Technological Feasibility: What are the current limitations of CCS technologies in terms of efficiency, scalability, and cost-effectiveness, and what research and development efforts are needed to overcome these barriers and make CCS more viable on a large scale?

Carbon Capture and Storage (CCS) faces several limitations in efficiency, scalability, and cost-effectiveness. Currently, CCS systems capture only about 85–90% of CO_2 from industrial emissions, but this process is energy-intensive, requiring 25–40% more energy from power plants (IPCC, 2022). This "energy penalty" reduces overall efficiency and increases operational costs.

Scalability is another major issue. Global CCS capacity is around 50 million metric tons per year, while annual CO_2 emissions exceed 36 billion metric tons (Global CCS Institute, 2023). Expanding CCS infrastructure would require massive investments in pipelines, storage sites, and retrofitting existing power plants and factories.

Cost-effectiveness remains a significant hurdle. Current CCS costs range from $50 to $120 per ton of CO_2 captured (IEA, 2023), making it economically unviable without strong government subsidies or carbon pricing mechanisms. For comparison, renewable energy sources like solar and wind have become much cheaper and more scalable alternatives to emission reductions.

To overcome these barriers, research efforts focus on:

- **Advancing Direct Air Capture (DAC):** New materials like metal-organic frameworks (MOFs) improve capture efficiency.
- **Reducing Energy Penalties:** Integrating CCS with low-carbon energy sources can offset extra energy consumption.
- **Enhancing Storage Solutions:** More research on safe, long-term geological storage is needed to prevent leaks.

While CCS has potential, prioritizing renewable energy and phasing out fossil fuels remains a more sustainable climate solution.

Sources:

- IPCC (2022). AR6 Climate Change Report.
- Global CCS Institute (2023). Status Report.
- IEA (2023). "CCS Costs and Development."