Supercritical CO_2 and the flexible future of fossil fuels

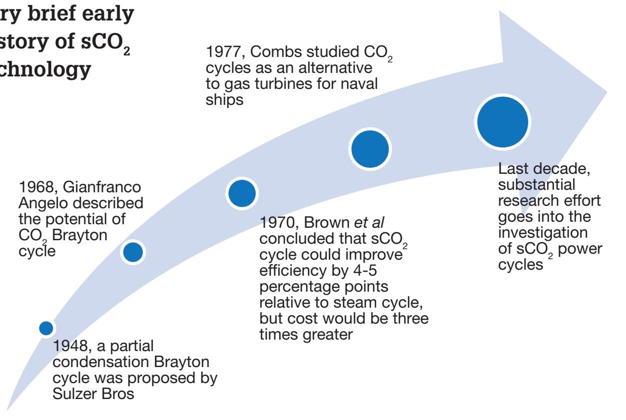
sCO2-FLEX is an EU funded project that brings together key academic and industrial stakeholders to demonstrate how supercritical CO_2 could contribute to Europe's climate change and energy transition goals by making fossil-fuelled power production more capable of supporting a smarter and more flexible energy market.

Fossil fuelled power plants are increasingly expected to provide fluctuating back-up power, to foster the integration of intermittent renewables energy and provide stability to the electrical grid. Therefore, there is a need to develop innovative and cost-effective ways of enabling existing and future fossil fuelled power plants to be flexible enough to deal with load fluctuations and also achieve reduced emissions.

In this context, the sCO_2-Flex project, funded for three years with a €5 million grant from the EU Horizon 2020 programme, and led by French utility EDF, brings together an interdisciplinary group of partners including researchers, technology providers and industry experts covering the whole value chain (see Figure 1)[1] with the aim of adapting fossil fuelled power plants to future energy system requirements. To do this it is developing and validating a scalable/modular design for a 25 MWe Brayton cycle plant using supercritical[2] CO_2, a working fluid that will enable an increase in the operational flexibility (faster load changes, start-ups and shut-downs) and efficiency of fossil fuelled power plants, with much more compact turbomachinery.

Supercritical CO_2 cycles are not a completely new technology (Figure 2). Already by the end of the 1960s several researchers and engineers from different countries were studying the potential advantages of such cycles.

Figure 2. A very brief early history of sCO_2 technology



In 1968, Gianfranco Angelino proposed the forerunner of the modern recompression cycle architecture, the most interesting and studied cycle configuration due to its high efficiency and low complexity.

Around the same time Ernest Feher investigated the concept and came to conclusions similar to those of Angelino: supercritical CO_2 cycles enable higher efficiencies to be achieved than those of conventional power plants, even at moderate turbine inlet temperatures.

During the early 1970s these investigations shifted from purely thermodynamic calculations to more detailed design studies, especially coupled to nuclear power and shipboard applications.

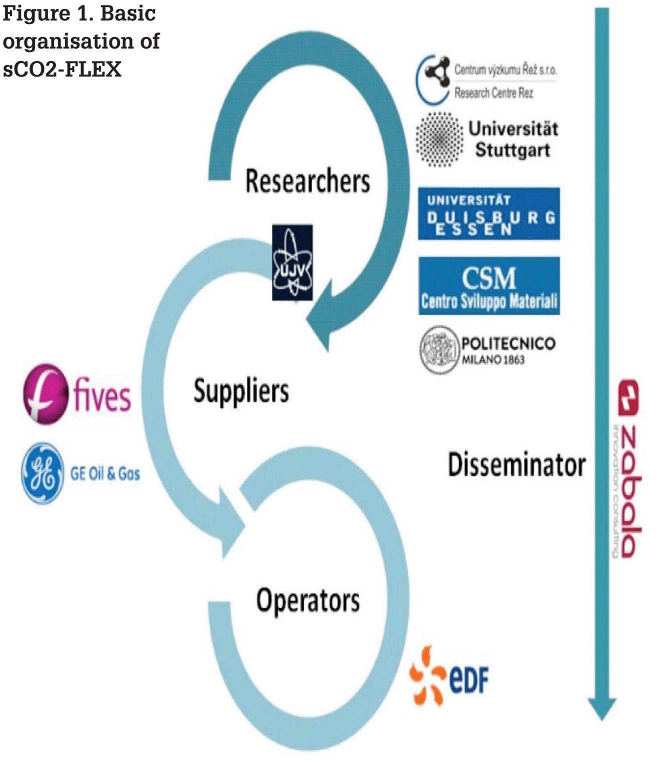
Despite all this work, the sCO_2 cycle has not been deployed in practice, mainly due to poor turbomachinery experience and lack of suitable compact heat exchangers.

In recent years, starting from Vaclav Dostal's work at MIT on the adoption of sCO_2 cycles with high temperature gas cooled nuclear reactors, interest in supercritical carbon dioxide power cycles enjoyed a revival. The research and development effort on sCO_2 cycles has focused predominantly on three main power generation types: concentrating solar power (CSP); "Generation IV" nuclear reactors; and fossil fuelled power plants.

The US National Renewable Energy Laboratory and its partners, under the 2012 SunShot CSP programme, are developing a turbine design able to demonstrate the feasibility and economic viability of a multi-MW power cycle using sCO_2 as the working fluid.

With regards to fossil fuel applications, a 50 MWt demonstration plant for electricity generation from natural gas using an oxyfuel direct fired sCO_2 cycle, the Allam cycle, has been built by NET Power

Figure 1. Basic organisation of sCO2-FLEX



[1] As well as EDF the consortium includes: Baker Hughes; UJV Rez; Centro Svillupo Materiali (Rina-Consulting-Centro Sviluppo Materiali); Centrum Vyzkumu; Fives Cryo; Zabala Innovation Consulting; Politecnico di Milano; Universitaet Duisberg Essen; Universitaet Stuttgart

[2] For CO_2, the critical point pressure and temperature are respectively 73.8 bar and 31°C. Under these supercritical conditions carbon dioxide has characteristics of a gas (eg expanding to fill its container) and a density akin to a liquid. The thermodynamic properties of supercritical carbon dioxide allow the use of compact turbomachinery designs (with smaller diameters and fewer stages than with steam or other gases – eg, helium – machines) enabling higher flexibility and reduced materials requirements (resulting in lower costs).

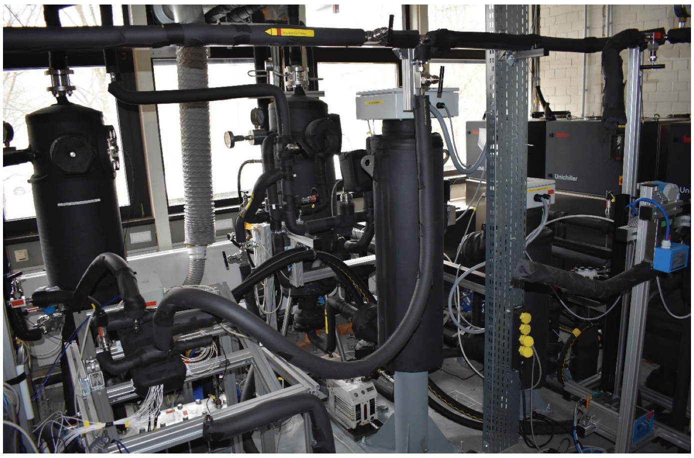


Figure 3. SCARLETT facility – testing of heat exchanger plates as part of the sCO_2 effort (photo: A. Wahl, IKE, University of Stuttgart)

and Toshiba and is undergoing commissioning at a site in La Porte, Texas.

Building on the outcomes of the H2020-funded sCO_2-Hero project (http://www.sco2-hero.eu/) – which enabled proof-of concept to be established – sCO_2-Flex aims to bring sCO_2 cycle technology closer to market uptake. Indeed, as already noted, the sCO_2 cycle has been identified as a promising technology to increase flexibility and efficiency as well as to reduce GHG emissions. Therefore the sCO_2-Flex partners have decided to join forces to demonstrate that a supercritical CO_2 Brayton cycle can provide greater flexibility than existing steam cycles by focusing on the integration of flexibility requirements into the cycle design. The main technical and technological challenges to be addressed are:

- design of highly efficient and compact turbomachinery;
- design of a heat exchanger taking into account numerous constraints;
- design of an effective instrumentation and control system, with increased adaptability to load variations to ensure that the nominal and part-load performance of the sCO_2 cycle is achieved with quick response.

Moreover, the consortium aims to demonstrate that the deployment of such a technology will enhance cycle efficiency and reduce environmental impacts in a cost-effective way.

Specifically, the project's objectives and expected outcomes – technical, economic, environmental, dissemination & exploitation – can be listed as follows:

- *Technical*. Increase in fossil fuelled power plant operational flexibility by:
  - enabling entire load range optimisation with fast load changes, fast start-ups and shut-downs;
  - development of advanced equipment (boiler, turbomachinery system, compact heat exchangers (see Figure 3) and materials concepts, contributing to increased modularity and reduced maintenance costs;
  - validation of the concept at component level and at system level by simulating different scenarios, including critical and nominal use cases;
  - design of a 25 MWe facility employing the sCO_2 cycle ready for implementation in a demonstration project, from 2020 onwards.

- *Economic*. Enabling market uptake and industrial deployment of the flexible supercritical CO_2 Brayton cycle from 2025 by:
  - establishing the sCO_2 Brayton cycle as an optimal fossil fuel power plant technology in terms of costs through optimised design and component integration;
  - optimisation of the sCO_2 cycle plant's operation and maintenance costs through selection of robust materials and components and through dynamic instrumentation & control concepts, yielding a 5% increase in capacity factor relative to conventional coal;
  - achieving a levelised cost of electricity (LCOE) for coal and lignite fuelled sCO_2 Brayton cycle plants that is 6 to 16% lower than the estimated LCOE of future supercritical coal plants with CCS.

- *Environmental*. Mitigating coal and lignite plant environmental impacts and fostering the acceptance of sCO_2 technology by:
  - avoidance of water use in the thermodynamic cycle/heat rejection section, employing air-cooling instead;
  - reducing CO_2 emissions and fossil fuel consumption for an equivalent power output;
  - making provision for addition of a post combustion CO_2 capture system and evaluating the benefits of CCS by carrying out a comprehensive life cycle assessment;
  - reducing the quantity of metal alloys needed for turbomachinery and the overall environmental footprint of the plant by at least 25% by decreasing the size of power block components/increasing power density.

- *Dissemination & exploitation*. Fostering proper dissemination, exploitation and uptake of the project's findings by:
  - encouraging uptake and making preparations for implementation of the first demonstration project with appropriately sized equipment;
  - organising and launching a European alliance dedicated to sCO_2 technology

The sCO_2-Flex project aims at enabling coal and lignite plants to run at very low minimal load (20%) with a high degree of flexibility while reaching a nominal efficiency of 48%. The table below compares sCO_2-Flex performance in terms of flexibility and efficiency with 'conventional' coal, lignite and combined cycle.

	sCO_2-Flex	Coal (state of the art)	Coal (current average)	Lignite (state of the art)	Lignite (current average)	CCGT (current average
Flexibility criteria						
Minimum load	20%	25%	40%	50%	60%	40%
Ramp-rate % nom load/min	>6	4	1.5	2.5	1	5-6
Hot start in h. (after <8 hours off)	<2	2.5	3	4	6	1
Cold start in h. (> 72 hours off)	<4	5	10	8	10	3
Efficiency criteria						
Efficiency at nominal load	>48 %	46%	33%	43.5	36%	55-60%

Potentially game changing

sCO_2-Flex has the potential to become a game-changing project for coal/lignite power plant technology, by putting at the disposal of suppliers and end-users a 25 MWe sCO_2 Brayton cycle plant design with high flexibility, high efficiency and minimised environmental impact and costs.

As project co-ordinator A. Cagnac (EDF) states:

"We believe that sCO_2 based technology has the potential to meet EU objectives for highly flexible and efficient conventional power plants, while reducing greenhouse gas emissions, residue disposal and, above all, water consumption. The project aims at building expertise on sCO_2 for fossil electricity generation and EDF is also interested in investigating its possible application to renewables such as CSP (concentrated solar power) and biomass."

The project, by bringing the sCO_2 cycle to TRL6, will pave the way to future demonstration projects and to a potential commercialisation of the technology.