresponds to about 3% of health care expenses.[265]

For biomedical materials, cold plasma treatments resulting in the stable grafting of polar chemical groups provide since the late 1970s probably the best known biomedical product of plasma technology so far, ie, the disposable Cell-Culture PolyStyrene (CCPS) Petri dishes,[266] characterized by hydrophilic cell-adhesive plasma treated surfaces. The surface plasma-hydrophilization of soft silicone-hydrogel Contact Lenses for reduced uptake of tear lipids and improved comfort for prolonged wear is another example of a successful cold plasma process.[267] Thermal plasma spray processes, instead, provide established porous hydroxyapatite coatings on metal dental and orthopaedic implants for faster and better osseointegration.[268]

2.6.2 | Established potential

The potential of plasmas, especially non-thermal plasmas, to inactivate microorganisms has been established beyond doubt. In principle, no toxic chemicals are needed to kill bacteria and yeasts. However, if considered beneficial, plasma can in addition be easily combined with conventional approaches. Plasma itself can in many cases be generated from air or with noble gases. Potent, but transient reactive species are generated as a result and effectively disable or disassemble biological cells. Interestingly, the susceptibility of mammalian cells, eg, skin cells, is different and microorganisms are more easily affected.[241,269,270] Besides on cell type, cell responses depend on plasma intensity, ie, the concentrations of species that are generated and exposure times. So far, no detrimental effects or cell responses, such as an increased mutagenicity, have been found.[271] However, the complex nature of medical treatments and interactions will require further studies. Conversely, the complex mix of different simultaneously generated reaction chemistries and physical agents (UV light, electric fields) provides different possibilities to affect cells.[272,273] Therefore, there has been no evidence to date of general resistances that bacteria could develop against plasma. Accordingly, exposures were found as effective against antibiotic resistant as against their non-resistant counterparts. However, the challenge for all plasma treatments of biological matter is to understand and control the different interaction mechanisms that plasma provides. As such a better understanding of how cell proliferation and other cellular functions are affected by the different plasma components requires more investigations. This will be crucial for the development of new therapies and applications beyond wound healing. It is worth pointing out that reactive species

FIGURE 7 Direct and indirect exposures to non-thermal plasmas have been successfully employed for the treatment of chronic wounds.[263] Possible effects are due to a reduction of bacterial contaminations but also a possible beneficial effect on cell proliferation. In the meantime, plasmas are further investigated for other medical applications, such as cancer treatments

generated by plasma in air or in water, or in close proximity to water, can actually dissolve in and react with the medium and provide antimicrobial properties that can last for a couple of days. Water or air that was treated in this way can then be used for rinsing vegetables or fruits and impede spoilage. With the limited life time of the plasma-provided antimicrobial characteristics, there should be no active residues left when the treated products are placed on the shelf for sale, however, further studies towards this aspect are still needed. Another indirect antimicrobial effect that plasmas provide is the possibility to furnish antimicrobial coatings, eg, with copper, with a particular interest in coatings for temperature-sensitive plastic materials.[274] Tailoring surface biomedical properties of devices of different shape and function, ie, from tubes as in catheters to porous systems as in membranes and biodegradable polymer scaffolds, is a key advantage of non-thermal plasmas.

2.6.3 | Unique solutions

The unique, but also challenging characteristic of plasma with respect to the exposure of cells and living matter are complex and simultaneously acting different mechanisms. Accordingly, different biological responses can be induced simultaneously. In the case of the treatment of chronic wounds, the burden with infectious microorganisms can be alleviated concurrently with the stimulation of tissue regeneration processes. At the same time, there are many different ways to control and adjust plasma properties by changing the operating parameters and ambient conditions. This permits one to address specific cellular functions and biochemical pathways either directly or by modifying the environment of cells and tissues. The latter can be exploited for furnishing antimicrobial coatings, but also to either device cell-adhesive or cell–repellent surfaces, which can for example improve osseointegration of implants. The development of antibacterial surfaces on prostheses, for example, would reduce the infections around implanted prostheses in an aging society with multi-morbidities.

2.6.4 | Emerging applications

Along with an increasing understanding of the interaction mechanisms of plasma with cells and living systems, there are ongoing discoveries of new possibilities and potential applications. These are commonly based on the unique characteristics and mechanisms that are provided by the plasma. For the field of plasma medicine, there is currently a particular interest in the initiation of apoptosis in cancer cells, and thus providing the potential for novel tumor therapies.[238,275] This can be achieved either by direct plasma exposures or by processes, such as stress responses, triggered by reactive oxygen and nitrogen species (RONS) that are delivered by plasma. Stress responses are also of interest for the manipulation of plant cells, either for seeds or during plant growth. There is already reasonable evidence that germination rates can be increased or a more robust growth of plants could be promoted in this fashion.[276,277] Therefore, plasma treatments might offer possibilities that so far require gene manipulation or the use of environmentally unfriendly chemical treatments. Plasma methods might, in fact, also offer the possibility to replace or at least reduce the need for pesticides and herbicides in agriculture. This has in part already been achieved for the post-harvest treatment of fruits, vegetables, and especially seeds and cereals with the goal to eliminate microorganisms that cause spoilage. Especially indirect plasma treatments have been shown to be economically competitive and ongoing developments aim for including these methods in production- and packaging lines.[243,278] Another potential application in post-harvest processing of plants is the possibility to increase extraction yields of nutrients and pharmacological substances as well as the use in mass volume applications, such as the generation of biofuels. The ability of plasma to provide different and primarily physical means of action is further encouraging the use of plasmas to attack pathogens that are difficult to address or cannot be addressed at all by conventional disinfection methods. Effectiveness against multidrug resistant bacteria and viruses has already been demonstrated.[279,280] Accordingly, plasma is expected to contribute to a solution for the growing problem of hospital acquired infections. New disposable materials and stricter regulations also require new approaches for the sterilization of medical products. Prions in particular are a major concern and plasmas are being investigated as a possible method for their inactivation.[281,282] Recent developments of non-thermal plasma-synthesized surfaces of biomedical interest further include also the deposition of nano- and nano/bio-composite coatings from aerosol-assisted atmospheric pressure plasma deposition processes[283], the deposition of free-standing ultra-thin films and of vesicles of sub micrometric dimensions.[284]

2.6.5 | Research needs

Given the relatively young research in the field of plasma medicine together with the stringent requirements for medical devices, there is still considerable research needed for a better understanding of underlying primary mechanisms of the interaction of plasma and of plasma-modified surfaces with living cells, as well as for induced secondary biological responses. Many different ways to generate plasma along with different effects and the simultaneous action of biologically active mechanisms are presenting a challenge but also an opportunity. At the moment, it is therefore difficult to define standard exposure conditions, similar for example to the “dose” that is used in radiation therapy. Moving the technology from the laboratory to the hospital requires solutions to several issues that have to be overcome and plasmas need to prove themselves in clinical trials in particular. The prerequisites for this stage have so far only been satisfied for dermatological applications, especially the treatment of chronic wounds, resulting in the development of plasma sources that have obtained medical device certification. The development of plasma sources for other indications will have to follow similar pathways and include respective studies on safety and possible side effects. The experience with wound treatment already suggests how to proceed with the development of improved devices, eg, for the treatment of larger areas. Other applications, such as tumor treatments, will probably have different requirements on plasma sources. Applications in agriculture, food processing, and biotechnology in general seem to be less stringent at a first glance. Unless geared towards decontamination, many of these applications are in the early stages of their investigation. Before they can leave the laboratory, more research is necessary. However, questions of efficiency and consumer safety need to be addressed eventually.

2.6.6 | Outlook

Discoveries that enabled the manipulation of cells by plasma, aiming not just for their destruction, have led to the investigation of novel medical treatments that compete or are not even possible with other methods. Even for the more conventional goal of decontamination, plasma offer characteristics to expand scope and efficacies. The "white paper on plasma for medicine and hygiene: Future in plasma health sciences" compiled the state-of-the art in this field together with expert opinions on future challenges and developments.[44] Similarities of response mechanisms of mammalian and plant cells have recently encouraged the use of plasma in agriculture and other biotechnologies and may well succeed in providing a competitive advantage, at least for selected problems. Ongoing progress is tightly linked to the continuous development of atmospheric-pressure plasma sources, which are critical for the treatment of living matter.

3 | CONCLUSION AND PERSPECTIVES

This paper aims to highlight several areas of high-value applications of significant societal and economic impact where future progress depends critically on further advances in basic and applied plasma science and technology. While this paper limits the discussion to the areas of (1) Energy and Power, (2) Optics and Glasses, (3) Aerospace and Automotive, (4) Plastics and Textiles, (5) Environment, and (6) Medicine and Hygiene, there are other emerging technology verticals that may also benefit from advances in plasma science and technology. For each area of application described here, an assessment is made of success stories, the established technology potential, and, to the extent possible, a market share study. Area-specific unique solutions are presented and emerging and potentially new applications are highlighted. Basic and applied research needs required to advance these technologies are identified. The latter part is of particular significance as the rapid development of plasma applications has often occurred by trial-and-error, ie, without having a good understanding of the underlying basic science.

While the specific recommendations for needed basic and applied research differ somewhat from one area of application to another, there are a few common aspects of research requirements that impact essentially all areas. These include the continued development, refinement, and characterization of plasma sources that can operate stably at atmospheric-pressure, preferably in in ambient air. Spatially extended sources that allow the uniform treatment of large 2D-areas are of particular importance as are miniaturized jet sources that can deliver the plasma into very narrow, often irregularly shaped cavities or channels such as the roots of a tooth or interconnected sub millimetric pores as in scaffolds for Regenerative Medicine. Concurrently, more research into the diagnostics of plasma sources is needed, with a particular emphasis on spatially and temporally resolved studies that will allow a detailed understanding of its electrical, thermal, and chemical properties. Time- and space-resolved mapping of the electron density in the plasma and the identification of electron energy distribution functions have a high priority.

Regardless of the operating principle, most plasma applications rely on the plasma-initiated generation of chemically reactive species. A basic understanding of some of the key plasma chemical reaction pathways in certain applications has been established, this level of insight is lacking in many other areas, most notably in the rapidly growing field of Plasma Medicine. One of the great remaining challenges is to achieve coupling the plasma physics to the plasma chemistry with respect to particular applications. The objective would be to control the operating parameters of the plasma in a way that would allow the user to provide an application-specific plasma chemistry. The plasma on in an atmospheric-pressure plasma that is in touch with an object such as a surface to be treated or living cells is rather complex. The plasma action relies on a combination of plasma-generated constituents (reactive species, ions, UV radiation). Potential synergistic effects may play an important role, but have rarely been studied.

A critical step in successfully leveraging the breakthroughs from basic plasma research to create new products and processes is the commercialization of the intellectual property (IP) resulting from basic research. A patent search using the keywords "plasma," "cold plasma," "non-thermal plasma," and "gas discharge" revealed more than 1 000 000 granted patents worldwide since 1976, of which about 750 000 have not expired to date. Arbitrarily assuming a 50:50 split between patents dealing with fusion plasmas and plasmas not related to fusion, there is a large body of accumulated IP around non-thermal technological plasmas with the potential to be commercialized. This remains true, even acknowledging that a significant number of patents in the area of non-thermal plasma processing of semiconductors and microprocessors have already resulted in commercial applications. Other products and processes that have benefitted, perhaps to a lesser extent, from the commercialization of existing plasma-related IP, but still have a significant untapped commercial potential include excimer lamps in the extreme UV, materials processing, surface modification, nanoparticle synthesis, ozone generation, and environmental remediation. Plasma medicine is an emerging field, where major advances were made possible by the development of plasma sources that are biocompatible (ie, satisfy strict conditions in terms of their electrical, chemical, and thermal properties) and can generate copious amounts of reactive radicals and deliver them to biological tissue via plasma jets. Many of these designs have been patented, yet only a few have been commercialized.

Patent policies differ from country to country, therefore it is difficult to address the topic of technology transfer and IP commercialization in a general, ie, globally applicable way. In the United States, the Bayh-Dole act of 1980 significantly accelerated the technology transfer out of universities. The Bayh-Dole act gave the universities the right to control IP derived from federally funded research. In the years that followed, essentially all US universities developed rather similar patent and IP policies, which basically require any employee to bring a potentially protectable invention to the attention of the university. The university has the right of first refusal to take over all rights to the invention. If the university assumes IP-rights, it will cover all expenses related to the protection of the IP, eg, costs for filing and maintaining a patent. Concurrently, a revenue-sharing agreement with the inventors will be established. (At New York University, for instance, inventors receive 42.5% of the net revenue generated from the IP or patent, respectively.) University technology transfer offices typically follow three main routes of IP commercialization: (1) licensing of the technology to an industry partner, (2) entering into a joint development agreement with an industrial partner to further develop the technology, or (3) creating a startup company. In recent years, there has been a shift away from licensing towards the creation and support of startup companies as an attractive route to commercialization with a high potential return on investment, notwithstanding the fact that many startups will fail.

Challenges to successfully transfer technology out of universities include: (1) the need to generate enough data to substantiate commercially viable patents, (2) an understanding of the preference of industry partners and venture capital investors to seek out and invest in more mature technologies, and (3) the general lack of experience of academic inventors in market knowledge and basic business matters. Many universities have responded to these challenges by providing funding and other support for translational research, eg, through proof-of-concept funding and/or technology acceleration grants, and the creation of a supportive academic entrepreneurial ecosystem in efforts to bridge the gap between lab breakthrough and early-state startup or a valuable commercial license. The outlined commercialization strategies are in a similar way already in place at many other research institutions or are at least encouraged. This of course requires administrations and policy makers to establish respective structures and provide funds.

Plasma science and plasma technology have addressed important societal problems and have created significant economic impact through the interplay between basic science, applied science, and technological challenges for more than 150 years. Many products and processes that we have come to take for granted in everyday life would not exist, if it were it not for plasma-based processes that play a crucial role in their fabrication. The important role of plasma processes often remains hidden in the value of the final product and its crucial role is not readily obvious. The "hidden value" of plasma technology and the basic science that drives novel developments have resulted in unsteady and unpredictable research funding for the field, which makes it difficult to build and sustain world class research groups in plasma science (outside of the field of fusion plasmas). The fact that plasma research is carried out at universities and research institutes in departments with distinct and limited profiles ranging from physics to electrical engineering to mechanical engineering to chemical engineering and is thus a truly cross-disciplinary field has proved to be a liability rather than an asset when it comes to securing research funding for the field. Most funding agencies and funding mechanisms continue to be strongly compartmentalized and discipline-specific. Encouraging cross-disciplinary research is more often than not merely lip service, but does not translate into actual funding streams and funding programs for cross-disciplinary research.

The two Workshops on the "Future of Plasma Science" that were held in 2015 and 2016 had the objective to assess the current state of plasma science and technology and to identify scientific challenges and technological opportunities for the future. The intended audiences for the outcomes of these workshops are not primarily scientists and engineers, but rather the general public and political decision makers, who – among other things – have the responsibility to identify and set priorities for future research funding.

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ENDNOTE

[1] Numerals are given according to conventions of American English, ie, in particular the number 1 000 000 000 is designated as 1 billion.

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