NEWSLETTER

COMPASsCO$_2$

Contents

APRIL 30, 2025

Issue : IX

This project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. 958418.

Team: 12 partners from 7 countries

Research focus: New particles, metal alloys and heat exchanger

Duration: 1 November 2020 – 30 April 2025

Main Accomplishments

COMPASsCO$_2$ Scientific Outcomes & Achievements

WP 1 (Materials operation conditions and their feasibility studies): This WP focused on defining system parameters and evaluating the feasibility of materials and technologies for a supercritical CO_2 (sCO_2) solar power system. Ten different sCO_2 Brayton cycle configurations were assessed, leading to the selection of optimal process conditions—including a 700°C turbine inlet temperature at 260 Bars and particle/sCO_2 heat exchange parameters—towards a maximized efficiency of approx. 49%. Based on these conditions, candidate materials for both heat exchanger components and heat-transfer particles were pre-selected for their ability to perform under extreme thermal and mechanical stress. WP1 also investigated both low- and high-pressure heat exchanger designs, performing thermo-mechanical stress analyses to validate material choices, and ultimately finalized a modular industrial-scale heat exchanger design capable of transferring over 200 MW_{th} with 15 MW_{th} per module. A comprehensive techno-economic analysis was carried out, evaluating the production costs of novel particles and estimating heat exchanger costs using experimental and commercial benchmarks. Five concentrated solar power (CSP) plant configurations were analyzed in terms of cost, efficiency, and levelized cost of electricity (LCOE). Additionally, novel Cr-based alloys and coatings from WP3 were assessed, confirming the economic feasibility of coatings such as Cr/Si slurry (~750 €/m²), while bulk Cr alloys face ductility limitations. The work also included market studies targeting the Mediterranean and MENA regions, identifying broader applications for the developed materials, such as Cr-Si coating for gas turbine blades and industrial process heat at high temperature and harsh environment.

WP2 (Development and Testing of Particles): It focused on the development, testing, and optimization of novel heat-transfer particles for use in high-temperature solar applications. State-of-the-art particles do not maintain a constant solar absorptance after thermal testing, making them suboptimal for use in Concentrated Solar Power (CSP) applications. Novel particles developed by Saint-Gobain offer significant performance improvements, including stable solar absorptance, better mechanical stress distribution, and can be produced at a similar cost. Among these, FerOx particles were selected as the best option due to their increased hardness compared to other granulated particle generations, despite having relatively lower solar absorptance. To enhance solar absorptance, three coatings with different compositions and application techniques were

developed by CIEMAT, DLR, and DFI. Environmental and thermal testing have shown that the coatings maintain stable optical properties. After thermal tests, DFI coatings exhibited the highest solar absorptance, while CIEMAT coatings experienced the lowest decay. Notably, DLR coatings slightly improved solar absorptance after testing, indicating that the heat treatment applied after deposition was insufficient to fully complete the curing process. In terms of abrasion resistance, all three coatings performed similarly at ambient temperatures. However, during abrasion testing at operational temperatures, the DFI coating experienced the greatest loss in solar absorptance, while the DLR coating showed the lowest absorptance loss. The highest solar absorptance at the end of the test was achieved by the CIEMAT coating.

WP3 (Development of Metals): This WP focused on the development of advanced chromium-based materials for high-temperature, corrosive environments typical of particle-to-sCO_2 heat exchangers. The team designed and synthesized Cr-NiAl bcc-superalloys[1] and Cr-Si alloys[2] that demonstrated excellent thermal stability up to 1000°C, high strength, and superior oxidation and corrosion resistance, all at a lower material cost than conventional nickel-based superalloys. However, their application as structural materials was limited by their brittleness, due to high ductile-to-brittle transition temperatures (above 600–700°C). To address this, WP3 also developed and patented an innovative Cr/Si slurry diffusion coating process, which was successfully applied to commercial steel and nickel alloys such as Inconel 740 and Rene 80. These coatings exhibited outstanding oxidation resistance, showed no catastrophic corrosion even under long-term and cyclic conditions, and proved highly effective against hot corrosion in sodium sulfate environments. Mechanical and environmental tests, including small punch and creep experiments, confirmed high strength but also brittleness in the bulk alloys. In contrast, coated materials performed well under erosion and oxidation, with TEM and EPMA analysis revealing the formation of stable SiO_2 and Al_2O_3 subscales. To support material design, machine learning and thermodynamic modeling were used to screen alloy compositions, identifying eight promising candidates—five of which matched the desired BCC-B2 microstructure upon experimental validation. Atomistic simulations further refined predictions related to ductility and phase stability.

WP4 (Evaluation and Modelling of Metal/Medium Interaction): It evaluated the performance and degradation behavior of heat exchanger materials under realistic high-temperature and high-pressure environments. The erosion behavior of materials is influenced by particle type, particularly hardness, and velocity, with Cr-Si coatings showing a beneficial effect in mitigating erosion. In terms of creep behavior, the observed data aligns with literature values, with minimum creep rates under all selected loads being less than 10^-6 s^-1. Sanicro 25 showed higher creep rates in CO2, while IN-617B displayed similar behavior, and there were some deviations observed among the superalloys. Overall, the atmosphere had very little impact on the creep behavior, and the load had a minimal effect on surface degradation. Demonstrator tests conducted at 700°C and 120 bar required developments in sealing, pumps, and sensors. For state-of-the-art (SOTA) alloys, formed layered oxide scales were observed, with IN740 showing the lowest oxidation. Novel alloys exhibited similar behavior to SOTA alloys, although some grain boundary oxidation was noted. In the field of modeling, experimental data was successfully implemented, revealing that fractures are likely to initiate due to impacts at surface oxide asperities. Lifetime modeling was completed by estimating the wear rate and depth for HEX materials.

WP5 (Technology Validation): This WP focused on the design, testing, and validation of a high-performance particle/sCO_2 heat exchanger (HEX) for concentrated solar power applications. A HEX mock-up was designed, manufactured and tested, incorporating insights from WP1 through WP4 to select optimal

[1] https://doi.org/10.1016/j.actamat.2023.119183

[2] https://doi.org/10.1007/s11085-024-10257-8

materials—such as coated steels and Cr-based alloys—and configure the heat exchanger geometry. Key design challenges, including pressure drop, mechanical stress, particle flow, and manufacturability, were systematically addressed. Initial cold loop testing evaluated particle flow behavior, helping to determine the ideal tube pitch and arrangement for balancing thermal efficiency and particle flow pattern. Subsequent hot-loop testing was conducted using a lab-scale rig operating at ~750°C, where the abrasion resistance of state-of-the-art materials, as well as the WP3 Cr-based materials and coatings, was evaluated. In addition, the impact resistance of various ceramic materials was assessed. These tests provided insight into wear durability and coating stability under cyclic operation. In the final phase, a mock-up particle/sCO2 heat exchanger was manufactured and tested, integrating actual particle flow and a functioning sCO_2 loop. The testing confirmed thermal performance under representative conditions, achieving Technology Readiness Level 5 (TRL 5). Finally, experimental data from WP5 fed back into techno-economic assessments from WP1, refining industrial HEX design, improving performance forecasts, and enhancing cost models for commercial-scale CSP deployment.

WP5 Final test rig – integrated particle/sCO2 heat exchanger mock-up

Project Management & Coordination

Regular project meetings, quarterly phone calls, and monthly WP meetings ensured smooth coordination across the COMPASsCO_2 consortium, allowing partners to align on technical progress, challenges, and next steps. These interactions fostered effective collaboration, kept the project on track, and helped maintain a high standard of scientific and technical excellence. In addition, three review meetings with an external expert were held to present project findings, and get an evaluation of the work conducted (see below).

Project Meetings

Eight Project Meetings (General Assembly – GA) were organized to discuss the overall progress, in terms of milestones, deliverables, technical progress achieved, risk/deviations and corrective actions, etc. While the Kick-off meeting had to be organized online because of the Covid19 pandemic, three physical meetings were held in 2022, 2023 and 2024.

Fourth GA Meeting at Plataforma Solar de Almeria (PSA), Tabernas, Spain, 30 November - 1 December 2022

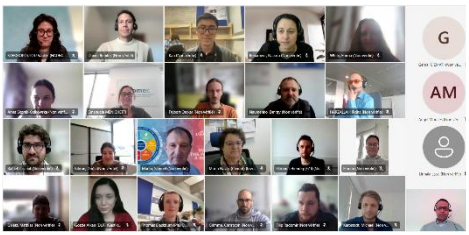
Fifth GA Meeting at FZJ, Jülich, Germany, 6-7 June 2023

Sixth GA Meeting at SGCREE, Cavaillon, France 31 January – 1 February 2024

Review Meetings

Throughout the COMPASsCO$_2$ project, **3 Review Meetings** with the European Commission and an independent expert were held to assess progress, share key results, and align on future activities. These meetings provided valuable feedback, ensuring that technical achievements, dissemination efforts, and project management remained on track. Each review confirmed the quality of the work performed and highlighted COMPASsCO$_2$'s strong contribution to material research, sCO$_2$ processes and CSP technologies.

First Review Meeting at JCR, Seraing, Belgium, 7 April 2022



Second Review Meeting, Online, 21 March 2024

Third Review Meeting at CVR, Husinec u Řeže, Czech Republic, 25 April 2025

Communication, Dissemination & Exploitation Activities

The COMPASsCO$_2$ project has effectively shared its findings through a variety of prestigious international and interdisciplinary platforms. These include published papers in renowned scientific journals, engaging presentations at conferences and workshops, informative papers, workshops and webinars. The project's impact was also extended through digital platforms (e.g. website, Zenodo, social media) and other outreach efforts, ensuring widespread dissemination of research outcomes.

Papers Produced by COMPASsCO$_2$ Team

The COMPASsCO$_2$ project has generated a wide range of impactful **scientific publications in peer-reviewed journals (13 in total)** addressing major challenges in concentrating solar power (CSP) technologies and high-temperature materials. In the field of particle development and coatings, a technical guideline was published on the SolarPACES website in May 2022, standardizing methods for evaluating the optical properties of solar absorber particles. Further research published in May and November 2022 demonstrated significant performance improvements through the use of black oxide and aluminum-incorporated deep black pigment coatings. Additional work on soiling characterization variability appeared in

Solar Energy Materials and Solar Cells in July 2023, alongside research published in January 2024 on spinel absorber coatings enhancing CSP receiver efficiency. Durability testing of novel particles was also reported in Solar Energy Materials & Solar Cells in November 2024. In the area of alloy development, publications in Physical Chemistry Chemical Physics (May 2023) and Acta Materialia (July 2023) explored advanced techniques for precipitate measurement using deep learning and the strengthening of chromium-based bcc-superalloys through iron supplements. Protective coating technologies were further advanced through research on Cr/Si-slurry diffusion coatings published in Materials (December 2023), as well as studies on nanocrystalline Y_2O_3-modified coatings and chromium-silicon slurry coatings, which appeared in Surface and Coatings Technology (June 2024) and High Temperature Corrosion of Materials (July 2024), respectively. A collaborative Round Robin Test on absorptance and emittance measurements was also presented at the SolarPACES 2022 Conference in March 2024. Finally, a study focusing on material challenges and alloy selection for particle/supercritical CO_2 heat exchangers was accepted for publication in Solar Energy in 2024. Altogether, these publications across high-impact journals such as Solar Energy Materials and Solar Cells, Coatings Journal, Materials, and Acta Materialia reflect the project's strong scientific output and its significant contribution to advancing CSP technology and high-temperature material performance.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Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Chromium-based bcc-superalloys strengthened by iron supplements

Kan Ma[a], Thomas Blackburn[a], Johan P. Magnussen[a], Michael Kerbstadt[b], Pedro A. Ferreirós[a,c], Tatu Pinomaa[c], Christina Hofer[d], David G. Hopkinson[e], Sarah J. Day[e], Paul A.J. Bagot[d], Michael P. Moody[d], Mathias C. Galetz[b], Alexander J. Knowles[a,*]

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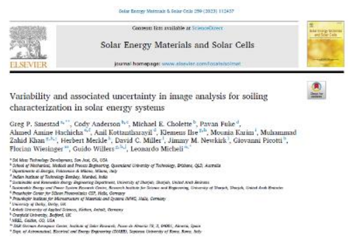
[b] DECHEMA-Forschungsinstitut, High Temperature Materials, Theodor-Heuss-Allee 25, 60486, Frankfurt am Main, Germany
[c] VTT Technical Research Centre of Finland Ltd, 02150, Espoo, Finland
[d] Department of Materials, University of Oxford, Parks Road, Oxford, OX1 3PH, United Kingdom
[e] Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, Oxfordshire, OX11 0DE, United Kingdom


Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

Variability and associated uncertainty in image analysis for soiling characterization in solar energy systems

Greg P. Smestad, Cody Anderson, Michael E. Cholette, Pavan Fuke, Ahmed Amine Hachicha, Anil Kottantharayil, Klemens Ilse, Mounia Karim, Muhammad Zahid Khan, Herbert Merkle, David C. Miller, Jimmy M. Newkirk, Giovanni Picotti, Florian Wiesinger, Guido Willers, Leonardo Micheli


High Temperature Corrosion of Materials
https://doi.org/10.1007/s11085-024-10257-8

ORIGINAL PAPER

Novel Chromium–Silicon Slurry Coatings for Hot Corrosion Environments

M. Kerbstadt[1] · K. Ma[2] · E. M. H. White[1] · A. J. Knowles[2] · M. C. Galetz[1]

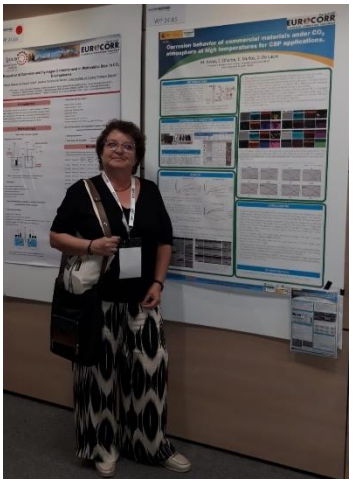
Beyond the project's duration, the COMPASsCO$_2$ project will produce **more than 15 papers** focused on materials for high-temperature applications, especially in concentrated solar power (CSP) systems. Topics include the oxide scale formation and hot corrosion resistance of chromized Ni-based alloys, novel Cr-Si alloys for high temperatures, and the stability of coatings in particle heat exchangers under thermal cycling. Additional studies will address high-temperature erosion, abrasion testing of coated particles, and screening of chromium-based high entropy superalloys. Research will also explore oxidation behavior of materials for CSP plants with CO_2 heat-transfer systems and the design of BCC superalloys. Finally, papers will cover the development of chromium-silicon slurry coatings and the creep behavior of Fe- and Ni-based alloys in CO_2 environments. These studies will continue to contribute to material advancements beyond the project's completion.

In addition to scientific papers, he COMPASsCO$_2$ team produced informative papers to share key project results with a general audience to raise awareness of research developments and their industrial applications for a Net Zero Carbon future. Three papers were released:

1. **First Paper** (March 2022) – Focused on the development and testing of new particles for high-temperature concentrating solar receivers, highlighting innovations from COMPASsCO2. 10.5281/zenodo.11386468
2. **Second Paper** (November 2023) – Covered new metal alloys for sCO2 heat exchangers in next-gen solar plants, including properties of bulk materials, coatings, and interactions with heat exchanger steel. 10.5281/zenodo.11385843
3. **Third Paper** (April 2025) – Discussed the development of chromium-based alloys for future concentrating solar technologies. 10.5281/zenodo.15310616

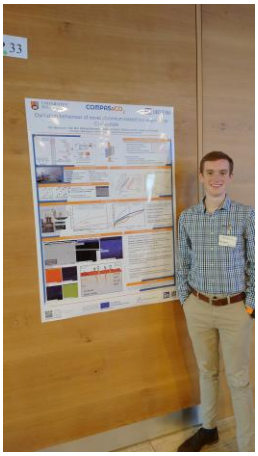
COMPASsCO$_2$ Participation at Conferences

The COMPASsCO$_2$ project has been widely presented at various international conferences, workshops, and events. Presentations **(69 in total)** include detailed discussions on new material solutions for thermal energy storage at SolarPACES2021, and contributions on BCC-superalloys and Cr-Si alloys at TMS 2022. The project also featured several oral presentations and posters at conferences such as ICMCTF, Plansee Seminar, and SolarPACES, highlighting topics like the development of advanced coatings for CSP systems, oxidation behaviors of superalloys, and thermal and environmental durability of novel particles. Other notable sessions included corrosion behavior in molten salts, mechanical testing of materials for solar heat exchangers, and innovations in high temperature corrosion and erosion resistance. Other presentations covered topics like alloy development, material testing, and performance evaluation at major conferences such as TMS 2025 and SolarPACES 2024.

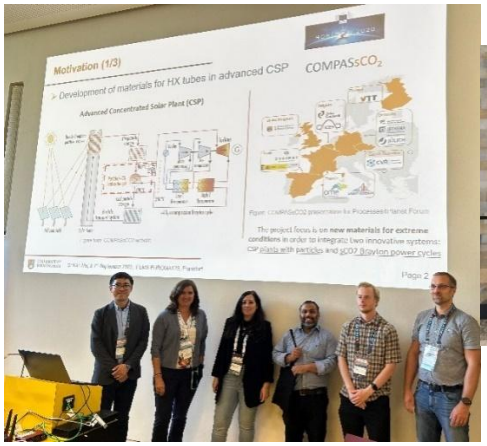


Marta Navas (CIEMAT) at EUROCORR 2024 conference, Paris, France, 2-5 September 2024

Florian Lebendig (FZJ) Wins Best Poster Award at HTCPM 2024 Symposium, Île des Embiez, France, 9 -14 June 2024



Tom Blackburn (UoB) at the High Corrosion and Oxidation Workshop 2023, Marktheidenfeld, Germany, 25-29 September 2023



COMPASsCO2 partners at the EUROMAT2023, 03-07 September 2023, Frankfurt, Germany

CIEMAT colleagues at the 2023 MRS Conference, San Francisco, USA, 14 April 2023

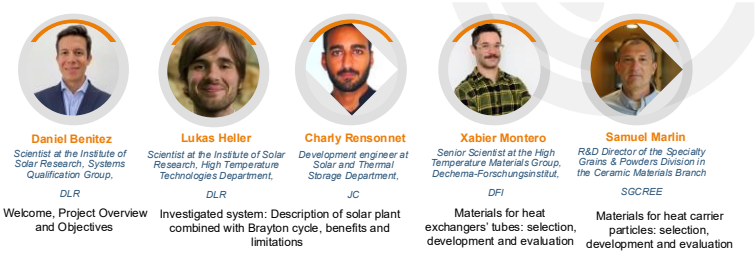
Florian Lebendig (FZJ) at the trade fair for industry that was organized from 22 to 26 April 2024 at Hannover, Germany. with Ms. Victoria Petrova, Head of Unit (HaDEA, Industry Unit).

COMPASsCO$_2$ Workshops

COMPASsCO$_2$ Stakeholders Workshops

In order to interact with stakeholders to exchange knowledge, validate results and identify areas for collaboration, the first COMPASsCO$_2$ stakeholders workshop was organized on 10 June 2021 via video-conferencing. The workshop had the purpose to introduce the project, discuss the main research activities conducted, and identify areas in which to cooperate with other projects, institutions or companies. The main focus areas for this workshop were: the use of concentrating solar technology and its integration in the Brayton cycle; evaluation of state-of-the-art materials that could withstand the extreme operating conditions; and research, development and testing of innovative materials that guarantee reliability and sustainability under harsh conditions.

The Second Stakeholders Workshop of the COMPASsCO$_2$ Project was held on 25 September 2023 in a hybrid format (Marktheidenfeld, Germany and online), at the occasion of the international conference on high temperature corrosion and oxidation. The workshop was organized around two main sessions, the first dealing with advanced materials for abrasive environments and the second one focusing on material behaviour in sCO$_2$ environments. Representatives from the COMPASsCO$_2$ consortium presented the preliminary results of their analysis and had the opportunity to interact with experts industry and academia to further advance on the work and validate the findings. The meeting saw the participation of about 60 participants.



First Stakeholders Workshop

Second Stakeholders Workshop

COMPASsCO$_2$ Final Workshop

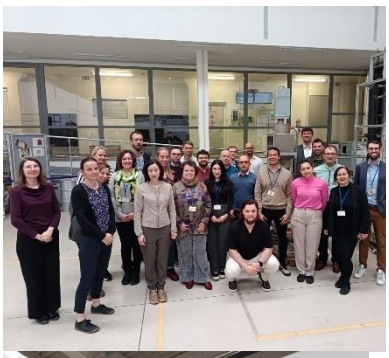
The COMPASsCO$_2$ Final Workshop took place in a hybrid format on 24 April 2025 – at CVR premises, in Husinec u Řeže, Czech Republic and online—bringing together leading experts to reflect on four years and a half of innovation in supercritical CO$_2$ (sCO$_2$) power systems. Under the theme "***Back to the Future: A Forward-Thinking Approach to Concentrating Solar Technologies***", the workshop agenda (shown below) was structured in such a way to highlight the main innovations brought by the project: advancements in CST receiver technologies using new particle materials; design and testing of high-temperature alloys and coatings; real-world validation of materials and systems under extreme conditions; and final industrial design and business case for sCO$_2$ implementation. The afternoon technical tour offered participants a hands-on look at: sCO$_2$ autoclave & erosion test lab, sCO$_2$ loop & heat exchanger test setup, and material testing & hot cell labs.

AGENDA

Time	Topic	Speaker(s)
9:00 – 9:30	Registration & welcome coffee	
	Introductory session	
9:30 – 9:40	Opening and welcoming remarks	Otakar Frýbort, CVR
9:40 – 10:00	Keynote speech: Status and perspectives of CST	Luka Lackovic, DLR
10:00 – 10:10	Main challenges addressed and innovations brought by COMPASsCO2	Daniel Benitez, DLR
10:10 – 10:25	Plant layout and state-of-the-art materials selection	Daniel Benitez, DLR
	Thematic sessions	
10:25 – 10:55	Receiver technology innovation: lessons learnt in the development and testing of new particles	Ana Gonzalez Alves, DLR Samuel Marlin & Nassira Benameur, SGCREE
10:55 – 11:15	Coffee break	
11:15 – 11:45	Materials innovation: novel alloys design for the extreme conditions of CST	Sandy Knowles, UoB Mathias Galetz, DFI
11:45 – 12:15	From research to operation: results from the validation of metal/medium interactions	Ceyhun Oskay, DFI Florian Lebendig, FZJ Patricie Halodová, CVR
12:15– 13:30	Lunch	
13:30 – 14:15	Turning theory into action: Lessons learned from testing technology in realistic conditions, validation on experimental infrastructure	Radomir Filip, CVR
14:15 – 14:30	Final industrial design and business case	Ridha Harzallah, JCR
14:30– 17:00	Technical tour	

COMPASsCO$_2$

14:30 – 17:00	**Technical tour**	
	sCO2 autoclave and erosion test laboratory	Radomir Filip
	sCO2 loop and HX mock-up test setup	Otakar Frybort
	Material labs	Patricie Halodová
	Hot cells and irradiated material labs	Petr Svrcula
17:00	**End of the meeting**	



Final Workshop at Husinec u Řeže, Czech Republic, 24 April 2025

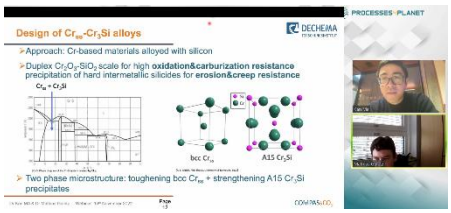
Synergies with other Projects & Joint Dissemination Activities

The COMPASsCO$_2$ project has fostered strong synergies with several other research networks and consortia, driving collaboration and knowledge exchange in the field of sustainable energy and high-performance materials.

- CO2OLHEAT Network: COMPASsCO$_2$ contributed to multiple webinars within this network, including a session on “R&D Activities on sCO$_2$ in Europe” in September 2022 and a webinar in June 2023 focused on heat exchangers for sCO$_2$ systems, where COMPASsCO$_2$ presented on developing high-efficiency particle-sCO$_2$ heat exchangers for CSP applications. This was organized as an EC Sustainable Energy Day.
- HIPERMAT Network: This collaboration led to a webinar in November 2022, where COMPASsCO$_2$ researchers presented on “Novel Cr-based alloys strengthened by intermetallics for structural and coating applications at high temperatures above 800°C.” Additionally, COMPASsCO$_2$ co-organized a joint session on "High Performance Materials for Sustainable Energy Applications" at MSE 2024 on 24-26 September 2025.
- ASTEP Network: Notably, COMPASsCO$_2$ was presented at an ASTEP workshop in October 2022, and the network helped identify and promote innovative research results, further supporting the sustainability of CSP technology.

These collaborations have significantly enhanced the dissemination and application of COMPASsCO2's research across the broader energy technology and materials innovation landscape.

Webinar on R&D Activities on sCO2 in Europe, 22 September 2022



Webinar on Novel high performance materials & components, 15 November 2022

Alexander Knowles (UoB) at MSE 2024, Darmstadt, Germany, 24-26 September 2024

How to Access COMPASsCO$_2$ Outcomes

With the COMPASsCO2 project coming to an end, stay engaged by accessing our results, publications, and final achievements on our website, social media, and Zenodo!

Project Website

Zenodo

LinkedIn

X

For more information

Check the project's website: www.compassco2.eu

Contact us: contact@compassco2.eu

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