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CarNe - Carbon Negative Biochar-based Building Insulation Materials

Techno-economic and ecological feasibility

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Zusammenfassung

Dieses Forschungsprojekt untersucht die Machbarkeit eines biobasierten, CO_2-negativen Gebäudedämmstoffs. Die durchgeführte Materialentwicklung basiert auf der Verwendung von organischem Abfallmaterial, das mit natürlichen Bindemitteln und einem anschließenden Karbonisierungsschritt weiterverarbeitet wird.

Die Untersuchung liefert eine umfassende Analyse der potenziellen Abfallströme in der Schweiz für die Entwicklung von CO_2-negativen Dämmstoffen. Pferdemist erwies sich als optimaler Abfallstrom für die Herstellung von thermisch leistungsfähigen Dämmstoffen, die sich durch niedrige Entstehungskosten und einen geringen ökologischen Fußabdruck auszeichnen. Es konnten durchgängig Wärmeleitfähigkeiten von 0,035 W/(m·K) gemessen werden. Die Untersuchungen bestätigten auch die Reziklierbarkeit von gebrauchtem Dämmmaterial, was zu einer Verringerung der thermischen Leistung um etwa 20 % führte.

Die Forschung zeigt die grosse Bedeutung des Bindemittels für die ökologische Gesamtleistung des Dämmstoffs. Während Gluten aus technischer Sicht das beste der untersuchten natürlichen Bindemittel war, ergaben sich durch die Produktion von Gluten ein hohes Treibhauspotenzial sowie weitere relevante Umweltauswirkungen (Eutrophierung, Versauerung, Landnutzung) durch die landwirtschaftliche Produktion des Rohstoffs Weizen. Tiefere allgemeine Umweltauswirkungen aber dafür höhere Treibhausgasemissionen werden mit einem PVAc-basierten Kleber erreicht. Für die zukünftige Entwicklung wäre es wünschenswert alternative Bindemittel zu finden, die ebenfalls auf biogenen Abfall- oder Nebenströmen basieren, um trade-offs zu vermeiden und die allgemeinen Umweltauswirkungen des Dämmstoffs möglichst niedrig zu halten.

Betrachtet man nur die Produktion und Entsorgung von Dämmstoffen, so ist die Klimabilanz von CarNe-Materialien vergleichbar mit der von herkömmlichen Dämmstoffen auf fossiler Basis. Dies ändert sich jedoch, wenn die Möglichkeit der dauerhaften Kohlenstoffspeicherung in den biobasierten Dämmstoffen berücksichtigt wird. Basierend auf der Verfügbarkeit der Abfallströme zeigt das CarNe-Dämmmaterial für die Schweiz ein signifikantes jährliches Potential für Negativemissionen von -113'000 t CO_2-eq und 194'000 t CO_2-eq für Pferdemist bzw. Siebüberlauf. Dies entspräche der Dämmung von ca. 3 resp. 7.8 million m^2 Gebäudeflächen mit einem U-Wert von 0.15 $W/(m^2{\cdot}K)$.

Résumé

Ce projet de recherche étudie la faisabilité d'un matériau d'isolation des bâtiments biosourcé et neutre en CO_2. Le développement du matériau est basé sur l'utilisation de déchets organiques qui sont ensuite traités à l'aide de liants naturels et d'une étape ultérieure de carbonisation.

La recherche fournit une analyse approfondie des flux de déchets potentiels en Suisse pour le développement de matériaux d'isolation négatifs en carbone. Le fumier de cheval s'est avéré être un flux de déchets optimal pour la fabrication de matériaux isolants thermiquement performants, caractérisés par de faibles coûts de production et une faible empreinte écologique. Des conductivités thermiques de 0,035 W/(m·K) ont été mesurées en permanence. Les recherches ont également confirmé la recyclabilité des matériaux isolants usagés, ce qui a entraîné une réduction de la performance thermique d'environ 20%.

La recherche montre la grande importance du liant pour la performance écologique globale de l'isolant. Alors que le gluten était le meilleur des liants naturels étudiés d'un point de vue technique, sa production a entraîné un potentiel de réchauffement global élevé ainsi que d'autres impacts environnementaux importants (eutrophisation, acidification, utilisation des terres) dus à la production agricole de la matière première, le blé. L'impact environnemental général est plus faible mais les émissions de gaz à effet de serre sont plus élevées avec un adhésif à base de PVAc. Pour le développement futur, il serait souhaitable de trouver des liants alternatifs, également basés sur des

déchets biogènes ou des flux secondaires, afin d'éviter les trade-offs et de maintenir l'impact environnemental général de l'isolant aussi bas que possible.

Si l'on considère uniquement la production et l'élimination des matériaux d'isolation, le bilan climatique des matériaux CarNe est comparable à celui des matériaux d'isolation traditionnels à base de combustibles fossiles. Cependant, cela change si l'on tient compte de la possibilité de stocker durablement du carbone dans les matériaux d'isolation biosourcés. En se basant sur la disponibilité des flux de déchets, le matériau d'isolation CarNe montre un potentiel annuel significatif d'émissions négatives pour la Suisse de

-113'000 t CO_2-eq et 194'000 t CO_2-eq pour le fumier de cheval ou le débordement de tamis. Cela correspondrait à l'isolation d'environ 3, respectivement 7,8 millions de m2 de surfaces de bâtiments avec une valeur U de 0,15 W/(m2·K).

Summary

This research project evaluates the techno-economic and ecological feasibility of bio-based, carbon negative building insulation material. The material development is based on the use of organic waste material which is further processed using natural binders and a subsequent carbonization step.

The research provides an extensive analysis of potential waste streams in Switzerland for the development of carbon negative insulation materials. Horse manure emerged as the optimal waste stream for the creation of thermally high performing insulation material featuring low source cost and a small ecological footprint. Thermal conductivities as low as 0.035 W/(m·K) could be consistently measured. The research also verified the recyclability of used insulation material, leading to a decrease in thermal performance of about 20%.

The research shows the great importance of the binder for the overall ecological performance of the insulation material. While gluten was the best of the natural binders investigated from a technical point of view, the production of gluten resulted in a high global warming potential and other relevant environmental impacts (eutrophication, acidification, land use) due to the agricultural production of the raw material wheat. Lower general environmental impacts but higher greenhouse gas emissions are achieved with a PVAc-based adhesive. For the future development, it would be desirable to find alternative binders that are also based on biogenic waste or side streams in order to avoid trade-offs and keep the general environmental impact of the insulation material as low as possible.

When only looking at production and disposal of insulation materials, the global warming potential (carbon footprint) of CarNe materials is comparable to that of traditional fossil-based insulation materials. This changes when the permanent carbon storage opportunity of the bio-based insulation materials is considered. Based on the availability of the waste streams, for Switzerland, the CarNe insulation material showed a significant annual carbon removal potential of -113’000 t CO_2-eq and 194’000 t CO_2-eq for horse manure and sieve overflow, respectively. This would correspond to the insulation of approx. 3 or 7.8 million m^2 of building surfaces with a U-value of 0.15 W/(m^2-K).

Contents

Abbreviations

- **CH_4:** Methane
- **CO_2:** Carbon Dioxide
- **DQRv2:2022:** Database Quality Guidelines version 2, 2022
- **EBC:** European Biochar Certificate
- **EF:** Environmental Footprint
- **EN:** European Norm
- **EPS:** Expanded Polystyrene
- **FM:** Fresh Matter
- **GLO:** Global
- **GWP:** Global Warming Potential
- **IPCC:** Intergovernmental Panel on Climate Change
- **ISO:** International Organization for Standardization
- **KBOB:** Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (Coordination Conference of the Construction and Property Agencies of the Public Building Owners)
- **LCA:** Life Cycle Assessment
- **LCIA:** Life Cycle Impact Assessment
- **LRV:** Luftreinhalte-Verordnung (Air Pollution Control Ordinance)
- **OCDE:** Organisation for Economic Co-operation and Development
- **PAH:** polycyclic aromatic hydrocarbon
- **PIR/PUR:** Polyisocyanurate/Polyurethane
- **PVAc:** Polyvinyl Acetate
- **RER:** Rest of Europe
- **TGA:** Thermogravimetric Analysis
- **U-value:** Thermal Transmittance
- **XPS:** Extruded Polystyrene
- **σ10:** Stress at 10% Strain
- **w%:** Weight Percent

1 Introduction

1.1 Background information and current situation

The building industry accounts for a large part of resource use, with globally 4.7 t of limited mineral materials per capita and year (OCDE, 2019). At the same time, 140 Gt of organic waste are accrued every year (Tripathi et al., 2019). From this organic waste, biochar can be created via pyrolysis, releasing process gas usable for heat or electricity production. By variation of the pyrolysis parameters, the properties of biochar can be tuned to high porosity, low thermal conductivity, high mechanical strength and/or high solar absorptance. This opens the field for new, bio-based materials for the building sector and its application e.g. as thermal insulation.

Several examples for the exploitation of organic waste streams for material development employing pyrolysis can be found in literature. Yuan et al. (2016) pyrolysed wheat bread and achieved thermal conductivities down to 60 mW/(m·K) and high compressive strength up to 3.6 MPa. Similar mechanical properties were reproduced using bread- and cake-based carbon foams (Mountain-Tuller, 2018). Part of the wheat flour can be substituted by ground rice husk, an agricultural waste product (Lazzari et al., 2019)[1] demonstrating the possibility of using waste materials as ingredients to create carbon foams.

These examples indicate that biochar likely is a promising raw material for the development of thermal insulation. However, it is also clear that the used raw materials are not suitable for large scale application in the building sector since they are food and hence their use would endanger food supply and result in too high cost for the insulation. Furthermore, the reported insulation performances are not competitivie for mass market application.

Hence, lower value biomass should be considered as possible raw materials for biochar insulation. In Switzerland, there is a high theoretical potential for the use of biomass by-products or waste for material synthesis. According to an analysis of WSL (Thees et al., 2017) there is 613 kt forest waste wood, 156 kt landscaping waste wood, 26 kt untreated waste wood, 132 kt agricultural by-products (mostly chaff) and 1529 kt animal manure. Of course, the increasing competition for biomass to be used as raw material for products as well as for energy generation needs to be taken into account.In recent years, biochar has gained attention in research as well as in industry because of its porous nature and thus its thermally insulating property, but also because of its capacity to bind atmospheric CO_2. In this sense, there are several activities reported where biochar is used as an additive e.g. in concrete or conventional insulation materials.

A commercial company called Carbonauten (https://carbonauten.com/) entered the market in 2017 with the production of biochar plants for the so called “minus CO_2 factory”. More specifically, in the domain of biochar-based materials development, the startup company Kohlenkraft (https://kohlenkraft.ch/) was founded in 2023, offering building insulation material and insulating plaster as well as acoustic absorbers and paints. For the insulating plaster a thermal conductivity of 0.08 W/(m·K) is indicated, for the insulation materials no technical specification is found so far.

In conclusion, the use of biochar as a precursor for synthesis of materials for a broad spectrum of applications is gaining momentum and first competitors in the domain of biochar-based insulation materials are entering the market. For a true comparison of the material developments, a detailed technical specification would be needed, which is not available for the moment. In order to offer a competitive biochar-based insulation material, the thermal conductivity is key and needs to be in the same range as today’s conventional insulation materials with values in the order of 0.035-0.04 W/(m·K). The material development pursued in this project thus follows the target of synthesizing a

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[1] The authors report thermal conductivities of their wheat/ rice-husk pyrolysed foam of around 20 mW/(m·K). In porous solids such low thermal conductivities can only be achieved by using a low-thermal conductivity filler gas or by creating an aerogel-like pore structure, both of which is clearly not the case in the reported study. Hence, the data cannot be taken at face value.

biochar-based insulation material with a competitive performance and its added potential for carbon negativity when stored in the soil after its use phase in the building.

1.2 Purpose of the project

We propose to use biochar to design novel, carbon negative building materials (CarNe materials) and components for application as thermal insulation, and at a later stage drywall boards based on the shaping into boards and a pyrolysis process. The goal is to arrive at a relatively low-tech, low-cost and simple way to produce building materials and components based on abundantly available organic waste or low-value materials.

Utilization of carbon neutral organic materials for production of functional building materials within an upcycling process has the potential to significantly reduce embodied emissions in construction and further store carbon for long time, leading to a net negative carbon balance. Such carbon dioxide removal is a key feature for the decarbonisation of our energy and material system as it allows to quickly reduce CO_2-emissions to stay within required reduction goals and ultimately reach net zero carbon.

Key in the upcycling process (from plant-based waste materials to a functional material) considered here is the pyrolysis of organic waste or low-value materials. Through pyrolysis of this materials, some combustible gases are emitted which can be thermally exploited for internal and external utilization such as district heating. About half of the carbon contained in the biomass remains bound to the material ending up as biochar. This biochar shows favourable properties to be used as building insulation materials when synthesized with organic binders. The resulting, fully organic, building insulation products thus store most of the carbon initially absorbed from the atmosphere when used and reused again in the building. When being ultimately recycled to yield again new building insulation materials or being disposed and brought back to the natural cycle, carbon could even be stored for hundreds of years. The full cycle is shown in Figure 1.

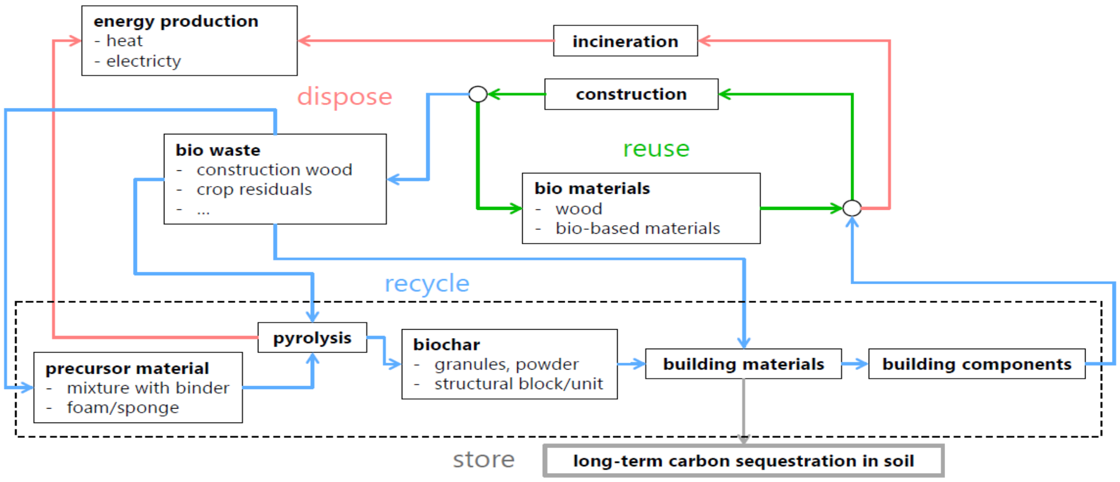


Figure 1: Materials life-cycle: Recycling process based on pyrolysis of bio-based materials to create novel, sustainable negative carbon building materials.

1.3 Objectives

Specifically, this project focuses on the development of biochar-based building insulation materials. In this context, there is a clear lack of available data regarding the potential of biochar as a precursor for building insulation material, synthesis, process parameters, availability of suitable, local and organic substrates but also regarding the economic feasibility and the life cycle performance along with the carbon reduction potential. Consequently, this project will shed light on the development of carbon negative building insulation materials and create insulation materials that are competitive to existing, fossil-based insulation materials.

The research questions for this project are directly derived from the development goals of the project.

Main goals can be stated as:

- Exploration of the material synthesis based on the binding and subsequent pyrolysis for the development of organic carbon negative building insulation materials
- Development of building material samples and first scale-ups in the form of insulation boards
- Identification of ecologic and economic potentials for suitable organic substrates available in Switzerland to supply the building insulation material development and manufacturing
- Definition of best suited recipes, synthesis approaches and process parameters for the manufacturing of building insulation materials
- Assessment of the carbon dioxide removal potential of the developed building insulation materials and evaluation of the life cycle performance of potential material candidates with comparison to standard insulation materials used in construction today

Based on these goals, main research questions are:

- What thermal conductivity can be achieved with organic waste or low-value materials using pyrolysis and what are optimal process parameters?
- What are most suitable and abundantly available source materials in Switzerland and in how far do they need to be in pure form, or can they be heterogeneous?
- What are advantages of synthesis approaches, e.g. different binder systems, pyrolysis conditions?
- What will be the carbon and ecological footprint of the studied materials?
- How well can the developed insulation material be recycled and thus kept within the technical cycle?

2 Overall procedures and methodology / structure of report

This report provides the results of the techno-economic analysis and the ecological assessment of newly designed carbon-negative building insulation material. The work in the project is structured into three work packages, being **WP1** – Materials & Synthesis, **WP 2** – Source availability / assessment of ecological and economic potential and **WP3** – Environmental life cycle assessment and greenhouse gas mitigation potential.

Research work started with WP2, where are large screening of available waste streams was performed with a subsequent evaluation and rating of the materials based on the technical, economic and ecological properties. Criteria for the evaluation and rating of precursor materials was done in collaboration of all WPs.

Based on selected candidate materials from within WP2, material synthesis and characterization was performed within WP1. Based on material and process parameter selection in WP1, a life cycle assessment (LCA) was performed in WP3, where first insights from the LCA were again fed back into WP1 for further improvement of the insulation material composition.

Specific methods, results and conclusions are reported within dedicated work package chapters, followed by an over-all conclusion for the project.

3 WP 1 – Materials & Synthesis

In this WP, the biochar insulation was produced from different raw materials. In phase 1, an initial comparison was made between the top three raw materials identified by WP2 to determine the most suitable candidate for thermal insulation. In phase 2, this preferred material was screened in more detail and upscaled.

3.1 Methodology

3.1.1 Phase 1

In the first phase of this WP, the three most promising materials were characterised and compared in terms of their thermal and mechanical properties.

Screening of binders

Different natural binders that could bind wood fibres, horse manure and deinking sludge (top 3 substrate selection – see WP2 description) were studied. For that, samples with wood fibres (Gutex Thermofibre) and the same amount of different binders were created and the thermal and mechanical properties of the bound samples were compared to self-bound wood fibre samples at the corresponding density.

Loose material

The three raw materials – wood fibres, horse manure and deinking sludge – where pyrolysed in loose form and their thermal conductivity was measured. While wood fibres and deinking sludge are already in an appropriate size, the horse manure had to be shredded before further use and characterisation to achieve a suitable size. For wood fibres, Gutex wood fibres (GUTEX Thermofibre | GUTEX) were used as a surrogate for wood fibres made from screen overflow. Horse manure (a mixture of horse excrement and straw) was procured from a local stable and deinking sludge was kindly provided by Perlen Papier AG.

The thermal conductivity of the loose pyrolysed material was measured using a proprietary guarded hot plate device in analogy to EN 12667, with an accuracy ≤ 10%, after conditioning the samples at 23°C and 50% relative humidity until the sample weight was stable. The guarded hot plate has an asymmetrical setup with a guarded hot plate at the top and a cold plate at the bottom. The results were reported for a calculated mean temperature of 10°C.

Compounded samples

To prepare compounded samples, raw biomass of the three raw materials was mixed with gluten and water to prepare a homogeneous mixture. Biomass and gluten was used in an 80 to 20% ratio. The same ratio was used for all three raw materials in order to compare the performance of the compounded materials at the same conditions. The samples were compounded in moulds of size (60 x 60 x 12) mm^3 and then dried in a microwave oven for several minutes inside the moulds. Afterwards, the samples were demoulded, pyrolysed and then conditioned at 23°C and 50% relative humidity until their weight was stable.

Thermal conductivity was measured in the same way as described above for the loose material. Compressive strength was determined according to EN 826 using a Zwick Allroundline Z005 machine after measuring thermal conductivity. Tensile strength was determined according to EN 1607 on the same device (cf. Fig. 2).

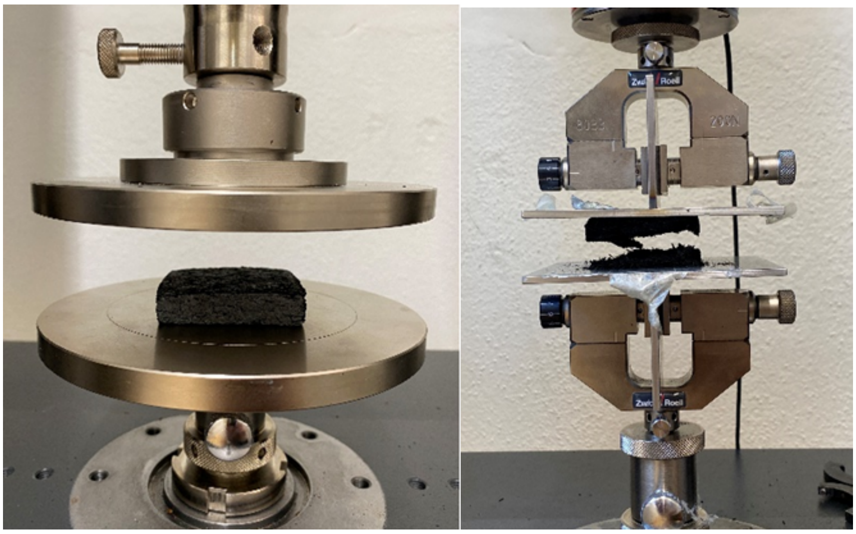


Figure 2: Experimental setup for the mechanical characterization for small samples of biochar insulation: Compressive (left) and tensile test (right).

3.1.2 Phase 2

After selection of the best material out of three, a more in-depth characterisation was performed with this one. Also, due to intermediate results of the LCA from WP3, indicating a very high contribution of gluten to the final insulation's footprint, a PVA-based wood glue was evaluated as an alternative. With this binder, a 25% mass fraction was necessary. Wood glue was then used for the upscaling, fire test and recyclability tests.

Upscaling

The feedstock used for scaling up the insulation boards was horse manure, and the binder chosen was wood glue diluted in water for workability purposes. The binder solution was added to the horse manure feedstock while mixing. The mixture was poured into a 500 x 500 mm^2 mould, at thicknesses of 46, 24 and 21 mm for the three samples, respectively. The samples were subsequently dried in an oven and then conditioned at 23°C and 50% relative humidity for thermal conductivity measurement according to EN 12667 in a large guarded hot plate device. It consists of a hot plate in the middle, and two nominally identical specimens of the tested material below and above. However, for the present experiments, the horse manure and wood glue upscaled sample was placed on the bottom, and a reference sample of known thermal conductivity on the top. With this setup, the accuracy of the measurements was ±3%. Thermal conductivity was measured for a mean temperature of 10, 20 and 30°C and it was reported for Tm=10°C. The sample was subsequently pyrolysed, conditioned at 23°C and 50% relative humidity and thermal conductivity was measured again.

Fire test

The test was carried out following ISO 11925-2 under the edge flame impingement method. For that, a horse manure sample of size 220 x 80 x 35 mm^3 was conditioned at 23°C and 50% relative humidity and subsequently attached to a vertical stand in a fume hood. A burner designed according to the standard and fuelled with 95% propane gas was directed at the sample for 15 s (cf. Fig. 9). The combustion was observed in terms of appearance and size of a flame as well as droplets from the material for 20 s.

Recyclability

Biochar insulation samples made with wood glue as described above were broken down into small pieces after their full characterisation and were rebound with wood glue into a new insulation boards.

This proof-of-concept of recyclability was done for two samples of a size of 60 x 60 x 12 mm^3. They were conditioned and their thermal conductivity was measured.

PAH

A sample of loose horse manure biochar was evaluated for its content of polycyclic aromatic hydrocarbons (PAH's) according to EN 17503 by the Eurofins institute.

3.2 Results

3.2.1 Phase 1

Screening of binders

Gluten showed the best combined performance – thermal and mechanical – and was hence selected for the screening of the three raw materials. Samples prepared with wood glue (PVA) also showed good characteristics, however, this glue was not initially used due to its fossil origin.

Loose material

The measured insulation performance of loose pyrolysed raw materials is shown in Figure 3.

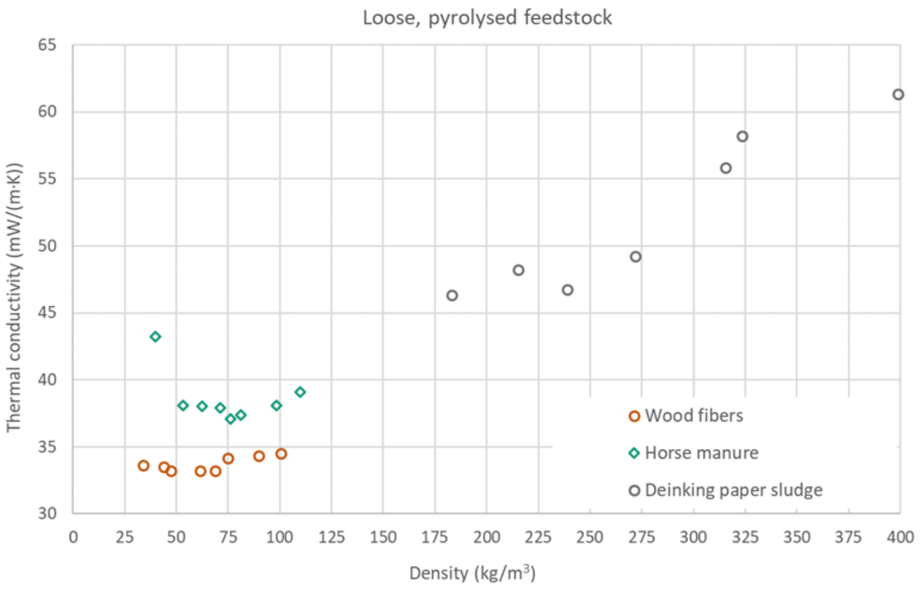


Figure 3: Thermal conductivity of loose, pyrolysed wood fibres, horse manure and deinking sludge.

These results were used to determine the optimal density range for making compounded samples. For that, the minimum of the thermal conductivity vs. density relationship was identified, which is in the range of 50 to 80 kg/m^3 for both wood fibres and horse manure. For deinking sludge, the minimum could not be determined as it was not possible to create samples with a sufficiently low thermal conductivity.

Compounded samples

The thermal and mechanical performance of the compounded samples are shown in Figure 4 and Figure 5. The combined performance is presented in Figure 6.

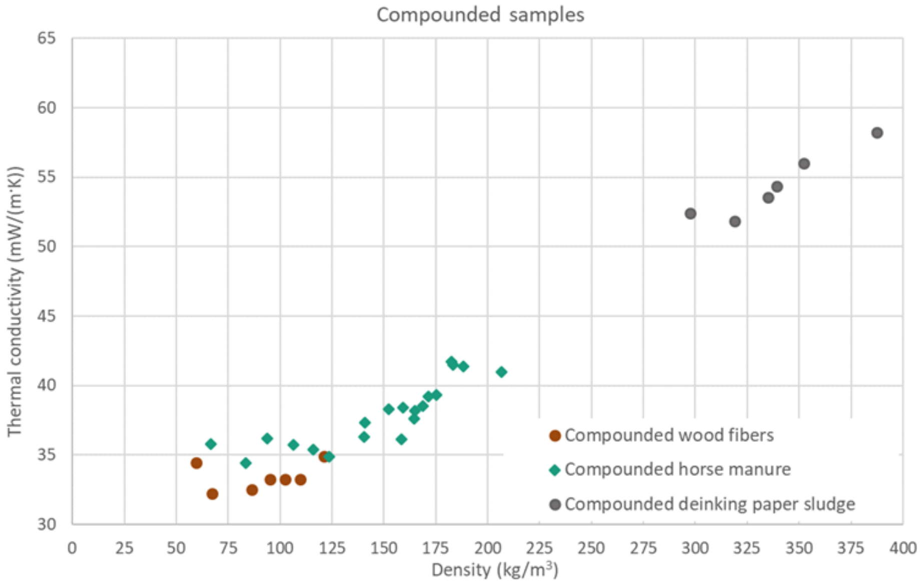


Figure 4: Thermal conductivity of pyrolysed compounded samples.

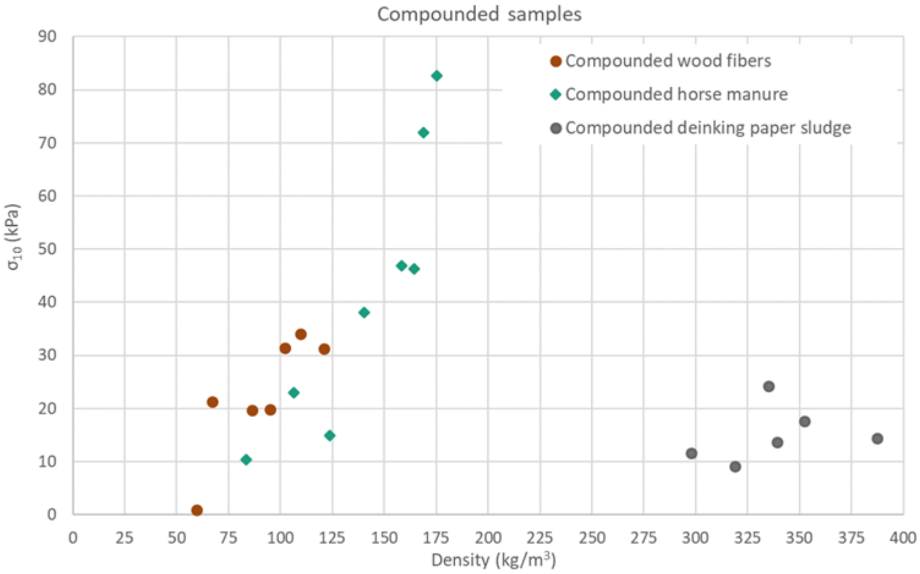


Figure 5: Stress at 10% strain, σ10, of pyrolysed compounded samples.

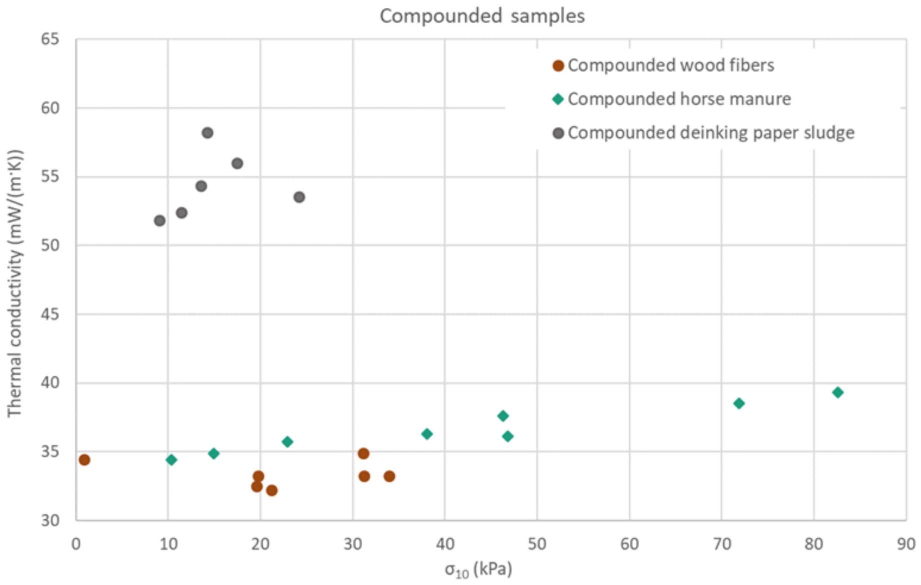


Figure 6: Thermal conductivity vs. stress at 10% strain, σ10, of pyrolysed compounded samples.

These results show that wood fibres and horse manure have a significantly lower thermal conductivity. Also, the increase of thermal conductivity with increasing mechanical strength is not too high. Sample strengths in the range of 20 to almost 100 kPa were reached, a typical range for thermal insulation boards.

Selection of best material for phase 2

The data shows that the thermal performance of wood fibres is best, followed by horse manure and deinking sludge. However, the thermal conductivity of the deinking sludge samples is much higher than the other two and about 60% higher than good conventional insulation materials. Thus, it is not very suitable as thermal insulator.

As expected, compressive strength increases with density, with a steep increase for both wood fibres and horse manure and a very shallow slope for the deinking sludge. The compressive strength of the deinking sludge is at the lower end of wood fibres and horse manure. Furthermore, the samples were also brittle compared to wood fibre and horse manure samples.

Thus, based on the thermal and mechanical data, the pyrolysed deinking sludge was clearly less suitable as thermal insulator.

Between wood fibres and horse manure, wood fibres have slightly better combined thermal and mechanical properties. This can also be seen in Figure 6 where the ideal sample would be located on the bottom right, i.e. a strong sample with low thermal conductivity. Both wood fibres and horse manure samples do not show a very strong penalty in thermal conductivity with increasing compressive strength.

However, wood fibres need to be produced via an energy intense milling process, whereas horse manure is an actual waste. Hence, horse manure was selected as the most sustainable raw material to continue the study with due to its good thermal and mechanical performance and its low environmental footprint as waste material.

3.2.2 Phase 2

As mentioned above, gluten as binder was re-evaluated after the preliminary evaluation of its impact on the environmental of the biochar insulation boards. As an alternative, horse samples with 25%

wood glue were made, pyrolysed, characterised and compared to the gluten-bound samples (Figure 7). The two material types showed a very similar combined thermal and mechanical performance, possibly with a slight advantage of wood glue at higher strengths (i.e. smaller increase of thermal conductivity).

Hence, wood glue was used for further analyses.

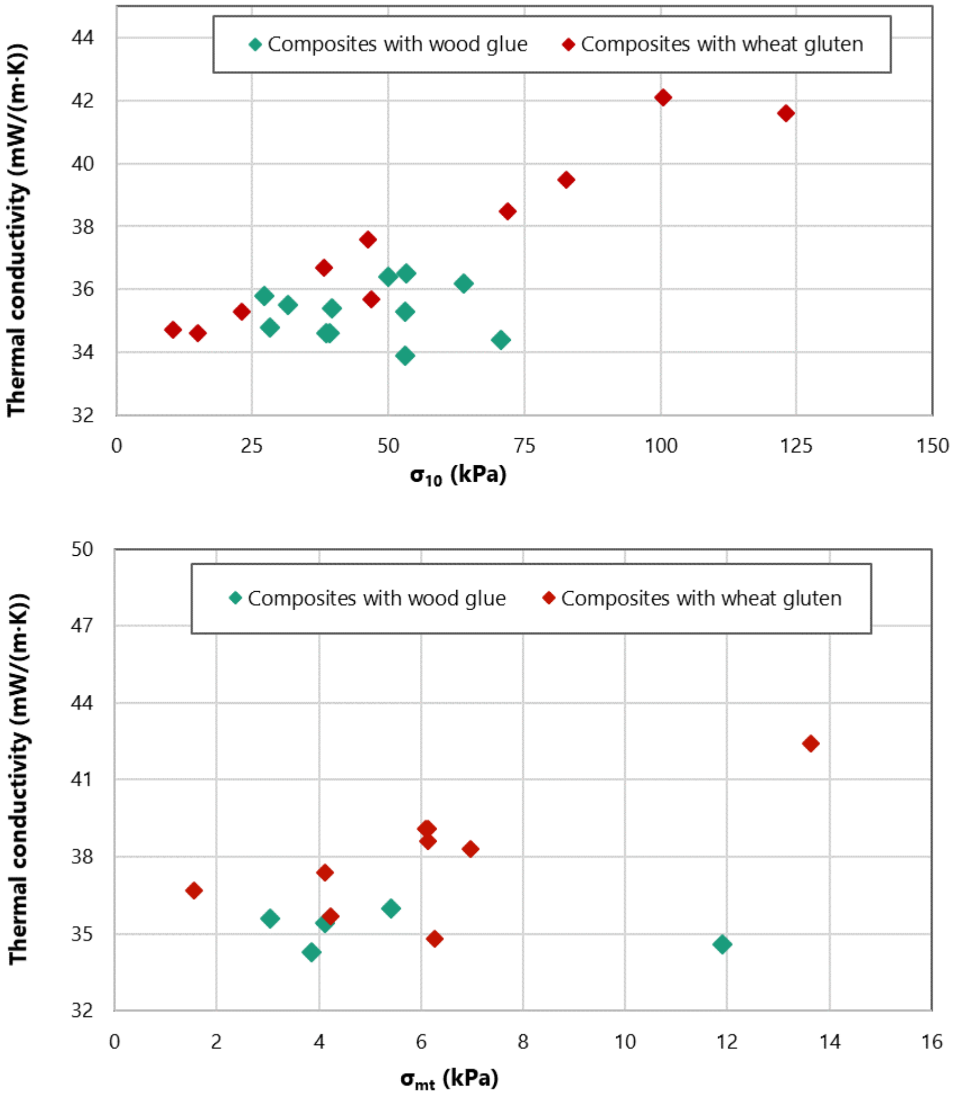


Figure 7: Thermal conductivity vs. stress at 10% strain, σ_{10}, (top) and vs. Tensile strength, σ_{mt}, of pyrolysed compounded samples, comparing wood glue and wheat gluten as binders.

Upscaling

The upscaled horse manure samples had a thermal conductivity of 35.7, 37.7 and 37.5 mW(m·K), respectively, with final densities of 85, 91 and 78 kg/m^3, respectively. Hence, the thermal conductivity was in the range of the small-scale samples. The samples' mechanical properties were not optimal and they had to be handled with care as damage could occur easily during handling (Figure 8). This could be optimsed by increasing the sample density or by adding reinforcements such as fibres.

The upscaling demonstrates the reproducibility of the thermal properties, not only at lab scale but on a typical insulation board size and measured according to standard, i.e. EN 12667.

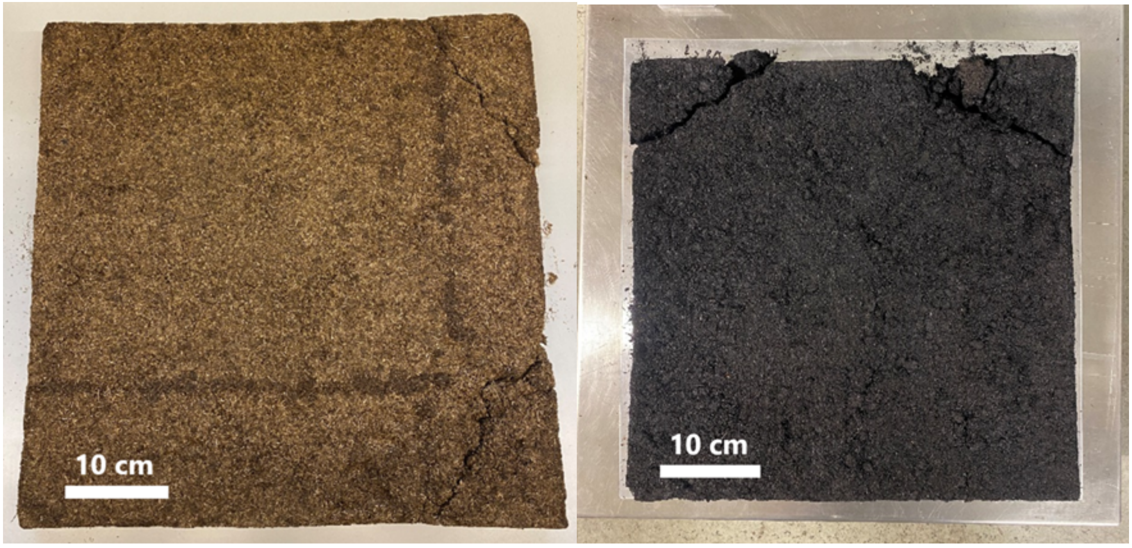


Figure 8: Upscaled horse manure sample before and after pyrolysis.

Fire test

During the whole fire test, ignition did not occur for the horse manure biochar specimen. The flame tip did not reach 150 mm above the flame application point, which is the criterion for the passing of the test. In fact, there was no flame at all on the sample itself. There were no flaming droplets or particles causing ignition of the filter paper. The test specimen did change colour when the flame was applied, but only in the near surroundings of it (Figure 9).

Hence, the material would be rated at least as class E according to EN 13501. This is the same classification as EPS and most biomass-based thermal insulation materials. Hence, it can be used in a wide range of applications such as external thermal insulation composite systems (ETICS) below the skyskraper limit. As a next step, a test for class D would be recommended. This was out of the scope of this project since it would require much larger samples and a specialised test setup.

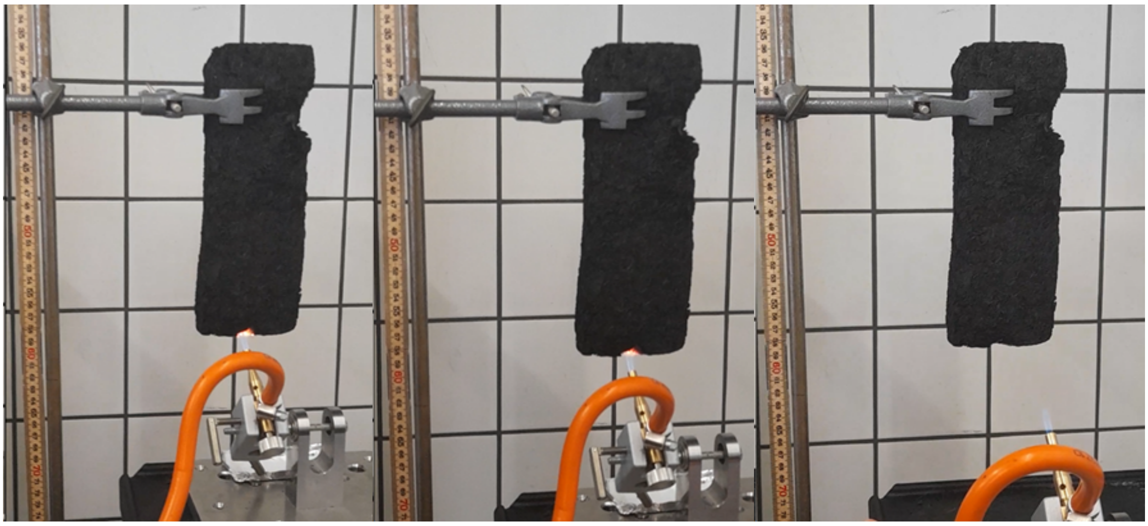


Figure 9: Fire test on a horse manure samples, images taken at 1 s, 15 s and 20 s after beginning of flame application.

Recyclability

It was possible to re-compound already used samples into new ones by the addition of new binder. The two samples had a measured thermal conductivity of 42.4 and 42.3 mW/(m·K) and compressive strengths of 47 and 107 kPa, respectively. Hence, there is a penalty in thermal conductivity of about 20% when recycling the biochar insulation boards in this way, comparing to the best results at around 35-37 mW/(m·K). The measured compressive strength on the other hand is on the upper end of all measured samples.

PAH

In the PAH test the sum of the 8 EFSA-PAH (excluding the determination limits) was not detectable. The sum of the 16 EPA-PAH (excluding the determination limits) was 2.5 mg/kg, with 2.0 mg/kg measured for Naphthalin and 0.5 mg/kg for Phenanthren, while all other PAHs were below the determination limit of 0.1 mg/kg. These values are below the strictest requirements of the European Biochar Certificate (EBC-FeedPlus and EBC-AgroBio) for PAHs of 1.0 mg/kg for the 8 EFSA-PAH and 6.0 mg/kg for the 16 EPA-PAH.

3.3 Conclusion

The experiments in this WP show that functional thermal insulation boards can be made from horse manure with either wood glue or gluten as binder. They are characterised by low thermal conductivity compared to other biomass-based insulation materials as well as mineral or fossil-based materials. To compare, EPS has a thermal conductivity ≥ 29 mW/(m·K) - with typical products in the low 30ies - glass wool ≥ 32 mW/(m·K) and stone wool ≥ 34 mW/(m·K), with typical products in the mid 30ies. The very best biomass-based thermal insulation has a thermal conductivity of 36 mW/(m·K), i.e. in a similar range as the materials presented here, whereas typical materials are between 40 and 60 mW/(m·K). Hence, the biochar insulation is performing well compared to conventional materials and very well compared to other biomass based materials.

The fire behaviour of the biochar insulation boards is at least as good as all biomass-based thermal insulation materials, namely class E, with potential for a higher classification.

The recyclability showed the conformity with the principles of circular economy and the suitability of the soil application with respect to PAHs after a single or several uses in the built environment was confirmed.

Regarding aspects that should be improved, the binders used here are not optimal from an LCA point of view (cf. WP3) and should be reconsidered in further research. Furthermore, while the compressive strength of the studied samples is in the typical range of insulation boards between ca. 20 and 100 kPa, the upscaling demonstrated the need for further improvements of mechanical properties as these are not sufficient yet in terms of the ability to handle the samples without damage.

4 WP 2 – Source availability / assessment of ecological and economic potential

The availability and properties of side-stream biomass are key factors for the production of insulation material for the building industry. Substrate properties will have an influence on product quality, the market competition will define prices and sustainable criteria also need to be addressed.

4.1 Methodology

In close collaboration with WP1 and the other partners the following aspects have been considered and worked on in three different phases. In Phase one the criteria have been defined for technological, economic and sustainable criteria. An Excel file was created in which all criteria and weighting factors were taken into account. In a further step, all biomasses were transferred to this file and assessed. The different biomass sources were selected on the basis of previous studies and additional expert assessments. The results were discussed, reviewed and adjusted several times with the research partners. The results from phase 1 and 2 showed a number of biomasses that could be potential raw materials. For this reason, it was decided to select ten substrates and to collect further information on current market availability, competitive situations on the market and prices for these substrates (phase 3) to select the final Top three substrates.

Substrate selection

From the reports of Gutzwiler et al. (2020), Mosberger et al. (2018), Thees et al. (2017) and the Empa reports MatCH production/consumption (2018) and MatCH synthesis (2019) substrates were listed which the authors believed to be of interest for further investigations. The biomass sources where cross-checked with experts in the field as well as the original Authors. The potential substrates were sorted according to material flows. The material flows were defined according to the method of Thees et al. (2017).

Evaluation criteria

The criteria for evaluating the potential of raw materials are divided into three groups: Technical-, Sustainability- and Market-/Economic-criteria. Those three groups are further split into hard and soft criteria. Hard criteria meaning quantitative, measurable aspects, soft criteria meaning qualitative aspects.

Hard sustainability criteria contain the yearly energy potential, the calorific value, the purity of the biochar and the pollutants in the gas fraction. A substrate should have a high calorific value which means a high energy potential. The biochar should fulfil the European Biochar Certificate criteria in order to be utilized as a soil optimizer after it has served as insulation material. The exhaust gas must fit the requirements according to Art. 71 od. 74 LRV and cannot exceed the threshold for pollutants such as dioxins. This would further increase the carbon removal potential and would have positive effects on the life cycle assessment.

Soft sustainability criteria include the substrate not requiring long transport distances and the ability to be stored without losing energy potential or causing emissions. Furthermore, the substrate should need little pre-treatment such as homogenization, drying or shredding. No scarce nutrients such as nitrogen should be destroyed in pyrolysis. Social risks and benefits need also be considered. The utilization of a substrate as insulation material can only be considered if the substrate is not used as food, feed, or cultivated solely for the purpose of pyrolysis. A substrate should not be considered further, if another utilization pathway, which is preferable in its sustainability, is already established (e.g. biogasplant with additional use as fertilizer).

Hard market and economic criteria contain the yearly minimal available amount of substrate, how much char this would result in and what the approximate costs would be. Soft criteria regard the questions if the substrate would be available long-term, throughout the year and how susceptible it is to market movements. Technical criteria contain the percentage of dry matter, the bulk density as well as form and size of the particles.

Scoring System

To evaluate based on the identified criteria, a scale of 1-4 is proposed in accordance with the class 1-4 system from the EBC (European Biochar Certificate), where 4 is best. Regarding the hard criteria, the substrates will be ranked 1-4 on which substrate is closest to the optimal value. 4 points will be given if the value in question is in the quantile closest to the optimal value, 1 point if the value is in the quantile furthest away from the optimal value. In the soft criteria the ranking stands for 1 = criterion not fulfilled, 2 = criterion almost not fulfilled, 3 = criterion almost fulfilled, 4 = criterion fulfilled. The score will be indicated through color-coding.

Weighting of the criteria

For the purpose of a multiple-criteria decision analysis, the score for each criterion will have to be multiplied by how much the specific criterion is weight. How each criterion is weight was discussed, reflected, and decided on by the authors. The substrates with the highest overall score will be chosen for continued investigation. The scores will be multiplied by a weighting factor from 1- 4.

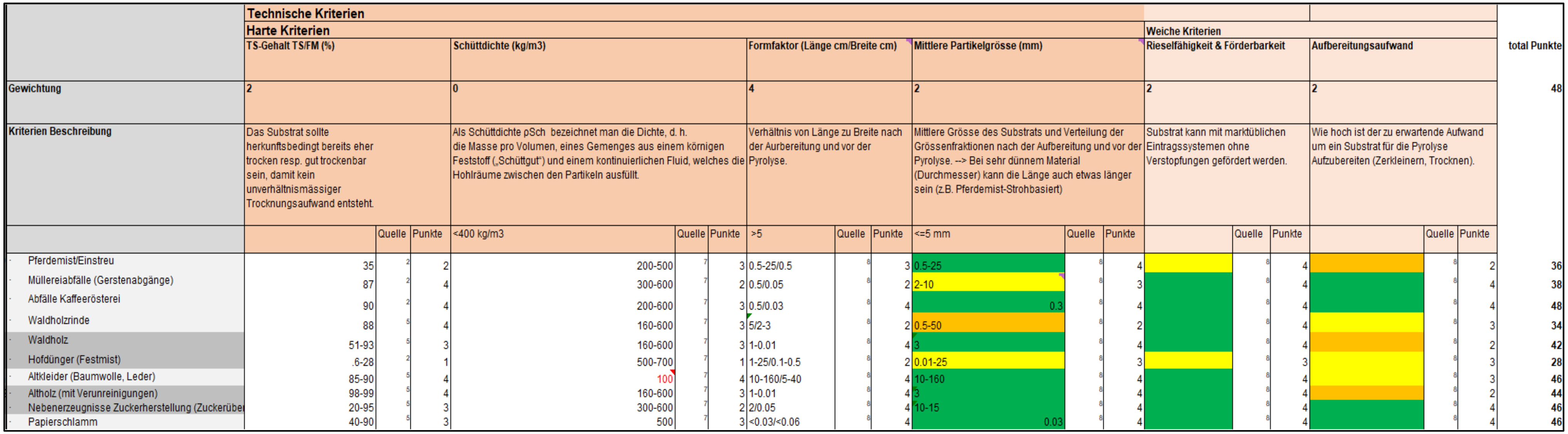
Determining the scores for each substrate

For each criterion and substrate, the most recent data available for Switzerland was gathered, scored, and multiplied as described above to get the total score for each substrate, as shown in Figure 3. The total scores were sorted to determine the TOP 10 substrates which reached the highest overall score. The substrates with their corresponding score were presented in a spider diagram as shown in Figure 4.

4.2 Results

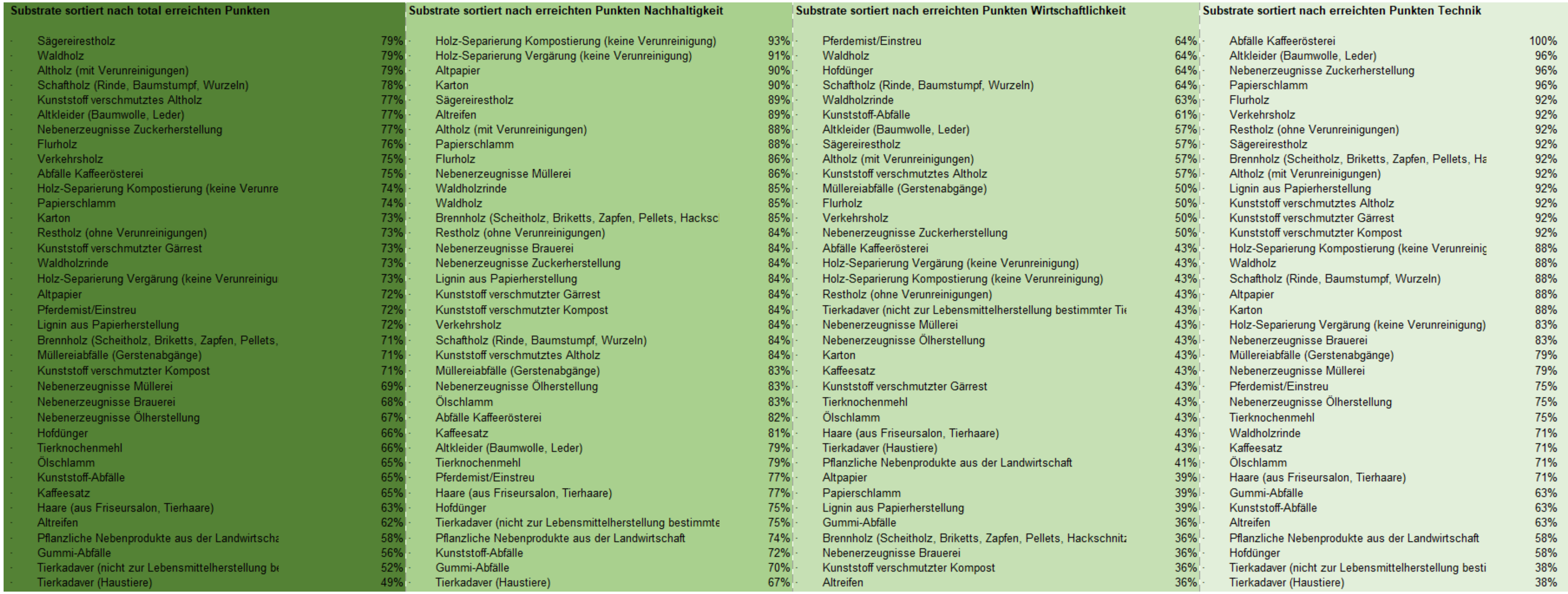
Selecting the TOP 3 Substrates

For the selected TOP 10 the price and the available amounts in Switzerland per year were investigated. The total available amount, as well as the technological and economical available amount were determined. The results were peer reviewed by representatives of different branches (Jürg Messerli (Ökostrom Schweiz), Konrad Schleiss (UMWEKO GmbH), Philip Gassner (SwissFarmerPower Inwil AG), Michael Kronauer (Wädenswil), Pierre Nydegger (Perlen Papier AG), Urs Baier (Vorstand, Biomasse Suisse), Albin Kälin (CEO, epeaswitzerland), Fabian Treichler (Forst Oberaargau). The detailed description of the Top 3 selection is explained below.



	Technische Kriterien																		
	Harte Kriterien												**Weiche Kriterien**						
	TS-Gehalt TS/FM (%)			**Schüttdichte (kg/m3)**			**Formfaktor (Länge cm/Breite cm)**			**Mittlere Partikelgrösse (mm)**			**Rieselfähigkeit & Förderbarkeit**			**Aufbereitungsaufwand**			**total Punkte**
Gewichtung	**2**			**0**			**4**			**2**			**2**			**2**			**48**
Kriterien Beschreibung	Das Substrat sollte herkunftsbedingt bereits eher trocken resp. gut trockenbar sein, damit kein unverhältnismässiger Trocknungsaufwand entsteht.			Als Schüttdichte pSch bezeichnet man die Dichte, d. h. die Masse pro Volumen, eines Gemenges aus einem körnigen Feststoff („Schüttgut") und einem kontinuierlichen Fluid, welches die Hohlräume zwischen den Partikeln ausfüllt.			Verhältnis von Länge zu Breite nach der Aurbereitung und vor der Pyrolyse.			Mittlere Grösse des Substrats und Verteilung der Grössenfraktionen nach der Aufbereitung und vor der Pyrolyse. --> Bei sehr dünnem Material (Durchmesser) kann die Länge auch etwas länger sein (z.B. Pferdemist-Strohbasiert)			Substrat kann mit marktüblichen Eintragssystemen ohne Verstopfungen gefördert werden.			Wie hoch ist der zu erwartende Aufwand um ein Substrat für die Pyrolyse Aufzubereiten (Zerkleinern, Trocknen).			
		Quelle	Punkte	<400 kg/m3	Quelle	Punkte	>5	Quelle	Punkte	<=5 mm	Quelle	Punkte		Quelle	Punkte		Quelle	Punkte	
· Pferdemist/Einstreu	35	2	2	200-500	7	3	0.5-25/0.5	8	3	🟩 0.5-25	8	4	🟨	8	4	🟧	8	2	**36**
· Müllereiabfälle (Gerstenabgänge)	87	2	4	300-600	7	2	0.5/0.05	8	2	🟨 2-10	8	3	🟩	8	4	🟩	8	4	**38**
· Abfälle Kaffeerösterei	90	2	4	200-600	7	3	0.5/0.03	8	4	🟩 0.3	8	4	🟩	8	4	🟩	8	4	**48**
· Waldholzrinde	88	5	4	160-600	7	3	5/2-3	8	2	🟧 0.5-50	8	2	🟩	8	4	🟨	8	3	**34**
· Waldholz	51-93	5	3	160-600	7	3	1-0.01	8	4	🟩 3	8	4	🟩	8	4	🟧	8	2	**42**
· Hofdünger (Festmist)	.6-28	2	1	500-700	7	1	1-25/0.1-0.5	8	2	🟨 0.01-25	8	3	🟨	8	3	🟨	8	3	**28**
· Altkleider (Baumwolle, Leder)	85-90	5	4	100	7	4	10-160/5-40	8	4	🟩 10-160	8	4	🟩	8	4	🟨	8	3	**46**
· Altholz (mit Verunreinigungen)	98-99	5	4	160-600	7	3	1-0.01	8	4	🟩 3	8	4	🟩	8	4	🟧	8	2	**44**
· Nebenerzeugnisse Zuckerherstellung (Zuckerübe	20-95	5	3	300-600	7	2	2/0.05	8	4	🟩 10-15	8	4	🟩	8	4	🟩	8	4	**46**
· Papierschlamm	40-90	5	3	500	7	3	<0.03/<0.06	8	4	🟩 0.03	8	4	🟩	8	4	🟩	8	4	**46**

Figure 2: Criteria catalogue with criteria for evaluating the potential of raw materials. Note: The Exel-File containing all informations is given as a supplement to this report. For each criterion and substrate the most recent data available for Switzerland was gathered, scored and multiplied to get the total score for each substrate. In the soft criteria the color ranking stands for 1 (red) = criterion not fulfilled, 2 (orange) = criterion almost not fulfilled, 3 (yellow) = criterion almost fulfilled, 4 (green) = criterion fulfilled.



Substrate sortiert nach total erreichten Punkten		Substrate sortiert nach erreichten Punkten Nachhaltigkeit		Substrate sortiert nach erreichten Punkten Wirtschaftlichkeit		Substrate sortiert nach erreichten Punkten Technik	
Sägereirestholz	79%	Holz-Separierung Kompostierung (keine Verunreinigung)	93%	Pferdemist/Einstreu	64%	Abfälle Kaffeerösterei	100%
Waldholz	79%	Holz-Separierung Vergärung (keine Verunreinigung)	91%	Waldholz	64%	Altkleider (Baumwolle, Leder)	96%
Altholz (mit Verunreinigungen)	79%	Altpapier	90%	Hofdünger	64%	Nebenerzeugnisse Zuckerherstellung	96%
Schaftholz (Rinde, Baumstumpf, Wurzeln)	78%	Karton	90%	Schaftholz (Rinde, Baumstumpf, Wurzeln)	64%	Papierschlamm	96%
Kunststoff verschmutztes Altholz	77%	Sägereirestholz	89%	Waldholzrinde	63%	Flurholz	92%
Altkleider (Baumwolle, Leder)	77%	Altreifen	89%	Kunststoff-Abfälle	61%	Verkehrsholz	92%
Nebenerzeugnisse Zuckerherstellung	77%	Altholz (mit Verunreinigungen)	88%	Altkleider (Baumwolle, Leder)	57%	Restholz (ohne Verunreinigungen)	92%
Flurholz	76%	Papierschlamm	88%	Sägereirestholz	57%	Sägereirestholz	92%
Verkehrsholz	75%	Flurholz	86%	Altholz (mit Verunreinigungen)	57%	Brennholz (Scheitholz, Briketts, Zapfen, Pellets, Ha	92%
Abfälle Kaffeerösterei	75%	Nebenerzeugnisse Müllerei	86%	Kunststoff verschmutztes Altholz	57%	Altholz (mit Verunreinigungen)	92%
Holz-Separierung Kompostierung (keine Verunre	74%	Waldholzrinde	85%	Müllereiabfälle (Gerstenabgänge)	50%	Lignin aus Papierherstellung	92%
Papierschlamm	74%	Waldholz	85%	Flurholz	50%	Kunststoff verschmutztes Altholz	92%
Karton	73%	Brennholz (Scheitholz, Briketts, Zapfen, Pellets, Hacksc	85%	Verkehrsholz	50%	Kunststoff verschmutzter Gärrest	92%
Restholz (ohne Verunreinigungen)	73%	Restholz (ohne Verunreinigungen)	84%	Nebenerzeugnisse Zuckerherstellung	50%	Kunststoff verschmutzter Kompost	92%
Kunststoff verschmutzter Gärrest	73%	Nebenerzeugnisse Brauerei	84%	Abfälle Kaffeerösterei	43%	Holz-Separierung Kompostierung (keine Verunreinig	88%
Waldholzrinde	73%	Nebenerzeugnisse Zuckerherstellung	84%	Holz-Separierung Vergärung (keine Verunreinigung)	43%	Waldholz	88%
Holz-Separierung Vergärung (keine Verunreinigu	73%	Lignin aus Papierherstellung	84%	Holz-Separierung Kompostierung (keine Verunreinigung)	43%	Schaftholz (Rinde, Baumstumpf, Wurzeln)	88%
Altpapier	72%	Kunststoff verschmutzter Gärrest	84%	Restholz (ohne Verunreinigungen)	43%	Altpapier	88%
Pferdemist/Einstreu	72%	Kunststoff verschmutzter Kompost	84%	Tierkadaver (nicht zur Lebensmittelherstellung bestimmter Tie	43%	Karton	88%
Lignin aus Papierherstellung	72%	Verkehrsholz	84%	Nebenerzeugnisse Müllerei	43%	Holz-Separierung Vergärung (keine Verunreinigung)	83%
Brennholz (Scheitholz, Briketts, Zapfen, Pellets,	71%	Schaftholz (Rinde, Baumstumpf, Wurzeln)	84%	Nebenerzeugnisse Ölherstellung	43%	Nebenerzeugnisse Brauerei	83%
Müllereiabfälle (Gerstenabgänge)	71%	Kunststoff verschmutztes Altholz	84%	Karton	43%	Müllereiabfälle (Gerstenabgänge)	79%
Kunststoff verschmutzter Kompost	71%	Müllereiabfälle (Gerstenabgänge)	83%	Kaffeesatz	43%	Nebenerzeugnisse Müllerei	79%
Nebenerzeugnisse Müllerei	69%	Nebenerzeugnisse Ölherstellung	83%	Kunststoff verschmutzter Gärrest	43%	Pferdemist/Einstreu	75%
Nebenerzeugnisse Brauerei	68%	Ölschlamm	83%	Tierknochenmehl	43%	Nebenerzeugnisse Ölherstellung	75%
Nebenerzeugnisse Ölherstellung	67%	Abfälle Kaffeerösterei	82%	Ölschlamm	43%	Tierknochenmehl	75%
Hofdünger	66%	Kaffeesatz	81%	Haare (aus Friseursalon, Tierhaare)	43%	Waldholzrinde	71%
Tierknochenmehl	66%	Altkleider (Baumwolle, Leder)	79%	Tierkadaver (Haustiere)	43%	Kaffeesatz	71%
Ölschlamm	65%	Tierknochenmehl	79%	Pflanzliche Nebenprodukte aus der Landwirtschaft	41%	Ölschlamm	71%
Kunststoff-Abfälle	65%	Pferdemist/Einstreu	77%	Altpapier	39%	Haare (aus Friseursalon, Tierhaare)	71%
Kaffeesatz	65%	Haare (aus Friseursalon, Tierhaare)	77%	Papierschlamm	39%	Gummi-Abfälle	63%
Haare (aus Friseursalon, Tierhaare)	63%	Hofdünger	75%	Lignin aus Papierherstellung	39%	Kunststoff-Abfälle	63%
Altreifen	62%	Tierkadaver (nicht zur Lebensmittelherstellung bestimmte	75%	Gummi-Abfälle	36%	Altreifen	63%
Pflanzliche Nebenprodukte aus der Landwirtscha	58%	Pflanzliche Nebenprodukte aus der Landwirtschaft	74%	Brennholz (Scheitholz, Briketts, Zapfen, Pellets, Hackschnitz	36%	Pflanzliche Nebenprodukte aus der Landwirtschaft	58%
Gummi-Abfälle	56%	Kunststoff-Abfälle	72%	Nebenerzeugnisse Brauerei	36%	Hofdünger	58%
Tierkadaver (nicht zur Lebensmittelherstellung be	52%	Gummi-Abfälle	70%	Kunststoff verschmutzter Kompost	36%	Tierkadaver (nicht zur Lebensmittelherstellung besti	38%
Tierkadaver (Haustiere)	49%	Tierkadaver (Haustiere)	67%	Altreifen	36%	Tierkadaver (Haustiere)	38%

Figure 3: Sorted total scores to determine the top ten substrates Note: The Exel-File (Kritierienkatalog) containing all informations is given as a supplement to this report. The total score for each substrate was determined and sorted for each of the criteria category as well as for the overall score.

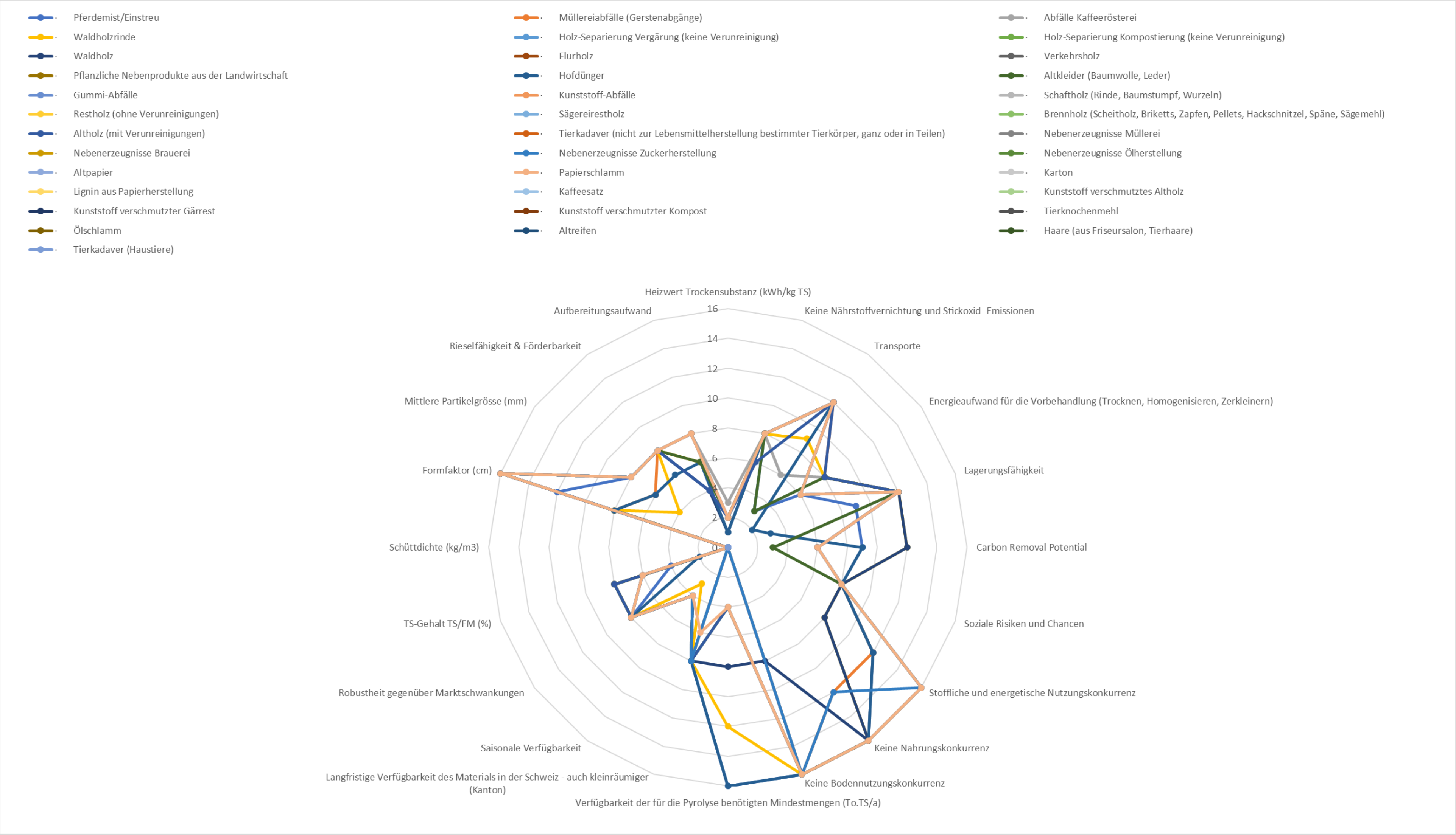
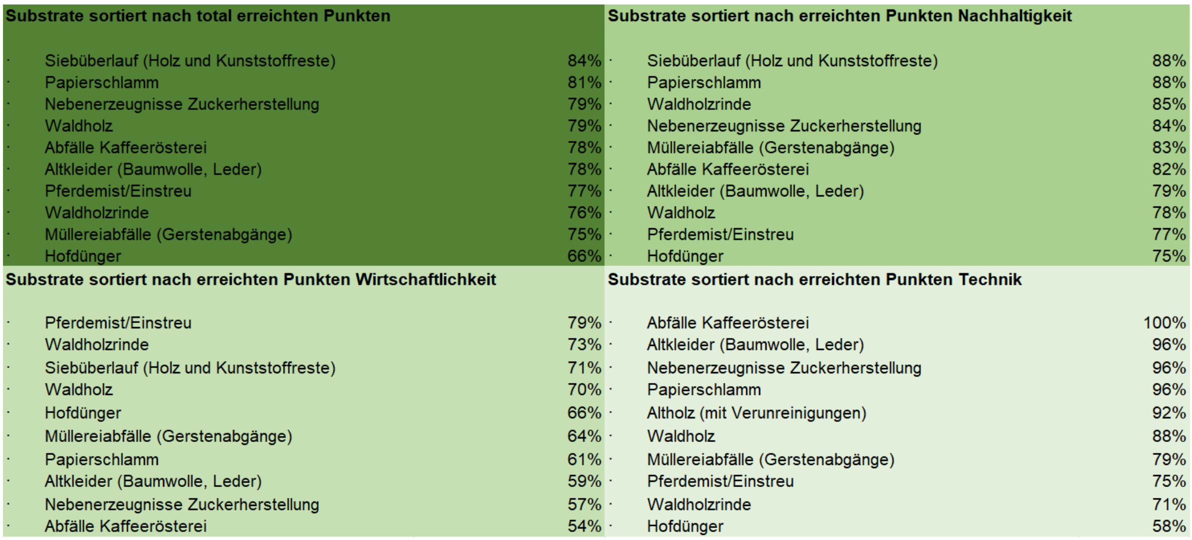


Figure 4: The potential substrates with their corresponding score for each criterion.

Selection of TOP 3 substrates

The analysis of the availability and prices of biomass on the Swiss market has turned out to be more difficult than initially assumed. Depending on the view of the experts, the scenarios for the selected biomass differ in quantities, utilisation paths and prices. The recommendation for the TOP 3 Substrates was in the end, among other criteria's, mainly based on "non-competition" with other existing utilization pathways. The TOP 3 will undergo from here on technical treatment to produce the final insulation product. Should the investigations show that pyrolysis with the selected substrates does not produce satisfactory results, then other raw materials can be considered based on the selection. Should a better utilisation path emerge from other materials, then possible competitive situations should not be avoided. If higher market prices can be paid, the biomass will transfer from the existing utilisation paths to the new application. Changes in the market are common in the biomass sector and vary depending on the situation. The market will regulate supply and demand.

Based on their total scores and on the input of different experts (as mentioned above) the TOP 10 (Figure 5) were ranked as follows:



Substrate sortiert nach total erreichten Punkten		**Substrate sortiert nach erreichten Punkten Nachhaltigkeit**	
· Siebüberlauf (Holz und Kunststoffreste)	84%	· Siebüberlauf (Holz und Kunststoffreste)	88%
· Papierschlamm	81%	· Papierschlamm	88%
· Nebenerzeugnisse Zuckerherstellung	79%	· Waldholzrinde	85%
· Waldholz	79%	· Nebenerzeugnisse Zuckerherstellung	84%
· Abfälle Kaffeerösterei	78%	· Müllereiabfälle (Gerstenabgänge)	83%
· Altkleider (Baumwolle, Leder)	78%	· Abfälle Kaffeerösterei	82%
· Pferdemist/Einstreu	77%	· Altkleider (Baumwolle, Leder)	79%
· Waldholzrinde	76%	· Waldholz	78%
· Müllereiabfälle (Gerstenabgänge)	75%	· Pferdemist/Einstreu	77%
· Hofdünger	66%	· Hofdünger	75%
Substrate sortiert nach erreichten Punkten Wirtschaftlichkeit		**Substrate sortiert nach erreichten Punkten Technik**	
· Pferdemist/Einstreu	79%	· Abfälle Kaffeerösterei	100%
· Waldholzrinde	73%	· Altkleider (Baumwolle, Leder)	96%
· Siebüberlauf (Holz und Kunststoffreste)	71%	· Nebenerzeugnisse Zuckerherstellung	96%
· Waldholz	70%	· Papierschlamm	96%
· Hofdünger	66%	· Altholz (mit Verunreinigungen)	92%
· Müllereiabfälle (Gerstenabgänge)	64%	· Waldholz	88%
· Papierschlamm	61%	· Müllereiabfälle (Gerstenabgänge)	79%
· Altkleider (Baumwolle, Leder)	59%	· Pferdemist/Einstreu	75%
· Nebenerzeugnisse Zuckerherstellung	57%	· Waldholzrinde	71%
· Abfälle Kaffeerösterei	54%	· Hofdünger	58%

Figure 5: Sorted total scores to determine the top three substrates Note: The Exel-File (Kritierienkatalog-Top 10) containing all informations is given as a supplement to this report. The total score for each substrate was determined by including the availability in terms of quantity at the market as well as the current price and market situation. In addition to the Excel-File "Kriterienkatalog" those new informations have been added to the File. Therefore, the ranking has changed slightly. Out of those Top 10 the raking has been conducted.

Rank 10: Sugar beet pulp (total score: 79 %)

- **Available quantity of material:** 0 t (Due to its use for animal feeding) (J. Messerli, personal communication 04/10/23)
- **Current market price and situation:** 80-110 CHF/t fresh matter (FM). Sugar beet pulp is a valuable source in animal nutrition and should for ethical reasons not be used. (J. Messerli, personal communication 04/10/23)
- **Decision:** Discarded, as it is used in animal nutrition.

Rank 9/8: Milling waste (total score: 75 %)

- **Available quantity of material:** (80'000 t) (J. Messerli, personal communication 04/10/23)
- **Current market price and situation:** 0 to -20 CHF/t fresh matter (FM). According to market experts, all the material available in Switzerland is being used for biogas production. Access to

this material would only be possible through higher purchase prices and would thus lead to a strong material and price competition. (J. Messerli, personal communication 04/10/23)

- **Decision:** Discarded, as it is completely sold out for energy production in biogas plants at the moment.

Rank 9/8: Coffee roasting waste (total score: 78 %)

- **Available quantity of material:** (5'000 t) (J. Messerli, personal communication 04/10/23)
- **Current market price and situation:** 30 to 60 CHF/t fresh matter (FM). Market investigations for coffee roasting waste (and spent coffee grounds) revealed that this source is already tapped by biogas plants as a valuable co-substrate and therefore not available on the market, or only for a higher price. The use of this resource would lead to a competitive situation between energy production and material use. (J. Messerli, personal communication 04/10/23)
- **Decision:** Discarded, as it is currently completely sold out for recycling in biogas plants.

Rank 7: Forest wood (total score: 79 %)

- **Available quantity of material:** 580'000 t (Agroscope, 2021)
- **Current market price and situation:** The market price depends strongly on the quality of the wood and utilization pathway. It ranges from industrial wood at 60 CHF/m^3, to firewood at 80-120 CHF/m^3 to building wood at 90-100 CHF/m^3 and for higher quality wood at up to 160 CHF/m^3. Switzerland imports 50 % of its wood demand. Wood prices in Switzerland are high compared to resources from outside (40-45 CHF/m^3 in the midlands). Nevertheless, there is still a large potential for wood in Switzerland located in the pre-alpine and alpine regions. The prices are estimated to be almost double (70-80 CHF/m^3) compared to the midlands as accessibility in these areas is very limited, which makes the harvest expensive. If this source should be accessed a higher market price needs to be paid (Fabian Treichler; Forst Oberaargau, 2023).
- **Decision:** Discarded, as it is an expensive source and has strong competition in energy and material use. Additionally, it is less innovative compared to other possible substrates.

Rank 6: Forest wood bark (total score: 76 %)

- **Available quantity of material:** 730'000 t (Agroscope, 2021)
- **Current market price and situation:** 20 to 50 CHF/m^3. Nowadays, forest bark mostly accumulates directly in the forest during harvest or while the harvested wood is being processed in sawmills. Debarking in forests is mostly used for pest control, which means that the bark is accumulating very decentralised. In many cases, the bark is used to reinforce the tracks for the harvesting machines. Collecting this source of raw material would be very time-consuming and expensive. The bark that accumulates centrally in sawmills is dried and used for heating purposes, which makes it unavailable for other uses. (Fabian Treichler; Forst Oberaargau, 2023).
- **Decision:** Discarded, as it is an expensive source and has strong competition in energy and material use. Additionally, it is less innovative compared to other possible substrates.

Rank 5: Solid Digestate (total score: 66 %)

- **Available quantity of material:** 182'000 t (Baier *et al.,* 2022)
- **Current market price and situation:** 0 to 50 CHF/t. The market price is still low, even though solid digestate is presenting with good fertilizing qualities. Farmers are getting reimbursed for using industrial solid digestate as fertilizer but must cover the costs for transportation and field application. Agriculturally based solid digestate is sold for around 20 CHF/t to landscaping companies. It is to be expected that this substrate will achieve higher market prices once its mineral fertilizer equivalent is getting more expensive. Furthermore, there might be a possible nutrient loss during material production. (J. Messerli, personal communication 04/10/23)

- **Decision:** Discarded, as to not be competing with its demand as fertilizer as well as due to its overall score which is the lowest out of the selected TOP 10 candidates.

Rank 4: Discarded clothes (total score: 78 %)

- **Available quantity of material:** 27’500 t (A. Kälin, personal communication 04/15/23)
- **Current market price and situation:** -200 to 900 CHF/t. There is a substantial amount of used clothes being marketed in Switzerland. Depending on the quality some of those must be disposed (-200 CHF/t) or achieve up to 900 CHF/t on the market. However, their purity plays an important role for their use in coal production. Nowadays, the majority of garments contain a proportion of plastic fibres. Their properties during pyrolysis and subsequent use have not yet been sufficiently researched. For this reason, only cotton-based garments can be considered at present. (A. Kälin, personal communication 04/15/23)
- **Decision:** Discarded. It is unsure whether this char would meet EBC guidelines. If only the broken and soiled ones from the total quantity and only those made of cotton are taken into consideration, the available quantity might be too small.

Ranks 3/2/1: Horse manure (total score: 77 %)

[The colour indicates the substrate as a Top 3 substrate and 3/2/1 stands for Top 3 without further ranking]

- **Available quantity of material:** 481’000 t (Schweizer Pferdeverband, 2021)
- **Current market price and situation:** 0 to -20 CHF/t. In Switzerland, large quantities of horse manure (dung and bedding) are produced. Due to its properties (high straw content), it is not in great demand as a fertiliser. Only a small part is used for biogas production, as most biogas plants are not technically designed for such a high straw content. Commercial horse owners cannot easily accommodate horse manure in agriculture. The market price reflects this structure. In the vast majority of cases, horse owners have to pay for manure disposal. Due to its good suitability for pyrolysis and its excellent market availability, this substrate is a very suitable source. (Schweizer Pferdeverband, 2021)
- **Decision:** Recommended. This substrate is likely to be suitable for pyrolysis, has a negative market price and is available on the market since it is not yet needed for other relevant applications.

Ranks 3/2/1: Paper sludge (total score: 81 %)

- **Available quantity of material:** 86’000 t (P. Nydegger, personal communication 04/22/23)
- **Current market price and situation:** -50 to -150 CHF/t. Paper sludge is a side product of the paper industry and due to its low quality not recyclable for other paper products. For disposal, the paper sludge is usually separated from the liquid phase and taken to waste incineration plants. Depending on the moisture content, disposal fees must be paid. The separated paper sludge could however have very good properties for pyrolysis. (P. Nydegger, personal communication 04/22/23)
- **Decision:** Recommended. This substrate is likely to be suitable for pyrolysis, has a negative market price and is available on the market since it is not yet needed for other relevant applications.

Ranks 3/2/1: Screen overflow wood (wood and plastic residues) (total score: 84 %)

- **Available quantity of material:** 297’000 t (Baier *et al.,* 2022)
- **Current market price and situation:** -50 to -100 CHF/t. In addition to kitchen waste, woody biomass components are also collected during green waste collection. This leads to contamination with plastics from households, especially in residential areas. In composting and biogas plants, the larger woody biomass components are sorted out before or after the digestion process depending on the plant type. Due to the contamination, this fraction is sorted out in order to prevent plastics from entering the environment. Therefore, this biomass has to be incinerated which leads to disposal costs. There is no competition with other

applications for this biomass fraction. Furthermore, could it be used for pyrolysis with only little pre-treatment. (P. Gassner, personal communication 04/20/23)

- **Decision:** Recommended. This substrate is likely to be suitable for pyrolysis, has a negative market price and is available on the market since it is not yet needed for other relevant applications.

In the following figures 4-6 the scores (1 to 4 points) for the TOP 3 substrates will be presented for the three criteria categories: sustainability, market and economy, technical criteria. The results show an almost even distribution of the evaluation points between the three preferred substrates with only slight deviations. This explains the basic suitability of these substrates for the production of insulation boards.

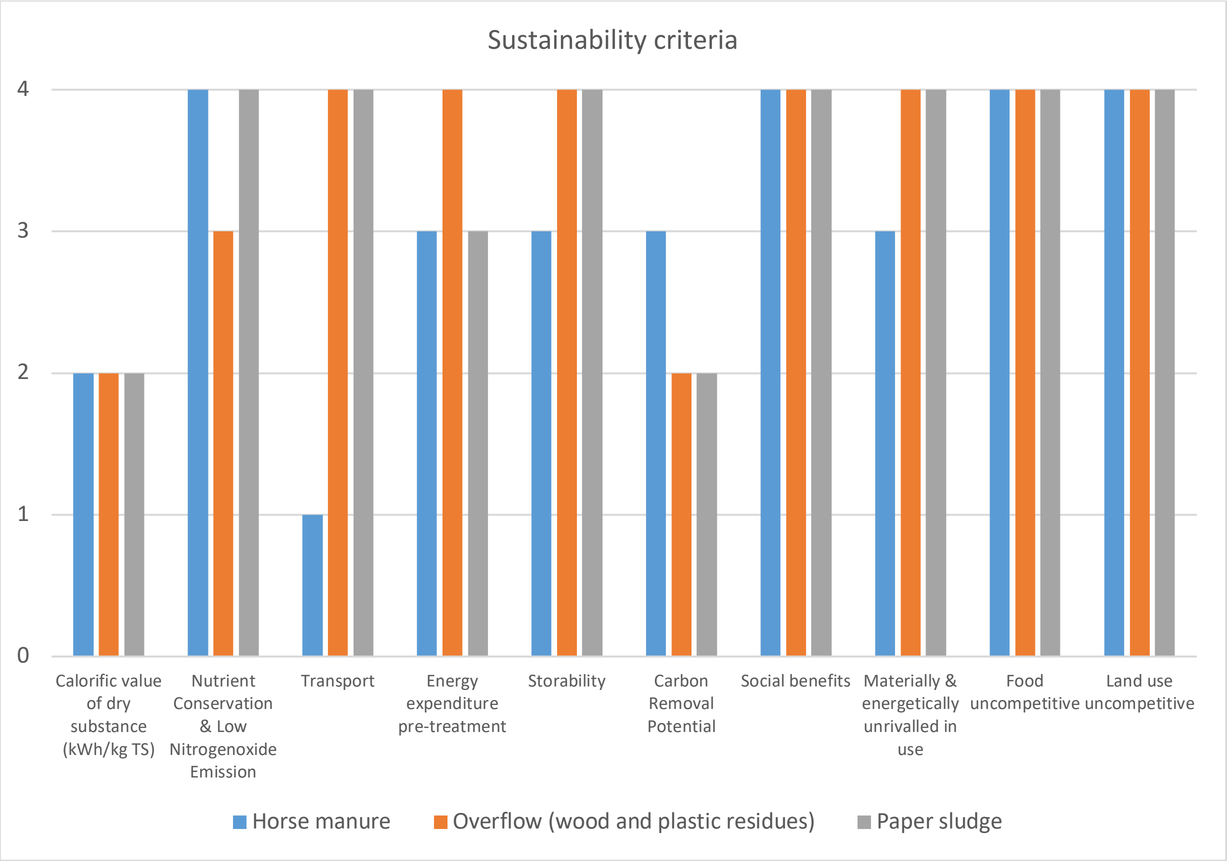


Fig. 6: Scores from 1 to 4 for the selected TOP 3 substrates for the sustainability criteria.

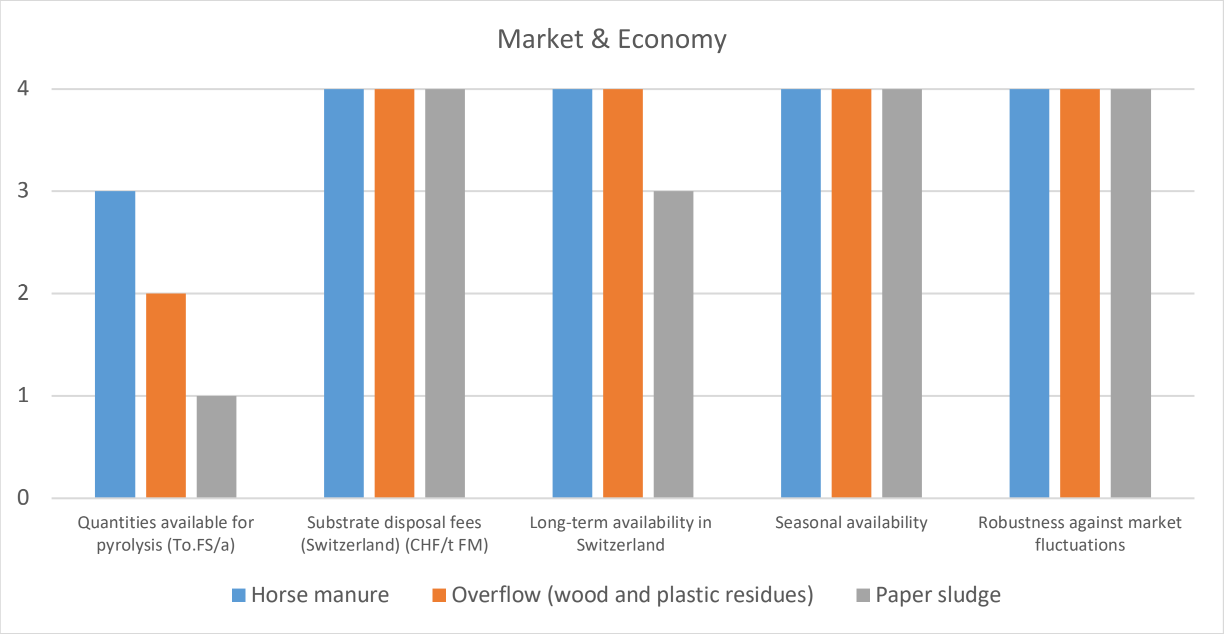


Fig. 7: Scores from 1 to 4 for the selected TOP 3 substrates for the market and economy criteria.

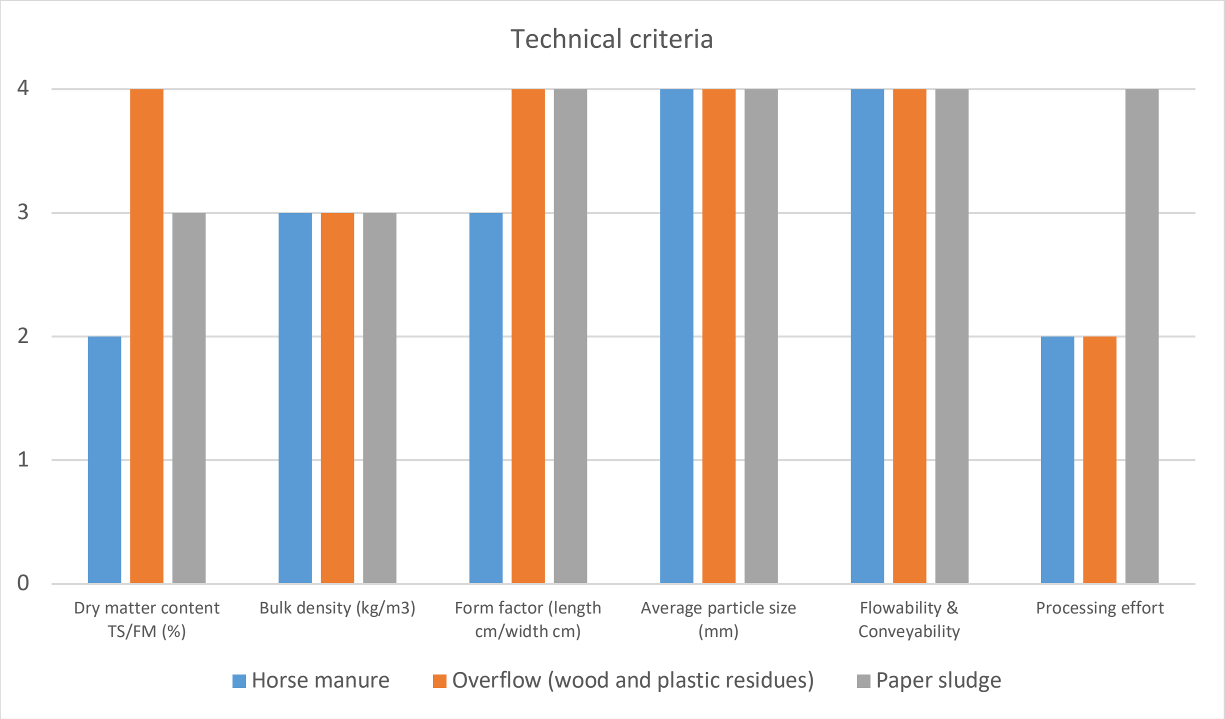


Fig. 8: Scores from 1 to 4 for the selected TOP 3 substrates for the technical criteria.

Table 1 summarizes the technical data for the TOP 3 substrates Horse manure, Sieve Overlfow and Paper sludge.

Table 1: Technical data for the TOP 3 substrates. (Baier et al., 2022; Ifl-Bayer, o. J.; M. Kronauer, personal communication 04/20/23; Mollet, o. J.; P. Gassner, personal communication 04/20/23; Phyllis.nl, o. J.; P. Nydegger, personal communication 04/22/23; Schweizer Pferdeverband, 2021; Waldschweiz, o. J.; J. Messerli, personal communication 04/10/23)

	Calorific value (kWh/kg TS)	**Available quantities (To.FS/a)**	**Disposal fees (CHF/t FM)**	**Dry matter content TS/FM (%)**	**Bulk density (kg/m3)**
Horse manure	5	481’800	0 -20	35	200-500
Sieve Overflow (wood & plastic residues)	4.4	297’000	50-100	>98	160-600
Paper sludge	0.3-5	86’000	50-150	40-90	500

4.3 Conclusion

- Search for potential biomass in Switzerland that has suitable properties to build insulation materials that address technical, economic, and sustainable criteria combined in a criteria catalogue was carried out.
- Although potential biomass in Switzerland is often used in other utilization paths, it is mainly used for energetic use. Some of the resources, such as wood bark, are not available due to their special distribution.
- Not all biomass resources are suitable for building insulation materials as their properties do not comply with the requirements.
- After market research and discussion with experts, out of 10 preselected substrates, three top substrates, horse manure, paper sludge, and wood screen overflow, were selected and proposed for further investigation.
- All three selected substrates are suitable from their properties, do not interfere with other utilization pathways, are available in relevant quantities and have a negative market price.

5 WP 3 – Environmental life cycle assessment and greenhouse gas mitigation potential

Within WP3, a life cycle assessment (LCA) of different CarNe materials was conducted. Goal of the LCA was to assess the environmental performance of insulation materials made from different biochar feedstocks based on different impact categories in comparison to conventional insulation materials, and to quantify their greenhouse gas mitigation potential.

Based on the results from first material tests within WP1, three different material combinations of substrates (wood fibres, horse manure) and binders (wheat gluten, polyvinyl acetate) were analysed. Table 2 summarizes the material compositions as well as the specific densities and thermal conductivities after pyrolysis, which were measured in WP1.

Insulation material based on deinking sludge was not considered in WP3, as the analyses in phase 1 of WP1 revealed that the thermal and mechanical performance of this material after pyrolysis was not suitable for building insulation.

Table 2: Composition of insulation materials considered within the LCA of the CarNe project; values for density and thermal conductivity refer to measurements of insulation plates after pyrolysis.

	Substrate	Binder	Density	Thermal conductivity
Case 1	Wood fibres, 80w%	Wheat gluten, 20w%	70 kg/m^3	35 mW/(m·K)
Case 2	Horse manure, 80w%	Wheat gluten, 20w%	90 kg/m^3	40 mW/(m·K)
Case 3	Horse manure, 86w%	Polyvinyl acetate (PVAc), 14w%	115 kg/m^3	35 mW/(m·K)

5.1 Methodology

To reach the goal of WP3, a cradle-to-grave life cycle assessment (LCA) of the CarNe materials was carried out following the ISO 14040 and ISO 14044 standards (ISO, 2006, 2017).

This chapter describes the analysed product system, the corresponding functional unit and references flows, and the applied impact assessment methods.

5.1.1 Functional unit, reference flows and system boundaries

The functional unit of the LCA was set to

1 m^2 of thermal building insulation with a transmittance (U-value) of 0.15 W/(m^2·K).

All environmental impacts shown in the following chapters refer to this functional unit. Using the same U-value allows for a meaningful comparison between different insulation materials. The reference flow, which is the needed amount of insulation material to fulfil the functional unit, depends on the specific thermal performance and the specific density of the considered material. In general, the reference flow for a material A was determined using to the following equation:

$$reference\ flow_A\ [kg] = density_A\ \left[\frac{kg}{m^3}\right] \cdot \frac{thermal\ conductivity_A \left[\frac{mW}{m \cdot K}\right]}{U-value \left[\frac{W}{m^2 \cdot K}\right] \cdot 1000} \cdot 1m^2$$

The resulting reference flows for the three analysed CarNe materials and for conventional insulation materials which were considered for comparison are listed in Table 3. The densities and thermal conductivities considered for the conventional materials are given in Appendix 10.1.

Table 3: Quantities (reference flows) of different insulation materials to reach 1 m^2 building insulation with transmittance (U-value) of 0.15 W/(m^2·K).

	Insulation material	Reference flow
CarNe materials	Wood fibres + gluten	16.3 kg
	Horse manure + gluten	24.0 kg
	Horse manure + PVAc	26.8 kg
Conventional (KBOB) materials	Expanded polystyrene (EPS)	3.36 kg
	Extruded Polystyrene (XPS)	8.00 kg
	Polyurethane rigid foam (PIR/PUR)	4.00 kg
	Stone wool	9.07 kg
	Glass wool	7.47 kg
	Wood fibre board	39.5 kg
	Cellulose	12.7 kg
	Straw bale wall	86.0 kg

The LCA covered the whole life cycle of the insulation materials. This included the provision and pre-processing of the substrates and binders, the pyrolysis, as well as the disposal of the insulation materials at their end-of-life, as shown in the system model in Figure 9.

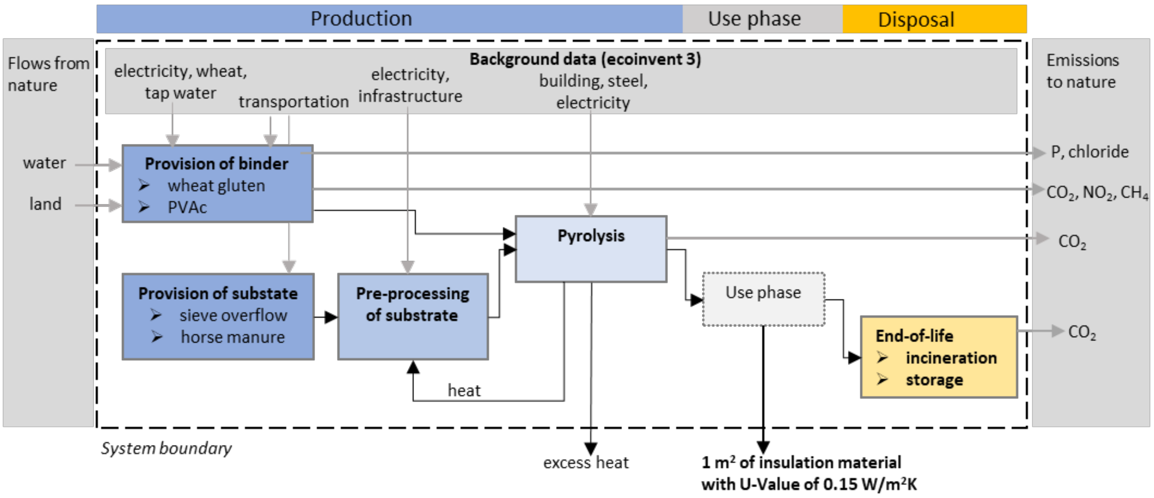


Figure 9: System model showing the processes which were included in the LCA of the CarNe materials.

Following the cut-off approach, the provision of substrates from waste materials (horse manure, wood as sieve overflow) only included transportation. The pre-processing of the substrates included drying and shredding to obtain fibres sizes which are suitable for pyrolysis. The provision of binders considered provision of raw materials, the production of the binder and transportation to the pyrolysis facility.

Regarding pyrolysis, the pyrolysis facility was modelled as well as the emissions from the pyrolysis process (mainly CO_2 and heat). The use phase of the insulation materials in buildings was not connected to any direct environmental impact which could be attributed to the material, and was therefore not specifically modelled. The end-of-life phase included the disposal of the insulation materials, either via incineration or via permanent storage in soil.

The considered processes and the related life cycle inventory are described in more detail in Chapter 5.2.

5.1.2 Software and data sources

The LCA modelling was carried out using the software SimaPro 9 (PRé Consultants, 2019). Within SimaPro, foreground data regarding CarNe materials were combined with background data from the ecoinvent v3.9.1 database (ecoinvent Centre, 2023). The environmental impact of conventional insulation materials was assessed based on the UVEK LCA database DQRv2:2022 (UVEK, 2022), which forms the basis of the Swiss KBOB database containing generic LCA data for average building materials (KBOB: *Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren*).

Foreground data such as material compositions, mass loss during pyrolysis, as well as density and thermal conductivity after pyrolysis were obtained from WP1 of the project. Data gaps, for example related to the production of gluten binder, were filled with literature values. In some cases, existing ecoinvent data sets were modified as approximation for the life cycle inventory of the CarNe materials. As approximation of future pyrolysis processes on industrial scale, a STELLA Architect (isee, 2024) model of the pyrolysis of wood chips was used.

Within the ecoinvent database, the system model “Allocation cut-off by classification” was used. This system model allocates the environmental impact of recycling processes to the recycled product, while all impacts before recycling (i.e. resource extraction, production and use of primary product) are allocated to the primary product. Accordingly, horse manure and sieve overflow as waste streams were modelled free of environmental burden and only the transportation and pre-processing before pyrolysis were taken into account.

Two multi-output processes within the life cycle modelling required allocation: the production of gluten and the pyrolysis process. Regarding the production of gluten binder, a mass allocation was applied to distribute the environmental impacts of processing wheat flour to the output flows starch and gluten, based on the assessment by Deng et al. (2013). Concerning the pyrolysis process, all environmental impacts were attributed to the pyrolysed insulation material (i.e. the char) and none to the excess heat.

5.1.3 Environmental impact assessment methods

The environmental impact of the CarNe materials was primarily assessed based on the following two environmental indicators:

- the midpoint indicator **Global warming potential** (GWP) on a 100a horizon according to the Intergovernmental Panel on Climate change (IPCC, 2021), expressed in kgCO_2-eq; the GWP is also known as carbon footprint;
- the single score indicator **overall environmental impact** according to the ecological scarcity method (Frischknecht et al., 2021), expressed in eco-points. In the current version, the ecological scarcity method aggregates 20 environmental impact categories to one single indicator using weighting factors on a distance-to-target principle. In the Swiss version of the method, weighting factors are derived by comparing current emissions to national emission targets as well as international targets supported by Switzerland.

To assess potential ecological trade-offs and side effects, additional relevant midpoint indicators according to the **Environmental Footprint (EF)** method v3.1 (Fazio et al., 2018) were assessed. The identification of relevant EF midpoint indicators was carried out in an iterative approach based on the normalization and the weighting factors as implemented in the EF method. The relevant indicators were mainly related to agricultural processes: freshwater eutrophication, terrestrial eutrophication, acidification, freshwater ecotoxicity, land use, and use of fossil resources.

5.1.4 Assessment of yearly greenhouse gas mitigation potential on national level

The yearly greenhouse gas mitigation potential related to the CarNe materials was assessed based on two parameters:

- The total potential net negative emissions resulting from the permanent storage of pyrolysed material in soil at the end-of-life, and
- The total avoided emissions from replacing conventional insulation materials.

The greenhouse gas mitigation potential was determined assuming that the total available waste streams for sieve overflow and horse manure in Switzerland (see Table 1) were used for the production of CarNe materials. The maximum amount of producible insulation material was determined taking into account dry matter content of the substrates and mass loss during pyrolysis.

The total potential net negative emissions expressed in t CO_2-eq. were determined as the sum of the GWP related to the production of the CarNe materials and the potential negative emissions related to the permanent storage of the material in soil at the end-of-life. Both GWP from production and negative emissions from storage were results from the LCA carried out in WP3.

Avoided emissions from replacing conventional insulation material were derived for the three materials EPS, glass wool and stone wool. The total building area which could be insulated with CarNe materials with an U-value of 0.15 W/(m^2·K) was calculated, based on the material requirement (reference flow) for 1 m^2 (see Table 3). The avoided emissions represented the GWP from production and disposal of the amount of conventional material needed to insulate the same building surface with the same U-value.

5.2 Life cycle inventory and data sources

In the following sections, the modelled life cycle inventory (LCI) and the corresponding data sources are described for each life cycle stage.

Transportation

It was assumed that both substrates were transported within Switzerland on average 100 km via lorry to the pyrolysis facility. Considering moisture content, content of substrate in the CarNe material and mass loss of 65% during pyrolysis, this resulted in a transportation of 0.233 tkm per 1 kg pyrolysed insulation material for case 1, 0.653 tkm for case 2, and 0.702 tkm for case 3. The higher values for cases 2 and 3 are due to the high moisture content of horse manure.

Binders were assumed to be bought from the global market. Their transportation was not specifically modelled. Instead, an average transportation was taken into account within the market background data sets used for the provision of raw materials.

Provision of raw materials

Both, waste wood and horse manure were considered as waste streams which are available without environmental burden (cut-off approach). Consequently, no inventory had to be considered for the provision of these substrates, apart from transportation.

Regarding the gluten binder, 571 g of wheat gluten was needed to produce 1 kg of insulation material for cases 1 and 2, considering a binder content of 20w% and a mass loss of 65% during pyrolysis. The provision of gluten was modelled based on the assessment by Deng et al. (2013) on the production of gluten and starch from flour. A mass allocation between the two output flows gluten and starch was assumed (Deng et al., 2013). Using this approach, the production of 1 kg wheat gluten required 1.11 kg of wheat flour (from the global market) and 2.33 kg of tap water and showed an electricity demand of 2.42 kWh. The complete life cycle inventory used for gluten is given in Appendix 10.2.

For case 3, 400 g of PVAc binder was needed per 1 kg produced insulation material, considering the binder content of 14w% and a mass loss of 65% during pyrolysis. To model PVAc, the ecoinvent 3 data set *Vinyl acetate {GLO}| market for vinyl acetate* was used.

Pre-processing of substrate

In order to be suitable for pyrolysis, waste wood had to be processed to obtain wood fibres which were mixed with water and binder, compacted and then dried. To model this process on industrial level, the ecoinvent data set *Fibreboard, soft {CH}| fibreboard production, soft, from wet processes* was used as approximation. Compared to the original data set, the input from dry wood chips was set to 0 (corresponding to the use of waste wood). Furthermore, the input from binder was also set to 0, as the provision of binder was modelled separately. The heat input was also set to 0, as it was assumed that output heat from the pyrolysis process was used for all drying processes.

Referred to 1 kg of insulation material, 2.29 kg of wood fibres were needed (considering a wood content of 80w%, as well as the mass loss of 65% during pyrolysis). This corresponded to the input of 0.0163 m^3 fibreboard, since the assumed density of fibreboard was given as 140 kg/m^3 within the original ecoinvent data set.

Compared to wood, the preparation of horse manure was considered to be less energy demanding, as only drying and shredding is needed. As approximation for shredding, a new data set was created, reducing all inputs from the background data set *Fibreboard, soft {CH}| fibreboard production, soft, from wet processes* to one third (and again setting inputs for wood, binder and heat to 0).

Considering its weight content and mass loss, 2.29 kg of dried and shredded horse manure were needed as input to produce 1 kg of insulation material for case 2. For case 3, 2.46 kg of dried and shredded horse manure was needed to produce 1 kg of insulation material.

Pyrolysis

Within the CarNe-project, pyrolysis of the insulation material was carried out on lab scale. However, the LCA of the new insulation materials was supposed to reflect the future situation, where insulation boards would be produced on an industrial scale. Consequently, assumptions were made concerning the pyrolysis facility as well as emissions and generated output heat.

The generated heat and CO_2-emissions were derived with a system model which had been developed at ZHAW in a previous project using the STELLA Architect software (Abplanalp, 2020). The confidential model was originally developed for an already existing pyrolysis facility with a thermal power of 400 kW, a through-put of 300 kg of material per hour, and a yearly production time of 7000 h. The model used wood chips as input material and assumed that all by-products (CH_4, pyrolysis oil) were completely burnt. Consequently, emissions and output flows only consisted of CO_2, heat and ash. Table 4 summarizes the process parameters from the STELLA Architect model for a pyrolysis temperature of 450°C.
Accordingly, the assumed pyrolysis process resulted in the emission 0.680 kg CO_2 per kg input material. In the LCI, these emissions were accounted for as biogenic CO_2 emissions for the pyrolysis of biogenic material (wood, horse manure, gluten), whereas the corresponding emissions from the pyrolysis of PVAc were modelled as fossil CO_2 emissions.

Within the pyrolysis model, 0.125 kWh of output heat per kg input material is used for the drying of wood chips. For the CarNe materials, the amount of heat needed within the pre-processing of wood fibres and horse manure was estimated to be 0.850 kWh per kg dry material before pyrolysis, based on the heat demand given in the original background data set *Fibreboard, soft {CH}| fibreboard production, soft, from wet processes*. Accordingly, the remaining excess heat was reduced to 0.584 kWh per kg input material for all CarNe materials.

Table 4: Process data of the pyrolysis of wood chips, derived with a STELLA Architect model which was developed at ZHAW.

Process parameter	Value	Unit
Wood chips input	332.0	kg/h
Biochar output	68.8	kg/h
Stored CO_2-eq. in produced biochar	224.6	kg/h
Ash output (to be disposed)	0.1	kg/h
CO_2 emissions	225.8	kg/h
Total heat output	661.1	kWh/h
Output heat used for drying of wood chips	41.5	kWh/h
Output heat used within pyrolysis process	185.1	kWh/h
Remaining excess output heat	434.5	kWh/h

The LCI of the pyrolysis facility itself was taken from the study by Gutzwiller et al. (2022), which included the LCI per kg processed material for different existing facilities. The facility type *PyroFarm* was used (see Table 28 in (Gutzwiller et al., 2022)), which had a similar throughput of material as the facility assumed in the STELLA model.

Use phase

The use phase represents the time during which the insulation material is used as building component. It was assumed that the use phase was not related to any environmental burden. This approach is in line with commonly used LCA data for building materials, such as KBOB data.

End-of-life phase

As worst-case scenario concerning disposal, it was assumed that the insulation materials were disposed via incineration at their end-of-life. Regarding cases 1 and 2, the ecoinvent data set *Disposal, building, fibre board, to final disposal/CH* was modified in the way that only wood and no synthetic binder was burnt, to take into account that only biogenic CO_2 would be emitted from the incineration. Regarding case 3, the same data set was modified to account for 14w% content of synthetic PVAc binder.

As best-case scenario concerning disposal to derive values for maximum CO_2-mitigation potentials, it was assumed that the pyrolysed insulation plates were shredded at the end of their life cycle and that the (bio)char was applied to soil and permanently stored (i.e. at least 100 years) with a 100% carbon stability in soil. This way of disposal was accounted for as negative emissions according to biogenic carbon content of the materials. A carbon stability of 100% in soil is a best-case assumption, as achievable stability values are still the matter of research (Matuštík et al., 2020). Furthermore, an application to soil was assumed for all three cases, regardless of the current regulatory situation concerning biochar applications (see also considerations in chapter 5.4).

The CarNe project did not include measurements of carbon contents. Therefore, the same carbon content of 75w% was taken as approximation for all CarNe materials, based on measurements by Gutzwiller et al. (2022). Only the permanent storage of biogenic carbon can be attributed to a removal of CO_2 from the atmosphere. The biogenic carbon contents of the CarNe materials were 75w% for the cases 1 and 2 using gluten as bio-based binder, and 64.5w% for case 3 using the fossil-based PVAc binder. These biogenic carbon contents were translated into CO_2 equivalents based on the mol masses of C and O with the factor 3.667 kg CO_2-eq./kg C_{bio}. The resulting corresponding negative emissions from permanent storage were -2.75 kg CO_2-eq./kg insulation material for cases 1 and 2, and -2.37 kg CO_2-eq./kg insulation material for case 3.

Due to the general level of uncertainties of the conducted LCA, only the best-case and the worse-case scenario were modelled regarding end-of-life. Other possible end-of-life options such as recycling and reuse as well as lower carbon stability in the soil would lead to results between these two scenarios.

Summary of life cycle inventory modelling of CarNe insulation materials

The inventory modelling of the three considered cases is given in Table 5, which shows the input data as well as the used ecoinvent 3 background data sets and data sets created within WP3 for each life cycle stage of the insulation materials.

Table 5: Overview of life cycle inventories of CarNe material insulation plates with different material compositions.

		Case 1		**Case 2**		**Case 3**	
		1 kg of insulation material made from wood fibres and gluten		**1 kg of insulation material made from horse manure and gluten**		**1 kg of insulation material made from horse manure and PVAc**	
Life cycle stage	Input data set	Amount	Unit	Amount	Unit	Amount	Unit
Transportation	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified	0.233	tkm	0.653	tkm	0.702	tkm
Provision of binder	Wheat gluten, production of, per kg, mass allocation	0.571	kg	0.571	kg	-	
	Vinyl acetate {GLO}| market for vinyl acetate	-		-		0.400	kg
Provision of substrate	Fibreboard, soft {CH}| fibreboard production, soft, from wet process, only waste wood, no binder, no heat input	0.0163	m^3	-		-	
	Processing of dry horse manure, cutting, per kg	-		2.286	kg	2.457	kg
Pyrolysis of insulation plate	pyrolysis of wood chips, per kg dwood chips- LCI from Stella model of ZHAW (450oC, 80% mass loss)	2.857	kg	2.857	kg	-	
	pyrolysis of 86% wood chips and 14% synthetic binder , per kg dry input material - LCI from Stella model of ZHAW (450oC, 80% mass loss)	-		-		2.857	kg
	pyrolysis facility, (referring to 1 kg of dry input material)	2.857	kg	2.857	kg	2.857	kg
Disposal	Disposal, building, fibre board, to final disposal/CH U, ONLY WOOD	1.000	kg	1.000	kg		
	Disposal, building, fibre board, to final disposal/CH U, incl. 14% synthetic Binder	-		-		1.000	kg

5.3 Results of WP3

5.3.1 Carbon footprint and overall environmental impact of CarNe materials without permanent carbon storage

The conducted LCA of the CarNe insulation materials resulted in a specific carbon footprint of 1.25 kg CO_2-eq. per kg insulation material for case 1 (wood fibres, gluten), 1.23 kg CO_2-eq./kg for case 2 (horse manure, gluten), and 1.91 kg CO_2-eq./kg for case 3 (horse manure, PVAc), if the disposal via incineration was considered.

As shown in Figure 10, the corresponding carbon footprints per m^2 insulated building surface range between 20 and 52 kg CO_2-eq., taking into account the different reference flows which are needed to reach the same U-value of 0.15 W/(m·K). In general, the CarNe material based on wood fibres leads to a lower carbon footprint per m^2 than the two materials based on horse manure, because less material is needed to achieve the same insulation effect due to a lower thermal conductivity.

Independently from the material combination of substrate and binder, the production of the binder shows the highest contribution to the carbon footprint, reaching from 57% for case 3 to 86% for case 1. In contrast, the provision and pre-processing of substrates is connected to much lower contributions. The main reason for this difference is that in each case, the binder is based on primary material and therefore is specifically produced for the CarNe materials, while for the substrates only waste streams without any environmental burden are used. In fact, 570 g of gluten and 400 g of PVAc as primary material, respectively, are needed per kg of final insulation material, due to the high weight percentage of binder in the materials and due to the mass loss during pyrolysis.

Another reason for the low contributions related to the substrates is that output heat from the pyrolysis was assumed to be used for drying within the pre-processing of the substrates.

For case 3 (horse manure, PVAc), the pyrolysis process and the disposal via incineration show relevant contributions to the carbon footprint of 14% and 21%, respectively. Both processes have negligible contributions in the two cases using gluten as binder. The reason is that wood fibres, horse manure and gluten are biogenic materials which lead to biogenic CO_2 emissions, both during pyrolysis and incineration. In contrast to this, the pyrolysis and the incineration of the synthetic PVAc binder result in the emission of fossil CO_2, which contribute to climate change.

The transportation of substrates shows contributions of 3 to 8% to the carbon footprint of all CarNe materials. In absolute terms, the transportation of horse manure is related to a higher carbon footprint than the transportation of wood, due to higher reference flows and higher moisture content of horse manure before pre-processing.

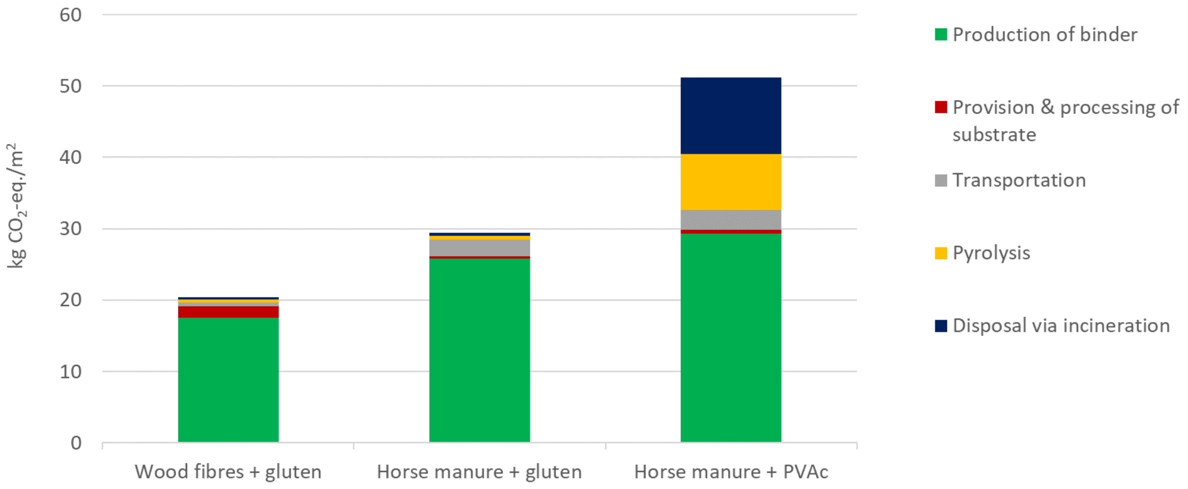


Figure 10: Carbon footprint of 1 m^2 pyrolysed insulation material with a thermal transmittance (U-value) of 0.15 W/m^2K; comparison of three material compositions analysed within the CarNe project.

The overall environmental impact of the three CarNe materials according to the ecological scarcity method are shown in Figure 11, referring to the functional unit of 1 m^2 building insulation with an U-value of 0.15 W/(m·K). In addition to climate change, the overall environmental impact takes into account other environmental impact categories such as water pollutants, land use, and emissions to soil. Consequently, CarNe materials using gluten binder show higher results than the case using PVAc binder, mainly due to the environmental impact of agricultural processes in wheat cultivation, as can be seen in more detail in Figure 12.

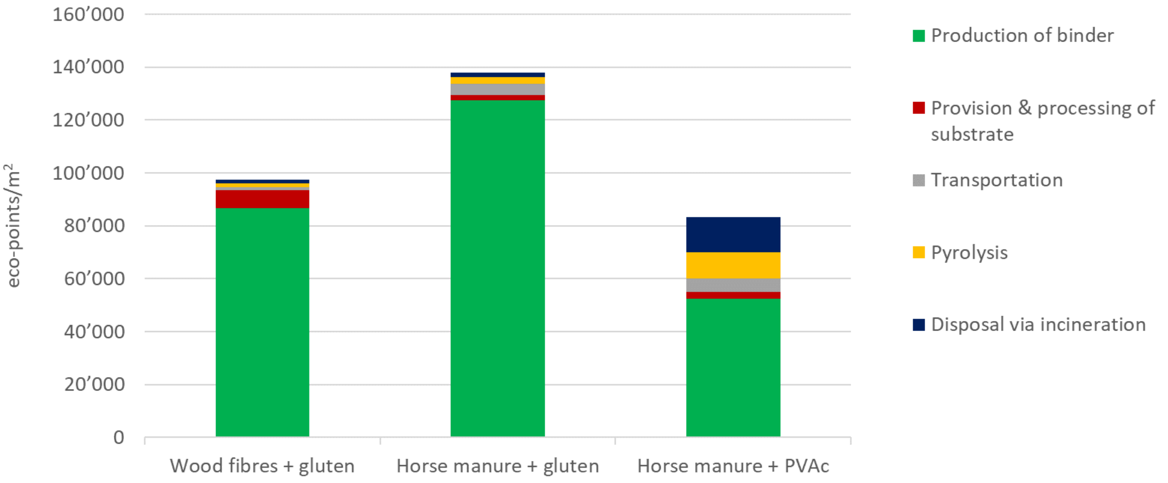


Figure 11: Overall environmental impact (according to ecological scarcity method) of 1 m^2 pyrolysed insulation material with a thermal transmittance (U-value) of 0.15 W/m^2K; comparison of three material compositions analysed within the CarNe project.

Figure 12 compares the different contributions of the considered environmental impact categories to the overall environmental impact of the CarNe materials.

Regarding the case 3 using the fossil-based PVAc binder, climate change forms the most relevant impact category, with a contribution of about 60%. Other relevant impacts are also mainly attributed to the production of the binder, such as the use of energy resources and main air pollutants and particulates.

For the cases using gluten binder, the relative contribution of climate change is smaller (about 20%) since the cultivation of wheat is connected to additional environmental impacts apart from climate change. This leads to relevant contributions to the overall environmental impact caused by the use of water resources (~5%), land use (~18%), water pollutants (~20%) and pesticides to soil (~14%).

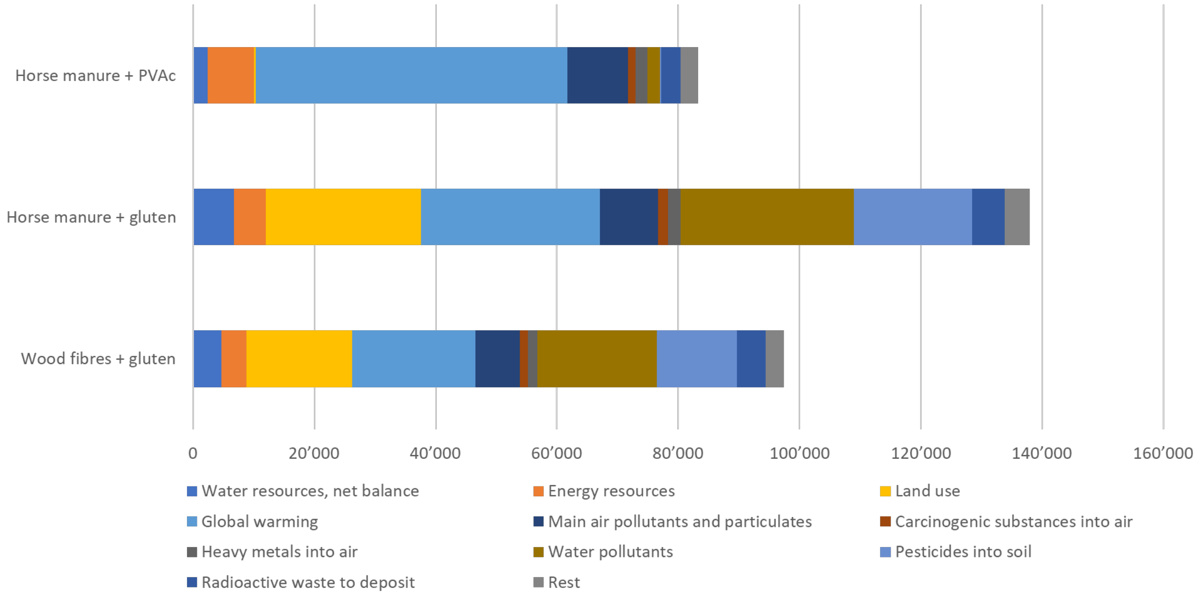


Figure 12: Contributions of environmental aspects to overall environmental impact (according to ecological scarcity method) of 1 m^2 pyrolysed insulation material with a thermal transmittance (U-value) of 0.15 W/m^2K; comparison of three material compositions analysed within the CarNe project.

5.3.2 Comparison to conventional insulation materials

The carbon footprint of CarNe materials per functional unit is compared to the carbon footprint of conventional insulation materials in Figure 13. The results shown for CarNe materials without permanent carbon storage are those already shown above in Figure 10, with the difference that the contributions from the provision of binder and substrate and from the pyrolysis are summed up to an aggregated production phase (shown in blue), while the contributions from the disposal via incineration are shown in orange.

Additionally, results for the CarNe materials assuming a permanent carbon storage at the end-of-life are presented. These results do not show any emissions resulting from the disposal, as no incineration is assumed. Instead, the application of the char into soil leads to negative results for the disposal, representing the assumed permanent storage of the biogenic carbon content in the ground.

The results show that the carbon footprint of CarNe materials is in the range of conventional materials, if no permanent carbon storage is considered. Especially the two cases using gluten as binder show similar results as the conventionally used fossil-based insulation foams made from expanded polystyrene (EPS) and from polyurethane (PIR/PUR). In contrast, extruded polystyrene (XPS) is connected to about 2.5 to 5.5 times higher emissions than the CarNe materials. This is because the market mix of XPS includes a share of material which is produced using the hydrofluorocarbon HFC-134a, which has a high global warming potential. In addition, the reference flow for XPS is about 2 times higher compared to EPS and PIR/PUR, due to its higher thermal conductivity and higher density.

The results for the CarNe materials with permanent carbon storage show that, if permanent carbon storage at the end-of-life is achieved, the amount of negative CO_2 equivalents from the application into soil exceeds the positive emissions from the production. Consequently, the CarNe materials would become an overall carbon sink.

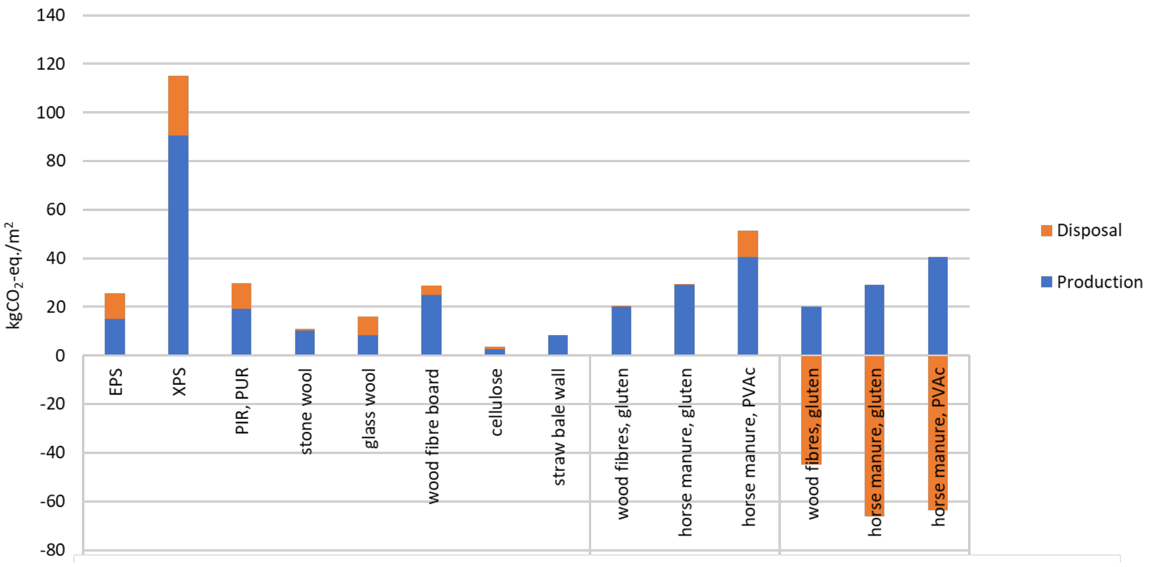
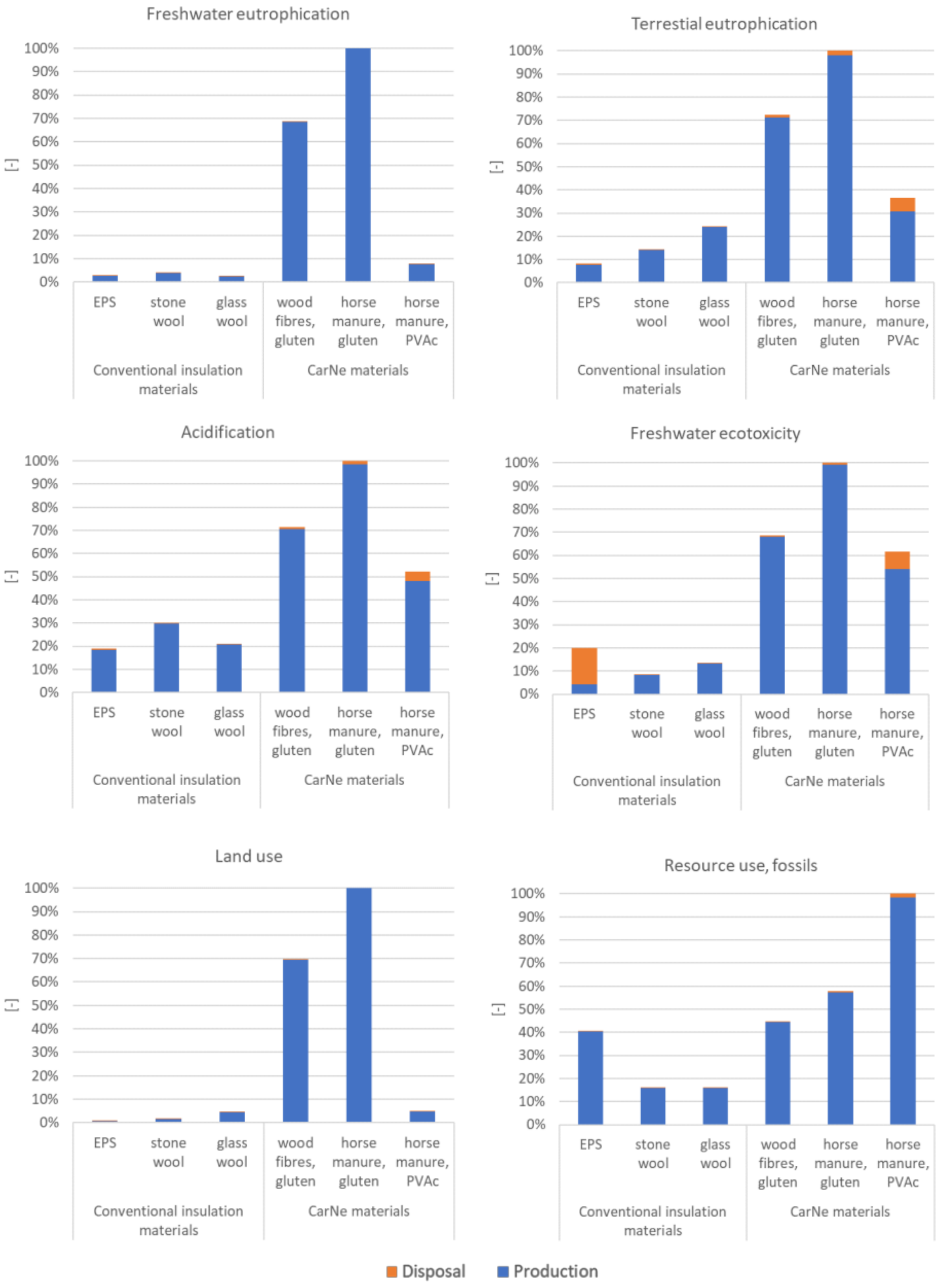


Figure 13: Comparison of carbon footprint of conventional insulation materials and CarNe materials; all results refer to 1 m^2 insulation material with a thermal transmittance (U-value) of 0.15 W/m^2K.

To illustrate potential trade-offs, Figure 14 shows the comparison of environmental impacts of CarNe materials and the most common conventional insulation materials (EPS, stone wool, glass wool) regarding relevant EF impact indicators on midpoint level.

The comparison shows that CarNe materials using gluten binder lead to significant trade-offs with respect to freshwater and terrestrial eutrophication, acidification, freshwater ecotoxicity and land use. The reasons for the significantly higher results in these impact categories lie in the agricultural production of wheat. Using PVAc instead of gluten binder reduces the impact of the CarNe materials in these categories. For freshwater eutrophication and land use, the results for the CarNe material using PVAc are similarly low as the results of the conventional insulation materials.

The CarNe material using PVAc shows a trade-off regarding the use of fossil resources, with results about two times higher than CarNe materials using gluten. This is due to crude oil as raw material for the PVAc and to the energy consumption of the production process of PVAc. In contrast, the fossil resource use connected to the CarNe materials using gluten binder is in the range of the result for EPS and is mainly due to the electricity use for gluten production.


Freshwater eutrophication

Terrestial eutrophication

Acidification

Freshwater ecotoxicity

Land use

Resource use, fossils

Figure 14: Relative comparison of conventional insulation materials and CarNe materials for midpoint impact indicators according to the EF method; all results refer to 1 m^2 insulation material with a thermal transmittance (U-value) of 0.15 W/m^{2}K and are normalised to the highest result for the corresponding impact category; the values for disposal of the CarNe materials refer to the case of incineration.

5.3.3 Yearly greenhouse gas mitigation potential on national level

The yearly greenhouse gas mitigation potential related to CarNe materials was assessed assuming that the entire available quantities of sieve overflow and horse manure in Switzerland would be used as base material for the pyrolysis. The assessment resulted in possible net negative emissions of yearly -194’000 t CO_2-eq. from the usage of insulation material based on sieve overflow (i.e. wood fibres), assuming permanent carbon storage after usage by applying the biochar into soil. The corresponding results for material based on horse manure were -113’000 t CO_2-eq. of yearly net negative emissions if using gluten binder, and -58’600 t CO_2-eq. of yearly net negative emissions if using PVAc binder.

The available material flows of sieve overflow and horse manure, as well as corresponding building areas which could be insulated are compared in Table 6. The table also contains the comparison of potential net negative greenhouse gas emissions, as well as related avoided emissions from replacing conventional insulation material and estimates for the usable excess heat from the pyrolysis process.

Although the yearly available amount of horse manure is 1.6 times higher than the amount of sieve overflow, the achievable insulated building surface is considerably lower for material based on horse manure (~3 Mio. m^2) than for material based on sieve overflow (~7.8 Mio. m^2). One reason is the low dry matter content of 35% of horse manure, compared to 98% used for sieve overflow. In addition, the CarNe materials based on horse manure show a higher density and partially also a higher thermal conductivity than the CarNe material based on wood fibres, which means that more material is needed to achieve the same U-value.

The estimations of excess heat from the pyrolysis process are proportional to amount of dry material to be pyrolysed. Consequently, the differences between the three CarNe materials are directly linked to the different available dry material flows in combination with the binder content.

The differences between the CarNe materials regarding avoided emissions from replacing conventional insulation materials are proportional to the differences in achievable insulated building surface. Stone wool, glass wool and EPS represent the most common conventional insulation materials used in Switzerland. Of these three, stone wool shows the lowest carbon footprint per m^2 insulated building surface, while EPS shows the highest. As low estimate, Table 6 gives the avoided emissions assuming that stone wool would be replaced.

Table 6: CO_2 mitigation potential, estimated excess heat and related process data related to the usage of pyrolysed insulation material based on nationally available waste streams for sieve overflow and horse manure.

Waste stream as base material		**Sieve overflow**	**Horse manure**	**Horse manure**
Binder		**Gluten, 20w%**	**Gluten, 20w%**	**PVAc, 14w%**
Available quantity of base material, CH,	[t/a]	297’000	481’000	481’000
Available quantity of base material, CH, dry matter	[t/a]	291’060	168’350	168’350
Producible insulation material via pyrolysis	[t/a]	127’000	73’600	68’500
Corresponding insulated building area with U-value of 0.15 W/m^{2}K	[m^2/a]	7’796’000	3’069’000	2’553’000
Excess heat from pyrolysis	[MWh/a]	212’000	127’000	114’000
Avoided emissions from replacing stone wool as insulation material	[t CO_2-eq./a]	-84’100	-33’100	-27’500
Net negative emissions if permanent C-storage at end-of-life is achieved	[t CO_2-eq./a]	-194’000	-113’000	-58’600

The different contributions of production and disposal into soil to the net negative emissions are shown in Figure 15 for the CarNe material based on wood fibres and gluten (left), as well as horse manure and gluten (right). For both CarNe materials, the figure also shows the full range of corresponding avoided emissions from the replacement of stone wool, glass wool and EPS.

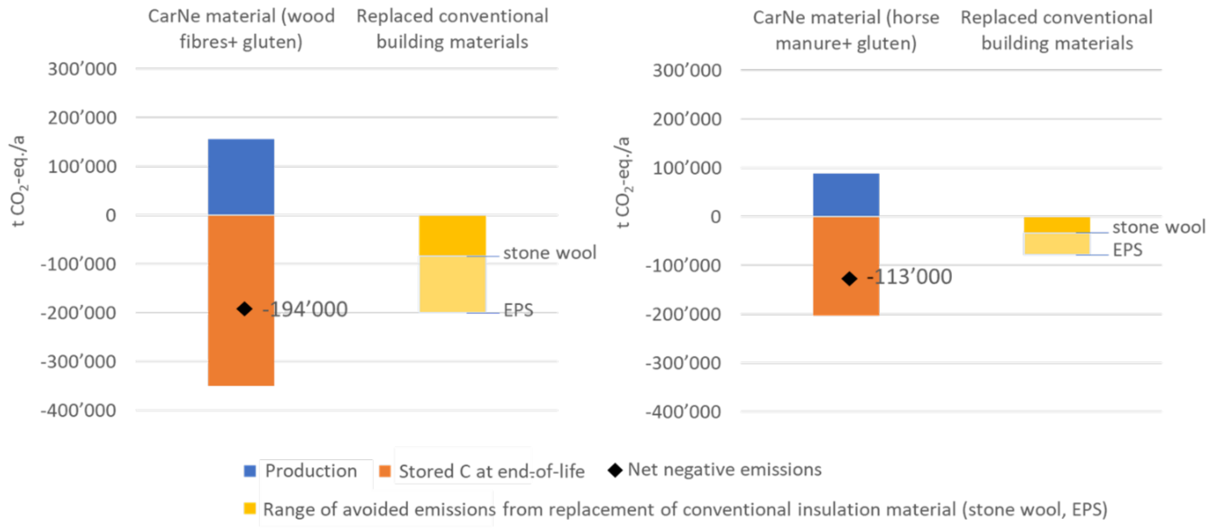


Figure 15: Yearly CO_2 mitigation potential resulting from the usage of nationally available quantities of sieve overflow (left) and horse manure (right) for biochar-based insulation materials and for replacing conventional insulation materials.

5.4 Considerations on data quality, uncertainties and limitations of the LCA

Foreground data used in this LCA study such as material compositions, density and thermal conductivity of CarNe materials had been specifically determined in WP1 and therefore have a high data quality.

Nonetheless, it is important to acknowledge that the LCA results from WP3 are connected to relevant uncertainties resulting from approximations and assumptions made within the life cycle inventory modelling.

The given LCA results for the CarNe materials strongly depend on the considered mass loss during pyrolysis. With higher mass loss, more substrate and binder is needed to produce the same amount of insulation material. This is particularly important regarding the needed amount of binder, as the production of gluten and PVAc as primary material emerged as the process with the highest contribution to the environmental impact of the CarNe materials. The results shown in this report consider a mass loss of 65% during pyrolysis, which is the value determined on lab scale in WP1. The actual mass loss of a production on industrial scale will strongly depend on the realised pyrolysis facility.

Another parameter that strongly depends on the pyrolysis process is the amount of excess heat generated. The values for usable excess heat from the pyrolysis in Table 6 are estimations based on the used STELLA Architect pyrolysis model. The actual excess heat will depend on the future design of the pyrolysis facility and on the share of output heat used for the pre-processing of materials before pyrolysis. If the heat demand of the pre-processing was not covered by output heat from the pyrolysis, the environmental impact connected to the pre-processing of the substrates would increase significantly (about 10 times higher than results shown in Figure 10, if the heat demand was covered based on fossil fuels).

Regarding gluten, a source of uncertainty is the inventory of the gluten production from wheat flour which was derived from an assessment by Deng et al. (2013), as there was no background data set implemented in the ecoinvent 3 database. For future assessments, the modelling of gluten should be re-evaluated and updated, if needed.

The carbon content of pyrolysed materials was not measured but estimated to be 75% for all CarNe materials, based on the measurements by Gutzwiler et. al (2022). This leads to uncertainties regarding possible negative CO_2 emission from permanent carbon storage in soil at the end-of-life and thus to uncertainties on the given estimates for greenhouse gas mitigation potentials of CarNe materials. In future applications on industrial scale, the actual carbon content will depend on the material compositions as well as on the pyrolysis process.

Regarding carbon storage in soil, the shown results are a potential best-case scenario, where 100% of the carbon is assumed to be permanently stored in the ground. This is a simplification, as there is still not enough conclusive evidence on residence times and the stability of biochar in soil (Matuštík et al., 2020). Lower biochar stability in soil would result in lower CO_2 mitigation potentials of the CarNe materials. A sensitivity analysis showed that the CarNe materials could still serve as carbon sinks with permanent stabilities in soil as low as 50% for cases 1 and 2 using gluten binder and 70% for case 3 using PVAc binder, which are below the assumed stability of 80% after 100 years as presented e.g. in (Matuštík et al., 2020). Another important aspect are regulations regarding biochar. In this LCA study, it was assumed that all CarNe material would be allowed to be applied into soil[2].

Another simplification made in the inventory modelling is the neglection of the plastic residue content in the sieve overflow. Plastic contained in the wood fibres would increase emissions of fossil CO_2 both

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[2] The new fertilizer ordinance, being based on EU regulations, came into force on 1 January 2024. This means that the restriction to introduce biochar to the soil only if based on "untreated wood" no longer applies. Of course, all biochar materials brought into the soil need to adhere to certain quality criteria, e.g. as defined in the European Biochar Certificate.

during pyrolysis and incineration at end-of-life. Furthermore, the potential negative emission from permanent storage in soil would decrease due to a lower biogenic carbon content in the CarNe material. However, the impact of excluding plastic on the LCA results was estimated to be very small since the plastic content in sieve overflow was measured to be maximal ~1% by Gassner et al. (2023). Nevertheless, no systematic measurements of plastic content in sieve overflow have been carried out so far.

Finally, a relevant source of uncertainty is related to the use of different background libraries for CarNe materials (ecoinvent 3) and conventional materials (KBOB). This leads to an inconsistency in the comparison of the materials. However, considering the overall uncertainties of the LCA result, this inconsistency is not expected have any impact on the conclusions of the study.

5.5 Conclusions from WP3

The assessment of the environmental impact of CarNe materials demonstrated that pyrolysed building insulation materials based on the biogenic waste streams of sieve overflow and horse manure have the potential to serve as carbon sinks, if a permanent storage at the end-of-life is achieved.

Maximum potential yearly net negative emissions of -194’000 t CO_2-eq. and -113’000 t CO_2-eq., respectively, were estimated for the case that the total amounts of sieve overflow and horse manure in Switzerland were used to produce insulation material. Additional benefits of the proposed materials are related to avoided greenhouse gas emissions from replacements of conventional insulation material as well as useable excess heat from the pyrolysis process.

In the current version, the conducted LCA is connected to considerable uncertainties, as relevant process parameters such as mass loss during pyrolysis and thermal material parameters are still not available for large scale production processes. Nonetheless, the findings proved the importance of including LCA results already in early stages of the development phase in the sense of eco-design, as it helped to identify hotspots and to propose effective design improvements with respect to the environmental aspects.

The used binders based on wheat gluten and PVAc emerged as dominant ecological hotspot of the investigated materials. Both binders were based on primary materials, which were specifically produced for the insulation materials. This resulted in considerable contributions from the production processes to the GWP. In addition, the agricultural production of wheat as raw material for gluten led to significantly higher impacts regarding eutrophication, ecotoxicity and land use, compared to conventional insulation materials. The fossil-based binder PVAc, on the other hand, led to considerable fossil CO_2 emissions during pyrolysis and during incineration at the end-of-life (if a permanent storage is not achieved).

Further development steps should focus on the investigation of alternative binder materials. From an ecological perspective, the used binder should ideally be made from a bio-based waste stream. In any case, a refined LCA should be carried out once material composition is fixed and process data on large scale are available.

6 Over-all conclusions

This project was structured in three work packages that were conducted in separate streams of research but with significant interaction between each other. In this sense, the background knowledge of WP1 was decisive for the definition of technical and economic feasibility criteria for the selection of suitable waste streams within WP2. WP3 in turn provided the ecological criteria relevant for anearly evaluation of the waste streams. Further, WP3 delivered important feedback to the material development process in WP1 by means of early results from the LCA, allowing for an effective “eco design”.

Ultimately, the project led to broad set of insights and results that are crucial for the continuation of the material development and the subsequent marketing of this promising technology. In the following, these results are being summarized as a collection of main conclusions.

- A large **overview of potential waste streams** available for subsequent material development process was presented. This can be seen as a rather complete summary, combining results from different studies identifying the Swiss biomass potentials and will be of use even beyond this very project.
- Through the introduced **classification and selection scheme** most promising waste streams could be identified and further explored in the synthesis of carbon negative insulation materials. With an adaptation of the selection criteria the material selection process could be adapted to other processes than insulation material development.
- The waste material selection process rated **wood fibres** (from sieve overflow), **horse manure** and **deinking sludge** the highest, thus with the best qualification for the creation for a techno-economic and ecologically viable insulation material. Performance-wise, wood fibres and horse manure were superior to deinking sludge and processing of wood waste to yield small-scale fibres is energy intensive, **horse manure was selected as the top candidate.**
- The material synthesis and subsequent performance analysis showed that **competitive CarNe insulation materials** can be manufactured with **thermal conductivities** in a high performance range (compared to other bio-based materials) of **0.035-0.04 W/(m·K)** and low flammability.
- When upscaling small samples to larger insulation boards, the **mechanical strength appears to be still too limited** to allow for a regular and damage-free handling of the boards.
- Experiments with different binder materials and its **LCA revealed the criticality of some binders**, in spite of their biobased nature. Namely, gluten, qualifying for a good binder when being judged from a compound testing of thermal conductivity and compressive strength, shows a significant environmental footprint because of its high resource and land use intensity in the production process. This led to the selection of a fossil-based wood glue (PVAc), showing similar binding performance with smaller over-all ecological impact.
- When comparing the **climate performance of production and disposal of the CarNe materials to conventional fossil-based façade insulation materials** (EPS, PUR/PIR), it was found that they are very similar. This can be explained by the resource intense material synthesis process of the CarNe materials (e.g. mass loss of binder through pyrolysis).
- The comparable climate impact of the production and disposal of CarNe materials with conventional materials points to the **necessity of permanent storage of the carbon bound to the CarNe materials**. When considering this, a significant carbon removal potential of the CarNe materials can be identified.
- The estimated maximum **carbon removal potential of CarNe insulation material** based on horse manure ranges from **-20 to -35 kg CO_2-eq./$m^2_{insulation}$**, considering the required amount of material to achieve an insulation performance of 0.15 W/(m^2·K) and assuming that 100% of the contained carbon can be permanently stored at the end-of-life. When exploiting the available source potential in Switzerland for **horse manure** and sieve overflow this would lead to a total annual carbon removal potential of **-113’000 t CO_2-eq** and 194’000 t CO_2-eq respectively. These figures would correspond to the total of about **3 Mio. m^2** and 7.8 Mio. m^2 of façade area insulated with CarNe materials at a U-value of 0.15 W/(m^2·K), which is a very good thermal performance for the building envelope. Both materials together could theoretically cover two thirds of the yearly use of insulation material in Switzerland (which is

about 3 million m^3 according to Jakob et al., 2016). The combined carbon sink potential of both materials would be about 0.3 Mt CO_2-eq/a, i.e. 0.6% of the annual Swiss greenhouse gas emissions. The potential for emission avoidance, due to the fact that other conventional building insulation materials would not be utilised, is on the same order of magnitude. This potential is feasible regarding the end-of-life utilisation of the biochar materials as soil enhancer, as there is enough agricultural land to take up the total yearly amount of biochar insulation material from horse manure and screed overflow wood at the recommended rate of 1 t of biochar per hectar and year.

- At the current state of development, LCA results for the CarNe materials and thus the reported carbon removal potentials are connected to high uncertainties, mainly due to assumptions made concerning future pyrolysis processes on industrial scale.
- Before bringing CarNe materials to the natural cycle and storing the bound carbon in the soil, used insulation material could be reused and potentially recycled, e.g. when damaged. A **preliminary test confirmed recyclability** by adding new binder material, leading to a **slightly reduced thermal performance** with a thermal conductivity of about 42 – 43 W/(m·K). Of course, this would increase its overall footprint due to the addition of the binder.

In summary, the CarNe project confirmed the techno-economical and ecological feasibility of carbon negative materials for the application of building insulation. While CarNe materials show a comparable thermal and climate performance to today's high performance insulation materials, they further have the potential to act as a true carbon sink when brought to the soil for long-term storage. Open questions are seen for the soil integration asking for more detailed studies in this context along with adaptation of current regulations within Switzerland and Europe.

From a resource point of view CarNe materials are highly interesting as they allow for exploitation of actual waste streams for which there is no or little competition with other uses such as thermal exploitation. This is also reflected on an economic scale as true waste streams are cheaply available or even show negative prices.

On the level of material development, basic feasibility could be proven but at the same time potential for further optimizations could be identified. These mainly focus on the exploration of alternative binder materials for better ecological performance and higher mechanical strength. To do so, a better understanding of the surface chemistry of the biochar materials could be helpful in order to identify suitable, powerful binding systems. In general, binders based on biogenic waste streams would help to avoid trade-offs and improve the ecological performance of the CarNe materials.

7 Outlook and next steps

This project served as a techno-economic and ecological feasibility analysis for the carbon-negative building insulation material. Within further projects, the investigations pursued within the frame of this project will be continued by further optimization of insulation material performance as well as its ecological performance. With this, the maturity of the insulation material will be improved and consequently the technology readiness level (TRL) will be increased.

The material development of the carbon-negative insulation was initiated prior to this project and a respective patent application had been filed. A publication of the patent is expected in mid 2024. This patent will support the collaboration with potential industry partners for further material development and upscaling.

On a scientific level, publications on the material development and about the techno-economic and ecological performance are foreseen.

The dedicated use of a building material in the future and its application in the soil, most likely will need an appropriate regulatory and business context. In particular, a large scale uptake of carbon-negative materials will probably need financial or regulatory incentives in order to compete with technologically very mature materials such as EPS.

8 Publications

M. Stucki, H. Kröhnert, 2023. *Plant-based Insulation as Carbon Sink? Life Cycle Assessment of Biochar-Based Building Insulation Material* [conference presentation]; 11th International Conference on Life Cycle Management (LCM) 2023, Lille, France; September 6-8, 2023.

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10 Appendix

10.1 WP3: Specifications of conventional insulation materials¨

Table 7 summarizes the values for density and thermal conductivity which were used to determine the reference flow of conventional insulation materials within the LCA conducted in WP3.

Table 7: Specifications of conventional insulation materials which were used for the comparison with CarNe materials regarding their ecological performance.

KBOB-ID	Material	Density	Thermal conductivity
10.004	EPS	16.8 kg/m^3	30 mW/(m·K)
10.005	XPS	34.3 kg/m^3	35 mW/(m·K)
10.006	PIR, PUR	30 kg/m^3	20 mW/(m·K)
10.008	Stone wool	40 kg/m^3	34 mW/(m·K)
10.001	Glass wool	35 kg/m^3	32 mW/(m·K)
10.009	Wood fibre board	148 kg/m^3	40 mW/(m·K)
10.010	Cellulose	50 kg/m^3	38 mW/(m·K)
10.015	Straw bale wall	215 kg/m^3	60 mW/(m·K)

10.2 WP3: Life cycle inventory of wheat gluten

Table 8 summarizes the life cycle inventory and the corresponding ecoinvent 3 data sets which were used to model wheat gluten within the conducted LCA of WP3. The life cycle inventory was derived based on Figure A1 in Deng et al. (2013).

Table 8: Life cycle inventory modelling of wheat gluten which was used withing the LCA of CarNe materials in WP3.

Name, ecoinvent v3.9 data set	Amount	Unit	Comment
Gluten, from wheat flour	**1**	**kg**	
Input from technosphere: Materials/fuels			
Tap water {RER}| market group for tap water	2.33	kg	(210*0.15/13.5); 210kg tap water is needed in total to produce 13.5kg of gluten powder and 70kg starch; factor 0.15 accounts for mass allocation between gluten and starch
Wheat flour {RoW}| market for wheat flour	1.11	kg	(100*0.15/13.5); 100kg wheat flower are needed to produce 13.5kg of gluten powder and 70kg starch; factor 0.15 accounts for mass allocation between gluten and starch
Input from technosphere: electricity/heat			
Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U	0.127	kWh	(41.1/3.6)*0.15/13.5; In total, 41.1MJ electrictiy is needed to produce 13.5kg of gluten powder; and 70kg starch; factor

			0.15 accounts for mass allocation between gluten and starch
Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U	2.29	kWh	(111.2/3.6)/13.5; In total, 111.2 MJ electricity is needed for the drying of hydrated gluten to 13.5kg gluten powder, which are allocated completely to the gluten production
Outputs to technosphere: waste treatment			
Wastewater from maize starch production {GLO}| market for wastewater from maize starch production	9.45	L	63*0.15; 63kg of wastewater has to be treated to produce 13.5kg of gluten powder and 70kg starch, factor 0.15 accounts for mass allocation