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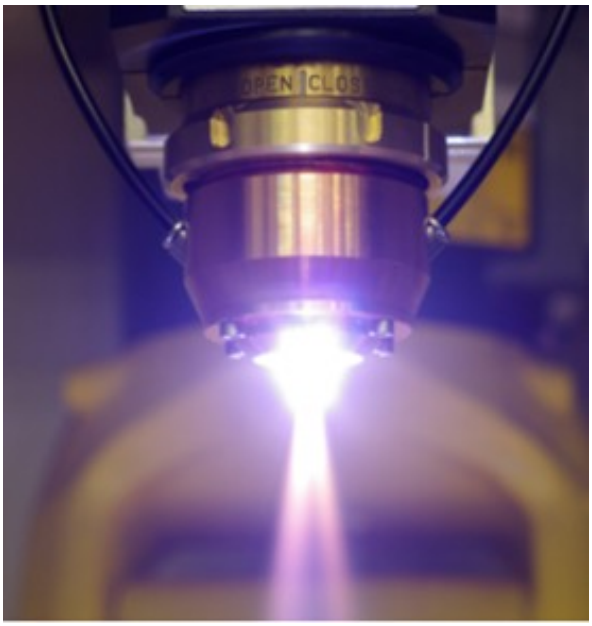
PlasmaCO2



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1 Inhaltsverzeichnis

1. Einleitung

The activation and conversion of carbon dioxide have become an important area of research in the context of climate mitigation, carbon circularity, and the electrification of high-temperature industrial processes. Established CO_2 utilization approaches are mainly based on catalytic, electrochemical, or thermochemical methods. Although widely developed, these routes often require elevated pressures, complex catalyst systems, or multi-step processing and may be constrained by thermodynamic equilibrium limitations or material stability issues at high temperature.

Thermal plasma processing offers an alternative pathway by enabling direct molecular dissociation of CO_2 at extremely high temperatures under atmospheric conditions. In plasma environments, CO_2 can be rapidly activated through electron impact, thermal decomposition, and radical formation, generating highly reactive species such as CO, atomic oxygen, and ionized fragments that can drive further chemical reactions. The combination of high temperature, high energy density, and non-equilibrium chemistry makes plasma systems particularly attractive for fast reaction kinetics and direct material transformation without the need for catalysts.

Plasma-based CO_2 conversion has been explored for applications such as synthesis gas production, fuel generation, and carbon material formation. However, most studies focus on gas-phase products, while the direct formation of solid carbon-containing materials, particularly under atmospheric pressure remains comparatively less investigated. This is partly due to the complexity of plasma–material interactions and the difficulty of controlling reaction pathways in highly reactive environments.

Within this context, the present work represents a broader exploratory study aimed at evaluating the practical use and process potential of CO_2 in thermal plasma environments, as well as identifying the fundamental physical and chemical limitations governing material conversion. Rather than targeting a single optimized synthesis route, the project focuses on understanding plasma–gas–solid interactions, carbon transport mechanisms, and the conditions required for stable carbon incorporation into solid phases. This includes assessing the influence of reaction atmosphere, residence time, energy input, and local chemical potentials on phase formation.

A central challenge arises from the fact that CO_2 dissociation inherently produces reactive oxygen species, which promote oxidation of materials and compete directly with reduction and carburization reactions. As a result, the plasma environment simultaneously provides both carbon-containing intermediate and strong oxidizing agents. Controlling this reduction–oxidation balance is therefore a key requirement for effective plasma-assisted CO_2 utilization and represents one of the primary scientific and technological challenges addressed in this work.

Understanding these competing mechanisms is essential not only for carbide formation but also for broader plasma-based material processing, including oxide reduction, carbon deposition, and high-temperature powder transformation. The findings of this study therefore contribute to the fundamental understanding of atmospheric plasma chemistry and provide a basis for future process development aimed at scalable and energy-efficient plasma-driven material synthesis.

Scientific and Process-Engineering Challenges of Plasma-Based CO_2 Utilization

The activation of CO_2 in high-temperature plasma environments is fundamentally different from conventional thermochemical processing. While elevated temperatures promote dissociation and increase reaction kinetics, the plasma environment simultaneously generates highly reactive oxygen species that can shift reaction equilibria toward oxidation rather than reduction. This duality makes plasma-assisted CO_2 conversion intrinsically complex.

In atmospheric plasma systems, chemical reactions are governed not only by bulk thermodynamics but also by non-equilibrium phenomena such as electron impact dissociation, radical recombination, and rapid quenching. As a result, classical equilibrium predictions only partially describe reaction outcomes. The effective oxygen chemical potential, local carbon activity, and residence time in the reactive zone become dominant design parameters.

From a process-engineering perspective, the key challenge lies in controlling these parameters simultaneously. High temperature alone does not guarantee successful carburization. Instead, selective control of oxidation–reduction balance, carbon transport mechanisms, and particle–plasma interaction time determines whether carbon is incorporated into solid phases or lost through competing reactions.

This study therefore approaches plasma-based CO_2 utilization not as a single-reaction problem, but as a coupled thermo-chemical system in which energy input, gas composition, and material transport must be engineered in concert.

Technological Relevance of Carbides and Carbon Materials

Carbides such as silicon carbide (SiC) and boron carbide (B_4C) are technologically important materials used in a wide range of demanding applications. Their exceptional hardness, high thermal stability, chemical resistance, and low density make them essential for high-temperature structural components, wear-resistant coatings, abrasives, and cutting tools.

- Silicon carbide is widely used in grinding media, cutting inserts, and precision machining applications where extreme hardness and thermal resistance are required. In addition, SiC plays a key role in semiconductor devices, particularly in high-efficiency power electronics for electric vehicles, renewable energy systems, and high-voltage transmission technologies.
- Boron carbide is widely used as wear resistant materials used in abrasive nozzles, e.g. for sand blasting and other applications. Additionally, areas of use are lightweight armor systems or neutron absorption in nuclear applications.

Figure 1. Wear resistant materials based on SiC and B4C

The industrial demand for advanced carbide materials has increased significantly in recent years, driven by the rapid expansion of electric mobility and high-efficiency power electronics. Silicon carbide power devices are increasingly replacing conventional silicon components due to their superior thermal conductivity and electrical performance. As a result, global carbides production capacity and investment in manufacturing infrastructure continue to grow. At the same time, conventional carbide production relies predominantly on high-temperature carbothermal reduction processes, typically exceeding 2000 °C, which are energy intensive and commonly depend on fossil-derived carbon sources. These processes are associated with substantial indirect CO_2 emissions due to both energy consumption and carbon feedstock use, making them relevant targets for process electrification and decarbonization.

Carbon based materials, including graphite, nanographite and graphene, represent another class of technologically important materials. They are widely used in energy storage systems such as lithium-ion batteries, in catalysis, electronic devices, thermal management materials, and conductive composites. Plasma-based synthesis offers potential advantages for producing such carbon materials with controlled morphology, high purity, and rapid processing rates, particularly under continuous high-temperature conditions.

The **PlasmaCO_2** project (Energieforschung 2023) addresses this challenge by systematically investigating plasma–material interactions under controlled atmospheric conditions and by evaluating strategies to enhance carbon incorporation while suppressing oxidation.
The core task was to test plasma-assisted synthesis routes in which CO_2 is used as a carrier gas and as a potential carbon source for the formation of graphite-like carbon and carbide phases.

Plasma Technology as a Multifunctional Materials Platform

Beyond carbide and carbon material formation, the project also explored the broader capabilities of the plasma system as a high-temperature processing tool. The reactor demonstrated the ability to drive rapid oxide reduction reactions, as shown in the plasma-induced formation of oxygen-deficient tungsten oxide phases. In addition, plasma exposure enabled morphological transformation of powders, including spheroidization of dendritic particles. These observations highlight that plasma torches can be applied to a wider range of industrially relevant processes, including metal oxide reduction, powder conditioning, particle spheroidisation, and feedstock preparation for additive manufacturing or thermal spraying.

The experimental work was based on a Plasma Powder Deposition (PPD) system, a thermal plasma processing platform capable of treating a wide range of materials. The system can process both metallic and ceramic powders, enabling melting, chemical activation and surface modification depending on the applied conditions. In addition to in-flight powder processing, the plasma jet can be directed onto solid substrates for surface activation, localized heating, and modification of surface chemistry. This dual capability allows the PPD system to function both as a high-temperature particle processing tool and as a surface treatment technology.

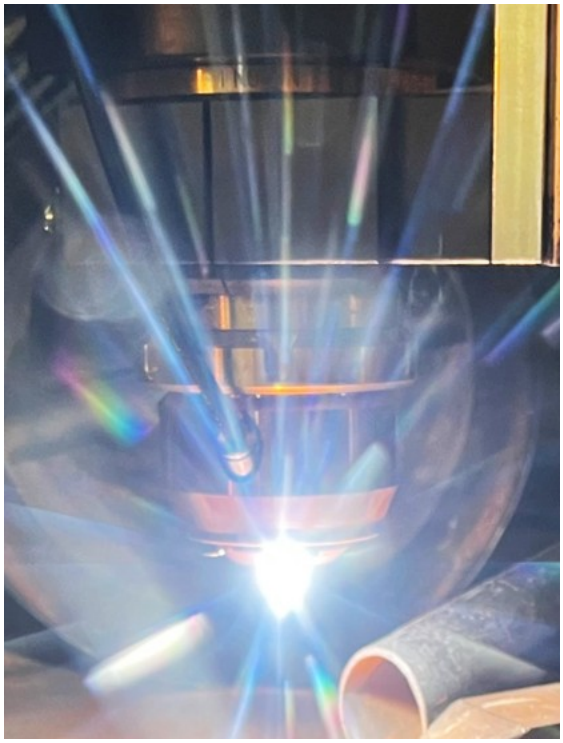

Figure 2. Plasma Powder Deposition (PPD) torch

Its stable plasma operation, controllable gas composition, and adaptable reactor design provide a versatile platform for advanced materials processing, including powder modification, functional coating, and plasma-assisted synthesis of materials.

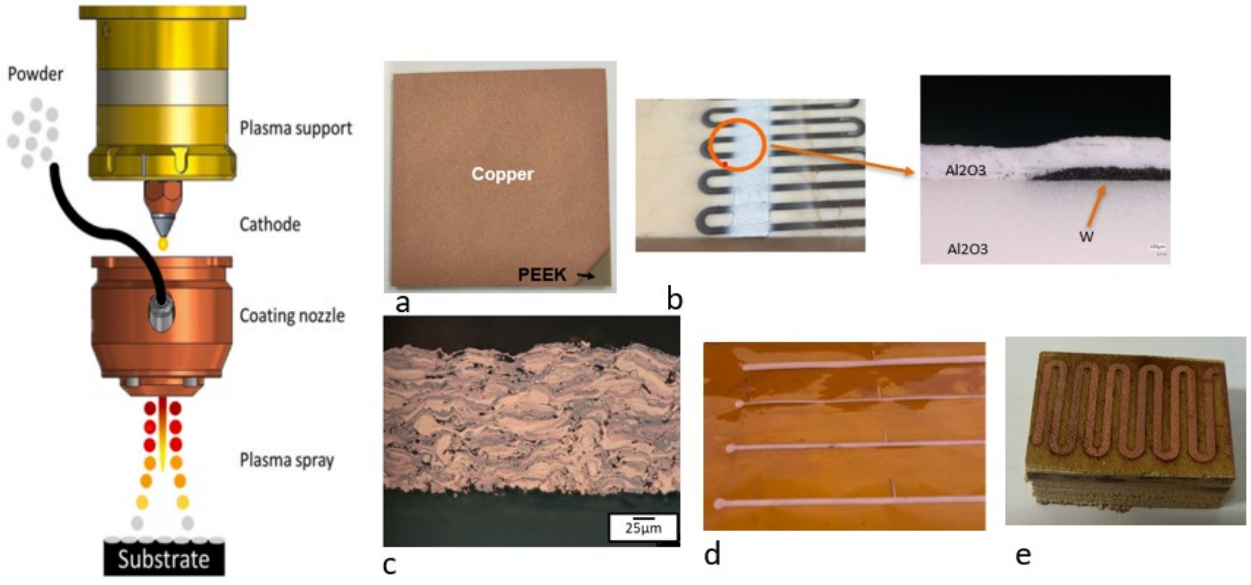

Figure 3. Left: Illustration of the plasma powder deposition process; the powder is fed from the powder feeder into the plasma jet of the torch, plasma jet (spray plume) from where it strikes the substrate surface and can produce layers of different materials. Right: a) Cu deposition on PEEK, b) Multilayer coating deposited Al2O3 on a W coated meander, c) cross-section of Cu layer on peel, d) Cu deposition on Polyimide foil, e) Cu deposition on Wood.

The work focused on three technical priorities:

1. **Establishing a safe and repeatable reactor platform** for atmospheric plasma experiments, including robust product collection and thermal management.
2. **Systematic screening of plasma–material interactions** using two complementary approaches: surface/bulk interaction and in-flight powder processing.
3. **Understanding limiting factors** for CO_2-based carbon incorporation, especially the balance between reduction/carburization and competing oxidation driven by oxygen-rich plasma chemistry.

The project aligns with the objectives of **Energieforschungs-Programm** by contributing to climate-relevant process innovation and electrification of energy-intensive synthesis routes. By exploring CO_2 utilization in high-temperature plasma environments, the project addresses long-term pathways toward resource-efficient and potentially low-emission materials production, with relevance for advanced ceramics, carbides, and functional carbon materials. The work is particularly relevant for advanced ceramics, carbides, and functional carbon materials, where plasma processing offers rapid heating, precise reaction control, and compatibility with continuous processing concepts.

The experimental work used an atmospheric plasma torch system combined with controlled reaction environments designed to regulate gas composition, particle residence time, and plasma–material interaction. Two principal reaction routes were investigated:

- **Surface and bulk exposure** of stationary materials, enabling investigation of carbon deposition, reduction behavior, and carbide formation at the plasma–solid interface under localized high-temperature conditions.
- **In-flight powder processing**, in which particles were injected into the plasma plume to study rapid gas–solid reactions, reduction, and carburization during short residence times followed by rapid quenching.

This dual approach allowed direct comparison between surface reactions and particle processing, providing insight into kinetic constraints, carbon transport mechanisms, and the influence of oxygen potential in atmospheric plasma environments.

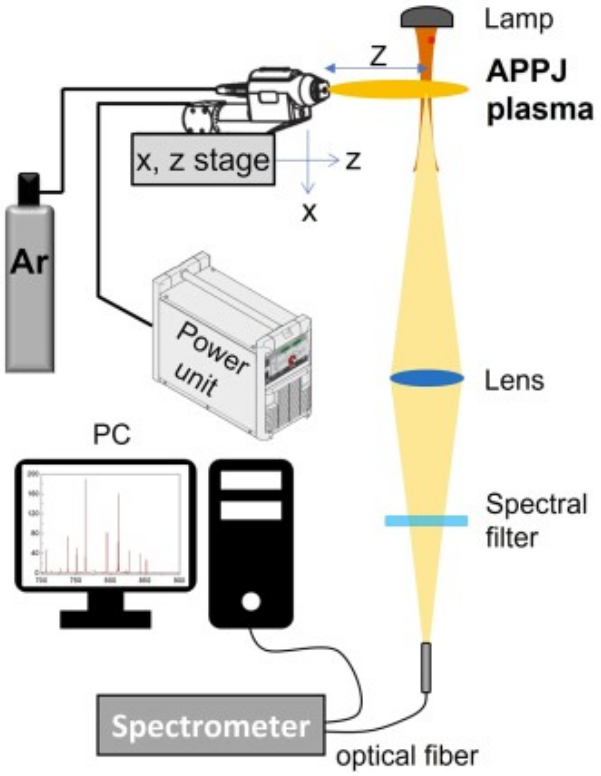

Figure 4. Schematic of experimental setup for optical emission spectroscopy of the atmospheric pressure Argon plasma jet. Jet nozzle of the industrial APPJ device mounted on a translation stage for spatially resolved OES measurements. Optical filters are placed in the detection beam path. Radiation of lamp used to check for optical absorption of the APPJ.

Materials characterization relied on standard solid-state analytical methods, including **XRD** for phase identification, **SEM/EDX** for microstructure and elemental mapping, and **optical emission spectroscopy (OES)** to qualitatively assess plasma emission and support interpretation of plasma–gas interaction.
For the tungsten oxide follow-up, complementary vibrational spectroscopy (FTIR and Raman, where applicable) provided additional insight into bonding changes and the formation of reduced oxide phases, enabling detailed evaluation of plasma-driven reduction mechanisms and oxygen vacancy formation

2 Inhaltliche Darstellung

The experimental work was carried out using an atmospheric thermal plasma processing platform based on a Plasma Powder Deposition (PPD) torch integrated into a modular reactor system. The setup was designed to enable controlled interaction between plasma, reactive gases, and solid materials under well-defined atmospheric conditions. The system allows both, surface treatment of stationary materials

and in-flight processing of injected powders, providing flexibility for investigating different reaction mechanisms within a single reactor configuration.

Plasma torch and reactor configuration

The plasma torch operates with inert or reducing plasma gases, primarily argon or argon–hydrogen mixtures, which are ionized to form a high-temperature plasma jet. The plasma is characterized by extremely high energy density and gas temperatures in the order of several thousand Kelvin, enabling rapid heating, melting, dissociation, and chemical activation of materials exposed to the plasma plume. The torch is mounted above a reaction chamber that allows controlled positioning of substrates or injection of powders into the plasma stream. The reactor includes gas supply systems, cooling units, and a product collection section, typically based on cyclone separation and filtration, enabling controlled recovery of processed materials. The modular design permits adaptation of the geometry and gas flow configuration depending on the experimental objective.

Process variables and adjustable parameters

The plasma processing system provides multiple controllable parameters that influence plasma–material interaction and reaction kinetics. These include:
• plasma power and current, which determine energy input and thermal intensity
• plasma gas composition (e.g., Ar, Ar/H_2), affecting temperature and chemical reactivity
• carrier or reactive gas composition (e.g. CO_2), influencing oxidation and reduction potential
• gas flow rates, which control residence time and mixing behavior
• torch-to-substrate distance or particle injection position, defining exposure time and thermal gradients
• powder feed rate and particle size, affecting heating dynamics and reaction completeness
• reactor pressure (atmospheric operation) and cooling conditions

By varying these parameters, the local reaction environment including temperature distribution, oxygen chemical potential, and particle residence time can be systematically adjusted. This enables targeted investigation of reduction, oxidation, carburization, and phase transformation processes.
The atmospheric plasma reactor was designed to provide controlled and reproducible plasma–material interaction while maintaining flexibility for different experimental configurations. The system integrates a plasma torch, gas supply and regulation units, powder injection equipment, and a collection system for processed material.

Reliable monitoring of plasma operation and reaction behavior was essential for systematic experimentation. Plasma stability was assessed through visual observation, electrical parameter monitoring, and emission behavior. Optical emission spectroscopy provided qualitative information on plasma species and supported interpretation of gas-phase reactions. Variations in emission intensity were used as indicators of changes in plasma composition and energy input.

Material characterization after plasma exposure provided indirect insight into the underlying reaction pathways. Phase composition, microstructure, and elemental distribution were analyzed to identify dominant transformation mechanisms.
X-ray diffraction (XRD) was used for phase identification and detection of crystalline transformations, enabling differentiation between starting materials, oxides, carbides, and reduced phases. Scanning electron microscopy (SEM), combined with EDX analysis, was applied to examine morphological changes, surface modifications, and elemental distribution.

The experimental strategy was designed to separate different reaction regimes and identify the governing mechanisms of carbon incorporation and oxidation. By combining surface exposure experiments with in-flight particle processing, the project enabled direct comparison between diffusion-limited surface reactions and rapid gas–solid interaction under non-equilibrium conditions.

The experimental program was structured into three synthesis routes:

Route A (surface/bulk interaction): Bulk materials and substrates were exposed to the plasma jet to probe surface carburization and carbon deposition. Prior to plasma treatment, selected powders were pre-compacted into solid samples and then plasma-sintered, enabling investigation of plasma effects on bulk material response and densified structures.
The reaction atmosphere was primarily CO_2-based, and additional gas compositions were systematically tested to evaluate their influence on plasma–surface reactions and oxidation behavior. This configuration enabled localized high-temperature treatment and direct observation of plasma–solid interface processes, including surface modification, densification, melting and re-solidification effects, oxide formation, and potential carbide formation within the reactive zone. The plasma provided intense localized heating and reactive species that drove rapid thermal and chemical transformations at the exposed surfaces.

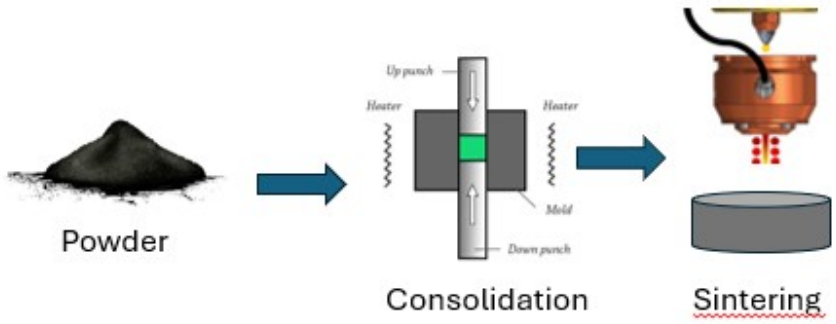

Figure 5. Right: Prior to testing Route A selected Powders were pre-compacted into solid samples.

Left: Pre compacted powder exposed to the Plasma Jet; the atmosphere was primarily CO_2. This configuration enabled localized high-temperature treatment and direct observation of plasma–solid interface processes

Route B (blown powder): injected powders were processed in-flight under an inert plasma atmosphere, while CO_2 was introduced as the carrier gas for particle transport. This configuration allowed separation of plasma thermal effects from the chemical influence of CO_2 and enabled evaluation of rapid reduction and carburization reactions during short particle residence times. The route simulated high-temperature gas–solid interaction under non-equilibrium conditions and allowed investigation of particle activation, phase transformation, and the influence of plasma chemistry on reaction kinetics.

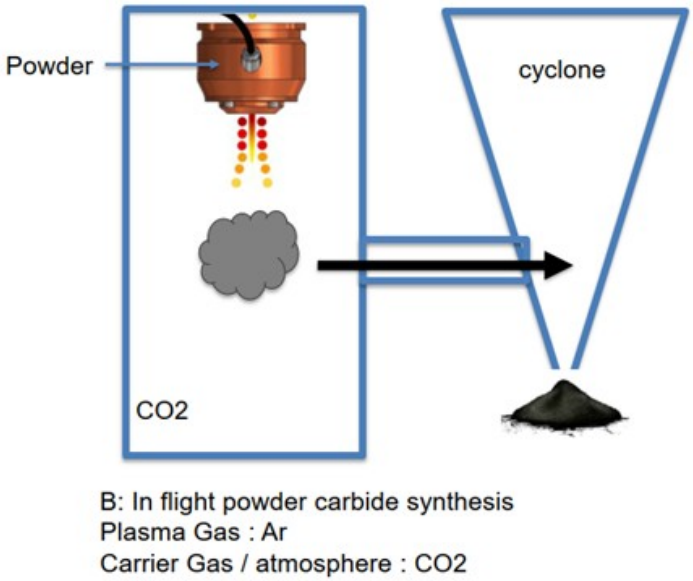

Figure 6. Injection of powder processed in-flight under an inert plasma atmosphere, while CO_2 was introduced as the carrier gas for particle transport. Thanks to a cyclone the powders are able to be cooled and separated

Route C (assisted carburization): Based on the results from Route B, an adjusted concept was tested in which carbon availability was controlled more directly to reduce dependence on CO_2-only carbon formation and to better suppress oxidation. For this purpose, silicon powder was premixed with solid carbon prior to injection into the plasma, ensuring direct local carbon availability at the particle surface. This approach aimed to reduce carbon supply from plasma-generated oxygen species and to evaluate how controlled local reaction conditions influence phase formation during in-flight processing.

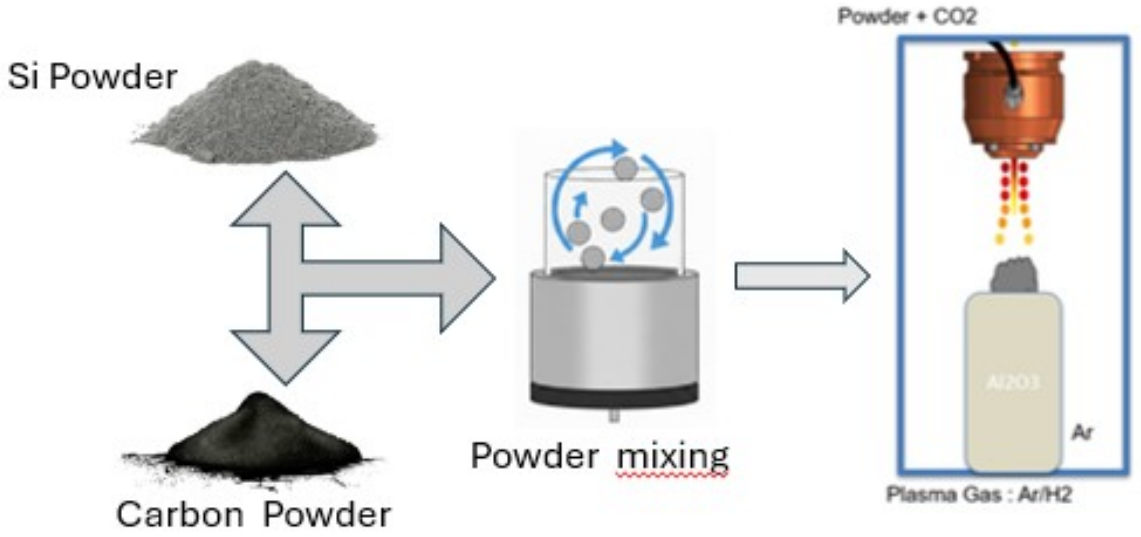

Figure 7. Silicon powder premixed with solid carbon prior to injection into the plasma, ensuring direct local carbon availability at the particle surface.

Together, these three routes provided a structured framework for identifying dominant reaction mechanisms, separating thermodynamic limitations from kinetic constraints, and assessing how carbon transport, oxygen activity, and residence time influence material formation under atmospheric plasma conditions.

Beyond carbide synthesis, the project also evaluated the broader technological potential of the plasma torch for reduction processes and powder conditioning. Plasma-driven oxide reduction and plasma-assisted spheroidization were considered as promising exploitation pathways. The ability to combine high-temperature heating, rapid reaction kinetics, and atmospheric operation offers advantages such as fast processing, electrical operation without combustion, and compatibility with continuous powder treatment concepts.

In parallel, WO_3 was used as a model oxide for a follow-up reduction study, because its visible color change provides a fast qualitative indicator of reduction progress and allows screening of reduction strength under plasma exposure. This model system enabled rapid evaluation of plasma-driven reduction capability, investigation of the balance between reduction and re-oxidation, and assessment of how atmospheric plasma chemistry influences oxide stability during in-flight processing. The WO_3 experiments therefore served not only as a scientific probe of reduction potential, but also as a proof of concept for plasma-assisted metallurgical applications.

Material analysis was carried out using complementary structural and spectroscopic methods. X-ray diffraction (XRD) was employed to identify crystalline phases and detect structural deviations from stoichiometric oxides toward reduced suboxide phases. Changes in peak position and intensity were used to assess phase transformation and oxygen deficiency. Scanning electron microscopy (SEM) provided information on particle morphology, melting behavior, and surface modification after plasma exposure. Energy-dispersive X-ray spectroscopy (EDX) supported elemental analysis and helped

correlate chemical composition with observed microstructural features. In selected cases, vibrational spectroscopy (FTIR and Raman) was used to evaluate bonding changes and confirm the formation of oxygen-deficient oxide species.

Together, these analytical methods enabled reconstruction of plasma reduction mechanisms and provided a basis for assessing the potential of the plasma torch as a versatile high-temperature processing tool for reduction, carburization, and powder transformation applications.

3 Ergebnisse und Schlussfolgerungen

Comparison of the three experimental routes demonstrates that reaction outcome is determined by the interplay of thermodynamic stability, reaction kinetics, and local chemical environment.
Surface exposure experiments highlight the sensitivity of plasma–solid reactions to oxygen availability, while in-flight particle processing emphasizes the importance of reaction time and mass transport. Assisted carburization experiments demonstrate that increased local carbon activity can partially shift reaction balance but does not fully overcome oxidation constraints under atmospheric conditions. These findings confirm that successful carbide formation in CO_2-containing plasma environments requires simultaneous control of oxygen potential, carbon supply, and reaction residence time.

Across the investigated routes, oxidation reactions dominated in many cases, and the direct synthesis of SiC and B_4C using CO_2 as the sole carbon source could not be demonstrated in a reliable, bulk-forming manner.

Nevertheless, the project produced scientifically valuable outcomes:

1) **The reactor platform** was successfully established and operated reproducibly, enabling systematic experimentation. The system consists of an atmospheric plasma torch integrated into a modular reactor chamber designed for controlled plasma–gas–solid interaction. The setup allows both surface treatment of stationary samples and in-flight processing of injected powders. Gas supply units enable controlled adjustment of plasma and carrier gas composition, while an integrated cooling system stabilizes reactor operation under high thermal load. Downstream, a cyclone-based separation unit and filter system provide controlled collection of processed materials. The flexible reactor design allows adjustment of torch position, particle injection geometry, and gas flow configuration, enabling reproducible control of exposure conditions and reaction environments.

2) **Route A** demonstrated that plasma–solid interfaces are highly sensitive to local oxygen activity. Even when carbon-related surface modifications and deposition phenomena were observed, oxide formation remained a dominant competing process. Detailed structural and microstructural analyses confirmed that plasma exposure can induce localized chemical and morphological

transformations, but these remain confined to thin reactive regions when oxygen chemical potential is not actively controlled. Analysis of the reactive zones after plasma exposure showed no clear formation of carbide. Significant amounts of oxide were detected, indicating that oxidation reactions competed strongly during the process.

Figure 8. Reaction Zone of B disc after plasma reaction

3) **Route B**: The in-flight processing studies further clarified the kinetic constraints associated with short particle residence times in atmospheric plasma environments. While suspended particles experienced rapid thermal activation and chemical interaction with plasma-generated species.
Attempts to enhance carbon activity through catalytic carbon generation demonstrated that transport limitations and reaction timescales restrict uniform phase conversion. For example, a nickel (Ni) mesh was introduced into the reaction zone to promote catalytic carbon formation. The Ni surface enabled local carbon deposition from CO generated during CO_2 dissociation, increasing carbon availability near the reacting particles. However, despite this catalytic pathway and localized carbon enrichment, complete conversion of silicon to SiC was not achieved, as confirmed by EDX mapping showing predominantly Si.
These results indicate that, although catalytic surfaces can enhance local carbon formation, limitations in carbon transport and short residence times constrain bulk carburization under atmospheric plasma conditions.

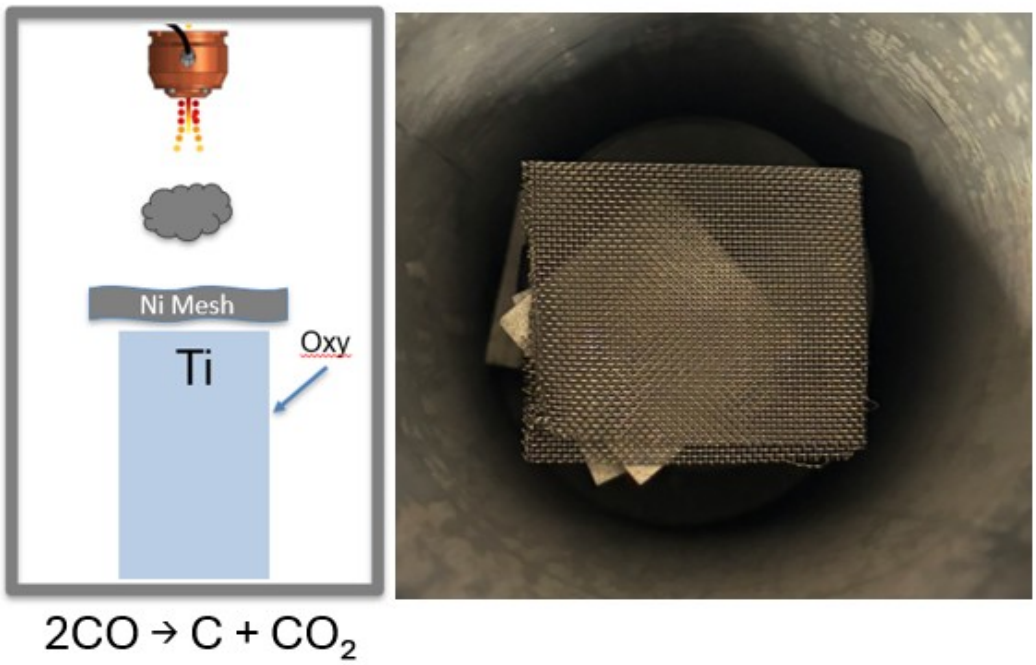

Figure 9. Use of Ni mesh for enhancing catalytic reaction

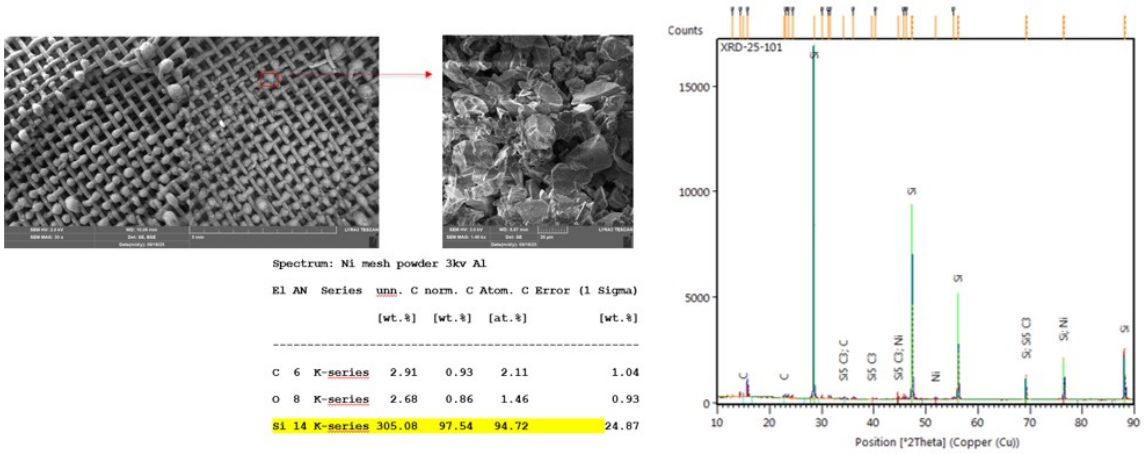

Figure 10. Left: SEM image and EDX quantification (20 µm area) of Si powder reaction. Right: XRD pattern of powder extracted from the Ni mesh

4) **Route C** showed that when carbon availability is controlled more directly, carbon-rich products can form more readily, indicating a promising optimization pathway even though full SiC conversion was not achieved. The observation of graphite formation under carbon-assisted conditions provides an important indication that plasma processing can enable the generation of structured carbon phases when local chemistry is properly tuned.

   Carbon based materials are technologically valuable due to their high electrical conductivity, excellent thermal conductivity, chemical stability, and lubricating behavior. These properties make them essential in applications such as battery electrodes, conductive fillers, thermal

interface materials, catalyst supports, and wear-resistant components. Depending on structure and morphology, carbon can also serve as a precursor for advanced materials such as graphene or nanostructured carbon networks.

The ability to form graphitic carbon under rapid in-flight plasma conditions suggests that high-temperature plasma environments can support graphitization and carbon structuring without conventional long-duration thermal treatments. This demonstrates the potential of the reactor platform not only for carbide synthesis but also for the controlled production and modification of functional carbon materials.

5) Plasma-Driven Reduction of WO_3 and Formation of Functional Suboxide Phases

A major additional result of the project was the demonstration of plasma-driven oxide reduction using WO_3 as a model system. During in-flight plasma processing, the yellow WO_3 powder transformed into blue and dark-blue material, indicating the formation of oxygen-deficient tungsten oxide phases (WO_{3-x}). The progressive color change directly reflects increasing oxygen vacancy concentration and therefore increasing reduction degree.

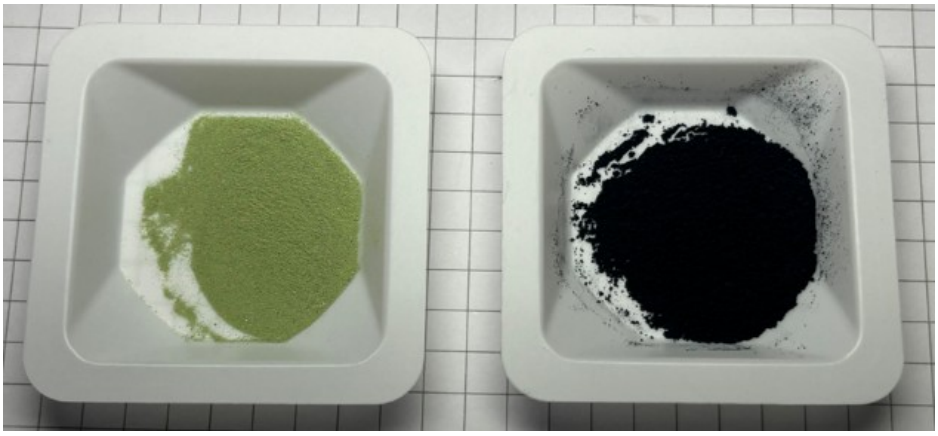

Figure 11. Visual appearance of WO_3 powders before and after plasma processing, illustrating the color transition from yellow to blue/dark-blue corresponding to increasing oxygen deficiency ($WO_3 \rightarrow WO_{3-x}$).

Structural and spectroscopic analyses confirmed the formation of reduced tungsten suboxides rather than metallic tungsten, showing that the plasma torch can drive rapid high-temperature reduction while full metallization remains limited under CO_2-containing atmospheric conditions due to re-oxidation.

The formation of WO_{3-x} is technologically relevant, as tungsten suboxide materials are widely used in functional coatings. Their strong optical absorption, electrical conductivity, and catalytic activity make them suitable for applications such as photothermal coatings, smart windows, gas sensing layers, electrochromic devices, and catalytic surfaces. These results therefore demonstrate not only reduction capability but also open potential pathways for plasma-based synthesis of functional oxide coatings.

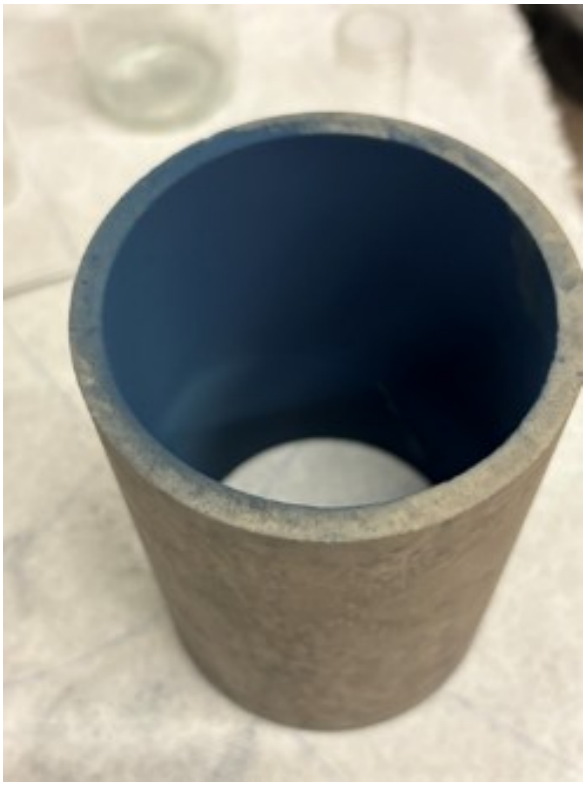

Figure 12. Tungsten suboxide coating on a Al2O3 substrate ($WO_3 \rightarrow WO_{3-x}$).

In addition, **plasma-induced spheroidisation** of powders emerged as a second important achievement within this application. Dendritic particles exposed to the high-temperature plasma plume underwent rapid melting and surface tension-driven reshaping into more spherical morphologies. This capability is highly relevant for powder conditioning, particularly for feedstock preparation in additive manufacturing, thermal spraying, and powder metallurgy, where spherical particle geometry is essential for flowability and process stability.

The reactor therefore demonstrated strong capability for powder activation, fast oxide reduction, morphology control, and controlled carbon incorporation when local reaction chemistry is properly managed. In particular, the formation of oxygen-deficient tungsten oxides confirmed the system's effectiveness for rapid plasma-driven reduction and functional material synthesis under atmospheric operation.

From a technological perspective, the project establishes atmospheric plasma processing as a flexible platform for rapid high-temperature material transformation, controlled chemical modification, and particle engineering. The results provide practical design criteria for future plasma-based synthesis and reduction processes and define boundary conditions for carbon incorporation under CO_2-derived atmospheres, while simultaneously revealing additional industrial exploitation pathways beyond the original project scope.

4 Ausblick und Empfehlungen

Beyond its original focus on CO_2-based carburization and carbide synthesis, the project demonstrated that the atmospheric plasma torch represents a versatile high-temperature processing platform with broad technological applicability. The experimental results indicate that the system can be used for a range of thermally driven chemical and morphological transformations under atmospheric conditions.

The atmospheric plasma torch used in this project is primarily designed as a coating and surface treatment technology, enabling high-temperature deposition, surface activation, and localized material modification. However, the experimental investigations demonstrated that the system can also function as a versatile high-temperature processing platform beyond its conventional coating role. Its ability to combine rapid heating, controllable gas chemistry, and atmospheric operation enables multiple material transformation routes within a single system.

Technology Readiness and Scale-Up Considerations

From a technology development perspective, the current plasma-based system can be classified as an experimental validation platform (approximately TRL 3–4). The reactor demonstrates reproducible operation and validated reaction capability, but further engineering optimization is required for industrial deployment.
Key challenges for scale-up include:

- Increasing particle residence time without sacrificing throughput
- Minimizing re-oxidation during atmospheric operation
- Improving energy efficiency and plasma stability
- Ensuring continuous, automated powder feeding and collection

Future reactor concepts may require elongated reaction zones, staged gas injection, or partial atmospheric isolation to reduce oxygen ingress. Additionally, advanced thermal management strategies will be necessary to maintain stable long-duration operation.

Despite these challenges, plasma technology offers significant advantages compared to conventional furnace-based systems. The use of renewable electricity, rapid heating rates, localized energy input, and modular reactor design provide strong potential for integration into electrified manufacturing chains. Long-term industrial implementation will depend on demonstrating continuous operation, predictable product quality, and favorable energy balances. The knowledge generated within this project provides the foundation for such optimization.

• Plasma-driven reduction of metal oxides
The reduction of WO_3 to oxygen-deficient phases confirms the strong reduction capability of the plasma. This opens potential for electrified oxide reduction and hydrogen-assisted metallurgical processes.

• Plasma-induced spheroidisation of powders

Rapid melting and reshaping dendric particles demonstrate suitability for powder conditioning. Spherical powders are critical for additive manufacturing, thermal spraying, and powder metallurgy.

• High-temperature material activation
The plasma provides localized, rapid thermal treatment suitable for surface activation, densification, and microstructural modification.

Short term, efforts should focus on improving process control within the existing reactor framework. This includes optimization of gas composition and flow management to reduce effective oxygen activity, as well as reactor adjustments that extend particle residence time in the reactive zone. Attention should be given to controlled reduction strategies, stabilization of local reaction environments, and improved carbon transport toward reacting particles. More precise control of plasma–particle interaction time will be essential for shifting reaction balance toward carburization and suppressing competing oxidation pathways. These developments will help establish reproducible operating windows for carbon incorporation under atmospheric plasma conditions.

Medium-term development should concentrate on translating the identified mechanisms into scalable processing concepts. Reactor geometries must be optimized to minimize re-oxidation, ensure homogeneous temperature fields, and allow flexible adjustment of gas atmospheres. Expanding beyond CO_2-only chemistry toward hybrid or alternative carbon-containing gases will enable improved control of oxygen potential and carbon activity.
Continuous powder processing concepts, enhanced gas handling systems, and improved thermal management will be essential. During this stage, plasma-driven reduction, carbon material synthesis, and spheroidisation should be advanced toward technically relevant production concepts with defined throughput and process stability.

Long-term development aims at integration of plasma-based material synthesis into industrial production chains powered by renewable electricity. Electrified plasma processing offers the potential to replace fossil-fuel-driven high-temperature synthesis routes and thereby contribute to low-emission materials manufacturing. Achieving this goal will require scale-up of reactor capacity, optimization of energy efficiency, and demonstration of process reliability under continuous industrial operation. In this perspective, atmospheric plasma processing could become a flexible platform for producing advanced ceramics, carbon materials, and reduced metal oxides within future electrified manufacturing systems.

Beyond direct process optimization, the PlasmaCO_2 project has already enabled concrete technological follow-up activities. The scientific and engineering insights gained during the project provided the foundation for the initiation of two subsequent research initiatives that extend the application range of plasma-based high-temperature processing.

Follow-up activities

The **mcPLASMA-lysis project**, conducted in collaboration with JOANNEUM RESEARCH within the Energieforschung 2024 program of the Austrian Research Promotion Agency, was successfully granted and started in October 2025. Building directly on the understanding of plasma-assisted carbon conversion and reaction control developed in PlasmaCO_2, this project investigates methane plasmalysis using a PPD plasma torch. The objective is the synthesis of advanced nanocarbon and carbide materials, including crystalline nano graphite, graphene, silicon carbide, and boron carbide. By operating under controlled plasma conditions and high-temperature reaction environments, the project aims to improve carbon conversion efficiency, tailor material structure at the nanoscale, and support both sustainable methane valorization and the development of high-performance functional materials.

A second initiative, the **Iron Heat** exploration project, submitted to the **Energieforschung 2025 call**, investigates hydrogen plasma reduction as a route for regenerating metallic iron. The concept combines accelerated plasma reaction kinetics with renewable electrical energy to create a flexible and CO_2-free alternative to conventional reduction processes. The approach directly applies reduction principles and plasma–oxide interaction mechanisms identified in the PlasmaCO_2 project to metallurgical processing. The proposal was submitted in the fourth quarter of 2025, and approval is currently pending.

Taken together, these follow-up activities demonstrate that the PlasmaCO_2 project has progressed beyond fundamental feasibility studies toward concrete technological implementation pathways. The project has established both a scientific knowledge base and an operational platform that support continued development of plasma-based material synthesis and electrified high-temperature processing. These developments position atmospheric plasma technology as a promising tool for advanced materials manufacturing within future sustainable energy and industrial systems.

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Unraveling Temperature-Dependent Plasma-Catalyzed CO2 Hydrogenation

6 Anhang

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