Untersuchung der nachhaltigen Verwertung von Kohlenstoff aus der Methanpyrolyse

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Graz, November 2021

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1. Executive Summary

1.1. Die vielfältigen Verwendungsmöglichkeiten von Kohlenstoff aus der Pyrolyse von Methan

CO_2-freier bzw. mit geringem CO_2-Fußabdruck hergestellter Wasserstoff wird in einem zukünftigen Energiesystem, das ausschließlich auf erneuerbaren Quellen beruht, eine zentrale Rolle einnehmen. Wasserstoff ermöglicht die Kopplung der Sektoren Strom, Gas und Wärme, die Speicherung von erneuerbarer Überschussenergie und liefert einen wichtigen Beitrag für eine klimaneutrale Mobilität sowie Industrieproduktion. Derzeit wird Wasserstoff unter Freisetzung von CO_2 überwiegend durch Dampfreformierung von Erdgas hergestellt und vor allem in der chemischen und der petrochemischen Industrie eingesetzt. Würde man die in Zukunft benötigte Menge an Wasserstoff ausschließlich über Wasserelektrolyse herstellen, so wären allein für Europa mehrere Tausend TWh an elektrischer Energie aus erneuerbaren Quellen notwendig.

Eine der möglichen **alternativen Produktionsrouten für erneuerbaren Wasserstoff** ist die Methanpyrolyse. Gegenüber anderen, alternativen Erzeugungswegen weist die Methanpyrolyse bei einer sehr hohen Wasserstoffausbeute den **geringsten Energieaufwand** (weniger als ein Viertel der Wasserelektrolyse) auf. Damit ist Wasserstoff aus der Pyrolyse von Methan im Hinblick auf den durch den Energieaufwand verursachten Umweltimpakt allen anderen Prozessrouten deutlich überlegen.

Da bei der **Methanpyrolyse fester Kohlenstoff als Nebenprodukt** erzeugt wird, ist der produzierte Wasserstoff CO_2-frei. Je Kilogramm Wasserstoff werden dabei gleichzeitig etwa drei Kilogramm an festem Kohlenstoff hergestellt - im Sinne einer **vollständigen Ressourcennutzung** kommt der nachhaltigen Verwendung dieses elementaren Kohlenstoffs eine wichtige Bedeutung zu. Die an der **Montanuniversität Leoben** durchgeführten wissenschaftlichen Untersuchungen bestätigen eine Korrelation der auftretenden Kohlenstoffmorphologie und des Pyrolyseprozesses bzw. dem verwendeten Katalysatormaterial. Somit besteht die Möglichkeit die Qualität des produzierten Kohlenstoffs hinsichtlich seiner Modifikation und Korngröße im Hinblick auf anwendungsspezifische technische Spezifikationen gezielt einzustellen[1].

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1   Der Kohlenstoff kann je nach vorliegender Modifikation (Grafit, Graphen, Ruß, Kohlenstoffröhrchen, turbostratischer Kohlenstoff, …) und Reinheit unterschiedlichen Verwendungen zugeführt werden. Möglichkeiten dazu sind einerseits die Nutzung in High-Tech Anwendungen wie Carbon Nanotubes, Hochleistungswerkstoffe, Superkondensatoren oder micro-porösen Kohlenstofftanks zur energieeffizienten Wasserstoffspeicherung und andererseits als Rohstoff in Gummi- und Kunststoffprodukte sowie der Asphalt- und Feuerfestindustrie, als Additiv in Schmiermitteln, Gießpulvern und Elektrodenmaterial für die metallurgische Industrie und als Ausgangsmaterial für Batterien und Speichersysteme für elektrische Energie.

Da bei der Produktion von Wasserstoff aus Methan **je Kilogramm Wasserstoff gleichzeitig etwa drei Kilogramm an festem Kohlenstoff hergestellt** werden, kommt speziell großvolumigen Anwendungen von Kohlenstoff eine besondere Bedeutung zu. Einerseits kann der Kohlenstoff in der **Baustoffindustrie als Zusatzstoff in Isolationsmaterialien** sowie in konstruktiven Baustoffen zur gezielten Beeinflussung der **physikalischen Eigenschaften** eingesetzt werden. Die **Technische Universität Graz** hat sich dazu befasst und erste Erkenntnisse über den Einsatz von festem Kohlenstoff in Baumaterialien erhoben. Darüber hinaus kann der Kohlenstoff auch als Bodenhilfsstoff in der Landwirtschaft angewendet werden, wobei hier insbesondere positive Effekte auf die **Nährstoff- und Wasserspeicherkapazität** des Bodens, ein gezielter Aufbau von Humus sowie ein positiver Beitrag auf klimaschädliche Bodenemissionen möglich sind. Darüber hinaus kann der Kohlenstoff auch als Additiv in der Kompostierung und bei der Herstellung von **organischen Düngerpellets** eingesetzt werden. Für einen möglichen Einsatz von Kohlenstoff in der Landwirtschaft ist eine entsprechende Reinheit des Kohlenstoffes maßgeblich. Durch die möglichen positiven ökologischen Effekte sind diese Anwendungen aber von besonderem Interesse. Hierzu hat die **BOKU** intensive Recherchen vorgenommen und vielversprechende Ergebnisse zur Anwendung von festem Kohlenstoff in der Landwirtschaft hervorgebracht.

Vor allem bei großvolumigen Anwendungen von Kohlenstoff ist davon auszugehen, dass im Hinblick auf die **Vermarktung des Kohlenstoffs** eine weitere Verarbeitung nur mit geringem Kosteneinsatz durchgeführt werden kann. Im Idealfall kann der bei der Pyrolyse von Methan entstehende Kohlenstoff ohne technologisch aufwändige Prozesse als Produkt verwendet werden. Daraus folgt, dass im Hinblick auf die Entwicklung der Pyrolysetechnologie sowie für die zukünftige Umsetzung in großtechnischen Anlagen ein wesentlicher Fokus auf die Wahl der Prozessroute der Pyrolyse sowie die Bestimmung der maßgeblichen Prozessparameter gelegt werden muss. Darüber hinaus muss gleichzeitig die **ökonomische und ökologische Bewertung möglicher Anwendungsoptionen** für Wasserstoff und Kohlenstoff im Sinne einer nachhaltigen Technologieentwicklung betrachtet werden. Eine möglichst vollständige Nutzung aller bei der Pyrolyse entstehender Stoff- und Energieströme darf dabei nicht außer Acht gelassen werden. Eine **volkswirtschaftliche Betrachtung** des Einsatzes von Kohlenstoff aus der Methanpyrolyse hat die **Universität Graz gemacht**, um Verdrängungseffekte, geopolitische Abhängigkeiten und Marktsituationen zu verstehen.

1.2. The diverse applications of carbon produced by methane pyrolysis

CO_2-free or low CO_2-intensity hydrogen production is going to play an integral role in a future energy system that is solely relying on renewable sources. Hydrogen enables coupling of the following sectors: electricity (production), gas and thermal heating, as well as energy storage from renewable overproduction. Furthermore, it contributes to climate-neutral mobility as well as industrial processes.

The state-of-the-art approach to hydrogen production, whilst emitting CO_2, is mostly conducted by steam reformation of natural gas and is commonly used in chemical and petrochemical industries. To produce sufficient amounts of hydrogen for future applications exclusively from electrolysis of water, in Europe alone several thousand TWh of electricity from renewable sources would be necessary.

One of the possible **alternative production-routes for renewable hydrogen** is methane pyrolysis. The comparison with other production schemes shows that methane pyrolysis offers very high yields with the **lowest energy consumption** (less than one quarter of the energy consumption used in water electrolysis) possible. Concerning impacts on the environment resulting from energy intensive hydrogen production, methane pyrolysis is the superior process compared to all others.

Hydrogen produced by methane pyrolysis is considered CO_2-free, because **solid carbon is generated as a byproduct**. For every one kilogram of hydrogen concurrently three kilograms of solid carbon are produced. For the purpose of a **complete resource utilization** a sustainable application of elementary carbon is of major significance. Experiments conducted at **Montanuniversität Leoben** confirm a correlation between the morphology of solid carbon and the pyrolysis-process or rather the catalyst material used. As a consequence, adjustments to the quality of produced solid carbon regarding its modification and grain size to specific technical specifications[2] are possible.

Because of the aforementioned fraction of **three kilograms of solid carbon for every kilogram of hydrogen** produced, a large-scale usage of carbon is of particular importance. On the one hand carbon can be used in **construction as an additive to insulating materials** as well as in building materials to enhance **physical properties**. Experiments concerning these applications conducted at the **Graz University of Technology** produced several promising findings. Furthermore, carbon can be used in **agriculture to promote storage of water and nutrients in the soil**, build up humus, and reduce the emission of greenhouse gases from the soil. Moreover, carbon can be used as an additive in composting and for the production of **organic fertilizers**. For agricultural use

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2 Carbon depending on its modification (graphite, graphene, black carbon, carbon nanotubes…) and purity can be used for different applications. Options are on the one hand applications in high-tech such as carbon nanotubes, high-performance materials, supercapacitors, or micro-porous carbon for the storage of hydrogen and on the other hand as a raw material in rubber and plastic products as well as in tarmac and in the refractory industry, as an additive in lubricants, casting powders and as electrode materials in metallurgic industries and as a starting material in batteries

high purity carbon is necessary. Due to the potential positive ecological effects these applications are of particular interest. Intensive research at **BOKU** shows promising results for the application of solid carbon in agriculture.

Especially for large-scale utilizations of carbon, **commercialization** and processing can be assumed to be sufficiently convenient. Ideally the carbon produced from methane pyrolysis can be used directly without the need for laborious technological processing. Therefore, with regards to the development of pyrolysis technologies as well as the future implementation in large-scale facilities, a specific focus has to be put on the choice of process-routes and the assessment of important process parameters. Furthermore, a simultaneous **ecological and economical assessment of possible applications** for hydrogen and carbon for the purpose of sustainable technology development needs to be conducted. A complete utilization of all arising material- and energy-fluxes from the pyrolysis process is considered mandatory. An **economic assessment** for the usage of carbon from methane pyrolysis has been carried out by the **University of Graz** to understand displacement effects, geopolitical dependencies and market situations.

2. Hintergrund zum Projekt

Die Montanuniversität Leoben plant gemeinsam mit Industriepartnern ein Verfahren zu entwickeln, welches in hohem Umfang **Wasserstoff aus Methan zur Verfügung** stellen kann, um den Energieverbrauch unter anderem großer Industriebetriebe, mittels der Methanpyrolyse als **Brückentechnologie**, auf eine nachhaltige Energiequelle umzustellen. Der aus dem Prozess erzeugte Wasserstoff kann neben dem **direkten industriellen Einsatz**, auch in anderen Zweigen, wie der Energieversorgung in Städten zum Einsatz kommen. Anwendungen des Wasserstoffs erstrecken sich von Industrie (z. B. Reduktionsmittel in der Roheisen- und Stahlerzeugung), über die Bereitstellung stationärer Energie (Heizen im urbanen Raum) bis hin zur Mobilität: Kraftstoff für Brennstoffzellen (z. B. Schwerlastverkehr).

Um die **gesamthafte Nachhaltigkeit des Ansatzes** zu gewährleisten und im Wissen, dass dieses Verfahren einige Unbekannte aufweist, sind die beteiligten Institutionen sehr daran interessiert, diese Route der Wasserstoffherstellung allen voran die Weiterverwendung des anfallenden Kohlenstoffs durch **externe Expert_innen evaluieren** zu lassen und etwaige blinde Flecke zu eruieren. Die Ergebnisse der Bewertung werden direkten Einfluss in die Umsetzungsentscheidung der Industriepartner finden.

Das gesamte Begleitprojektvorhaben unter ursprünglicher Leitung der Universität Graz, mit den LCAs (Life-Cycle-Assessment) von Wasserstoff und Kohlenstoff und den volkswirtschaftlichen Komponenten, wurde am **21. September 2020** am Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK) unter Anwesenheit von Sektionschef Jürgen Schneider, Abteilungsleiter Stv. Theodor Zillner, Referent für Klima, Florian Maringer, Referentin für Innovation Eva-Maria Titz, Karl Steininger (Universität Graz), Peter Moser (Montanuniversität Leoben), Robert Obenaus-Emler (Montanuniversität Leoben), Gerald Kalt (Universität für Bodenkultur) und Katrin Brugger (Climate Change Centre Austria – CCCA) vorgestellt. Anfang Dezember 2020 erfolgte die positive Rückmeldung an den ursprünglichen Projektleiter. Aufgrund der sich geänderten Rahmenbedingungen und dem **Fokus auf die Verwertung von Kohlenstoff aus der Methanpyrolyse**, erfolgte eine Adaptierung des Angebots unter administrativer Leitung des CCCA.

Mit **Ende Dezember 2020** erfolgte die Beauftragung und folgende Institutionen wurden als Projektpartner, wie im ursprünglichen Gesamtangebot vorgesehen, eingebunden:

Montanuniversität Leoben (MUL) – Bereitstellung Labordaten zu Methanpyrolyse und Ergebnisse aus Tests

Technische Universität Graz (TUG) – Anwendung Kohlenstoff in Baustoffen

Universität für Bodenkultur (BOKU) – Anwendung Kohlenstoff in der Landwirtschaft

Universität Graz (Uni Graz) – volkswirtschaftliche Rückwirkungen

Das Climate Change Centre Austria hat im Rahmen dieses Projektes die administrative **Koordination der Arbeitspakete**, die Zusammenführung der Ergebnisse, die Einbindung der Projektgruppe an der Montanuniversität herbeigeführt. Durch den **laufenden Austausch** zwischen MUL und den Projektpartnern war gewährleistet, dass die **Testdaten seitens der MUL** kontinuierlich an das wissenschaftliche Projektteam weitergeben wurden. Über die Laufzeit des Projektes wurden virtuelle Treffen zur Absprache abgehalten, von den Arbeitspaketleiter_innen individuell einberufen und gegen Ende Projektlaufzeit wurden Einzeltermine (19. Juli 2021 mit TUG; 22. Juli 2021 mit Uni Graz; 02. August 2021 mit BOKU) mit den jeweiligen Arbeitspaketleiter_innen vereinbart, um die Erkenntnisse aus dem Arbeitspaket zu besprechen und etwaige fehlende Information noch einzuholen.

Das Projekt startete mit einem **Kick-Off Meeting am 26. Jänner 2021**, bei welchem die Aufgaben nochmals koordiniert wurden und die zu **liefernden Meilensteine** mit allen Beteiligten **inhaltlich als auch terminlich** vereinbart wurden. Während der Laufzeit gab es ein **»Sharing first Results«-Meeting am 08. März 2021** und ein **Update-Meeting am 10. Mai 2021**, um notwendige Adaptierungen vorzunehmen und die Einhaltung des Zeitplans zu gewährleisten. Allen beteiligten Institutionen und Personen wurde der finale Bericht vor Abgabe zur Verfügung gestellt.

Das Projekt endete mit der **vorläufigen Endbewertung der verschiedenen Möglichkeiten der Kohlenstoffverwendung** hinsichtlich der Gesamtbelastung auf CO_2 Basis. Diese Bewertung stellt eine der grundlegenden Entscheidungskriterien für die Industriepartner dar, und ist eng verknüpft mit den weiterführenden Aktivitäten.

Die einzelnen Arbeitspakete wurden ob des internationalen Projektteams auf Englisch erarbeitet – die Zusammenfassung **der zentralen Aussagen der drei Arbeitspakete ist in Deutsch** erfolgt. Das zusätzliche Kapitel 2 »Methanpyrolyse« wurde im Laufe des Projektes etabliert und als notwendige Grundlageninformation zum Projekt bewertet. Fachlich bzw. inhaltlich lag die Verantwortung je Arbeitspaket bei den Wissenschafter_innen des Arbeitspakets. Das CCCA wurde mit der Projektleitung betraut, die in diesem Zusammenhang rein koordinativ zu verstehen ist. Damit übernimmt das CCCA für die inhaltliche Richtigkeit der Ergebnisse keine Verantwortung.

Methodisch folgten WPI und WPII einer großangelegten Literaturrecherche sowie wissenschaftlich fundierten und aussagekräftigen Praxisbeispielen, um daraus die Ergebnisse abzuleiten. WPIII baute auf den Berechnungen bzw. Ergebnissen der beiden anderen Arbeitspakete auf, um die volkswirtschaftlichen Komponenten zu errechnen.

3. WPx »Methanpyrolyse«

Autoren: Markus Lehner und Robert Obenaus-Emler – Montanuniversität Leoben

»Türkiser« Wasserstoff ist eine **vielversprechende Alternative zu grünem oder grauem Wasserstoff**. Bei der **Methanpyrolyse** wird Methan, in Abwesenheit von Sauerstoff und Wasser, bei Temperaturen über 800 Grad in Wasserstoff und festen Kohlenstoff gespalten.

Obwohl die kommerzielle Herstellung von **türkisem Wasserstoff** bis jetzt nicht umgesetzte wurde, könnten sich die zukünftigen Marktbedingungen im Kontext von erhöhtem politischem Druck und steigenden CO_2-Preisen erheblich verbessern.

Methanpyrolyse steht noch am **Anfang der technologischen Entwicklung** und hat noch enormes Innovationspotential. Gleichzeitig müssen Probleme bewältigt werden, allem voran das **Management des festen Kohlenstoffs** (Pyrolysekohlenstoff), der als Nebenprodukt erzeugt wird. Bei Produktion von türkisem Wasserstoff in Welt-Maßstab ist es zentral, dass eine Lösung für die Lagerung oder Entsorgung gefunden wird.

Gegenwärtig werden etwa 80 Prozent des weltweiten Energiebedarfs über die **fossilen Brennstoffe** Kohle, Erdöl und Erdgas gedeckt. Die Emissionen aus der Verbrennung dieser fossilen Energieträger, insbesondere das Treibhausgas CO_2, sind die **Hauptursache für die globale Erwärmung** durch den anthropogenen Treibhausgaseffekt. Die starke Begrenzung von CO_2-Emissionen – in vielen Bereichen sogar deren vollständige Vermeidung – ist essentiell, um die Ziele des Pariser Klimaabkommens zu erreichen. Der Klimawandel zwingt die internationale Gemeinschaft zu einem fundamentalen Wandel in der Energieversorgung. Ein Kernaspekt dieser Transformation ist die Identifizierung alternativer Energieträger, die nachhaltig genutzt werden können. Die **Dekarbonisierung des Energiesektors** soll hierbei durch den zunehmenden Einsatz von grünen Energieträgern, vor allem Wasserstoff, von statten gehen. Dabei ist jedoch nicht nur eine Umstellung vieler mit der Emission von klimaschädlichen Schadstoffen behafteter Prozesse und Anlagen nötig, sondern auch die Implementierung eines adäquaten Produktions- und Versorgungskonzeptes zwingend erforderlich[1]. Ein solches Konzept muss in der Lage sein, den **benötigten Wasserstoff in ausreichender Menge und Qualität**, insbesondere aber ressourcenschonend und möglichst emissionsneutral bereitzustellen.

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1 Hierbei ist das Augenmerk dieser Betrachtung auf die energieintensiven Industriezweige gerichtet, da das zugrunde liegende Projekt von eben diesen Industriepartnern betrieben wird. Eine gesamtheitliche, auch im gesellschaftlichen Sinne, Transformation zur Reduktion der CO_2 Emissionen sind allen Beteiligten bewusst.

3.1. Anwendungsgebiete von Wasserstoff

Wasserstoff stellt gegenwärtig einen wichtigen Rohstoff in der chemischen und petrochemischen Industrie dar. Wasserstoff wird hauptsächlich für die Synthese von Ammoniak, Methanol und anderen organischen Verbindungen sowie bei der Entschwefelung von Rohöl angewendet. Von untergeordneter Bedeutung ist aktuell noch die Rolle von H_2 im Energiesektor sowie in der Metallurgie und der Glasindustrie. In den kommenden Jahren ist jedoch aufgrund der angestrebten Dekarbonisierung des Energiesektors mit einer deutlichen **Zunahme an Anwendungen** in diesen Sektoren zu rechnen, sofern die hierfür erforderlichen technologischen und ökonomischen Anforderungen realisierbar sind.

In Abbildung 1 sind potenzielle, zukünftige Anwendungsgebiete von Wasserstoff dargestellt. Es lassen sich dabei vier Bereiche abgrenzen: Mobilität und Transport, Sektorenkopplung mit dem Erdgasnetz, Wärmebereitstellung sowie Wasserstoff als Reaktionspartner in chemischen, petrochemischen und metallurgischen Prozessen.
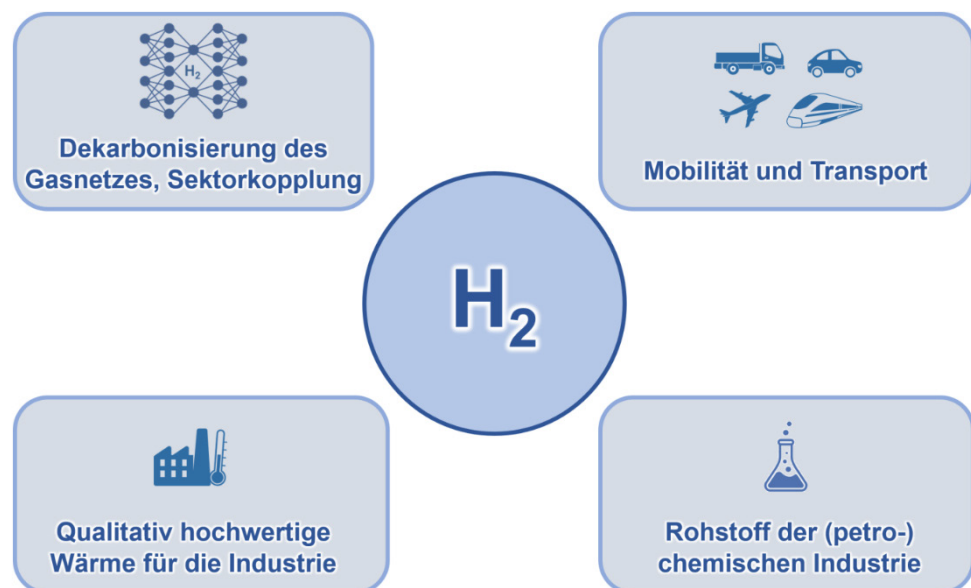
Figure 1: Zukünftige Anwendungsgebiete von Wasserstoff

Für die **Dekarbonisierung des Verkehrssektors** kann neben batterieelektrischen Antrieben zukünftig auch Wasserstoff eine zentrale Rolle einnehmen. Dort wird er in Brennstoffzellen emissionsfrei in elektrische Energie umgewandelt. Jedoch muss für eine breite Ausrollung der Wasserstoffmobilität auch eine entsprechende Tankinfrastruktur geschaffen werden, parallel zum Ausbau von Ladesäulen für die Elektromobilität.

Die stark fluktuierende Erzeugung von erneuerbarem Strom, insbesondere in Windkraft- und Photovoltaikanlagen, erfordert die azyklische Speicherung großer Strommengen über längere Zeiträume. Die **Langzeitspeicherung** kann dabei z. B. in Form von Wasserstoff oder synthetischem Methan erfolgen. Dabei wird der Strom beispielsweise in einer **Wasserelektrolyse** zur Erzeugung von Wasserstoff genutzt. Dieser kann nachfolgend mit CO_2 chemisch-katalytisch oder biologisch zu Methan umgewandelt werden ($4\,H_2 + CO_2 \leftrightarrow CH_4 + 2\,H_2O$), dass sich unbegrenzt in das Erdgasnetz einspeisen lässt. Die Kopplung des Stromnetzes mit dem Erdgasnetz wird als Sektorenkopplung bezeichnet. Die als »Power-to-Gas« benannte Kopplungstechnologie wird derzeit nur im Pilot- und Demonstrationsmaßstab untersucht. Der Bedarf an Wasserstoff als Reaktionspartner wird auch durch seine Verwendung in diversen Power-to-Liquid Prozessen deutlich ansteigen, wo beispielsweise aus CO_2 oder vergaster Biomasse und Wasserstoff, sowohl Basischemikalien als auch flüssige Kraftstoffe synthetisieren werden können.

Wasserstoff eignet sich aufgrund seines hohen spezifischen Energieinhaltes auch zur **Wärmebereitstellung** für viele industrielle Prozesse sowie die Wärmeversorgung von Gebäuden. Durch Beimischung von Wasserstoff zu Erdgas kann bei dessen thermischer Umsetzung nicht nur eine höhere Flammtemperatur erzielt, sondern auch eine deutliche Reduktion von CO- und NO_x-Emissionen erreicht werden.

In der Metallurgie dient Wasserstoff bereits jetzt als **Reduktionsmittel**, wo er unter anderem zur Herstellung feiner Metallpulver diverser Refraktärmetalle wie Wolfram und Molybdän Einsatz findet. Von mengenmäßig weitaus größerer Bedeutung wäre eine Umstellung der Eisen- und Stahlproduktion vom konventionellen Hochofenprozess auf wasserstoffbasierte Direktreduktionsverfahren. Eine solche Umstellung würde zu einer beträchtlichen Verringerung des CO_2-Fußabdruckes der Stahlindustrie, welcher derzeit in Europa bei etwa 1,9 t CO_2/t Rohstahl liegt, führen, jedoch auch einen Investitionsbedarf von rund 30 Mrd. € mit sich bringen.[23]

3.2. Produktion und Herstellung

Weltweit beträgt die **Wasserstoffproduktion** aktuell etwa 120 Mio. t/a, wovon knapp 70 Mio. t/a gezielt aus fossilen Rohstoffen gewonnen werden und die restlichen 50 Mio. t/a als Beiprodukte unterschiedlicher Industrieprozesse anfallen.[4] Innerhalb der europäischen Union beläuft sich die jährlich hergestellte Menge auf 11–12 Mio. t, davon stammen knapp 0,05 Mio. t aus Österreich.[5]

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2   Roland Berger GmbH (Hrsg.): The future of steelmaking – How the European steel industry can achieve carbon neutrality.

3   Rechberger K. et al.: Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. steel research international, 91 (2020), 2000110.

4   Statista: Produktion und Verwendungen von Wasserstoff weltweit im Jahr 2019. Internet: https://de.statista.com/statistik/daten/studie/1195241/umfrage/produktion-und-verwendung-von-wasserstoff-weltweit/ (Zugriff: 05.10.2021).

5   Statista: EU-28: production of hydrogen 2017 | Statista. Internet: https://www.statista.com/statistics/960589/production-hydrogen-european-union-eu-28/ (Zugriff: 11.10.2021).

Zu den etablierten Verfahren der Wasserstoffherstellung gehören vor allem die **Dampfreformierung** sowie die **Elektrolyse**, es existiert jedoch auch eine Vielzahl anderer Prozesse auf Basis der Fermentation, Oxidation oder Pyrolyse. Die Herstellung von Wasserstoff erfolgt derzeit global hauptsächlich **auf Basis fossiler Einsatzstoffe**: 48 % aus Erdgas, 30 % aus Erdöl und 18 % aus Kohle. Die verbleibenden 4 % werden durch Elektrolyseverfahren bereitgestellt, wobei weniger als 1 % mittels Wasserelektrolyse produziert wird.[6,7] Knapp 95 % der europäischen Wasserstoffproduktion stammt aktuell aus der Dampfreformierung bzw. autothermischen Reformierung von Erdgas.[8] In Abbildung 2 sind potentielle Wege für die Herstellung von Wasserstoff mit einem geringen CO_2-Fußabdruck dargestellt. Als Einsatzstoffe können Wasser, Biomasse oder fossile Kohlenwasserstoffe verwendet werden.
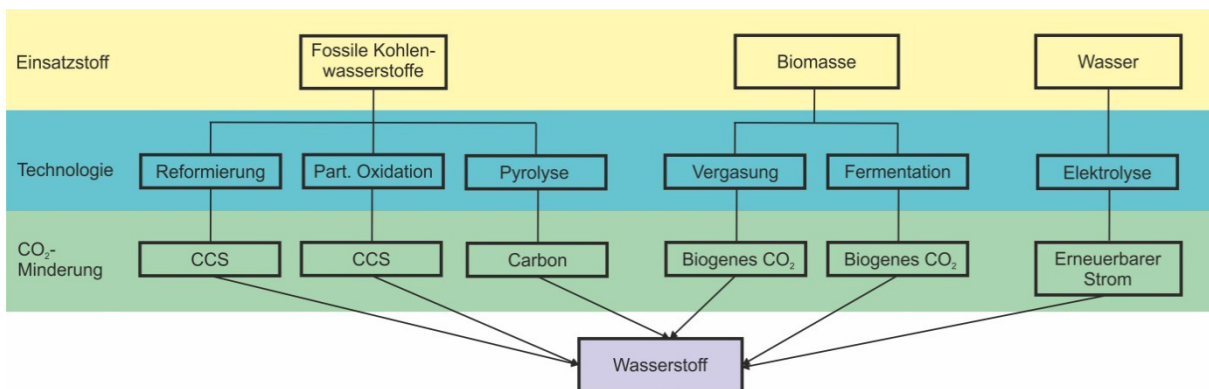
Figure 2: Einsatzstoffe, Technologien und CO_2-Minderungswege für die Produktion von Wasserstoff mit reduziertem CO_2-Fußabdruck

Die angewandten Technologien unterscheiden sich mitunter jedoch stark hinsichtlich des erforderlichen **Energieaufwandes pro Kilogramm** des produzierten Wasserstoffs, dem Ressourcenverbrauch sowie den bei der Herstellung entstehenden Emissionen. Nachfolgend erfolgt eine kurze Erläuterung der wichtigsten Verfahren zur Wasserstoffproduktion. Unter der Voraussetzung einer möglichst nachhaltigen und ressourcenschonenden Erzeugung ohne klimaschädliche CO_2-Emissionen muss dabei der Methanpyrolyse besondere Betrachtung geschenkt werden.

6   Abbas H. F. und W. Wan Daud: Hydrogen production by methane decomposition: A review. International Journal of Hydrogen Energy, 35 (2010), 1160–1190.

7   Catalan L. J. und E. Rezaei: Coupled hydrodynamic and kinetic model of liquid metal bubble reactor for hydrogen production by noncatalytic thermal decomposition of methane. International Journal of Hydrogen Energy, 45 (2020), 2486–2503.

8   Jan Cihlar: Hydrogen generation in Europe. Internet: https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1 (Zugriff: 05.10.2021).

3.2.1. Dampfreformierung

Die Dampfreformierung stellt gegenwärtig das **mengenmäßig bedeutendste Verfahren** zur Wasserstoffproduktion dar. In diesem Prozess können fossile Kohlenwasserstoffe zunächst in Synthesegas umgewandelt werden. Am Beispiel von Methan als Hauptbestandteil von Erdgas kann die Bruttoreaktionsgleichung der Dampfreformierung beschrieben werden:

$$CH_4 + H_2O \leftrightarrow CO + 3\,H_2 \qquad \Delta H_R^0 = 206,\ 3\ kJ/mol$$

Diese endotherme Gleichgewichtsreaktion benötigt eine externe Wärmezufuhr, die meist über Verbrennung von Erdgas aufgebracht wird. In einem nachfolgenden Prozessschritt wird ein Großteil des CO in der Wasserdampf-Shift Reaktion zu CO_2 ($CO + H_2O \leftrightarrow CO_2 + H_2$) umgewandelt, um die Wasserstoffausbeute zu erhöhen. Das entstehende CO_2 wird abgetrennt und in die Atmosphäre entlassen. Bei diesem Prozess werden insgesamt rund 12 $kgCO_{2,eq}/kgH_2$ emittiert.[9]

3.2.2. Wasserelektrolyse

Die Herstellung von reinem Wasserstoff mittels Elektrolyse erfolgt nach dem Prinzip der endothermen Wasserspaltung gemäß der Gleichung:

$$H_2O \leftrightarrow H_2 + \tfrac{1}{2}\,O_2 \qquad \Delta H_R^0 = 285,8\ kJ/mol$$
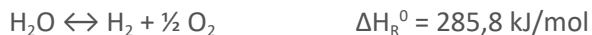
Grundsätzlich lassen sich hierbei **drei verschiedene Elektrolysetechnologien** unterscheiden: die Alkalidruckelektrolyse (AEL), die Polymermembranelektrolyt-Elektrolyse (Proton Exchange Membrane Electrolysis – PEM Electrolysis) sowie die Hochtemperaturelektrolyse (Solid Oxid Electrolyzer Cell – SOEC). Zwischen den einzelnen Technologien existieren jedoch noch **gravierende Unterschiede** hinsichtlich **des technischen Reifegrades, des Bedarfs an Edelmetallen, der Investitionskosten sowie des Wirkungsgrades** und des damit verbundenen spezifischen Energiebedarfs. Dieser liegt richtungsweisend für die AEL bei 50–51 kWh_{el}/kgH_2 und für die PEM bei 3155–58 kWh_{el}/kgH_2. Hochtemperaturelektrolyseure, welche zurzeit jedoch nur im Labormaßstab betrieben werden, weisen hingegen einen spezifischen Energiebedarf von 40–41 kWh_{el}/kgH_2 auf (ohne Berücksichtigung der benötigten thermischen Energie).[10] Das für die Elektrolyse benötigte Wasser muss in mehreren Aufbereitungsschritten gereinigt und demineralisiert werden, was zu einem Wasserverbrauch von etwa 12,5–15 l/kgH_2 führt.[11] Ein weiterer wesentlicher Faktor bei der großindustriellen Implementierung von Wasserelektrolyse ist der hohe Bedarf an Edelmetallen (insbesondere Iridium), welche als Katalysatoren der in der PEM-Elektrolyse verwendeten Elektroden eingesetzt werden. Bei einem durchschnittlichen Bedarf an Iridium von derzeit etwa 700 kg/GW würden bei

9   Cetinkaya E., I. Dincer und G. F. Naterer: Life cycle assessment of various hydrogen production methods. International Journal of Hydrogen Energy, 37 (2012), 2071–2080.

10 Kakoulaki G. et al.: Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conversion and Management, 228 (2021), 113649.

11 David Lampert et al.: Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels (2015).

der Umsetzung der europäischen Wasserstoffstrategie (2x40 GW Elektrolysekapazität für erneuerbaren Wasserstoff bis 2030[12]) fast die gesamte globale Produktionsmenge an Iridium benötigt werden.[13] Die Entwicklung eines effizienten Recyclingkonzeptes für Iridiumkatalysatoren, besseres Edelmetallmanagement sowie intensive Forschungen im Bereich der Materialentwicklung zur Senkung des Iridiumbedarfs sind gegenwärtig Gegenstand intensiver Forschungen.

Bei der Herstellung von Wasserstoff mittels Elektrolyse ist die **Verwendung von erneuerbarem Strom** im Hinblick auf das Ziel eines Produktes mit CO_2-reduzierten Fußabdruckes zwingend notwendig. Der Emissionsfaktor des im österreichischen Netz verwendeten Strommix liegt derzeit im Jahresmittel etwa bei 310 $kgCO_{2,eq}/MWh_{el}$.[14] [14] Daraus resultiert für elektrolytisch generierten Wasserstoff bei einem durchschnittlichen Energiebedarf von etwa 50 kWh_{el}/kgH_2 ein CO_2-Fußabdruck von etwa 1–5 kg $CO_{2,eq}/kgH_2$. Die Produktion **großer Mengen an grünem Wasserstoff** mittels Elektrolyse ist derzeit durch die **fehlende Erzeugungskapazität** von erneuerbarem Strom mit geringem CO_2-Fußabdruckes **limitiert**.

3.2.3. Methanpyrolyse

Die thermische Zersetzung von Methan (bzw. Methanpyrolyse oder thermisches Cracken von Methan) beschreibt die endotherme Aufspaltung von CH_4 in seine molekularen Bestandteile gasförmigen Wasserstoff und festen Kohlenstoff. Bei dieser chemischen Reaktion kommt es im Gegensatz zur Dampfreformierung zu keinen Emissionen von umweltschädlichen Treibhausgasen. Die Bruttoreaktionsgleichung der Pyrolysereaktion lautet:

$$CH_4 \leftrightarrow 2H_2 + C \qquad \Delta H_R^0 = 74,8 \text{ kJ/mol}$$

Diese endotherme Zersetzungsreaktion läuft für gewöhnlich in einem Temperaturbereich von 800–1200 °C ab, wobei Katalysatoren einen erheblichen Einfluss auf die Reaktionstemperatur, Zersetzungsrate und Morphologie des **entstehenden festen Kohlenstoffs** ausüben können. Im energetischen Vergleich mit der Wasserelektrolyse weist über den Pyrolyseprozess hergestellter Wasserstoff einen deutlich geringeren spezifischen Energiebedarf, etwa 13 kWh/kgH_2, auf.

Für die Methanpyrolyse existiert eine **Reihe unterschiedlicher Verfahren**. Prinzipiell lässt sich zwischen **katalytischen und nichtkatalytischen Prozessen** und in weiterer Folge zwischen **schmelzflüssiger, Feststoff- und Plasmapyrolyse** unterscheiden. Als Katalysatoren fungieren diverse feste Metalle und Oxide, Graphit oder flüssige Me-

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12 Dr. Christian Gebauer: Technikforum Wasserstoff.

13 Heraeus (Hrsg.): Meilenstein für Grünen Wasserstoff: Heraeus bringt neuen Elektrokatalysator auf den Markt. Internet: https://www.heraeus.com/de/hpm/hpm_news/2020_hpm_news/09_milestone_for_green_hydrogen.html (Zugriff: 05.10.2021).

14 https://www.energyagency.at/fileadmin/dam/pdf/projekte/klimapolitik/3_SEAP-Vorlage-Technischer-Anhang.pdf.

tallschmelzen. Während feste Katalysatoren durch Ab- und Adsorption von Reaktions-produkten mit fortschreitender Einsatzdauer an Effektivität verlieren können, tritt dies bei Verwendung schmelzflüssiger Metalle und Legierungen nicht auf, sofern sich keine Reaktionsprodukte mit Kohlenstoff bilden. Der Einsatz von Flüssigmetallen bietet zu-sätzlich den Vorteil einer potentiellen Absenkung der erforderlichen Reaktionstempe-ratur durch gezieltes Legierungsdesign. Durch die Kombination von katalytisch agieren-den Metallen wie Nickel mit niedrigschmelzenden Komponenten wie Zinn oder Bismut lassen sich aktive Katalysatorlegierungen mit moderaten Schmelzpunkten realisieren, deren Entwicklung Gegenstand zahlreicher Forschungsbemühungen ist.

Wie aus der Reaktionsgleichung ersichtlich, entsteht bei der Methanpyrolyse neben gasförmigem Wasserstoff auch fester Kohlenstoff. Dieser kann je nach vorliegender Modifikation (Grafit, Graphen, Ruß, Kohlenstoffröhrchen, turbostratischer Kohlen-stoff, …) und Reinheit unterschiedlichen Verwendungen zugeführt werden. Kohlenstoff aus der Pyrolyse stellt somit aus ökonomischer und ökologischer Sicht ein wertvolles zweites Produkt dar. Potentielle Anwendungsgebiete umfassen:

- den Einsatz als Rohstoff in der Asphalt- und Feuerfestindustrie

- diverse Gummi- und Aktivkohleprodukten

- Additiv in Schmiermitteln, Gießpulvern oder Anodenmaterial für die Metallur-gische Industrie im Bereich der Stahl- und Aluminiumerzeugung.

- Einsatz als Bodenhilfsstoff in der Landwirtschaft

Pyrolysekohlenstoffe hoher Reinheit können durch entsprechende Nachbehandlungs-schritte auch für qualitativ anspruchsvollere Anwendungen wie beispielsweise als Elek-trodenmaterial in Batterien oder in der Elektronik Einsatz finden. In wissenschaftlichen Studien konnte bereits eine Korrelation der auftretenden Kohlenstoffmorphologie und des Pyrolyseprozesses bzw. dem verwendeten Katalysatormaterial festgestellt werden. Dadurch besteht die Möglichkeit einer gezielten Einstellung der Qualität des produ-zierten Kohlenstoffs hinsichtlich seiner Modifikation und Korngröße im Hinblick auf an-wendungsspezifischen technischen Anforderungen. Aus ökonomischer Sicht muss für die Realisierung einer großtechnischen Wasserstoffversorgung mittels Pyrolyse jedoch auch ein entsprechender Absatzmarkt für den produzierten Kohlenstoff erschlossen werden, da je Kilogramm an produziertem Wasserstoff drei Kilogramm fester Kohlen-stoff erzeugt werden.

4. Zusammenfassung der Ergebnisse

Basierend auf der Aufgabenbeschreibung in Kapitel 1 »Hintergrund zum Projekt« und den spezifischen Arbeitspaketbeschreibungen im Projektantrag »Technical Work Package Reports« erfolgte die Aufteilung in die drei Arbeitspakete, wobei speziell die volkswirtschaftlichen Konsequenzen nicht nur auf die Verwendung des Kohlenstoffs abzielen, sondern auch den produzierten Wasserstoff miteinbeziehen, da die Entscheidung zwischen Methanpyrolyse und Stromelektrolyse auch einen Einfluss auf die Stromerzeugung und den Stromverbrauch in den energieintensiven Industrien hat.

Die **Ausgangssituation in Österreich** setzt sich für das Projekt folgendermaßen zusammen:

- Die heimische Industrie kann aufgrund der inländisch nicht annähernd ausreichend verfügbaren grünen Energiequellen keine großflächige Umstellung auf nachhaltige Energiequellen vollziehen, daher der Bedarf an weiteren, beständigen CO_2 neutralen Energiequellen.

- Österreich ist vom weltweiten Gaspreis, sowie der geo-politischen Stabilität hinsichtlich der Gaslieferungen in einer starken Abhängigkeit.

- Die Mengen des zu produzierenden Wasserstoffs bergen ob der 3-fach so großen Menge des »Nebenproduktes« Kohlenstoff eine enorme Herausforderung der sinnvollen Anwendung dessen.

Einerseits gilt es den im Zuge der Methanpyrolyse anfallenden festen Kohlenstoff sinnvoll in Verwendung zu bringen und die aus der Produktion verfügbaren Wasserstoff und Kohlenstoff zustande kommenden wirtschaftlichen Veränderungen zu beleuchten. Zur Verwendung des festen Kohlenstoffes sei hier angemerkt, dass eine Anwendung in der Landwirtschaft nach hier vorliegenden Ergebnissen, am verfolgungswürdigsten wirkt. Die Einbringung des Kohlenstoffes im Bausektor ist dafür noch zu wenig beforscht – auch auf globaler Ebene gibt es kaum Ergebnisse. Die volkswirtschaftlichen Änderungen durch Einbringung von Wasserstoff und Kohlenstoff aus Methangas in die österreichische Industrie- bzw Energielandschaft sind abhängig von den Entwicklungen von Gaspreisen, Energieverbräuchen, Gewinne/Verluste durch Kohlenstoffverkauf/-entsorgung mit vielen Annahmen behaftet, es kann aber eine Einschätzung von drei Pfaden vorgenommen werden.

Wohin kann die Reise gehen?

Dies Frage kann hier nur ansatzweise beantwortet werden, da viele Aspekte von **externen Ereignissen abhängig** und auch durch **politische Maßnahmen** entscheidend gelenkt werden können. Methanpyrolyse kann damit ein Beitrag zur klimaneutralen Industrie und Gesellschaft sein.

Wo bedarf es noch intensiverer Forschung?

Beide Anwendungsbereiche des Kohlenstoffs – Landwirtschaft und Bausektor – weisen klare Forschungslücken in unterschiedlichem Maße aus, wobei in der Landwirtschaft bereits Bio-Kohlenstoff durch viele Vorstudien verfügbar sind. Hier gilt es primär abzuklären, ob der Kohlenstoff aus der Methanpyrolyse gleiche oder sehr ähnliche Eigenschaften aufweist und ob durch das Ausbringen von Pyrolyse-Kohlenstoff (Methanpyrolyse-basierter Kohlenstoff auch pyo-char oder Pyrolyse-Kohlenstoff genannt) die Aufnahme von CO_2 aus der Atmosphäre beeinträchtigt wird. Im Bausektor gibt es weitaus weniger Studienergebnisse, um ein schlüssiges Bild zeichnen zu können. Daher wäre eine Vertiefung der Forschung in diesen beiden Bereichen wünschenswert. Besonders hervorzuheben wäre auch die Notwendigkeit der erweiterten Beforschung der Lebenszyklus-Effekte von Wasserstoff, um nicht nur im Bereich der Methanpyrolyse sondern ganz allgemein die Wasserstoffrouten zu vergleichen und auf die gesamtwirtschaftlichen Komponente hin zu prüfen.

Welchen Mehrwert hat dieses Projekt und dessen Ergebnisse für das Bundesministerium für Klimaschutz?

Dieses Projekt bzw. die vorliegenden Erkenntnisse sollen für das BMK als eine weitere Grundlage für zukunftsweisende Entscheidungen dienen, um Österreich zeitnah und anwendungsorientiert in eine CO_2 neutrale Zukunft zu führen. Alle involvierten Wissenschafter_innen und Expert_innen stehen für weiterführende Gespräche gerne zur Verfügung. Auch das CCCA in seiner Rolle als Plattform der Klimaforschung in Österreich steht jederzeit für die Vermittlung von weiteren Forschenden zur Verfügung und informiert auch über bekannte und ergänzende Projekte aus der Forschungsgemeinschaft.

4.1.   Erkenntnisse »Kohlenstoff in der Landwirtschaft«

Eine vielversprechende Möglichkeit ist die Anwendung von Pyrolysekohlenstoff auf Böden. Diese Überlegung speist sich aus der Anwendung von Bio-/Pflanzenkohle, die sehr positive Effekte auf den Boden hat und zudem Kohlenstoff in Böden bindet, anstatt in die Atmosphäre zu entlassen, d.h. ein negatives Emissionspotential besitzt. In der vorliegenden Arbeit wurde angenommen, dass Pyrolysekohlenstoff mit Biokohle-ähnlichen Eigenschaften hergestellt werden kann.

Pyrolysekohlenstoff wird von Mikroorganismen nicht als Kohlenstoff wahrgenommen und führt im Gegensatz zu Rohkohle nicht zur Reduktion des Nährstoffgehalts im Boden. Stattdessen gibt es einen positiven Einfluss auf die Bodenerträge, da das Wasserhaltevermögen des Bodens erhöht wird. Dabei müssen etwaige Umweltrisiken und Bodenkontamination durch das Ausbringen von Pyrolysekohlenstoffarten (abhängig von den jeweiligen Pyrolyseverfahren) vermieden werden.

In Feldexperimenten wurde gezeigt, dass Biokohleanwendung in gemäßigten Böden ein enormes Treibhausgaseinsparpotenzial besitzt, wobei vor allem Lachgas als bedeutendstes Treibhausgas in der Landwirtschaft vermieden werden kann. Zukünftige Forschung wird vertiefende Erkenntnisse über das Potenzial von Pyrolysekohlenstoff in der Bodenanwendung erzielen, die insbesondere in Europa von großem strategischem Nutzen sein kann.

Literaturübersicht: Zusammenfassung von beobachteten und potentiell erwartbaren Effekten von Nanokohlenstoff (auf Basis von Beobachtungen bei Biokohleanwendung) auf physikalische, chemische und biologische Bodeneigenschaften:

Physikalische Bodeneigenschaften:

- Erhöhtes Wasserhaltevermögen
- Mechanische Bodenstabilisierung und verminderte Erosionsgefahr
- Potenzielle Erhöhung der Aggregatbildung

Chemische Bodeneigenschaften:

- Erhöhung des pH-Werts des Bodens (Kalkungseffekt)
- Immobilisierung organischer und anorganischer Bodenverunreinigungen
- Verringerung der Nährstoffverluste (insbesondere Stickstoff)
- Potenzielle Erhöhung der (langfristigen) Kohlenstoffspeicherung in den Böden

Biologische Bodeneigenschaften:

- Veränderungen der mikrobiellen Gemeinschaften im Boden
- Veränderte mikrobielle Funktionalität, z. B. im Nährstoffkreislauf
- Abnahme der Enzymaktivitäten

Zusätzliche direkte Effekte auf Pflanzen:

- Erhöhte Samenkeimung
- Erhöhte Wurzellänge, Wurzelbiomasse, Anzahl der Wurzelspitzen
- Erhöhtes Triebwachstum und Ernteertrag
- Reduzierter Salz- und Trockenheitsstress
- Phytotoxizität bei hohen Konzentrationen
- Veränderungen der Wurzelstruktur und Rückgang des Wurzelwachstums

Es wurden Möglichkeiten der Modifizierung von Pyrolysekohlestoff identifiziert, zur Unterstützung positiver sowie Vermeidung negativer Auswirkungen. Wie Biokohle, könnte Pyrolysekohle mit organischen Reststoffen kombiniert, oder als Beschichtungsmaterial verwendet werden, um eine kontrollierte Nährstoffabgabe in den Boden zu erreichen.

Treibhausgaseinsparpotentiale

a.) Verringerung der CO_2-Emissionen durch mittel- oder langfristige Speicherung von Kohlenstoff in Böden

Die Umstellung der Verwendung von Erdgas auf türkisen Wasserstoff in Österreich würde pro Jahr 4,5 Millionen Tonnen Kohlenstoff erzeugen, die unter Annahme einer Anwendungsrate von 60t/ha 72.000 ha Landfläche benötigen würde, was ca. 5 % der landwirtschaftlichen Fläche Österreichs entspricht.

b.) geringere THG-Emissionen (insbesondere N_2O)

Ein großer Teil des über NPK-Dünger (NPK: Stockstoff-Phosphor-Kalium) zugeführten Stickstoffs geht als Distickstoffoxid (N_2O) verloren, einem starken Treibhausgas. Biokohle kann diese Emissionen um bis zu 50 % reduzieren (Durchschnitt: 38 % - ein ähnlicher Effekt ist auch für Pyrolysekohle erwartbar). Dadurch können bis zu 40.000 Tonnen CO_2-Äquivalente eingespart werden.

Fazit

Pyrolysekohlenstoff ist ein potenzielles Substitut für Biokohle, da die potenziellen Produktionsmengen weitaus größer sind. Es ist notwendig, dass die langfristigen Folgen von Pyrolysekohlezusatz auf das Ökosystem besser verstanden werden, was sich nur durch mittel- bis langfristige Feldexperimente ermitteln lässt.

4.2. Erkenntnisse »Kohlenstoff im Bausektor«

Eine denkbare Möglichkeit ist die Verwendung von Pyrolysekohlenstoff im Bausektor, als Substitut für CO_2-intensive Baumaterialien wie Stahl oder Beton. Dieser Bericht untersucht mögliche Anwendungsoptionen in einer systematischen Literaturanalyse, mit Expertenbefragungen und einer Lebenszyklusanalyse.

Systematische Literaturanalyse

Im Zuge des Literaturreviews wurden 29 Artikel ausgewertet und dabei unterschiedliche Anwendungsmöglichkeiten von Pyrolysekohlenstoff identifiziert. Erstens als **Füllstoff in Beton und Zement**, zweitens als **Mauersteine**, bei denen Kohle anstelle von Sand verwendet wird und drittens als **Wärmedämmungsmaterial**. Dabei wurden unterschiedliche Vor- und Nachteile, Technologiegrade und mögliche Anteile der Kohlenstoffverwendung identifiziert.

Expert_innen- und Industriebefragungen

Um Anwendungsmöglichkeiten in der Praxis zu erforschen, wurde Kontakt mit Experten und Industrievertretern auf dem Gebiet aufgenommen. Dabei wurde erstens die Möglichkeit der Nutzung von festem Kohlenstoff weiterverfolgt, und zweitens die Verarbeitung von Kohlenstofffasern als Baumaterialien untersucht, wobei festgestellt wurde, dass noch **keine Technologie existiert, mit der Pyrolysekohlenstoff zu Kohlenstofffasern** weiterverarbeitet werden kann.

Lebenszyklusanalyse

Erstens wurden die CO_2 Einsparmöglichkeiten von Pyrolysekohlenstoff als Ersatz für Füllstoff in Beton und Zement, in Mauersteinen und als Wärmedämmungsmaterial untersucht, unter der Annahme, dass keine Emissionen durch den festen Kohlenstoff zustande kommen und Emissionen durch die zu ersetzenden Materialien eingespart werden können. Dabei wurde insgesamt festgestellt, dass die Einbindung von festem Kohlenstoff in Baumaterialien offenbar nur einen **begrenzten Einfluss auf deren Treibhausgasemissionen** hat.
Zweitens wurde die hypothetische Möglichkeit der Verwendung von Kohlenstofffasern als Substitut für Stahl untersucht, auch wenn anerkannt wurde, dass bis dato eine Technologielücke bei der Verarbeitung von Pyrolyse-Kohlenstoffpulver zu Kohlenstofffasern besteht. Auch wenn bei der Berechnung viele unbekannte Variablen blieben, wurde bei dieser Möglichkeit ein höheres CO_2 Einsparpotential festgestellt.

Fazit

Für den mengenmäßig brauchbaren Einsatz von Pyrolysekohlenstoff im Bausektor gibt es aktuell noch zu wenige Literatur- und Machbarkeitsstudien, um hier langfristige Aussagen zu treffen. Dennoch gibt es eine Vielzahl von Möglichkeiten, wobei ein Einsatz von Kohlefasern wesentlich erfolgreicher scheint. Eine Methode zur »Umwandlung« von festem, pulvrigem Kohlenstoff zu Kohlenstofffasern ist aktuell nicht in Umsetzung.

4.3. Erkenntnisse »Volkswirtschaftliche Rückwirkungen«

Die volkswirtschaftliche Perspektive stellt eingangs die Zweckfrage. Ein bedeutender Beitrag zur Entwicklung einer klimaneutralen Struktur der österreichischen Volkswirtschaft kann über **Wasserstoff-basierte Anwendungen in der Industrie und im Güterverkehr** gelingen. Da Wasserstoff durch verschiedene Verfahren hergestellt werden kann, darunter fallen die Methanpyrolyse und Stromelektrolyse, ergeben sich relativ zueinander unterschiedliche volkswirtschaftliche Rückwirkungen. Der vorliegende Szenarienansatz bezieht explizit die Anwendung von festem Kohlenstoff im landwirtschaftlichen Bereich und im Bausektor ein.

Aufbau der Szenarien

Für die Szenarien werden zuerst **Schätzungen für Wasserstoffbedarf- und Produktion**, sowie der **Verwendung von festem Kohlenstoff** zusammengefasst und vorgestellt. Dabei wird ein Hauptszenario entwickelt, bei dem dieser zusätzliche Wasserstoffbedarf im Jahr 2030 mittels Elektrolysewasserstoff abgedeckt wird. Dieses Hauptszenario wird verglichen mit der alternativen Herstellung durch das Pyrolyseverfahren. Zusätzlich werden ein **unteres- und ein oberes Grenzszenario** entwickelt mit jeweils optimistischen- und pessimistischen Annahmen bezüglich Ertrag und Verlust von festem Kohlenstoff, Erdgas- und Strompreisen, sowie Zinsraten für Investitionen.

Daten und Rahmenbedingungen

Für das Jahr 2030 wird ein Anstieg im Wasserstoffbedarf angenommen, vor allem aufgrund von Anwendungen in der Eisenproduktion, sowie im Güterverkehr. Andere mögliche Bedarfe werden zunächst ausgeklammert. Darauf aufbauend wird ein steigender **Bedarf an Wasserstoff von 178.000 Tonnen für das Jahr 2030 in Österreich** geschätzt.

Bei der Wasserstoffproduktion liegen im Hauptszenario sowohl bei der Pyrolyse als auch bei der **Elektrolyse Stückkosten von 3 Euro pro Tonne** vor. Es wird angenommen, dass bei der Pyrolyse keine CO_2-Emissionen freigesetzt werden, sondern pro Kg Wasserstoff 3 Kg fester Kohlenstoff als Nebenprodukt produziert wird, der 38 €/Tonne einbringt. Da die Nutzung und Nachfrage des festen Kohlenstoffs schwer abschätzbar ist, wurde der optimistische Schätzwert von 198 €/Tonne und Entsorgungskosten von 5 €/Tonne für die jeweils oberen und unteren Grenzszenarien festgelegt. In einer Sensitivitätsanalyse für die unterschiedlichen Szenarien wurde ein Stückkostendifferential zwischen -39 % und +32 % zwischen Pyrolyse- und Elektrolyseverfahren errechnet.

Bei der zusätzlichen jährlichen Produktion von 178.000 Tonnen Wasserstoff würden **534.000 Tonnen fester Kohlenstoff anfallen**. Auch wenn Anwendungsmöglichkeiten in der Landwirtschaft und bei Baumaterialien noch mit Unsicherheiten belegt sind, wird auf Basis der Erkenntnisse der ersten beiden Arbeitspakete angenommen, dass damit 18 % der Zement- und Ziegelsteinproduktion mit festem Kohlenstoff angereichert werden kann, oder 7 % der landwirtschaftlichen Fläche (über einen Zeitraum von 25 Jahren). Die ökonomischen Effekte hängen jeweils vom angenommenen Preis für den festen Kohlenstoff als auch den Preisdifferentialen von Erdgas und Strom ab.

Ergebnisse der makroökonomischen Analyse

Für die makroökonomischen Analyse der unterschiedlichen Szenarien in der Wasserstoffherstellung und Pyo-Kohlenstoffnutzung wurde das **WEGDYN-AT Modell** benutzt. Im Hauptszenario wurde eine Preissteigerung von 2,6 % ausgemacht für Pyrolyseherstellung anstelle von Elektrolyseherstellung (0,9 % bei Einbeziehung indirekter Effekte). Allerdings hat das Pyrolyseverfahren bei Hinzunahme des zusätzlichen Werts des festen Kohlenstoffs einen Preisvorteil von 2,6 % (4,2 % bei Einbeziehung einer CO2-Bepreisung auf europäischer und nationaler Ebene als allgemein zugrundeliegende Rahmenbedingung). Aufgrund der hohen Unsicherheiten bei den Eingangsparametern der Stückkostenschätzungen (Erdgas- und Strompreise, Kohlenstoff-Bewertung bzw. etwaige -Entsorgungskosten), werden diesem Hauptszenario zwei weitere Sensitivitätsszenarien beigestellt. Im oberen (unteren) Grenzszenario wurde eine Preissteigerung bei Anwendung des Pyrolyseverfahrens von +38% (-27 %) im Vergleich zum Elektrolyseverfahren berechnet. Der wesentliche Treiber dieser hohen Bandbreite ist das zugrundeliegende Energiepreisdifferential. Auf makroökonomischer Ebene sind die Auswirkungen auf das Bruttoinlandsprodukt (BIP) im Jahr 2030 sehr gering, spiegeln aber die Produktivitätsveränderungen wider, mit positiven Auswirkungen im Hauptszenario bzw. im unteren Szenario, und negativen Auswirkungen im oberen Szenario.

Zusammenfassung und Diskussion

Die Pyrolyse benötigt pro Tonne Wasserstoff deutlich weniger Strom als die Elektrolyse, was im breiteren Kontext der Energiewende mit begrenzten (inländischen) Potenzialen für erneuerbare Energien von Bedeutung sein könnte. Die Pyrolyse verringert auch den zusätzlichen Kapitalbedarf, da bestehende Erdgasnetze und -infrastrukturen genutzt werden können. Elektrolyse ist angesichts des derzeitigen Finanzierungsumfelds mit niedrigen Finanzierungskosten (ausgedrückt in gewichteten durchschnittlichen Kapitalkosten) relativ attraktiver. Die Wettbewerbsfähigkeit von Pyrolyse im Vergleich zur Elektrolyse hängt wesentlich von der Erdgaspreisentwicklung und den damit verbundenen (geo-)politischen Rahmenbedingungen ab.

Der Mehrwert der Nutzung von festem Kohlenstoff im Agrar- und Bausektor kann noch nicht eingeschätzt werden und erfordert weitere grundlegende Forschungsanstrengungen, um die (bio-)physikalischen und wirtschaftlichen Implikationen sowie die erforderlichen Rahmenbedingungen einzugrenzen, damit sich die Potenziale entfalten können, die sich im Vergleich zu einem ausschließlich auf Elektrolyse basierenden Weg der Wasserstoffversorgung deutlich unterscheiden. Für die Entscheidung zwischen elektrolyse- und pyrolysebasierten Entwicklungspfaden ist daher – neben der Marktbewertung der Erdgaspreisentwicklung – eine zusätzliche und dedizierte Marktanalyse für die Kohlenstoffnutzung relevant. Zudem ist der Einsatz als Brückentechnologie aufgrund der Lebensdauer der Anlagen nur dann aus umwelpolititscher Sicht vertretbar, wenn der als Nebenprodukt entstehende Kohlenstoff dauerhaft gebunden bleibt und in dieser Bindung das Senkenpotential aus anderen Verfahren nicht verringert.

5. WPI »Kohlenstoff in der Landwirtschaft« Observed and potential effects of pyo-char on soil quality and greenhouse gas emissions

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Introduction and Background:

Pyo-char refers to (nano)-carbon/ carbon black derived from the thermocatalytic decomposition of methane (TCD). TCD yields a range of pyo-char products, depending on reaction parameters and catalysts. Like other (nano-)carbon materials, pyo-char could be applied to soil for improving soil quality indicators.

Achieving net zero through mitigation can only be achieved by switching from fossil fuels and introducing negative emission technologies (NET's), i.e. technologies that effectively and sustainably remove atmospheric CO_2 (IPCC, 2007).

Renewable energy addresses electrical demands, but thermal energy, makes up half of the total energy demand in Europe and is currently dominated (>66 %) by fossil fuel supply (Eurostat database). Substituting natural gas for green hydrogen in the gas thermal heating infrastructure is a transitional technology that could contribute to achieving the Austrian net zero goal by 2050. It has been suggested that of 10 % of methane could be substituted with hydrogen with no significant changes to the current infrastructure.

Production of hydrogen is traditionally through steam methane reformation and is extensively used in the fertilizer industry, and responsible for around 2 % of the global GHG budget with production of around 60 million t H_2 per year. SMR produces 10 t of CO_2eq for every metric ton of hydrogen produced and is commonly referred to as grey hydrogen. It is also possible to use coal or oil as the hydrocarbon source material for the hydrogen production process and this hydrogen is then referred to as brown hydrogen and has twice the CO_2 footprint. Green hydrogen is produced through the splitting of water through electrolysis but the required energy or electricity demand for the process is currently 40,000–53,000 kWh per t of hydrogen produced, making non-viable in the majority of contexts. However, if the electricity is produced through

renewable energy this is a CO_2eq free process, but the critics suggest the direct use of the renewable energy would be a more efficient route. Another green/blue technology (increasingly referred to as turquoise hydrogen), is methane pyrolysis, it is the conversion of methane into gaseous hydrogen and solid carbon in the absence of oxygen or water. Currently to crack methane, temperatures in excess of 800 °C are required but catalysts are being developed to effectively lower these temperatures. Evidently these systems are not carbon neutral but have lower carbon footprints compared to for SMR, at 2.5 t of CO_2eq per tonne H_2, this compared to 2.75 t of CO_2eq for every tonne of methane combusted. This is a promising technology and focus of this study (Parkinson et al., 2018).

Although a number of previous attempts at commercialization of the methane pyrolysis process have failed, given the new global and political pressures in the light of climate change these processes are being reexplored as they offer the opportunity for rapid and relatively friction free transition to near zero energy production for the energy providers. It should be stressed that the success or failure of an energy technology is dependent on the market price of the input products in addition to the value of the goods and services produced, and imbedded costs of the pollution produced. Whilst the costs of inputs, goods and services are generally driven by consumer demand, costs of pollution are rarely accounted for and if so, are usually imposed by the state. There is increasing pressure on governments around the world to impose a carbon tax as the impacts of climate change are becoming more evident. These changes in future carbon pricing will directly affect the commercial viability of methane pyrolysis and drive the development and innovation of this promising technology.

Methane pyrolysis is a nascent technology on the very low end of the innovation curve, possibly equivalent to solar in the 70's. In the light of the potential gains for the energy industry, combined with the availability of multinational venture capital for establishment of the production infrastructure and funds to fuel the research and development, it is clearly a technology that requires thorough investigation. Its unique competitive advantage, linked with the potential economies of scale and global reach, render it a research priority, conceivably a moon-shot priority. As such the challenges of methane pyrolysis, should not be underestimated, these include management of the solid carbon, which can foul the metal or metal oxide catalysts, the high temperatures required and the appropriate reactor designs. Advocates claim that these technical barriers could be overcome by process innovation and improvements in reactor design (Holladay et al., 2009). One of the major issues is the management of the solid carbon produced. Although there has been substantial interest from the carbon centric perspective, using methane pyrolysis exclusively for the production of high value carbon products such as Nano-carbon fibres and graphitic tubes, etc. global methane pyrolysis would quickly saturate these markets but could provide early adopter pyrolysis industries valuable primary income streams. It is estimated the combined global market for carbon products, including graphene, graphite, carbon black and coke is one Mt per year with product prices ranging from less than 100 USD to over billion USD per tonne (Pindyck, 2016). Clearly if methane pyrolysis is to have any global impact on carbon emissions, large scale production would be required and the storage and use of the resultant pyrolysis derived carbon a pertinent issue.

The application of the pyrolysis derived carbon to soil, is one option of many that is being explored, others including substitution of coking coal, use for production of

carbon black and use in construction, however the potential production of pyrolysis carbon would quickly outstrip markets. The impetus for the soil amendment line of enquiry, has been the observation of the positive benefits of adding an analogous product biochar to soil. Biochar is produced through the pyrolysis of solid organic matter yielding both energy and a product that is added to soil where it has been to persist in the soil for centuries to millennia with little few known negative impacts on yields or the environment. The term biochar infers that the product is added to soil for long term carbon sequestration, herein we will use the term pyochar to describe methane pyrolysis derived carbon that is intended for soil application. The notion is that pyochar will have many of the characteristics and soil benefits that biochar has and therefore a comprehensive comparative analysis has been undertaken.

Estimates have suggested that both soil carbon sequestration and addition of black carbon in the form of biochar (BC) to soil have significant negative emission potential (each 0.7 GtCeq. yr^{-1}, (Smith, 2016) with little impact on land, water use, nutrients, albedo, energy requirement and cost. Pyochar was not included in these estimates at the time. However even if only SMR technologies were substituted with methane pyrolysis, an additional 0.15 Gt per year of solid carbon would be produced and could possibly be sequestered into soils. To put this into perspective global cement production is 1.5 Gt per year. Soil-based approaches are socially acceptable solutions and easily implementable, so have fewer hidden costs than many other NETs. In Norway, for example, biochar application has been evaluated as the technology with the largest potential for increasing soil C storage (Klimakur, 2010-Norway). Although in this analysis we assume that pyochar would have similar manufactured structure and properties to biochar. We acknowledge that there would be considerable differences in the structure of the pyochar but would endeavour to create a comparable product and to draw on knowledge gained from biochar research to give us an early adopter advantage in the field.

There is an increasing interest in the manupulation of the carbon cycle for sequestration of carbon in agriculture as evident from the COP 4 per mille strategy, large EU projects such as EJP SOIL etc. Carbon sequestration in agriculture has additional benefits for the farmer, such as improved water and nutrient retention. Carbon is in all living things is constantly cycled from the atmosphere to the soil through photosynthesis. Usually carbon enters the soil in the form of dead plant material which is a mixture of sugars, celluloses, hemicelluloses and lignins. These raw carbon forms are degraded in the soil at different rates by the soil microbial biomass the fungi and bacteria living in the soil.

Respiration, root exudates	Particulate organic carbon Fresh residues, living organisms	Soil organic carbon 'Resistant' residues, physically protected	Persistant organic carbon. Protected SOC. Charcoal/biochar
Rapid turnover pool (RTP) <1y	Labile (POC) SOM 1-5 y	Slow (HOC) SOM 20-40 y	Stable (ROC) SOM 500-1000 y
60-80% loss in year 1		10- 40% remains	
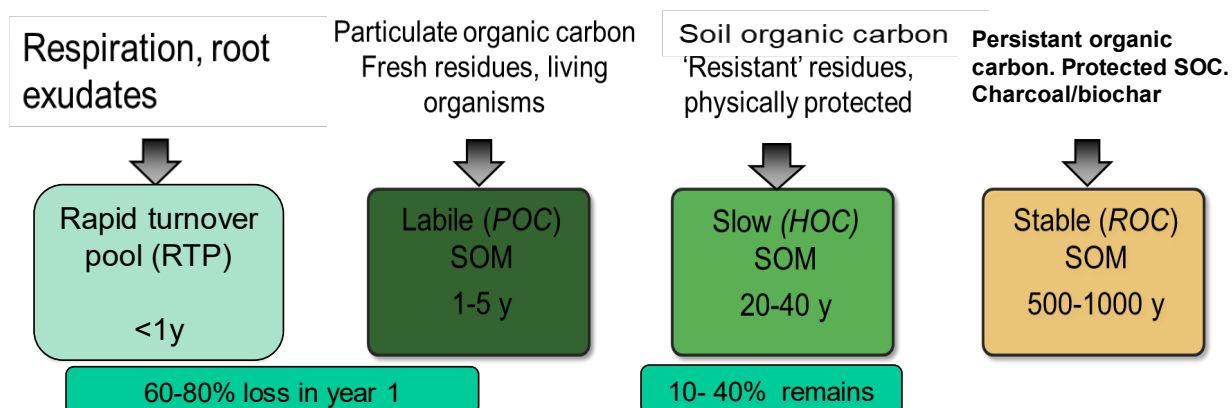
Figure 3: Carbon sequestration in agriculture

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Most raw carbon is decomposed and lost as CO_2 within the first year of addition, moreover initial addition of carbon to the soil usually coincides with a reduction in available nutrients, specifically nitrogen, which is the main plant nutrient. This reduction in available nutrients leads to significant plant-crop yield reductions, this is precisely the reason why we cannot just add raw carbon to soils for C sequestration. However, if we add pyrolysed carbon in the form or biochar or pyochar to the soil, this reduction in the availability of nutrients is much less and so we see no very little or reduction in yield, as it hypothesized that the soil microorganisms do not recognize it as available carbon. In fact, we often see positive effects on crop yields, as the biochar addition leads to improvements in soil water holding capacity, which means the soil can hold more water for growth, there is greater mass flow of nutrients, and runoff and/or leaching are lower.

Clearly when exploring the application of new products to soils care must be taken to avoid a number of associated environmental risks, such as soil contamination with salts or heavy metals. Currently state of the art large scale methane pyrolysis systems are based on molten liquid metal systems; some prototypes are plasma systems, but upscaling of these systems may prove difficult. The molten metal system facilitates the constant removal of carbon and reduce catalyst deactivation. Low temperature system with tin or lead have been thoroughly investigated and maximum conversion efficiencies of 57 % achieved (Plevan et al., 2015). However, using molten bubble columns combined with immiscible molten salt layers conversion efficiencies of over 95 % have been achieved (Upham et al., 2017). These salt and metal combination systems present challenges if the carbon is to be used as a soil additive. The resultant fine graphite powder produced can be collected in the gas stream of the reactor and separated out be cyclones, filtration or precipitators. Low temperature (650 °C) salt streams have been proposed to overcome some of the difficulties of surface carbon accumulation but again present problems for the carbon end use, although full salt recovery systems are envisaged.

Parkinson et al., 2018 have suggested without carbon incentives SMR techniques are presently the most cost-effective production systems but suggested that with future carbon price of anything greater than 21 USD t CO_2eq would tip the balance in favor methane pyrolysis. The social cost of carbon is estimated at 100 USD t CO_2eq and has been adopted as the target carbon price.

Various field experiments around Europe have shown that biochar applications to temperate soils has phenomenal decarbonization potential, with little or no detrimental effects on crop yields. The impact of biochar soil fertility was reviewed in a meta-analysis (Jeffery et al., 2011). In temperate soils biochar application led to neutral or minimal yield depressions of approximately 3 % increases on average even when including un-fertilized plots, whereas in tropical soils yields were increased yields by 25 %, with mean application rates of 15–30 t ha^{-1}. Numerous studies have now shown that biochar addition to soils can reduce globally significant greenhouse gas emissions, especially N_2O, one of the most important GHG in agriculture (Bruun et al., 2011; Cayuela et al., 2013a; Wang et al., 2011). Recently meta-analysis showed significant reductions in N_2O emissions on average 54 % of controls when soils were amended with biochar (Cayuela et al., 2013b).

In Austrian soils biochar studies have shown that biochar application contributes to long-term C sequestration, e.g. large quantities of wood-based biochar applied on two agricultural field sites (72 t ha^{-1} equivalent to 58 tonnes of C ha^{-1}) did not cause any adverse effects on crop yields, provided that the biochar was combined with the standard fertilization practice over the two cropping seasons (Hood-Nowotny et al., 2018; Karer et al., 2015) Further experiments showed that biochar acted an inert substrate rather than a carbon source for the soil microbial biomass, explaining the lack of inorganic N immobilization by the soil microbial biomass and neutral effect on crop yield despite large carbon inputs (Hood-Nowotny et al., 2018). Furthermore, two years after the initial biochar addition 54 tonnes C ha^{-1} were still stored in the soil (Hood-Nowotny et al., 2018). To put this decarbonization potential in to a broader perspective long term UK trials (>100 years) have suggested that annual additions of 35 tonnes of dry manure to arable land led to soil carbon increases of less than 50 t ha^{-1} over one hundred years, and that conversion of arable crop to permanent grasslands led to increases in soil carbon of only 15 tonnes ha^{-1} again over a century (Johnston, 1986), or increases in above ground biomass in forest systems of in 7.5 t C ha^{-1} per annum in Norway Spruce, (Ostonen et al., 2005).

TREATMENT	Biochar t/ha	Nitrogen kg/ha
BC 3	72	0
NPK	0	120
BC 1N	24	120
BC 3N	72	120
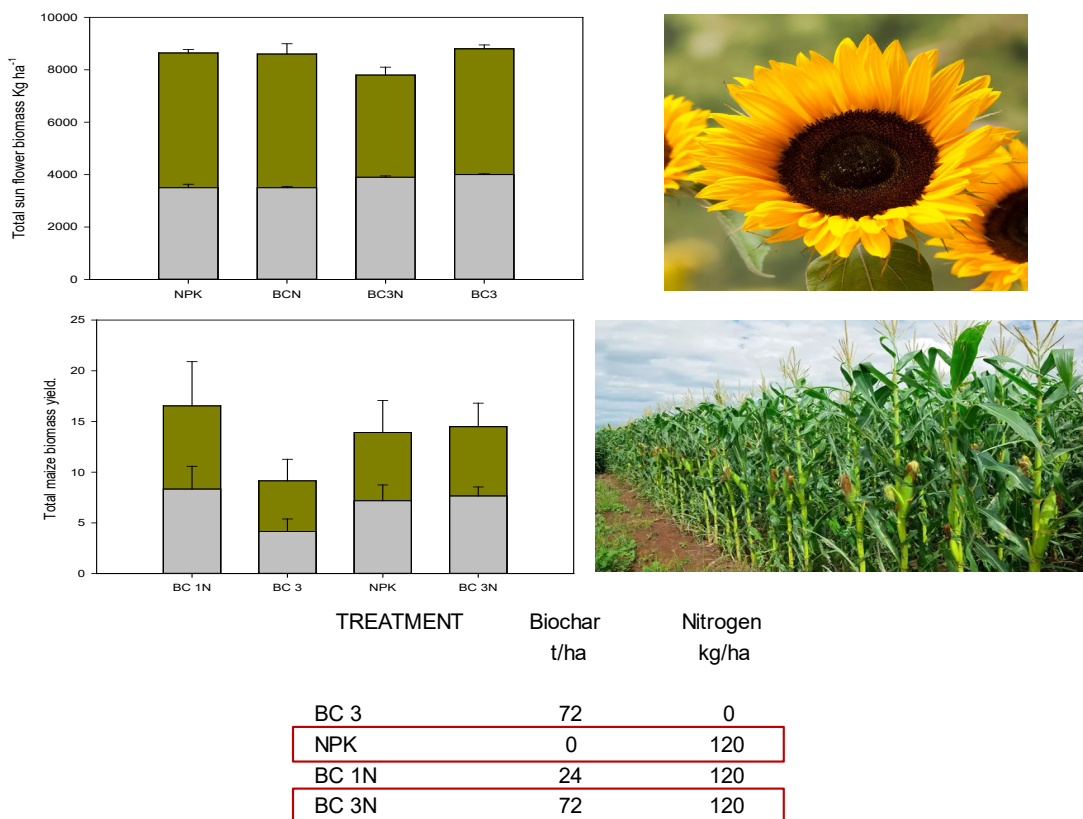
Figure 4: Effect of of biochar combined with nitrogen on the yield of sunflower (top) and maize (bottom).

The long-term fate of biochar and its impact on native soil organic C storage and its interaction with the soil biodiversity including; microbiome, mesofauna and macrofauna remain unclear to date. Biochar application has been found to alter soil microbial community structure (Prommer et al., 2014; Watzinger et al., 2014). Biochar has potential to alter concentrations in leachates such as ammonium, nitrate, dissolved organic nitrogen and carbon. Biochar may increase water-holding capacity as well as improve fertilizer efficiency, thus decreasing the need of fertilizer application whilst reducing N losses due to leaching (Karer et al., 2013) see below. But the effects are highly interdependent and dependent on the type of biochar and soil selected.

From a strategic perspective, research into the impact of biochar on soil processes offers a number of advantages. Biochar is perceived by the general public as an acceptable natural low risk carbon sequestration solution, and research in this area could possibly offer European industries early adopter advantages in bio- and pyo-char production and sales markets. The technical engineering excellence and experience of on farm solutions of European industries could lead to a competitive advantage in producing small scale pyrolysis units. As Europe particularly, Austria has a high percentage of organic (bio) farmers and an enormous forestry industry, push and pull market mechanisms are present within the European bio-economy offering an ideal opportunity for market development, given that the biochar used as a soil conditioner, is of on farm origin or has ECB-certification.

5.1. Literature review

Herein we summarize observed and potential effects of different types of spherical (nano-) carbon materials on soil physical, chemical and biological characteristics. Positive effects are shown in green color, negative effects in red. Potential effects (not yet observed) are shown in italics and are derived from observations on biochar.

Table 1 (please see next pages): Overview on the effects of biochar and nanocarbon on physical, chemical and biological soil properties as well as on plant growth. The assessment annotation is as follows: No/very limited evidence of an influence (0), some evidence (+), reasonable evidence (++), high evidence (+++). The categories are assigned based of numbers of papers published which show evidence and range from 0–1, 2–5, 6-10, >10 or R (review paper), respectively, for each of the categories - to +++. Note that for biochar and modified biochar only selected references are given in the respective columns. Positive effects (i.e. improved soil quality; increased plant growth) are given in green, negative effects (i.e. reduced soil quality; decreased plant growth) are given in red.

5.2. Physical/mechanical soil characteristics

- **increased water holding capacity:** Tan et al. (2016) observed increased water retention in nanocarbon-amended soil due to the significant specific surface area of nanocarbon. Several similar findings were also reported for biochar-amended soil, where increased water holding capacity was found due to the porous structure of biochar (Ding et all, 2016); as an example, an increase of 22 % was reported by Peake et al., 2014).

- **mechanical soil stabilization and reduced risk of erosion:** reduced tensile strength and therefore increased resistance to hydraulic deformation after drying, and reduced risk of erosion was reported to be due to Interfacial interactions between nanocarbon and soil particles. Likewise, biochar addition enhanced soil rigidity, especially in sandy soils, due to the formation of an internal pore structure able to better resist hydraulic deformation due to drying (Villagra-Mendoza and Horn, 2018). This stabilization will also likely contribute to reduced risk of erosion (Zhou et al., 2018; see also below for reduction of nutrient losses).

- **potential increase of aggregate formation and stability:** Biochar was found to improve microstructural stability in amended soils, supporting the formation of soil aggregates, which again improves the soil-plant-water environment. A similar observation for nanocarbon-amended soils has not been reported yet.

5.3. Chemical soil characteristics

- **increase of soil pH (liming effect):** Whereas liming effects are widely reported for biochar application (see e.g. Ding et al., 2016), only one report was found demonstrating a slight pH increase from 3.9 to 4.1 (Alsharef et al., 2016).

- **immobilization of organic and inorganic soil contaminants:** The immobilization of organic pollutants has been discussed in detail by Zhang et al., (2020). Similarly, adding nanocarbon to soils can also strongly enhance the adsorption of metal pollutants, as for example shown by Matos et al. (2017).

- **reduction of nutrient losses (in particular nitrogen):** Nanocarbon was found to reduce nutrient losses by reducing the risk of erosion (Zhou et al., 2018).

- **potential increase of (long-term) carbon storage in soils:** Biochar is a highly recalcitrant form of organic C in soils, and its mean residence time is estimated to be from decades to more than thousands of years (Jiang et al., 2020). It is likely that nanocarbon is similarly recalcitrant, but reports are not available on that.

Effects of biochar and nano-carbon on soil properties and plant growth - Literature survey

	Factors influenced by the presence of biochar/ modified biochar/ nanocarbon material in the soil	Presence of evidence for *biochar* impact in soil	References biochar	Remark biochar	Presence of evidence for *modified biochar* impact in soil	References modified biochar	Remark modified biochar	Presence of evidence for *nanocarbon* material impact in soil	References nanocarbon materials	Remark nanocarbon materials
Physical properties	increase in water holding capacity	+++	[Ding et al., 2016; R]		+	[Arthur et al.,2015]; [Lentz et al., 2019]	BC+manure stabilizing effect,water retention increase over time	++	[Tan et al., 2016]	effect likely due to physical similarity with BC having small particle size and high surface area
	reduced soil erosion	+++	[Soinne et al., 2014]; [Li et al., 2019]; [Chen et al., 2020]	effects more pronounced for small particle and nano-BC	0	[Doan et al., 2015]	BC+Vermicompost	0	[Zhou et al., 2018]	
	resistance to hydraulic deformation after drying; reduced tensile strength	++	[Villagra-Mendoza et al., 2018]; [Lehmann et al., 2011]					+	[Pengukuhan et al., 2018]	
	improved microstructural properties and aggregate formation	+	[Ouyang et al., 2013]; [Ajayi et al., 2016]	goes along with improved hydraulic conductivity						
	general improvement of soil hydraulic parameters	+++	[Edeh et al., 2020]	most pronounced for course-textured soils	+	[Al-omran et al., 2019]; [Abdo et al., 2020]	BC+compost , 40 g/kg-1 most effective,specifically applied for sandy soil / BC+Slurry,sandy soil			
	improved soil aggregation	+++	[Islam et al., 2021]	In acidic/neutral soils alkaline soils not affected						
	decreased yield of macro-aggregates				+	[Grunwald et al., 2018]; [Grunwald et al., 2016]	BC+slurry			

	Factors influenced by the presence of biochar/ modified biochar/ nanocarbon material in the soil	Presence of evidence for *biochar* impact in soil	References biochar	Remark biochar	Presence of evidence for *modified biochar* impact in soil	References modified biochar	Remark modified biochar	Presence of evidence for *nanocarbon material* impact in soil	References nanocarbon materials	Remark nanocarbon materials
Chemical properties	Increase in Carbon storage	+++	[Jiang et al., 2020; R]	effect stronger for high-temperature BC due to higher amount of aromatic C	+++	[Seki et al., 2018] [Dodor et al., 2018] [Dodor et al., 2019]	BC stabilizes labile organic carbon (e.g. in manure)			
	pH increase (liming effect)	+++	[Dai et al., 2017; R]					0	[Alsharef et al., 2016]	
	remediation of PAH-contaminated soils	+++	[Ahmad et al., 2014; R]; [Li et al., 2020; R]		+++	[Anae et al., 2020;R]	Engineered BC with digestate/microbial amendment	+++	[Zhang et al., 2020;R]	
	remediation of metal-contaminated soils	+++	[Beesley et al., 2011; R]		+++	[Abbas et al., 2020] [Chen et al., 2021] [Anae et al., 2020] [Karer et al., 2015] [Karer et al., 2018]		+	[Baragano et al., 2020] [Matos et al., 2017]	stabilization to immobilize heavy metals
	increase in soil fertility	+++	[Ding et al., 2016; R]	some studies report negative effects but BC could be designed to manage specific soil problems through controlling feedstock and pyrolysis conditions	+++	[Prost et al., 2013] [Bashir et al., 2020] [Doan et al., 2015] [Agegnehu et al., 2017; R]	effect stronger due to the composting of biochar			
	reduction of nutrient losses (other than N)	+	[Chen et al., 2020] [Kuo et al., 2020]	also observed for nano-BC	+	[Troy et al., 2014]; [Bradley et al., 2015]		+	[Zhou et al., 2018]	
	reduction of N losses and nitrate pollution of groundwater	+++	[Clough et al., 2013; R]							

	Factors influenced by the presence of biochar/ modified biochar/ nanocarbon material in the soil	Presence of evidence for *biochar* impact in soil	References biochar	Remark biochar	Presence of evidence for *modified biochar* impact in soil	References modified biochar	Remark modified biochar	Presence of evidence for *nanocarbon* material impact in soil	References nanocarbon materials	Remark nanocarbon materials
Biological properties	Increasesd microbial abundance and diversity	+++	[Lehman et al., 2011; R]	some studies reported decreased mycorrhizal abundance, possibly due to increased nutrient availability	+	[Brtnicky et al., 2019]; [Ye et al., 2016]	BC+ manure /compost have a synergistic effect			
	Increase in soil enzyme activities	0	[Ameur et al., 2018]	BC was activated using organic acids	0	[Sekaran et al., 2020]				
	Reduction of N_2O emmissions	+++	[Borchard et al., 2019; R]		+	[Zhu et al., 2014]; [He et al., 2019]	BC+compost reduction only at pF 2.0 /BC+manure in tea plantations			
	Reduction of CH_4 emmissions	+++	[Feng et al., 2012]; [Han et al., 2016];[Jeffery et al., 2016; R]	decrease especially for paddy soils or/and acidic soils with periods of flooding /some studies also reported an increase in methane emissions for alkaline soils with no flooding						
	Reduction of CO_2 fluxes				0	[Abagandura et al., 2019]	BC +manure for sandy loam 10 Mg ha-1			
	Decrease the microbial abundance and diversity									
	Alter the composition of the soil bacterial community	0	[Li et al., 2020]	observed for high BC addition rates only; rate of organic matter degradation might be decreased				++	[Hao et al., 2018]; [Kerfahi et al., 2015]; [Rodrigues et al., 2013]; [Wu et al., 2019]; [Shresta et al., 2013]; [Ren et al., 2015]; [Jin et al 2014]	effects are time dependent: recovery observed after 2 months
	Decrease in enzyme activity							+	[Chung et al., 2011]; [Chung et al., 2015]; [Jin et al., 2013]	negative relationship between surface area and decrease of enzyme activities
	Changed functionality of a microbial community (nutrient cycles)							+	[Wu et al 2020]; [Rodrigues et al., 2013]	
	Increases soil CO_2 fluxes	+++	[Song et al., 2017]; [He et al., 2017]	supressed CO_2 fluxes for N fertilized soils						

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Factors influenced by the presence of biochar/ modified biochar/ nanocarbon material in the soil	Presence of evidence for *biochar* impact in soil	References biochar	Remark biochar	Presence of evidence for *modified biochar* impact in soil	References modified biochar	Remark modified biochar	Presence of evidence for *nanocarbon material* impact in soil	References nanocarbon materials	Remark nanocarbon materials
Plant effects — Increased seed germination	+	[Uslu et al., 2020];[Das et al., 2020]	BC <40 Mg ha^{-1} / enhanced with 5 Mg ha^{-1} in acidid soil				+++	[Nair et al., 2012]; [Villagarcia et al., 2012]; [Ashfaq et al., 2017]; [Lahiani et al., 2013]; [Xiong et al., 2018]; [Anjum et al., 2014]; [Haghighi and da Silva 2014]; [Khodakovskaza et al., 2009]; [Khodakovskaza et al., 2011]; [Ratnikova et al., 2015]	effect mostly observed for multiwall carbon nanotubes (MWCNT)/experiments are conducted in a water medium or/and petri dish
Increased root length, root biomass, number of root tips	+++	[Xiang et al., 2017]; [Lehmann et al., 2011]	effect more depending on the BC temperature than the BC feedstock	+	[Zhang et al., 2020]	BC+manure	+	[Lahiani et al., 2013]; [Mondal et al., 2011]; [Wang et al., 2012]; [Nair et al., 2012]; [Tripathi et al., 2015]	Effect mostly observed for multiwall carbon nanotubes (MWCNT) in a water medium
Increased plant (shoot) growth	+++	[Diatta et al., 2020; R]		+++	[Wang et al., 2019]	effect stronger due to the composting of biochar, promoting BC's positive effects	+	[De La Tore-Roche et al., 2013]; [Mondal et al., 2011]; [Strivastava et al., 2014]	MWCNT water medium & soil
Increased crop yield	+++	[Jeffrey et al., 2011]		+++	[Agegnehu et al., 2017; R]				
Reduced salt stress	+++	[Ali et al., 2017]	BC reduces uptake of Na while increasing uptake of K	0	[Lashari et al., 2014]		+	[Pandey et al., 2018]; [Martinez-Ballesta et al., 2016]	Effect due to regulation of the expression of key genes of plant stress plus CNT physical interaction with positive charged ions (in virtro)

5.4. Biological soil properties

- **Changes of the soil microbial communities:** A change of microbial community composition was reported by e.g., Jin et al. (2014) and Hao et al., 2018. The effects seem to be, however, time-dependent: Rodriguez et al. 2013 found a complete recovery of the bacterial community 2 weeks after application, whereas no recovery was observed for the fungal community in this time period.

- **Changed microbial functionality, e.g. in nutrient cycling:** Wu et al. (2020) reported that two different carbon nanomaterials affected CO_2 fixation pathways, microbial degradation of diverse carbohydrates, secondary plant metabolites, lipids and phospholipids, proteins, as well as methanogenesis and methane oxidation. They also suppressed nitrogen fixation, nitrification, dissimilatory nitrogen reduction, eukaryotic assimilatory nitrogen reduction, and anaerobic ammonium oxidation (anammox). Phosphorus and sulfur cycles were less vulnerable.

- **Decrease in enzyme activities:** Jin et al. (2013) reported that the application of single-walled nanocarbon reduced soil enzyme activity and microbial activity. They also found a relationship between surface area and observed effects, suggesting that that greater microorganism—nanocarbon interactions could increase the negative effects of CNTs on microorganisms.

- potential decrease of greenhouse gas (GHG) emissions (see below)

5.5. Additional effects as soil additive, the following direct effects on plants were observed

Variable effects of carbon nanomaterials on plants were reported and discussed to depend on the nature of the nanomaterial, the plant species, the nanomaterial concentration, the soil, and the time of exposure (Vera-Reyes et al., 2018). Most of the studies were carried out in hydroponic solution. A comprehensive overview on plant effects is provided by e.g. Aacharya and Chhipa (2020).

Positive effects include:

- **increased seed germination:** Several papers reported a significant increase of seed germination rates, e.g. Khodakovskaya et al., 2009.
- **Increased root length, root biomass, number of root tips:** Increased root growth was found after treatment of seeds with oxidized multi-walled carbon nanotubes (Mondal et al., 2011).
- **increased shoot growth and crop yield:** Khodakovskaya et al., 2013 found that tomato plants grown in soil supplemented with CNTs produce two times more flowers and fruit compared to plants grown in control soil.
- Reduced salt and drought stress

Negative effects were reported for:

- **Changes in root structure and decrease of root growth:** Effects reported by Cañas et al. (2008) were largely plant species-specific: nonfunctionalized nanotubes inhibited root elongation in tomato but enhanced root elongation in onion and cucumber. Functionalized nanotubes inhibited root elongation in lettuce. Cabbage and carrots were not affected by either form of nanotubes.

- **Phytotoxicity at high concentrations:** MWCNTs showed phytotoxicity to *Brassica juncea* and *Phaseolus mungo* in seed germination and seedling growth at 40 ppm concentration (Ghodake et al., 2010).

Options for modifying pyo-char for supporting positive and avoiding negative effects:

- Mixing pyo-char with manure/slurry or with compost
- Co-composting of pyo-char with manure, slurry, other organic residues
- Activating pyo-char with (soil) microorganisms
- Using pyo-char for coating nitrogen fertilizers (e.g. urea)

The increase of soil quality upon biochar addition has good potential for increasing plant yields, e.g. due to the increased water holding capacity or retention of nutrients. However, pyo-char as such consists of carbon only and does not provide any nutrients to the soil. Like biochar, pyo-char might be combined with organic residues (e.g. compost, manure, etc.) and in this way combined with a nutrient rich material. Furthermore, pyo-char could be used as a coating material (e.g. for urea). In both approaches, nutrient release into soil would be achieved in a controlled manner. Finally, by activating the pyo-char with beneficial soil microorganisms pyo-char would act as a carrier material for bacteria and/or fungal organisms supporting plant-growth.

5.6. The potential of pyo-char for saving greenhouse gas (GHG) emissions

a.) reduced CO_2 emissions due to medium- or long-term storage of carbon in soils

Converting the annual natural gas consumption in Austria (8.9 billion m^3) by TCD to hydrogen would yield 4,5 million metric tonnes of carbon. Assuming a soil application rate of 60 t/ha, 74,200 ha would be needed, i.e. 5 % of the total agricultural land. A substantial part of this land is carbon deficient. For biochar, a degradation rate of ~2 %/year was found in the short term. Observations of *terra preta* in the Amazon region suggests that char-like carbon can remain sequestered in the soil for thousands of years

b.) reduced GHG (in particular N_2O) emissions

A large fraction of nitrogen added via NPK fertilizers gets lost as nitrous oxide-N_2O a powerful GHG. Biochar can reduce these emissions by up to 50 % (average: 38 %). Based on the annual N application in agriculture, ~40,000 tonnes of CO_2 equivalents could be saved due to the reduction of N_2O emissions; per hectare 0.15 t/ha CO_2 equivalents would be saved with the application of 40 t/ha biochar-carbon.

Estimation of the carbon sequestration potential and the amount of arable land needed:

In 2019, approximately 8.9 billion cubic meters of natural gas were consumed in Austria (https://www.statista.com/statistics/703616/natural-gas-consumption-austria/ accessed 18/03/2021), which corresponds to 5,933,333 metric tonnes of methane or 4,450,000 metric tonnes of carbon per year. Note these are theoretical maximum estimates current run at 95 % methane conversion efficiency. If we assume we can apply to soil at the rate of 60 t ha^{-1} then we need 74,166 ha of per year to bury the carbon if **all** methane production converted to pyochar production.

Estimation of reduced N_2O emissions:

88,000 t of different nitrogen fertilizers were used in Austrian in 2001 of which we assume a 30 % N content. 26,400 tonnes of N, **78,672 tonnes CO_2eq** lost as N_2O. **Cayuela (2014) suggested that biochar can reduce N_2O by 50 %** when added at rates of greater than 2 % mass. If we assume a blanket wide reduction in N_2O of this would be equivalent to an additional 39,336 CO_2eq tonnes.

Coating of urea with biochar showed a 20 % increase in fertilizer use efficiency in pot trials, but mainly due to reduced leaching (Jia et al 2021). There is some suggestion that addition of biochar to soil may improve the retention of added fertilizer as a result of reduced ammonia losses, as it is hypothesized that the ammonium ions are absorbed on to the surfaces or in the pores of the biochar. This maybe, of particular importance in systems where ammonia losses are high such as in poultry housing or intensive cattle production systems.

Assuming biochar application of 40 tonnes or (117 tonnes CO_2eq draw down... 0.8 *40 *44/12) per ha with all Austrian applications of nitrogen fertilizer we could assume a further reduction in 0,149 t CO_2eq additional reduction in nitrous oxide loss (assuming 100 kg N fert and 50 % reduction). If we apply C as a coating we could reduce CO_2 foot print by assuming 20 % increase in FUE we can assume 20 % less will be used leading to 3.6 kg CO_2eq per kg N produced, 19,008 t CO_2eq saved in production.

To coat all the nitrogen used in Austria we would need 56,571 tonnes of carbon per year, or 1.2 % of the total potential production. But note these reductions in FUE rates are based on high N application rates and urea. Emission Factor means that 1 kg of N_2O-N is emitted for every 100 kg of N applied as fertilizer (de Klein et al., 2006).

5.7. Conclusions and outlook

Black carbon from methane pyrolysis is a potential market competitor to biochar producers as its potential production volumes are far greater than of biochar. Another threat of substitution comes from alternative energies and bioengineering solutions, but many of these could not meet the needs of the fossil fuel intensive thermal heating requirements of European households. It is clear from the analysis of the industry

rivalry that BCMP and biochar production and use is still at an innovator/early adopter stage in terms of technological innovation diffusion.

For a technology to gain full public acceptance requires an understanding of its long-term consequences specifically in relation to issues close to the public's hearts such biodiversity and impacts on the ecosystem as a whole. It is possible to investigate the impacts of bio- and pyo-char addition to soil on biodiversity on both short- and long-term time scales and evaluate the perceived and actual risks of this NET. The true impacts of pyo-char on a soil biodiversity, and its consequences for ecosystem function can only be elucidated by conducting medium to long-term field experiments, across multiple ecosystems that have received carbon sequestration relevant amounts of BC, where pedoclimatic conditions differ, and where the same response variables are measured over comparable timescales in a concerted manner.
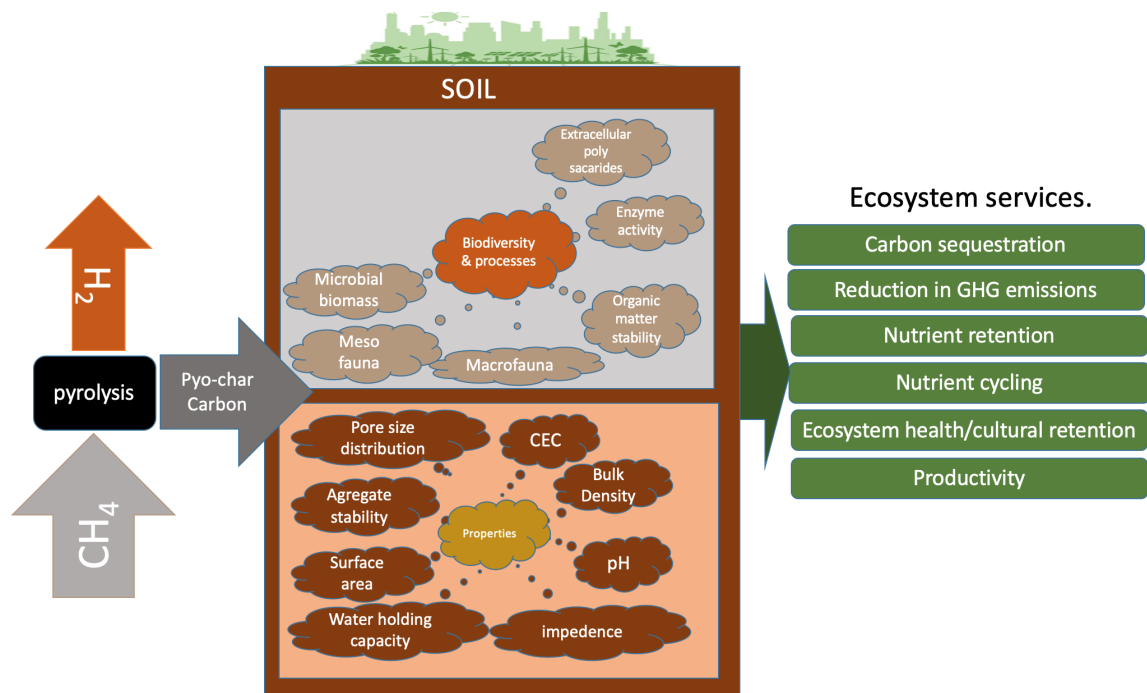
Figure 5: The overall potential effect of pyo-char application on soil quality and ecosystem services.

5.8.   References

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6. WPII »Kohlenstoff im Bausektor« Applications C in building materials

IIMBT

Investigation of the sustainable utilization of carbon from methane pyrolysis

Work Package 2: Applications C in building materials

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Background

Unlike conventional hydrogen production, methane pyrolysis does not produce carbon dioxide. CO_2 is avoided when decarbonizing fossil fuels by thermolysis, since reduced carbon is produced as a solid residue (Halloran, 2008). The positioning of methane pyrolysis as an environmentally and economically attractive solution for hydrogen production relies on finding plausible uses for the solid carbon generated. Due to the magnitude of solid carbon produced when methane pyrolysis is implemented in a large scale, suitable uses would have to incorporate a high amount of the carbon material.

Construction materials are heavily consumed by humanity, with research pointing to the fact that concrete is one of mankind's most consumed resources, second only to water (Waters et al., 2016). Additionally, the demand for urbanized areas is expected to grow significantly in the next decades, which requires the establishment of new infrastructure, traditionally built with steel and concrete. Building and construction materials can incorporate an immense amount of carbon products.

Research indicates that the solid carbon produced by methane pyrolysis can be advantageous in both tensile and compressive force-resisting materials (Muradov & Veziroğlu, 2008), which points to a feasible replacement of steel and concrete. However, the specialized scientific literature on the matter is scarce. Further investigation is paramount if methane pyrolysis is to represent a significant share of the hydrogen production market. Most importantly, due to steel and concrete's significant contribution to global greenhouse gas (GHG) emissions and their massive consumption, these potential uses of carbon can imply in a considerable reduction of GHG emissions on a global level. This work package aims to estimate the latter positive effect relying on Life Cycle Assessment. The attribution of the benefit to hydrogen shall also be studied, taking into account the avoided impacts associated to the displaced traditional production technologies.

6.1. Systematic Literature Review (SLR)

SLR Methodology

A first step of this project was to perform a systematic literature review (SLR) in order to answer to the following research question: "How can solid carbon produced from methane pyrolysis be used in building materials?". The Scopus database[1] was chosen for this SLR, as it hosts a large quantity of journals related to the construction sector. The search was executed in May 2021, excluding all papers not written in English, as well as grey literature. The "Abstract, title & keywords" section of the Scopus search tool was used. At first, the chosen keywords string was: **"methane pyrolysis" AND construction**. As an initial quick search did not lead to many results, the search was extended to the "All fields" section for this keywords string. 101 papers resulted from this search. The irrelevant articles were left out after successively reading the titles

1   https://www.scopus.com/

and abstracts of the obtained articles. Finally, the remaining articles were read in full to assess their relevance. Following all these steps, no paper was deemed relevant to answer the research question. The search was then renewed with an alternative keywords string: **"solid carbon" AND building***. 21 papers were found in the "Abstract, title & keywords" section of Scopus with these new keywords. After performing the same screening process, 3 papers were found to be relevant for the project. This relatively low number of papers which results from the different searches clearly indicates a research gap on the topic.

These three papers (Halloran, 2008; Halloran & Guerra, 2011; Kolibaba et al., 2020) investigated the use of char, either derived from coal or waste pyrolysis. Based on these papers, three applications of pyrolysis char were identified in the building sector:

- The use of the char as a filler for cement or concrete.

- The use of the char for composite masonry blocks.

- The use of the char as an insulation material.

Uncertainties, however, remained on the differences between the solid carbon obtained from methane pyrolysis and the other pyrolysis chars which were used in the literature. Even if the materials appear to have similarities, it could not be guaranteed that the materials would behave in the same way nor could be exchangeable. Even so, these three identified applications seemed promising and more research in the use of char in building materials had to be conducted, which is why a third keywords string was created for a final search: **char AND building***. This led to a result of 405 papers, among which 26 were found relevant after the different reading screens. Together with the 3 previously selected articles, this sums up to a final sample of 29 relevant articles. A summary of the SLR methodology is provided in Figure 6.
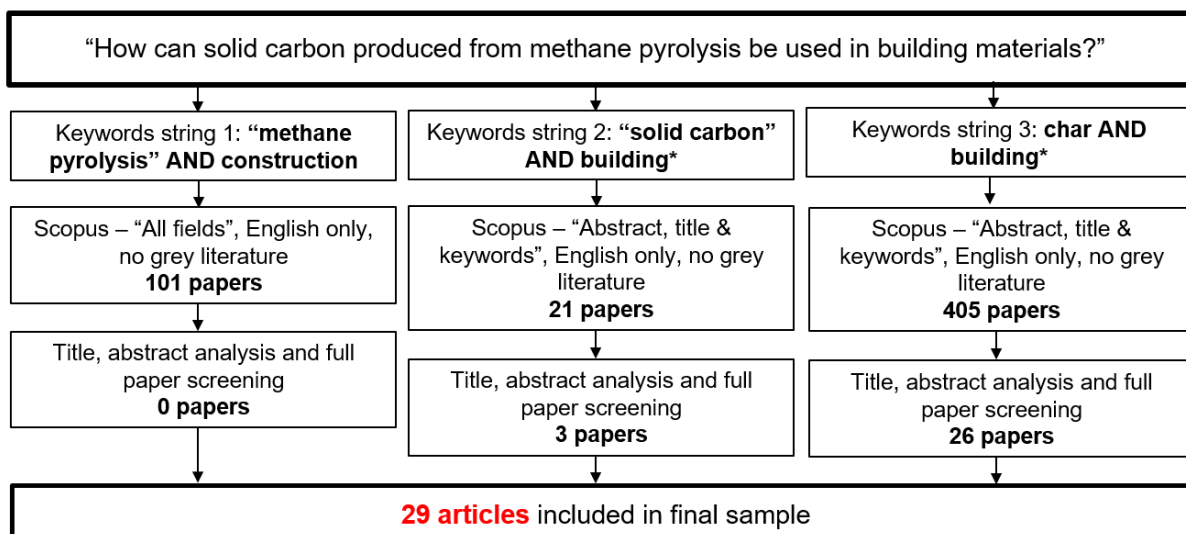
Figure 6: SLR methodology

In order to efficiently extract the information contained in these articles, a data extraction table was created. In this table, the following information was collected: the metadata (document title, year, authors, country/province, source), a description of the application of char in the construction materials (including the description and the quantity of the material which is replaced), the advantages and disadvantages of the technology, according to the paper, and a comment or critical remark from our side (to allow for an interpretation of the results). Based on the analysis of this table, the SLR results could be derived.

6.1.1. SLR Results

Figure 7 provides an overview of the materials which were investigated in the literature, for a possible incorporation of char. Concrete and cementitious pastes are highly investigated and account for a large majority of the studies with 71 % (52 % + 19 %) of the collected articles. Insulation materials and masonry blocks are then equally explored, but to a smaller extent, both accounting for 15 % of the studies composing the final sample of the SLR.
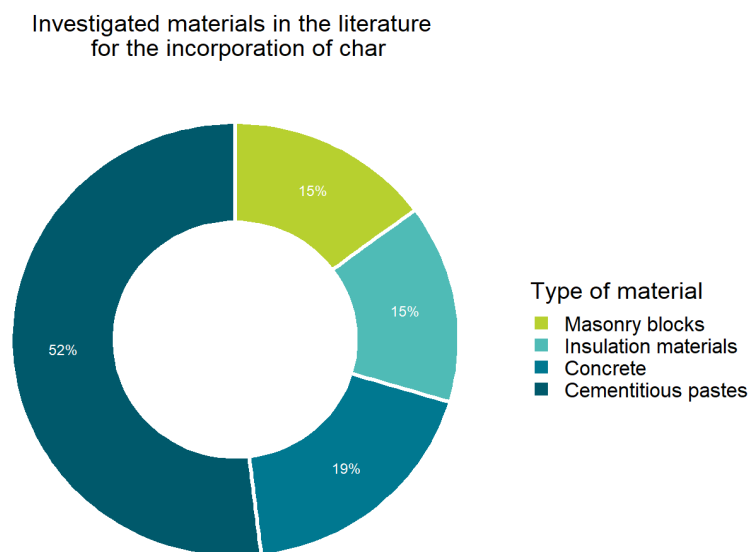
Figure 7: Investigated materials in the literature regarding the incorporation of char

For information purposes, Figure 8 illustrates the geographical origin of the 29 articles which constitute the final sample of the SLR. The papers have diverse origins and are not focused on a specific continent, as no geographical boundaries were set in the SLR. Interestingly, Italy published a lot of papers in the field, in comparison to other countries.
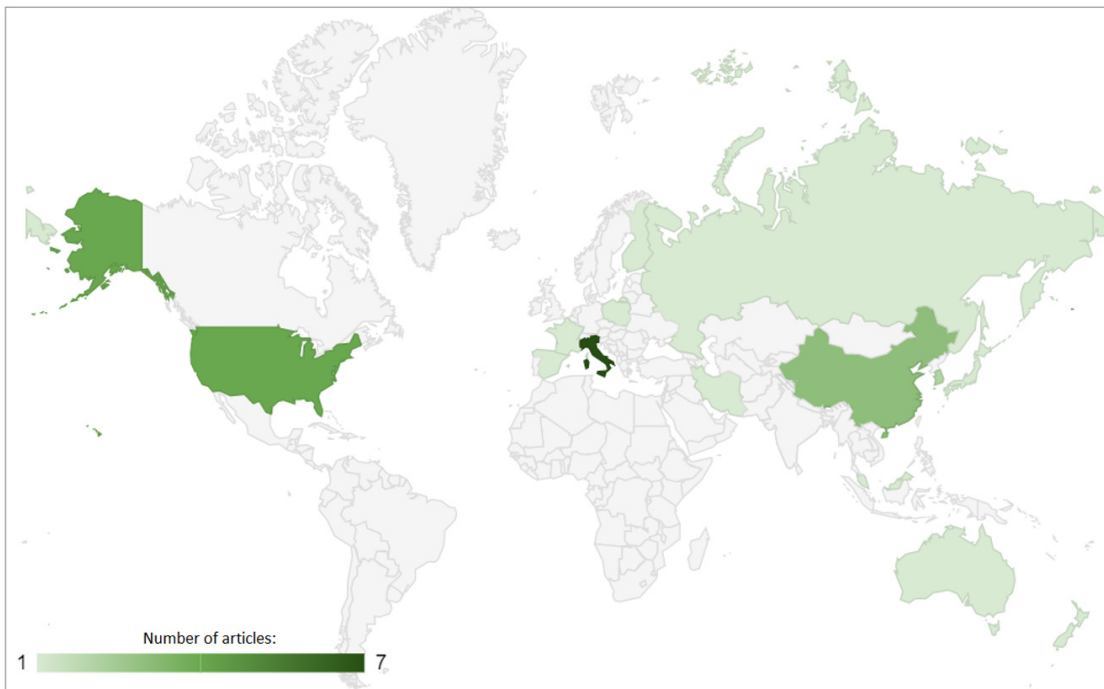
Figure 8: Geographical origin of the papers constituting the final sample of the SLR

The information contained in these papers could additionally allow for a more detailed analysis of the three different uses of char in the building sector, which were previously identified. As already highlighted in Figure 7, the most investigated application of char is its use as a filler in concrete and cement. This seems to be possible with the current technology. The main advantages of this application are, according to the literature, the following:

- Increased water tightness (Ahmad et al., 2020; Muthukrishnan et al, 2019; Ofori-Boadu et al., 2018).

- Improved CO_2 capture ability (Liu et al., 2020; Praneeth et al., 2020; Gupta & Kua, 2017).

- Better surface crack-sealing of concrete, especially in combination with other additives such as bacteria (Kua et al., 2019; Gupta et al., 2018).

- Improved conducting properties, allowing for electrical conduction monitoring (Kamaluddin et al., 2020).

As for the disadvantages, they can be described as follows:

- Increase in unpredictability of the mechanical properties (Praneeth et al., 2020; Cosentino et al., 2018).

- Uncertainty about the long-term durability properties (Praneeth et al., 2020; Gupta & Kua, 2017).

- High variability of these parameters depending on the source of char (pyrolysis parameters) and the incorporation amount (Ahmad et al., 2020).

- Low char incorporation potential: up to 20 % observed (Ofori-Boadu et al., 2018) but most studies are between 2–7 % (per weight of cement).

A second application of char in the construction industry is the manufacturing of masonry blocks, or char bricks, in which char is used to replace sand. Although uncertainties remain about the technological readiness level of this application, the main identified advantages are the following:

- Higher possible proportion of char, up to 50 % inclusion observed (per weight of sand) (Jiang et al., 2019).

- Decreased thermal conductivity (Lee et al., 2019; Yang et al., 2019; Jiang et al., 2019).

- Reduced costs, up to 18 % (Jiang et al., 2019).

- Reduced density (Vezzali et al., 2018; Halloran & Guerra, 2011; Jiang et al., 2019).

The main disadvantage of this utilization of the char is the observed trade-off between the thermal and mechanical properties: the higher the amount of char, the lower the compressive strength of the brick, but the higher its thermal resistance; the incorporated amount of char should, therefore, reflect the intended use of the block (Yang et al., 2019; Jiang et al., 2019).

The final identified application of char was its use for heat-insulating materials. The collected studies only focused on the incorporation of char in plasters and coatings, as a replacement of the sand usually used. This application is mostly at an early technological readiness level, and confers the following advantages, according to the collected studies:

- Higher possible amounts of char, up to 60 % inclusion observed (per weight of sand) (Jiang et al., 2019).

- Regulates indoor humidity and temperature (Kondo et al., 2012; Ryms et al., 2020; Jiang et al., 2019).

- Reduced costs, up to 10 % (Jiang et al., 2019).

- Low thermal conductivity (Jiang et al., 2019).

The main disadvantage is that these applications do not seem to be able to replace traditional insulation materials, but are more of a complementary solution, with additional indoor benefits (Kondo et al., 2012; Ryms et al., 2020; Jiang et al., 2019). This will, however, be further investigated in the life cycle assessment (LCA) calculations.

As a conclusion of this section, Figure 9 summarizes the proportion of char incorporated in construction materials, according to the SLR results. For concrete and cement, the relative percentage is calculated by weight of cement. For masonry blocks and insulation materials (coating and plasters), it is calculated per weight of sand. As previously mentioned, concrete and cement mostly have comparatively low incorporation potentials of char. Regarding masonry blocks, the proportion can be quite high or relatively low, depending on the needed mechanical properties of the bricks, hence the observed extended range of values. As for coatings and plasters, which do not need necessarily any specific strengths, the incorporation of char can be higher.

One must pay attention to the fact that, on the one hand, these percentages are expressed per mass of a constituent of the different materials, which differs per material (cement or sand), which means that the actual absolute values can be quite different; if there is way more cement in 1 kg of concrete than there is sand in 1 kg of brick, then a 5 % incorporation in concrete can lead to a higher absolute value than a 15 % incorporation in bricks. The available data in the articles did, unfortunately, not allow for a harmonization of the percentage which could have led to clearer conclusions. On the other hand, the quantity in which these materials are used in a building is also an interesting factor; concrete is, for example, used in larger quantities than plaster, which can compensate for these low incorporation rates. Based on these results, further LCA calculations are carried out in the next sections.
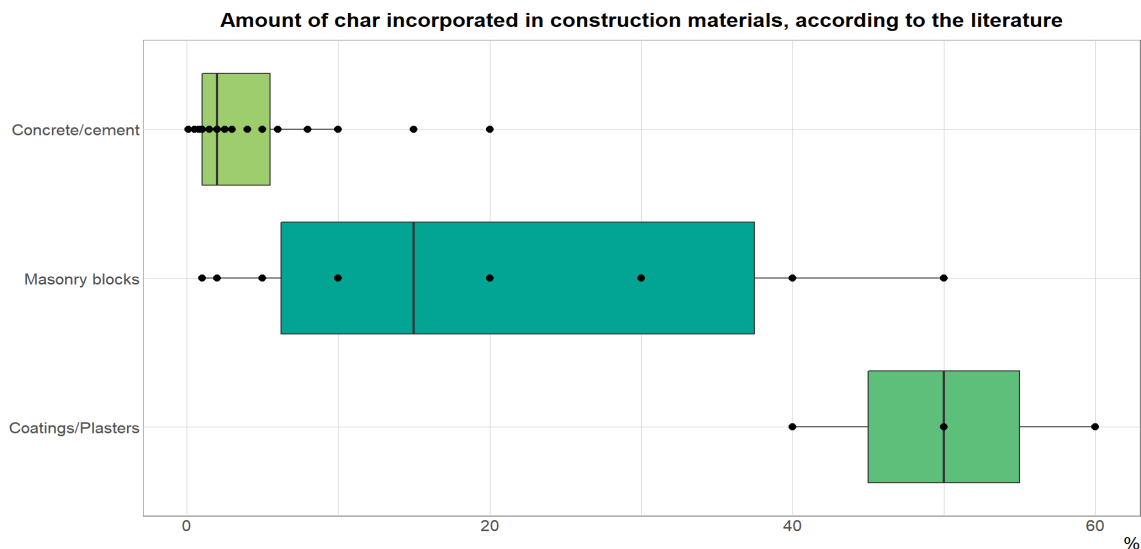
Figure 9: Proportion of char incorporated in construction materials, based on the SLR results

6.2. Data gathering from industries and experts

Considering the identified research gap and the scarcity of the studies investigating the use of solid carbon in the building industry, it seemed relevant to contact industries or experts in the field. To stay in line with the SLR results, we contacted the Ithaka institute[2], known for its expertise in production, post-production treatment, and use of biochar, and who developed numerous biochar-based products, including biochar plasters, bricks and concrete (Schmidt, 2008).

We contacted the head of the institute via e-mail, to get to know more about the thermal properties of these materials in relationship to the incorporated amount of

2   https://www.ithaka-institut.org/

biochar, as well as the incorporation limits. We were informed that the product obtained from the methane pyrolysis process "would certainly qualify as Carbon Black which is a standard material in concrete and composite materials. However, it will be quite different from the biochar we tested in several building materials." We could not obtain more information about the mechanical or thermal properties of materials incorporating this black carbon. Indeed, due to the "small aromatic structure" of the carbon, the physical properties would be quite different from the biochar that they tested which makes it difficult to predict. Specific tests and measures should be conducted on materials incorporating this particular solid carbon. It is, however, "very likely that it decreases the thermal conductivity" of the materials. Additionally, we were told that "when you need to maintain the same strength or becoming better, you should stick to less than 3 % biochar (w/w) in the concrete. If you use it as filler bricks, you can go up to replacing all sand by biochar." This statement is in accordance with the incorporation amounts which were observed in the literature (Figure 9).

We then expanded the scope of our research to investigate if other technologies used solid carbon in construction materials. We came across a range of companies using carbon fibers to manufacture construction materials. We first contacted a representative of Technocarbon[3], a start-up which develops composite construction materials made of stones (granite or basalt) and carbon fibers. He could not share with us any technical details, as they were confidential. He, however, provided us with some data which allowed for rough LCA calculations, which are presented in the next section. Regarding the possibility to transform our solid carbon into fibers, he told us that he does not think such a process exist or is being developed; it is, according to him, also a research gap. We later contacted a representative of CleanCarbon-Technology[4], which develops a similar technology to Technocarbon, incorporating carbon fibers into stone-composites. He informed us of another interesting manner to use the black carbon: in a wall composed of two layers of their stone/carbon composite plates, they would, in between, pour black carbon mixed in PUR foam, as an insulation material. He assumes that it's possible to "store 2kg of carbon black within m^3 of PUR-foam without doing harm to the mechanical properties of the foam." The limitation is, that this application would only be a way to store the solid carbon, but it wouldn't necessarily improve the thermal properties of the foam. The CleanCarbon-Technology representative believes that the carbon would be advantageous for the insulation properties, but this needs to be further investigated, as he has no evidence of it at the moment.

Still looking into the use of carbon fibers, we came across the manufacturing of reinforcing bars made out of carbon fibers, which are aimed at replacing traditional steel rebars. We contacted a researcher at TU Dresden and representative of the board of the C^3 network[5], a project investigating carbon reinforced concrete. He also directly raised concern about the fact that we would not be able to produce fibers. According to him, without directly having fibers, we would not be able to use the product for this application, and the discussion did not go further. By looking into the network of the project, we later found technical product sheets from Solidian[6], a company manufac-

3   https://tctf.eu/en/
4   https://cleancarbon.technology/
5   https://www.bauen-neu-denken.de/en/
6   https://solidian.com/

turing carbon fiber rebars. Based on this datasheet, first LCA calculations could be performed and are presented in the next section (assuming, still, that we would be able to have fibers).
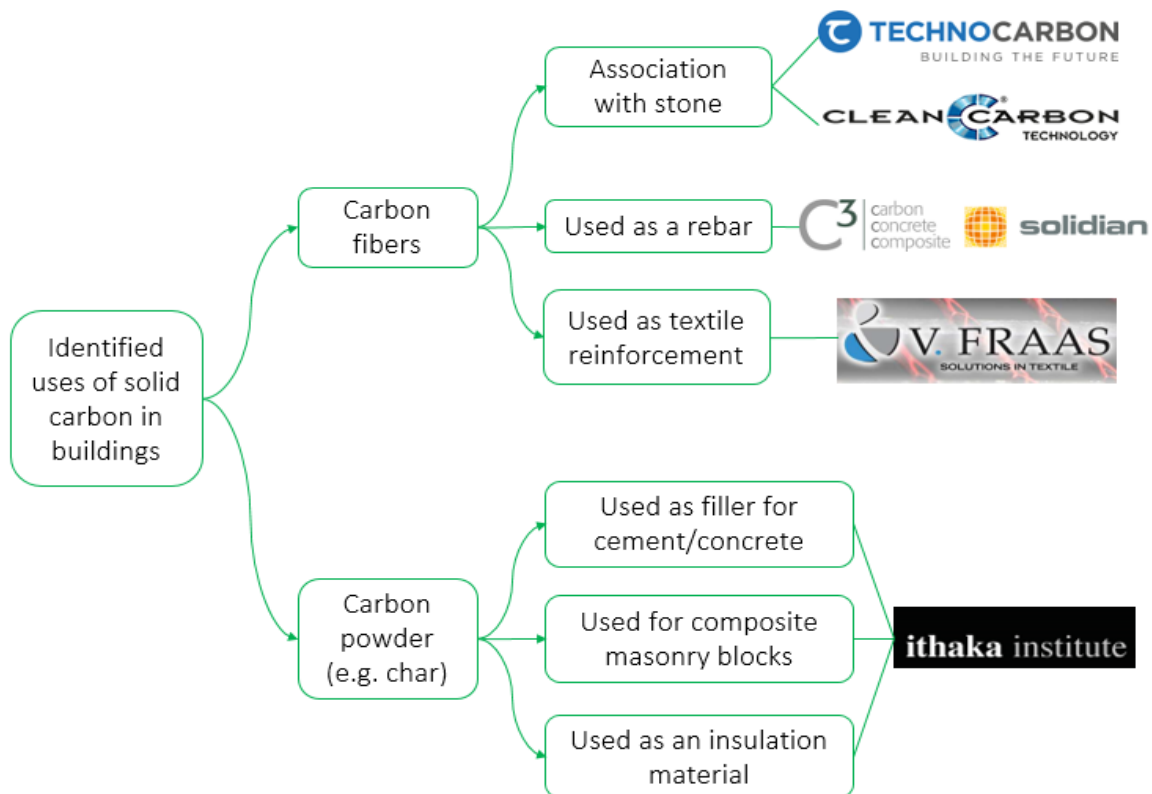
Figure 10: Identified applications of solid carbon and relevant companies/research institutes

A final identified use of the carbon fibers is the manufacturing of a textile reinforcement for concrete, instead of traditional rebars. Based on the concerns raised regarding the transformation of the carbon powder into fibers, this path was not further explored. After consulting with Mr. Robert Obenaus-Emler and looking into Paris & Peterlik (2009), regarding the transformation of powdery carbon into other structures, the conclusion was that this was, for now, not an accessible process.

A summary of the different identified applications of solid carbon and relevant companies/research institutes is provided in Figure 10.

6.3. Life Cycle Assessment (LCA) calculations

Calculations based on the SLR results

Building upon the SLR results, we decided to perform the following LCA calculations:

- For the use as a filler for concrete, an optimistic version of 20 % inclusion of solid carbon per weight of cement, and a more realistic version of 5 % inclusion.

- For the use in masonry blocks, basing ourselves on clay bricks, a load-bearing version with 5 % inclusion of solid carbon per weight of sand and clay, and an insulation version with 50 % inclusion.

- For the use as an insulation material (plaster), a 60 % inclusion per weight of sand.

An overview of the different LCA calculations is provided in Figure 11.
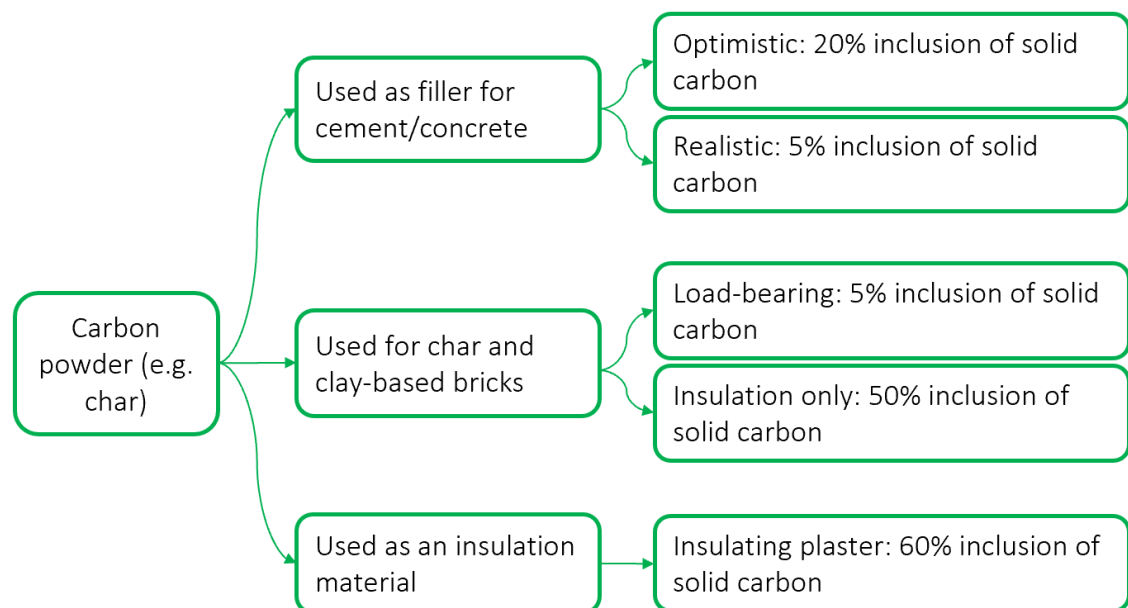
Figure 11: Overview of the different LCA calculations which are based on the SLR results

The LCA calculations were performed in accordance with the European standards regulating the LCA of construction materials (EN-15804, 2019). The goal was to calculate the greenhouse gas (GHG) reduction potentials which could be attained by incorporating solid carbon, or char, in the above-mentioned construction materials (concrete, brick and plaster). For that purpose, the global warming potential (GWP) is the only investigated impact category, expressed in $kgCO_2eq$ and assessed with the IPCC 2013 GWP 100a method, a method developed by the Intergovernmental Panel on Climate Change (IPCC). It was assumed that no impacts came from the solid carbon, following a cut-off approach. Cradle-to-gate assessments are performed (modules A1-A3 only, according to the classification of EN-15804). The calculations were carried out using the SimaPro[7] computation tool and the datasets used come from the Ecoinvent[8] v3.6 database.

7   https://simapro.com/
8   https://www.ecoinvent.org/

Regarding the concrete calculations, the chosen functional unit is the cubic meter of concrete, produced with the current available technology in Austria. The reference mix is the Ecoinvent dataset for "concrete, high exacting requirements, with CEM II/A", a Swiss data which is widely used as a proxy for Europe. The solid carbon is assumed to be used instead of limestone in CEM II/A, and then, if the limestone is fully replaced, instead of clinker. The amounts of clinker, limestone and carbon, as well as the GWP and the percentage of reduction in GWP of the two investigated mixes compared to the reference mix, are provided in Table 2.

Table 2: Results regarding the incorporation of solid carbon in concrete, with CEM II/A as a reference

	Reference mix	5 % carbon mix	20 % carbon mix
Amount of clinker (kg)	0,79	0,79	0,76
Amount of limestone (kg)	0,16	0,11	0
Amount of solid carbon (kg)	0	0,05	0,19
GWP (kgCO$_2$eq/m^3)	196,18	196,18	189,33
% of reduction	**0 %**	**0,010 %**	**3,5 %**

The GHG emissions reductions are relatively low, with a maximum of 3,5 % for a 20 % incorporation of solid carbon. This is mainly due to the fact that CEM II/A already contains a large amount of limestone with low embodied environmental impacts. Therefore, replacing it with solid carbon does not considerably reduce the GHG emissions. When only limestone is replaced (this is the case for the 5 % carbon mix), then the difference in emissions is negligible (less than 1 %). However, when the clinker starts to be replaced, because all the limestone is already changed into solid carbon (this is the case for the 20 % carbon mix), then the difference in emissions starts to be visible. There are, however, incorporation limits when it comes to fillers in concrete, and according to the results from the literature (Figure 9), 20 % is already very optimistic.

As a sensitivity analysis, the same calculations were performed using CEM I, containing considerably less limestone, instead of CEM II/A. For this analysis, the Ecoinvent dataset for "Cement, Portland {CH}| production | Cut-off, U" was used. The new values are provided in Table 3. As more clinker is replaced by solid carbon than with the CEM II/A, the attained percentages are consequently higher, up to 15 % for a 20 % incorporation of solid carbon. Nonetheless, pure Portland cement is no longer a "reference" in Austria, where the cement production is better represented by a CEM II/A.

Table 3: Results regarding the incorporation of solid carbon in concrete, with CEM I as a reference

	Reference mix	5 % carbon mix	20 % carbon mix
Amount of clinker (kg)	0,90	0,81	0,76
Amount of limese (kg)	0,05	0,05	0
Amount of solid carbon (kg)	0	0,05	0,19
GWP (kgCO$_2$eq/m^3)	223	200	189
% of reduction	**0 %**	**10 %**	**15 %**

Regarding bricks, the functional unit which was used for the calculations is one kg of brick, produced with the current available technology in Austria. The reference clay brick is taken from the Ecoinvent dataset for "Clay brick {RER}| production | Cut-off, U". The amount of sand used in these bricks being very small, it is entirely replaced by char in both cases. Then, to achieve the two incorporation percentages (5 % and 50 %), part of the clay is also replaced by solid carbon. These percentages are calculated based on the total amount of sand and clay contained in the brick. The results can be found in Table 4.

Table 4: Results regarding the incorporation of solid carbon in clay bricks, with a clay brick as a reference

	Reference mix	5 % carbon mix	50 % carbon mix
Amount of clay (kg)	1,40	1,30	0,68
Amount of sand (kg)	0,015	0	0
Amount of solid carbon (kg)	0	0,068	0,68
GWP (kgCO$_2$eq/kg)	0,228	0,227	0,224
% of reduction	**0 %**	**0,14 %**	**n/a**

The percentage of GHG reduction is very low with a 5 % incorporation of solid carbon, of about 0,1 %. For the bricks with a 50 % incorporation of carbon, this percentage was not calculated, to highlight the fact that these bricks are probably not load-bearing anymore and should not be compared to common load-bearing clay bricks. It is likely that they have enhanced thermal properties and that they could serve as insulation materials. Further investigation is needed to choose a relevant comparison material or functional unit. In any case, the difference in GWP isn't very significant. This can be due to the fact that the majority of the GHG emissions in brick production comes from their energy-intensive manufacturing process, more than their constituents.

Concerning char plaster, since it was presented in the literature as a material with thermal insulating capacities, the idea was to investigate if it could replace traditional insulating materials. For that purpose, a reference wall was designed, containing reinforced concrete, EPS insulation and a clay plaster. The specifications of the reference wall are provided in Table 5.

Table 5: Main characteristics of the reference wall, allowing for the comparison of the char plaster to EPS insulation

Material	Parameters	Reference
Reinforced concrete	Thickness (mm)	300
	Thermal conductivity (W.m^{-1}.K^{-1})	2,5
	Thermal resistance R (m².K.W^{-1})	0,12
EPS insulation	Thickness (mm)	300
	Thermal conductivity (W.m^{-1}.K^{-1})	0,048
	Thermal resistance R (m².K.W^{-1})	6,3
Clay plaster	Thickness (mm)	10
	Thermal conductivity (W.m^{-1}.K^{-1})	0,70
	Thermal resistance R (m².K.W^{-1})	0,015
Total thermal resistance R (m².K.W^{-1})		0,16

The second step was to calculate the thickness of char plaster which would be needed to entirely replace the plaster and the EPS of the reference wall, while keeping the total thermal resistance of the wall identical. The thermal conductivity of the char plaster is assumed to be 0,19 W.m^{-1}.K^{-1}, which is a value found in the literature (Jiang et al., 2019). Such a calculation would lead to a plaster thickness of 1,2 meters, which is highly unrealistic because, also based on the literature, the maximum thickness of the char plaster should be 200mm (Schmidt, 2008). Based on this result, a new version of the wall was designed, this time by fixing the thickness of the char plaster to 200mm, and compensating the missing thermal resistance by adding EPS. This would lead to an addition of 251mm of EPS, 49mm less than the reference wall. Although this wall would still be thick, its design is already more realistic than the previous one. The characteristics of the wall are provided in Table 6.

Table 6: Main characteristics of the reference wall designed with char plaster and EPS insulation

Material	Parameters	Reference
Reinforced concrete	Thickness (mm)	300
	Thermal conductivity (W.m^{-1}.K^{-1})	2,5
	Thermal resistance R (m².K.W^{-1})	0,12
EPS insulation	Thermal conductivity (W.m^{-1}.K^{-1})	0,048
	Needed thickness (mm)	**251**
Char plaster	Thickness (mm)	**200**
	Thermal conductivity (W.m^{-1}.K^{-1})	0,19
	Thermal resistance R (m².K.W^{-1})	1,03
Total thermal resistance R (m².K.W^{-1})		0,16

For the LCA calculation, the chosen functional unit is a m² of load-bearing wall containing a total thermal resistance of 0,16 m².K.W^{-1}. The Ecoinvent datasets which were used are the following:

- For concrete: "Concrete, high exacting requirements {CH}| concrete production, for building construction, with cement CEM II/A | Cut-off";

- For reinforcing steel: "Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U";

- For EPS insulation: "Polystyrene, expandable {RER}| production | Cut-off, U";

- For the clay plaster: "Clay plaster {CH}| production | Cut-off, U".

Regarding the modelling of the char plaster, solid carbon was assumed to replace sand, and to be incorporated up to 60 % of the total of weight of sand. The quantity of clay was left unchanged. The LCA results are first given in a comparison between the clay plaster and the char plaster, per kg, in Table 7.

Table 7: Results regarding the incorporation of solid carbon in clay plaster, with a clay plaster as a reference

	Reference mix	60 % carbon mix
Amount of clay (kg)	0,25	0,25
Amount of sand (kg)	0,55	0,22
Amount of solid carbon (kg)	0	0,33
GWP (kgCO$_2$eq/kg)	0,028	0,013
% of reduction	**0 %**	**52 %**

Using char plaster as a replacement of clay plaster, without looking at the insulation properties, achieves a high GHG reduction, with 52 %. As a sensitivity analysis, if the reference material was not clay plaster but a base plaster, made out of sand and cement, and if the solid carbon was used to replace sand, the obtained results would be actually quite different, and the reduction would only be of almost 10 % (Table 8). The data used for the base plaster is the Ecoinvent dataset "Base plaster {CH}| production | Cut-off, U". When using char plaster as a pure replacement of plaster, one must therefore be careful about the replaced plaster when calculating the environmental benefits, as it can highly influence the results.

Table 8: Results regarding the incorporation of solid carbon in base plaster, with a base plaster as a reference

	Reference mix	60 % carbon mix
Amount of cement (kg)	0,205	0,205
Amount of sand (kg)	0,772	0,309
Amount of solid carbon (kg)	0	0,463
GWP (kgCO$_2$eq/kg)	0,21	0,19
% of reduction	**0 %**	**9,6 %**

The final bills of quantities of the two modelled walls and LCA results are provided in Table 9.

Table 9: Results regarding the incorporation of solid carbon in clay plaster, at a wall level, taking into account the insulation properties of char plaster

	Reference wall	Wall with char plaster and EPS
Quantity of concrete (kg)	720	720
Quantity of reinforcing steel (kg)	36	36
Quantity of EPS (kg)	4,5	3,8
Quantity of clay plaster (kg)	9	0
Quantity of char plaster (kg)	0	116
GWP (kgCO$_2$eq/m² of wall)	141	140
% of reduction	**0 %**	**0,92 %**

Even when taking the clay plaster as a reference, with which the char plaster had a 52 % reduction in GHG emissions, the difference in emissions at a wall level is negligeable, less than 1 %. This is mainly due to the fact that the quantity of clay plaster in the reference wall was already quite low, but also because a large quantity of char plaster is needed to replace not even a kg of EPS. As a general conclusion, the incorporation of solid carbon in construction materials seems to have a limited influence on their GHG emissions.

6.4. Calculations based on data gathered from the industry

Rough calculations were also performed based on data gathered from the industry, assuming that it would be possible to obtain carbon fibers, which were also presumed not to have any environmental impacts (cut-off approach). Even though our discussions pointed out to the fact that there was a technological gap (to be able to turn the powder into fibers), it is still interesting to investigate the potential GHG reductions, if a solution to this technological gap was to be developed.

The first calculations were based on a document from Technocarbon, which was handed to us by the consulted representative. The document compared a carbon fiber stone (CFS), which they developed, to a high strength steel beam (300 x 20 x 20cm, load of 1460kN / 150t), assuming functional equivalency. The comparison was presented as displayed in Table 10, differentiating the GHG emissions per electricity mix (with the French one or the German one). No unit was given for the "carbon footprint", but we assumed it was calculated in the common kgCO$_2$eq unit.

Table 10: Data provided by Technocarbon

Material	Weight (kg)	"Carbon footprint" – FR electricity mix	"Carbon footprint" – DE electricity mix
CFS	105	14	140
Steel	195	270	301

Interestingly, the GHG emissions of their technology seems to be highly dependent on the electricity mix, which points in the direction of high energy requirements during the manufacturing process. Unfortunately, the provided document did not give more details about the manufacturing process or the methods behind these calculations. High uncertainties thus remain regarding these values, but without any other values to work with, we decided it would still be interesting to adapt these calculations to Austria. For that purpose, the emissions factors for the electricity mixes of France, Germany and Austria were taken from the ecoinvent database ("medium voltage electricity mixes") and are provided in Table 11.

Table 11: Emissions factors for the electricity mixes of France, Germany and Austria

Country	France	Germany	Austria
Emission factor (CO_2eq/kWh)	80,3	600	326

Based on these emission factors, and assuming that this would be the only change in the GWP of the CFS technology, as the data from Table 10 suggested, this would lead to a GWP for the CFS in Austria of 66 kgCO_2eq. By comparing this value with specific data for steel production in Austria (EPD Marienhütte, 2020), **a 23 % reduction** would be achieved. Although this result is promising, it is just a rough estimation based on uncertain data, and more specific calculations should be performed before drawing any conclusions.

A last calculation was carried out based on a technical sheet from Solidian, manufacturer of rebars made out of carbon fibers (64 % of the weight) and epoxy resin (36 %), which was found online[9]. To model these rebars, it was assumed that their manufacturing process (welding, rolling, etc.) was the same as for reinforcing steel. The functional unit which was used for the calculations is one kg of rebar, produced with the current available technology in Austria. For the solidian rebar, the following Ecoinvent datasets were used:

- "Epoxy resin, liquid {RER}| production | Cut-off, U" (adapted for Austria);

- "Hot rolling, steel {RER}| processing | Cut-off, U".

This led to a GWP of 1,94 kgCO_2eq/kg. As for the reinforcing steel, the Ecoinvent dataset representative of Europe was used (reinforcing steel, RER). It has a GWP of 1,99 kgCO_2eq/kg. The difference is relatively small, of **about 2,5 %**. However, the way the Solidian rebar was modelled was approximate and it's possible that the manufacturing

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9   https://solidian.com/downloads/

process is actually different. Furthermore, the technical performances were assumed to be identical, with this functional unit, but this may not be the case. With the Solidian rebar, there would not be the corrosion risk that exists with steel, which means that less concrete would be needed for the same application. Differences in strength can also exist. All these technical parameters might play a significant role in the GHG emissions and should be further investigated in more detailed studies, if this technology is of interest.

6.5.   Conclusion

Producing hydrogen with the methane pyrolysis process would create considerable amounts of solid carbon, for which applications would be needed. When looking into the building sector, through a systematic literature review, three applications for solid carbon (or pyrolysis char) in were identified: the use of the char as a filler for cement or concrete, the use of the char for composite masonry blocks (char bricks) and the use of the char as an insulation material (especially char plasters and coatings). Although solid carbon from methane pyrolysis was not specifically addressed in the literature, it was assumed that it would behave similarly to other types of pyrolysis chars. However, uncertainties remain regarding this assumption and the differences between the types of chars have not been investigated. Using the life cycle assessment methodology, the greenhouse gas emissions of such identified applications of solid carbon were performed and a comparison with traditional materials was made. Overall, the difference in GHG emissions was low; the incorporation of solid carbon in construction materials, therefore, seems to have a limited influence on their GHG emissions. Consultations with experts, however, raised awareness about the need to carry out specific tests with this solid carbon, as it may behave differently than other pyrolysis chars. Additional uses of carbon, in the form of fibers, were also singled out, such as rebars or stone-fibers technologies. No accessible technologies capable of turning carbon powder into fibers exist at the moment but, if a solution to this technological gap was to be developed, these new applications, with eventual higher GHG reduction potentials, could be reached.

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7. WPIII »Volkswirtschaftliche Rückwirkungen« Economic assessment of pyrolysis in Austria: supply and use of hydrogen and implications of carbon usage

Report synthesizing insights for the two sister projects **MUL** (commissioned by Montanuniversität Leoben) and **CarbonUsage** (commissioned by BMK "Bundesministerium für Klimaschutz")

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7.1. Introduction

The economic implications of hydrogen-based options for climate change mitigation in Austria are explored. Three strategies can give guidance in such low-carbon projects, with the strategy "inversion" reversing the approach to start from the actually addressed need, with "innovation" looking for development of also completely new options along the whole value chain, and with "integration" uncovering synergy potentials across sectors, agents and activities (Schleicher and Steininger 2018). In this respect we first estimate plausible amounts of hydrogen demand by 2030, particularly from structural changes endorsed in iron and steel production and freight transportation on the road ("inversion"). Second, we look at the corresponding supply-side options contrasting electrolysis and pyrolysis ("innovation"). On top, we study economic exploitation potentials of solid carbon[1] by-production connected to pyrolysis ("integration"). The economic analysis complements bio-physical (WPI[2] and WPII[3]) and environmental assessments in these projects.

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1 Note that other work packages denote it pyochar.
2 WPI: Work Package I on »Kohlenstoff in der Landwirtschaft«
3 WPII: Work Package II on »Kohlenstoff im Bausektor«

7.2. Data and scenario framework

The following sections specify options of hydrogen usage (2.1), hydrogen supply and solid carbon by-production (2.2), as well as solid carbon usage (2.3) for Austria. The projected year for the economy-wide assessment is 2030 and, where relevant, we give values for 2014, which coincides with the base year of the macroeconomic model, which is explained in Section 3.

7.2.1. Hydrogen usage

For the low-carbon transformation of the **iron and steel sector**[4], European and Austrian industry roadmaps point to hydrogen-based steelmaking. This pathway has been explored extensively in Mayer et al. (2019) and has led to various related research questions and respective assessments (Bachner et al. 2018a; Bachner et al. 2018b; Steininger et al. 2021). We here build on them and assume a partial switch from conventional iron ore reduction (the route blast furnace and basic oxygen furnace BFB) towards hydrogen-based direct reduction (with subsequent processing in electric arc furnaces HDE), with the latter reaching a market share of 30 % of overall Austrian steel production by 2030. The respective operating and capital expenditure components for the unit-cost assessment of both technological options are shown in Table 12. Assuming that overall steel quantities remain at similar levels as currently observed (around 7.8 Mio. Tons per year), hydrogen demand would scale to around 160 thousand tons by 2030. The unit-cost assessment of technologies, including operating and capital expenditures for the respective mix of technologies, is taken from Mayer et al. (2019).

Table 12: Technological data for iron and steel (based on Mayer et al., 2019).

Technology [€/t steel]	BFB	HDE
Total produced steel [t of steel] in 2014	7,876,000	-
Market share 2030 [%]	70 %	30 %
Total produced steel [t of steel] in 2030	5,513,200	2,362,800
H_2 demand* [t H_2]	-	159,218

Note: *67 kg of hydrogen consumption per ton of steel (assuming 0% scrap share).

Hydrogen also plays a role in reducing greenhouse gas emissions in the **sector of freight transportation services on the road**[5]. We use the recent bottom-up assessment provided by Sedlacek et al. (2021), who detail market shares for hydrogen-based driven mileages in Austria specific to certain use-cases by the year 2030. Use cases (UC) represent distinct market segments of road freight transport differentiating *inter alia* groups of carried goods, different mileages, or different characteristics and sizes of vehicles. We take the mileage projection from the mentioned study, which amounts to around

4   OeNACE sector C24 (manufacture of basic metals).
5   Subsector of OeNACE sector H49 (land transport).

22 billion ton-kilometres by 2030 (an increase of around 25 % compared to 2014) and a market share of hydrogen-based propulsion technologies of around 11 % (internal combustion engine ICE and fuel cell electric vehicle FCEV), see Table 13. The remaining share represents diesel trucks. The demand of the freight transportation sector on the road for hydrogen surmounts 18 thousand tons. Details on operating and capital expenditures for respective use cases are given in the reports of Duelli (2021) and Sedlacek et al. (2021). The technological data we draw upon specifically is summarized in Table 13. The cost of hydrogen is determined in the subsequent Section 2.2.

Table 13: Technological data for freight transportation services on the road (based on Sedlacek et al., 2021)

Use	Mio. Tkm		H_2 consumption	Market share			H_2 demand
case	2014	2030	kg/tkm	ICE H_2	FCEV	Diesel	[t]
UC1	50	105	0.039	0 %	3 %	97 %	123
UC2	40	37	0.048	0 %	5 %	95 %	88
UC3	688	892	0.015	0 %	10 %	90 %	1,366
UC4	1,369	3,105	0.012	3 %	5 %	92 %	2,910
UC5	2,637	3,021	0.005	3 %	10 %	87 %	2,006
UC6	2,273	2,649	0.005	3 %	10 %	87 %	1,589
UC7	603	789	0.012	1 %	15 %	84 %	1,564
UC8	523	728	0.013	3 %	10 %	87 %	1,260
UC9	1,412	1,699	0.006	3 %	10 %	87 %	1,362
UC10	1,225	1,263	0.005	3 %	10 %	87 %	787
UC11	1,241	2,292	0.016	0 %	10 %	90 %	3,720
UC12	2,906	3,334	0.004	0 %	5 %	95 %	609
UC13	1,956	1,358	0.008	0 %	10 %	90 %	1,049
Total	16,924	21,272		2 %	9 %	90 %	18,435

7.2.2. Hydrogen supply & solid carbon by-product

In this scenario we analyse an additional (i.e. on top of existing) hydrogen supply of up to 178 thousand tons by 2030 in Austria, with the larger share of its demand devoted to low-carbon steelmaking (90 %) and the remaining share for freight transport on the road as explained in the previous subsection. In this first analysis, we refrain from other potential uses such as in air or motorized passenger transportation or hydrocarbon production together with captured carbon dioxide from the cement sector, as it is currently explored in the C2PAT[6] project, to be used in the (petro)chemical and pharmaceutical industry. On the supply side, hydrogen is produced by either electricity-driven **electrolysis** (polymer electrolysis membrane PEM) or natural gas-fired **pyrolysis** (PYR).

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6   https://innovations.icac.com/carbon2productaustria-c2pat/

We chose reference technologies for both as they are techno-economically described and compared in Parkinson et al. (2018) but adjust the given monetary cost evaluation (in Parkinson et al. (2018) given for the United States) to resemble Austrian framework conditions, also in line with the analysis in WPI and WPII. This mainly concerns electricity and natural gas price assumptions, which we take from Austrian-specific statistics (E-Control 2021).

Interestingly, and for the main comparison with central parameter assumptions, PEM and PYR are similar regarding unit-cost with around 3 EUR per ton of hydrogen, but structurally different, with the former more intensive in capital expenditures and expenses for electricity and the latter relying more on natural gas inputs (Table 14). On top, and in contrast to Parkinson et al. (2018), we assume that PYR is neither directly nor indirectly connected to atmospheric CO_2 emissions by assuming renewable electricity supply on-site or from the market which is required during the production process of hydrogen. However, PYR is connected to the by-production of solid carbon with 3 kg solid carbon per kg hydrogen. Our main assumption is that solid carbon comes at a positive unit-revenue of 38 EUR per ton, which improves the unit-cost differential of PYR relative to PEM due to the additional economic value of the by-product. This positive unit-revenue is derived from the willingness to pay for solid carbon derived for the materials sector as specified and discussed later in Section 2.3.

However, we consider a broad range of solid carbon values to capture its implied sensitivity. For a high estimate, we refer to Hepburn et al. (2019), who give break-even abatement costs of 198 EUR per ton of biochar use in agricultural soil (based on the reported 54 EUR per ton of CO_2 for their low potential scenario)[7]. However, if the particular characteristics of the solid carbon produced as a byproduct of pyrolysis imply that it cannot achieve such positive market values (of neither 38 nor 198 EUR per ton) in the region where it occurs or at the very scale it occurs, pyrolysis could have to pay for carbon depositing. For this lower end estimate, we assume 5 EUR per ton of solid carbon depositing costs (instead of revenues). As a result of this sensitivity we suggest a detailed market analysis for the solid carbon here produced. This will allow to evaluate the likelihood of each of the very different scenarios we here employ, and contribute a fundamental criterion to inform any further pyrolysis decision.

For revealing the sensitivities of the unit-cost comparison between PEM and PYR, we further vary assumptions for prices of electricity and natural gas (taking the minimum, mean and maximum observations of E-Control (2021) for the period 2016–2020), the added value or depositing cost per unit of solid carbon (as specified previously) and the interest to be paid on investment requirements to install respective facilities (i.e. the weighted average cost of capital WACC). By applying three plausible values for the four

7   This rests on the same assumption as indicated in WPI that solid carbon from pyrolysis comes with similar characteristics and soil benefits as biochar, which is why its evaluation rests on several uncertainties.

parameters, this spans a range of eighty-one parameter combinations. The result is shown in Figure 12, where we find the spread between electricity and natural gas prices as the core driving factor of unit-cost differentials (Panel a). Additionally, solid carbon revenue or depositing cost assumptions can shift unit-cost differentials further but are found to play a comparatively minor role. Unit-cost differentials are also less sensitive to assumptions of WACC, as shown in Panel b. Based on this, we develop two extreme cases as upper and lower bounds, as shown in Table 14, where also the respective parameter combinations are visible. Compared to the main assumptions for techno-economics of PEM and PYR, the upper bound specification assumes a world with a low electricity price, a high gas price, a low WACC and a negative solid carbon revenues (i.e. depositing costs), leading to the highest cost disadvantage of PYR relative to PEM. The lower bound specification turns assumptions around. Overall, this leads to a broad range of unit-cost differentials between PYR and PEM of between -39 % to +32 % (incl. solid carbon evaluation).
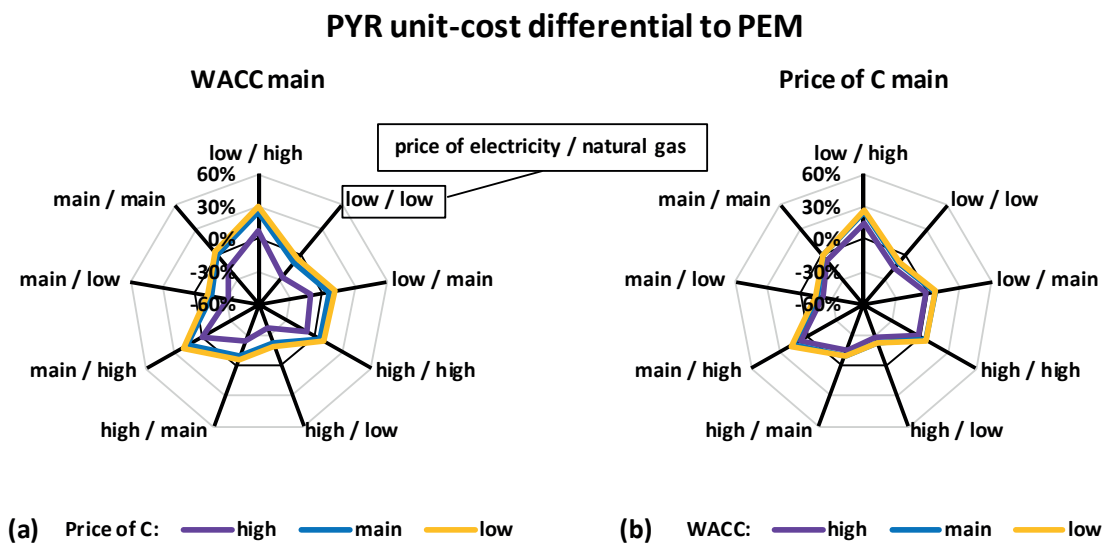

Figure 12: Panels give the percentage difference in the unit-cost of PYR relative to PEM. Panel (a) uses main WACC assumptions comparing different price assumptions for solid carbon (line colors), for electricity (first item) and for natural gas (second item). Similarly, Panel (b) uses main solid carbon price assumptions and varies WACC assumptions (line colors).

Table 14: Techno-economics of electrolysis (PEM) and pyrolysis (PYR) based on Parkinson et al. (2018) and adjusted for Austrian framework conditions; differences in sums are due to rounding

Item	Unit	Main		Sensitivities			
		PEM	PYR	PEM (upper)	PYR (upper)	PEM (lower)	PYR (lower)
Operating expenditures	EUR/t H_2	2,672	2,973	2,393	3,437	3,053	2,611
Electricity price	EUR/MWh	43	43	38	38	50	50
Electricity consumption	MWh/t H_2	55	13	55	13	55	13
Natural gas price	EUR/t CH_4	271	271	337	337	215	215
LNG consumption	t CH4/t H_2	-	8	-	8	-	8
Other	EUR/t H_2	315	261	315	261	315	261
Capital expenditures[31]	EUR/t H_2	383	161	339	143	823	347
Total investment	EUR/t H_2	7,470	3,150	7,470	3,150	7,470	3,150
WACC	I	2 %	2 %	1 %	1 %	10 %	10 %
Lifetime	Y	25	25	25	25	25	25
Unit-cost I (net of taxes)		3,055	3,134	2,732	3,580	3,876	2,958
Solid carbon revenue/depositing cost	EUR/t H_2	-	113	-	15	-	594
Unit-revenue of solid carbon	EUR/t C	38	38	-5	-5	198	198
C by-production	t C/t H_2	-	3	-	3	-	3
Unit-cost II (net of taxes)	EUR/t H_2	3,055	3,021	2,732	3,595	3,876	2,364
Unit-cost differentials	w/o C revenue/cost		2.6 %		31.1 %		-23.7 %
	Total		-1.1 %		31.6 %		-39.0 %

7.2.3. Solid carbon usage

Using pyrolysis for the supply of 178 thousand tons of hydrogen comes with solid carbon by-production of around 534 thousand tons. In the following, we specify solid carbon usage in the **materials**[1] and **agricultural sector**[2]. For simplicity and a first estimate of plausible configurations, we assume that each of the two sectors consumes half of total solid carbon produced.

Table 15: Techno-economics of reference (REF) and 5 % solid carbon enriched (5CM) concrete and bricks production; columns marked with * are based on WPII; differences in sums are due to rounding.

Concrete	REF*	5CM*	REF	5CM	REF	5CM	
						WTP	Actual
	[t] per [t concrete]		totals [kt]		[Mio. EUR]		
Clinker	0.79	0.79	3,888	3,888	203	203	203
Limestone	0.16	0.11	787	541	26	18	18
Carbon	-	0.05	-	246	-	8	9
5CM enriched concrete			4,922	4,922	229	229	230
Total concrete 2014				27,067	WTP [EUR/t]	33	
Carbon usage				246	Cost of C [EUR/t]		38
5CM share in total				18 %	Cost differential		0.5 %
Bricks	**REF**	**5CM**	**REF**	**5CM**	**REF**	**5CM**	
						WTP	Actual
	[t] per [t bricks]		totals [kt]		[Mio. EUR]		
Clay	1.40	1.30	420	390	27	25	25
Sand	0.02	-	4	-	0	-	-
Carbon	-	0.07	-	20	-	2	1
5CM enriched bricks			300	300	27	27	26
Total bricks 2014				1,652	WTP [EUR/t]	95	
Carbon usage				20	Cost of C [EUR/t]		38
5CM share in total				18 %	Cost differential		-4.0 %

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1 OeNACE sector C23 (manufacture of other non-metallic mineral products).
2 OeNACE sector A01 (crop and animal production, hunting and related service activities).

We assume that construction materials are enriched with solid carbon as specified in WPII. For the economic evaluation, we focus on solid carbon use in concrete and bricks only. The reference mix (REF) and the 5 % carbon mix (5CM) for both materials are shown in Table 15 and scaled to Austrian production figures of the base year taken from WKO (2016). Around 18 % of total concrete and bricks production is assumed to be enriched with solid carbon by 2030. By adopting average prices for clinker (0.05 EUR/kg), limestone (0.03 EUR/kg), clay (0.06 EUR/kg) and sand (0.01 EUR/kg), the cost of REF and 5CM can be compared to each other. The 5CM standard for both subsectors concrete and bricks would imply an average willingness to pay (WTP) of 38 EUR per ton of solid carbon to keep the aggregate material sectors production costs constant.[3] In the macroeconomic evaluation of the main scenario, we assume that the 5CM mix comes as a top-down material standard leading to the intake of solid carbon and keeping benchmark sectoral productivity constant. This may nevertheless imply eventual productivity losses (gains) for the concrete (bricks) subsector as its WTP is lower (higher) than for the aggregate materials sector. However, with the upper (lower) bound scenario and its distinct assumption on the solid carbon value of -5 (198) EUR per ton given in Table 14, productivity changes. Accounting for the implied unit-cost differential at the subsector level of concrete and bricks production and their together 12 % turnover share in the OeNACE C23 sector (Eurostat 2021), the corresponding change in productivity is -0.5 % (2 %) for the upper (lower) bound scenario. Implicitly, the materials sector gets paid in the upper scenario for "disposing" solid carbon.

Total arable land in Austria amounts to 1.3 million hectares. Deploying 60 tons of solid carbon per hectare land (Genesio et al. 2012) gives a total solid carbon use potential of 78 million tons. Within our scenario framework, 0.3 % of this overall potential is used for soil amendment with solid carbon produced in the single year of 2030, corresponding to 4,400 ha of arable land. Thereafter, and on the very same soil, only additions amounting to natural decay lasting several decades would be possible. Note that the cumulative impact would rather imply 7.5 % of overall potentials with a lifetime of pyrolysis facilities of 25 years and the chosen capacity to supply hydrogen demands. For the main scenario, and assuming a value of 38 EUR per ton of solid carbon, around 10 Mio. EUR represent solid carbon uptake by agriculture in our scenario for 2030. For the upper (lower) bound scenario given in Table 14 with -5 (198) EUR per ton of carbon, this estimate scales to -1.3 (53) Mio. EUR. Hence, the agricultural sector gets paid in the upper scenario for solid carbon "disposal". For the macroeconomic assessment, we do not touch on benchmark productivity for the agricultural sector because changes in the organic composition of soil and its quality are yet unclear as are variations in corresponding yields (i.e. productivity gains or losses). The WPI explores different aspects and plausible outcomes but given the described limitations, we stick to this most "neutral" assumption.

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3   (8,000+2,000) [th. EUR] / (246+20) [kt materials].

7.3. Method and scenario implementation

7.3.1. WEGDYN-AT CGE model

For the macroeconomic assessment of the supply and use of hydrogen and the implications of carbon usage, we use the WEGDYN-AT model (Mayer et al. 2021). It is a recursive-dynamic computable general equilibrium (CGE) model representing Austria as a small open economy. Firms maximize profits under perfect competition and constant returns to scale, while private and public households maximize utility from consumption. The model is calibrated to a social accounting matrix (SAM) of the year 2014, which includes 72 NACE-classified economic sectors, 12 private households and one public household. We implement a minimum wage, which mirrors the choice between, on the one hand, the willingness to work more due to actual wages (tied to the consumer price index) rising above reservation wages or, on the other hand, shirking ("voluntary unemployment"). Hence, we do not account for (seasonal, frictional or business-cycle related) problems of matching labour supply and demand leading to short-run involuntary unemployment. Further model details can be found in the given reference.

Gross domestic product (GDP) of the reference point in 2030 is calibrated (1.5 % p.a. relative to 2014) using exogenous assumptions for the growth of the effective labour force (1 % p.a.) and endogenous capital accumulation achieved by endogenous growth of total factor productivity. Energy inputs in economic activities are assumed to follow an autonomous trend of energy efficiency improvements (1.5 % p.a.). On top of the calibration procedure, structural changes (or local "shocks") are implemented as described in section 3.2, which allows to assess the trend deviation induced by changes in relative prices relative to the constructed reference point in 2030.

7.3.2. Scenario summary

For the economy-wide assessment of both routes of hydrogen production, we construct a reference point in 2030, in which a newly introduced subsector PEM supplies hydrogen. Its monetarized hydrogen output is demanded by the HDE technology of the iron and steel sector (hydrogen-based direct reduction and electric arc furnace) as well as the service sector of freight transport on the road (cf. Section 2.1). We compare the PEM reference to a scenario switching off PEM but activating PYR implementing the corresponding changes in unit-cost and the structural shifts in inputs as described in Table 14 of Section 2.2. In addition, the scenario activates by-production of solid carbon and its deployment in agricultural soil and construction materials (cf. Section 2.3). Note that the reference is calibrated using PEM cost assumptions. Hence, the change in hydrogen prices for steel and freight transport comes in as an endogenous response when switching to PYR. A summary of the main scenario comparison, isolating the

economy-wide effects of PYR relative to PEM, is shown in Table 16. As described for the unit-cost differentials of hydrogen production by PEM and PYR in Section 2.2, we change the underlying assumption of the evaluated solid carbon for upper and lower bound scenarios and do so for solid carbon demanding sectors accordingly.

Table 16: Scenario summary.

Directly affected sector		PEM 2030	PYR 2030
Supply	of hydrogen	by electrolysis (PEM)	by pyrolysis (PYR)
	of solid carbon by-product	No	Yes
Demand	of iron and steel for	H_2	H_2
	of road freight transport for	H_2	H_2
	of agriculture for	-	C
	of materials for	-	C

The following hypothesis are to be tested. In a *first* step, we refrain from the by-production of solid carbon and look at the direct and indirect effects of introducing the slightly costlier PYR technology. If direct effects dominate, H_2 prices will be slightly higher as the PYR technology requires more inputs for the same output. *Secondly*, by introducing carbon usage in materials and agricultural soils, more value can be extracted from the same inputs in hydrogen production, which renders PYR more productive, and H_2 prices will be lower. *Thirdly*, policymakers worldwide increasingly use carbon pricing as one out of several climate policy instruments for addressing emissions (World Bank 2020). This also pertains to Austria for which the corresponding indirect effects induced by carbon pricing (i.e. relative price effects on input and factor markets) might change the unit-cost differential of PEM and PYR, another reason to apply and merit of a computable general equilibrium (CGE) model. Hence, we introduce a CO_2 price of 100 EUR/t CO_2 in Austria by 2030, affecting all production-based emissions (i.e. domestic sectors covered by the EU ETS and under national effort sharing regulations). This is done for the reference run with PEM and the alternative run with PYR, which again allows isolating implications of switching from PEM to PYR (including solid carbon usage) but in a world including climate policy framework conditions. *Finally*, we test the combined economy-wide effect of lower hydrogen prices due to the switch from PEM to PYR on the one hand and the implied changes of productivity in the materials sector due to the mandated 5CM mix on the other hand.[4]

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4 Note that we do not deliberately change the electricity mix in our macroeconomic evaluation and allow only for model-endogenous adjustments based on the models' default functionalities (Mayer et al. 2021). Hence, there still is a substantial share of fossil-fired power generation. We neglect from such an additional adjustment, because we are interested in the isolated effect of switching from PEM to PYR, which would not change whether or not assuming a fully climate-neutral electricity system by 2030 in the "background".

7.4. Results

7.4.1. Hydrogen supply & downstream effects

Switching from PEM to PYR hydrogen production is associated with an increase of unit-cost by +2.6 % (Figure 13). Implementing PYR instead of PEM means that the economic structure is less capital- and less electricity-intensive, inducing lower indirect price deviations. Hence, indirect effects lead to a hydrogen price increase of only +0.9 %. The additional value of solid carbon usage leads to a productivity gain with a price advantage compared to PEM-based hydrogen of -2.6 %. With framework conditions including CO_2 pricing, conventional use of natural gas in production becomes more expensive. This raises natural gas prices already in the reference with PEM, a price pressure, which is less pronounced with PYR because natural gas can be used productively not as fuel but as a resource not bearing the burden of CO_2 pricing. Consequentially, the PYR competitiveness rises even further with a price differential of -4.2 %. However, overall there is a strong sensitivity with respect to unit-cost projections and the underlying assumptions of energy price differentials (mainly natural gas prices). Hydrogen prices range in between -38 % to +27 % for the lower and upper bound scenarios, respectively.
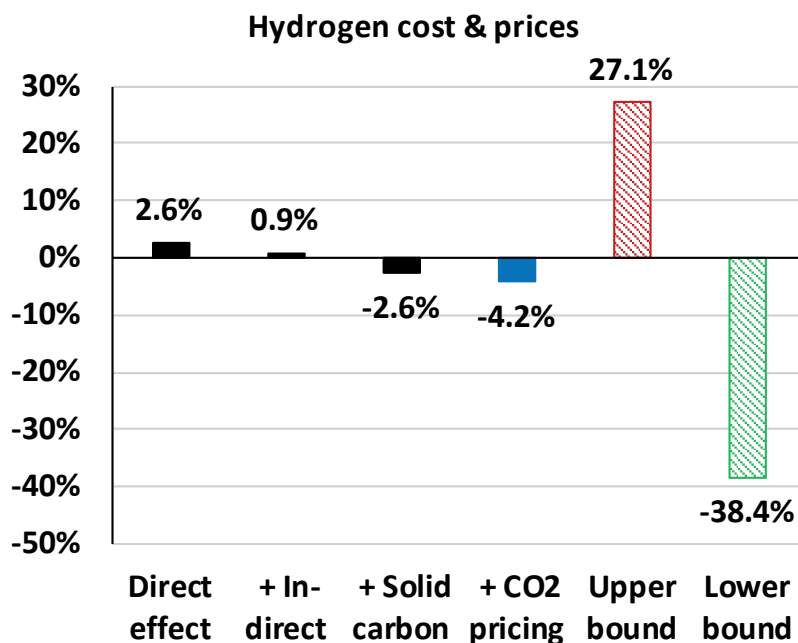
Figure 13: Comparison of hydrogen cost and price effects for PYR relative to PEM; direct effects (unit-cost) and price effects with stepwise inclusion of indirect effects (endogenous demand), solid carbon usage (value of by-product) and CO_2 pricing. The blue bar represents main scenario assumptions including all components and the red (green) bar indicates the upper (lower) bound scenario.

After the stepwise isolation of effects from direct plus indirect plus solid carbon value plus CO_2 pricing, we focus in Figure 14 on the main scenario specification and the upper

and lower bound variants. With a 30 % share of HDE (hydrogen-based direct reduction and electric arc furnace) in primary steelmaking, also steel mix prices react in the same direction as hydrogen but to a smaller extent because it only accounts for 33 % of HDE OPEX. Respective turnover effects mirror price effects. With a 10 % share of hydrogen-based propulsion technologies in the service sector of freight transportation on the road, we derive price and turnover effects in the same direction as for steel but they are less responsive as hydrogen accounts for only 3 % of the sectors overall OPEX. There is no relative price change for solid carbon as it does not exist in the "reference world" of PEM. However, solid carbon usage affects only the sectoral composition of agriculture but the intake is calibrated to neutral productivity changes due to the underlying uncertainty with respect to changes in yields. Almost invisible price and turnover effects represent the *indirect* effects from the general equilibrium. By contrast, solid carbon usage in the materials sector affects sectoral composition and its productivity, leading to increased prices and lower turnovers. This is particularly pronounced in the lower bound scenario with high assumptions for solid carbon values. Hence, a trade-off between prices for hydrogen and construction materials emerges.
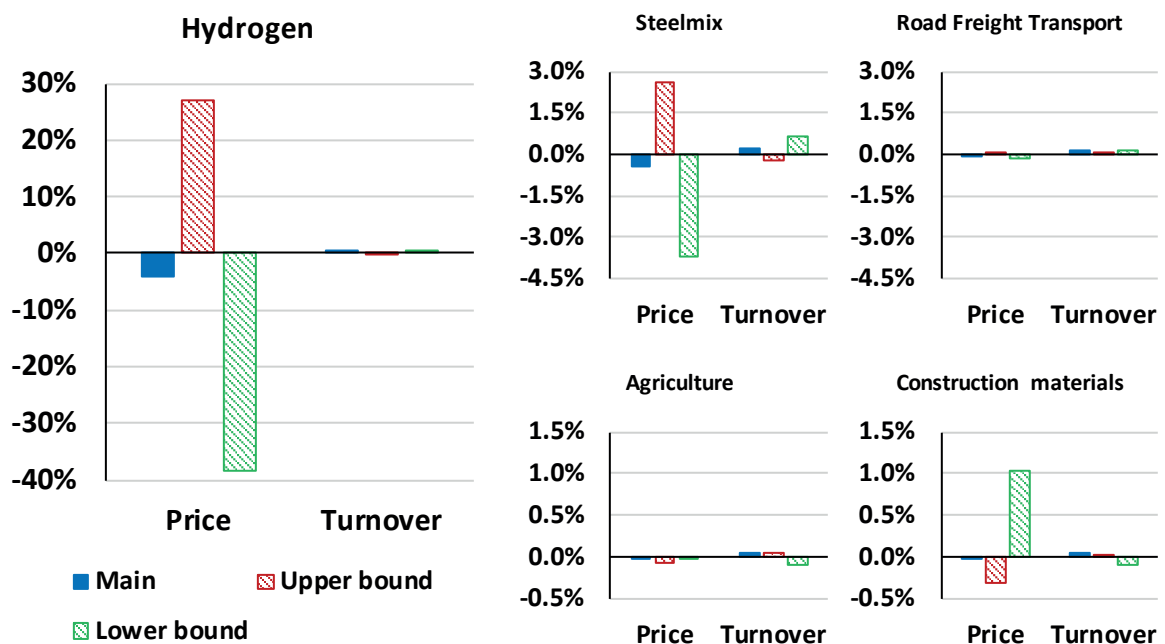
Figure 14: Comparison of price and turnover effects PYR relative to PEM for hydrogen supply (left Panel), hydrogen demand (top right panels) and solid carbon demand (bottom right panels); note different scaling of ordinates.

7.4.2. Sector distributional impacts

We explore sector distributional impacts by looking at larger groups of OeNACE sectors in Figure 15. A complete list of economic sectors and the corresponding aggregation can be found in Table A. 1 of the Appendix. There is a substantial structural shift away from electricity (ELYs) towards natural gas supply (GASs). Further impacts are visible

for the fossil fuel and mineral extraction sector, including upstream natural gas exploration (FMRO). The remaining sectors are less affected in terms of prices and turnover for the main scenario. Positive (negative) impacts are stronger with the upper (lower) scenario.
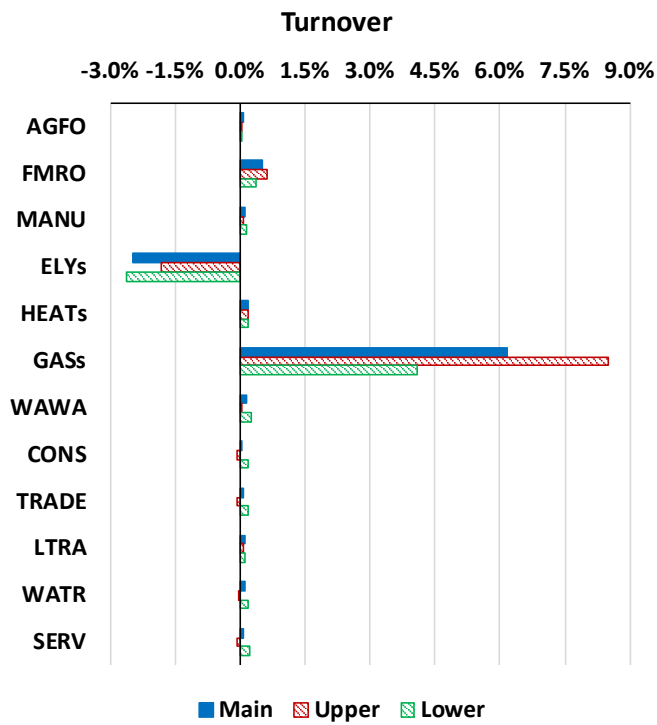
Turnover

Figure 15: Comparison of impacts on sector turnover PYR relative to PEM.

7.4.3. Macroeconomic implications

At the macroeconomic level, gross domestic product (GDP) effects in 2030 are very small but mirror productivity changes of PYR relative to PEM with positive effects in the main and lower scenario, respectively (Figure 16). Welfare[5] implications across scenar-

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5   Welfare measures consumption possibilities of households (private and public) and is often denoted Hicksian equivalent variation. It measures the willingness to pay (accept) for the assessed structural changes (not) to happen.

ios are less pronounced than changes in GDP due to relative price effects but point in the same direction. Economy-wide productivity gains also translate into increased employment (Figure 17).
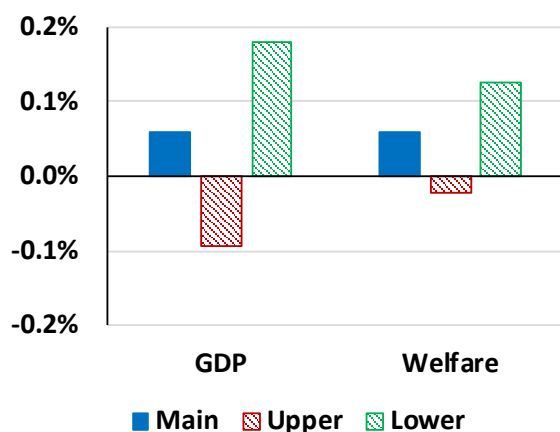
Figure 16: Comparison of GDP and welfare implications PYR relative to PEM.
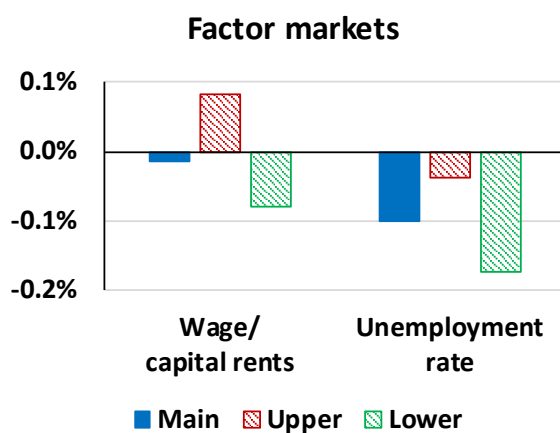
Figure 17: Comparison of impacts on factor markets PYR relative to PEM.

7.5. Discussion and Conclusions

Based on current estimates of techno-economic configurations, the following findings apply at the macroeconomic scale. Pyrolysis (PYR) requires much less electricity per ton of hydrogen than electrolysis (PEM). This could be relevant in the broader energy transition context with restricted (domestic) renewable electricity potentials, which

also implies less pressure on electricity prices (not shown here explicitly). PYR also reduces additional capital demand because existing natural gas networks and infrastructure can be used, which is also visible in a relatively higher demand for labour. Contrary, PEM is relatively more attractive considering the current financing environment with low finance costs (expressed in weighted average cost of capital). A strong caveat relates to the related homogeneous finance cost assumptions for PEM and PYR, which might not be the case, e.g. due to different (geo-)political risks associated with them.

The competitiveness of PYR relative to PEM largely depends on the natural gas price development and, again, associated (geo-)political framework conditions. This is especially relevant, as Austria strongly relies on natural gas imports. The recent surge in natural gas prices due to stronger than anticipated economic recovery after Corona-related crises measures underpins Europe's and Austria's weaker position in this imperfect energy market relative to foreign suppliers. With current natural gas prices in the European wholesale market having more than doubled recently to around 50 EUR/MWh (Tagliapietra and Zachmann 2021), even the upper bound scenario considered here would underestimate the cost disadvantage of pyrolysis considerably and consequentially also macroeconomic impacts. Also, Austrian biogas potentials with around 20 TWh (Baumann et al. 2021) are also insufficient to mitigate import dependencies, because hydrogen use in steel industry with around 30 % penetration and road freight transport with around 10 % penetration (in the here assumed scenarios for 2030) would already require the very same amount of methane for pyrolysis-based hydrogen supply.

Overall, macroeconomic impacts are small based on current techno-economic estimates but point to different sector distributional outcomes, with PYR to the benefit for the supply of natural gas and PEM to the benefit of electricity supply. Changes in productivity of hydrogen supply have stronger impacts on steel prices and fewer effects on prices of the services for freight transportation on the road. The eventually materializing additional value of solid carbon usage is assumed to fully offset productivity changes in the agricultural sector due to incomplete knowledge and the large variety of potential effects from a bottom-up perspective. Actual changes in agricultural yields may unfold in both directions, with losses and gains amplifying or compensating each other at the macro level. Similarly for the materials sector, for which we provide a first bottom-up unit-cost perspective and derive indications that, and in the Austrian context, the willingness to pay for solid-carbon enriched concrete and bricks is lower than the abatement cost of solid carbon usage in agriculture, confirming the findings of Hepburn et al. (2019).

Finally, the investigated nascent technologies for producing hydrogen as well as a market for solid carbon are yet under development and subject to upscaling with probably different learning rates during that phase. Under investigated framework conditions, a mandated standard in the materials sector to use solid carbon byproducts would likely raise the cost of materials and reduce economy-wide productivity. Solid carbon usage in general, and for the agriculture and materials sector in particular, needs further basic research efforts to narrow down their (bio-)physical and economic implications as well as required framework conditions to let their potentials materialize, which are clearly distinct compared to an exclusively electrolysis-based pathway of hydrogen supply. An additional and dedicated market analysis for carbon usage is thus – in addition to the market evaluation of the natural gas price development – relevant for deciding between electrolysis- and pyrolysis-based development pathways.

7.6. References

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7.7. Appendix

Table A. 1: List of economic sectors in the WEGDYN-AT CGE model.

Aggre-gate	Model sector	OeNACE code	Description
AGFO	AGRI	A 01	Crop and animal production, hunting and related service activities
	FORE	A 02	Forestry and logging
	FISC	A 03	Fishing and aquaculture
FMRO	FEXT	B 05-07; C 19	Mining of coal and lignite; Extraction of crude petroleum and natural gas; Manufacture of coke and refined petroleum products
	MEXT	B 08-09	Other mining and quarrying
	FOOD	C 10	Manufacture of food products
	BEVE	C 11 - C 12	Manufacture of beverages
	TEXT	C 13	Manufacture of textiles
	CLOT	C 14	Manufacture of wearing apparel
	LEAT	C 15	Manufacture of leather and related products
MANU	WOOD	C 16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
	PAPE	C 17	Manufacture of paper and paper products
	PRNT	C 18	Printing and reproduction of recorded media
	CHEM	C 20	Manufacture of chemicals and chemical products
	PHAM	C 21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
	PLAS	C 22	Manufacture of rubber and plastic products
	GLAS	C 23	Manufacture of other non-metallic mineral products
	META	C 24	Manufacture of basic metals
	MAME	C 25	Manufacture of fabricated metal products, except machinery and equipment
	MAED	C 26	Manufacture of computer, electronic and optical products
	MAEL	C 27	Manufacture of electrical equipment
	MACA	C 28	Manufacture of machinery and equipment n.e.c.
	MAVE	C 29	Manufacture of motor vehicles, trailers and semi-trailers
	MAVO	C 30	Manufacture of other transport equipment
	MAFU	C 31	Manufacture of furniture
	MAOT	C 32	Other manufacturing
	MARE	C 33	Repair and installation of machinery and equipment

Table A. 1 (ctd.): List of economic sectors in the WEGDYN-AT CGE model.

Aggregate	Model sector	OeNACE code	Description
ENER	ELYS		Electricity supply
	HEATS	D 35	Heat supply
	GASS		Natural gas supply
WAWA	WATE	E 36	Water collection, treatment and supply
	WAST	E 37-39	Rest of E
CONS	BUIL	F 41	Construction of buildings
	CIEN	F 42	Civil engineering
	CONT	F 43	Specialised construction activities
TRADE	TRCA	G 45	Wholesale and retail trade and repair of motor vehicles and motorcycles
	TRWH	G 46	Wholesale trade, except of motor vehicles and motorcycles
	TRRE	G 47	Retail trade, except of motor vehicles and motorcycles
LTRA	RAILPT		Rail passenger transport
	RAILFT		Rail freight transport
	ROADPT	H 49	Road passenger transport
	CITYPT		City passenger transport
	ROADFT		Road freight transport
	LTrest		Land transport rest
WATR	WTRA	H 50	Water transport
	ATRA	H 51	Air transport
SERV	STRAIL		Warehousing and support activities for rail transportation
	STROAD	H 52	Warehousing and support activities for road transportation
	STREST		Warehousing and support activites for other transportation
	POST	H 53	Postal and courier activities
	ACCO	I 55-56	Accomodation and food service activities
	SPUB	J 58	Publishing activities
	CINE	J 59	Motion picture, video and television pro-gramme production, sound recording and music publishing activities
	BRDC	J 60	Programming and broadcasting activities

Table A. 1 (ctd.): List of economic sectors in the WEGDYN-AT CGE model.

Aggre-gate	Model sector	OeNACE code	Description
SERV	TELE	J 61	Telecommunications
	SITC	J 62-63	Computer programming, consultancy and related activities; Information service activities
	SFIN	K 64	Financial service activities, except insurance and pension funding
	INPE	K 65	Insurance, reinsurance and pension funding, except compulsory social security
	SFIO	K 66	Activities auxiliary to financial services and insurance activities
	REAL	L 68	Real estate activities
	LEGA	M 69	Legal and accounting activities
	CNSU	M 70	Activities of head offices; management consultancy activities
	ARCH	M 71	Architectural and engineering activities; technical testing and analysis
	RADE	M 72	Scientific research and development
	ADVT	M 73	Advertising and market research
	FREO	M 74-75	Other professional, scientific and technical activities; Veterinary activities
	SRNT	N 77	Rental and leasing activities
	SLAB	N 78	Employment activities
	TRAV	N 79	Travel agency, tour operator and other reservation service and related activities
	SECO	N 80-82	Rest of N
	PUBL	O 84	Public administration and defence; compulsory social security
	EDUC	P 85	Education
	HEAL	Q 86	Human health activities
	NURS	Q 87-88	Residential care activities; Social work activities without accommodation
	ARTS	R 90	Creative, arts and entertainment activities
	CULT	R 91	Libraries, archives, museums and other cultural activities
	GMBL	R 92	Gambling and betting activities
	SPOR	R 93	Sports activities and amusement and recreation activities
	ASSO	S 94	Activities of membership organisations
	UREP	S 95	Repair of computers and personal and household goods
	SOTH	S 96	Other personal service activities