



# **Optimal Power Plant Integration of Post-Combustion CO<sub>2</sub> Capture**

**Dr. Tobias Jockenhövel  
Dr. Rüdiger Schneider  
Michael Sandell  
Lars Schlüter**

**Siemens AG, Energy Sector  
Germany**

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## **Abstract**

Siemens is developing a proprietary CO<sub>2</sub> capture process with minimal energy demand and optimal integration in conventional coal-fired power plants. Beyond developing this capture process, Siemens has the unique opportunity to adapt components such as the desulfurization unit and the CO<sub>2</sub> compression system to the requirements of a power plant with CO<sub>2</sub> capture. Optimized process configuration and power plant integration significantly reduce the energy demand and result in an efficiency penalty of only approx. 9 % points. The capture process is scheduled to be tested from August 2009 on with real flue gas in a pilot plant linked to an E.ON power plant in Germany.

## **1. Introduction**

Many current R&D activities are focused on developing and improving the CO<sub>2</sub> capture process. Since the most important application for CO<sub>2</sub> capture will be on existing fossil-fired power plants, the acceptance and attractiveness of a CO<sub>2</sub> capture process will strongly depend on the capture efficiency, the ease of integration of the new process into a standard power plant and the operability of the power plant with CO<sub>2</sub> capture.

The requirements for some power plant components will significantly change with CO<sub>2</sub> capture, e.g. steam extraction, flue gas cleaning such as dust removal and desulfurization, etc. In addition, capture-ready design is currently very much in the focus as power plant operators in Europe need to consider capture-ready measures for new power plants according to the new EC directive. Being a comprehensive supplier of power plant technology, flue gas cleaning systems and CO<sub>2</sub> compression equipment is therefore a great advantage for Siemens' development and optimal power plant integration of a CO<sub>2</sub> capture process.

## **2. Power plant components affected by CO<sub>2</sub> capture**

### **2.1 General remarks**

A thorough integration concept and adaptation of several power plant components to the requirements of the capture plant – and vice versa – is required in order to maintain adequate power plant efficiency even with CO<sub>2</sub> capture. As Siemens has in-house development and production of the concerned components, optimal integration of the CO<sub>2</sub> capture process into the power plant becomes possible.

## 2.2 Flue gas duct and desulfurization

One inevitable interface that is required for the connection of a CO<sub>2</sub> capture plant is a flue gas duct that links the FGD unit and the CO<sub>2</sub> capture plant. A blower conveys the flue gas through the cooler and the absorber columns. This means that additional flue gas ducting and control devices are to be foreseen in order to direct the flue gas either to the capture unit or directly to the stack in bypass operation. Furthermore, depending on the SO<sub>x</sub> levels tolerated by the selected capture process, it might become necessary to extend or upgrade the existing flue gas desulfurization plant, see Section 4.

Due to the amount of electrical energy and utilities, e.g. steam and cooling water, required for the capture plant operation, further integration between the power plant and the capture unit is necessary. Using and extending power plant facilities for operating the capture plant is more beneficial both in terms of efficiency and economics than designing and operating the capture unit as a separate plant with its own energy supply. This implies further interfaces beyond the described flue gas connection as well as subsequent changes in design and operation of several power plant systems and components.

## 2.3 Steam turbine

### *Steam conditions*

An important interface is the steam extraction from the turbine as a heat supply for solvent regeneration. Due to the amount of heat and the required temperature level, the necessary heat for solvent regeneration is to be provided by low pressure steam. The currently needed large amount of steam does not allow for the utilization of extraction lines. For this reason, the cross-over pipe between the intermediate (IP) and low pressure (LP) steam turbine sections is considered as the most suitable extraction point. In terms of power plant performance alone, it is favorable to lower the conditions of the extracted steam as much as possible. However, the actually feasible conditions are limited by several factors. There is an optimum temperature level in the solvent reboiler in terms of specific energy consumption for solvent regeneration. Reducing this temperature might result in an increase of the specific energy demand, which in turn raises the steam demand. This effect can invert the supposed gain in power output. On the other hand, there is also an upper limit to the solvent regeneration temperature as it negatively impacts upon the plant performance and because the thermal stability of the solvent is limited.

The heat for the regeneration of the solvent is provided mostly by condensation of the extracted low pressure steam, which allows for compact equipment. The capture plant normally requires saturated or slightly superheated steam at a constant temperature even through part load. Since the steam at the cross-over pipe is superheated, cooling the extracted steam down and transferring its heat to the main condensate can yield an efficiency advantage. This measure requires additional equipment, such as a steam condensate heat exchanger and corresponding piping.

### ***Impact of steam extraction on turbine***

In comparison with conventional operation, steam extraction from the cross-over pipe in a standard turbine set corresponds to a pressure decrease at this point. This is due to the fact that the flow rate in the low pressure turbine and the upstream pressure are interdependent. This implies a change in the operating conditions of both IP and LP turbine. Operating limits of the applied turbines of major importance are: the admissible temperature difference between IP turbine inlet and outlet and increased steam velocity.

Furthermore, it is necessary to install a throttle flap upstream of the LP turbine in order to adjust the appropriate extraction pressure determined by the steam conditions for solvent regeneration. Throttling losses can be minimized through an appropriate redesign of the IP and LP turbine, which would aim at adequate transfer pressure conditions considering the extracted amount of steam. However, a throttle flap is imperative in order to maintain constant extraction pressure in part load operation. Consequently an optimized integration with minimum losses will not be possible in most cases without extensive adaptations of the steam turbine compared to today's typical design. Nevertheless, redesigning the IP and LP steam turbines for adequate steam extraction conditions for the capture unit implies restrictions for the operation without CO<sub>2</sub> capture: In non-capture operation, not all of the available extra steam can be fed through the LP turbine, and even less be converted into additional electric power.

## **2.4 Further plant components affected by CO<sub>2</sub> capture**

Further affected plant components are:

- Turbine building influenced by the outline of adapted steam turbine, connection and routing of process steam piping, connection and routing of condensate feed-back

pipings from capture plant as well as installations for low grade heat integration from CO<sub>2</sub> compression intercoolers with connection to the condensate system.

- Cooling system connected and charged with additional heat loads or extension and connection with additional heat sinks.
- Water logistics consisting of raw water supply incl. make-up water, demineralized water and waste treatment to be fitted and connected to new consumers.
- Electrical auxiliary power supply fitted and connected to new consumers.
- Process automation and monitoring prepared for operation and monitoring of additional power plant equipment.

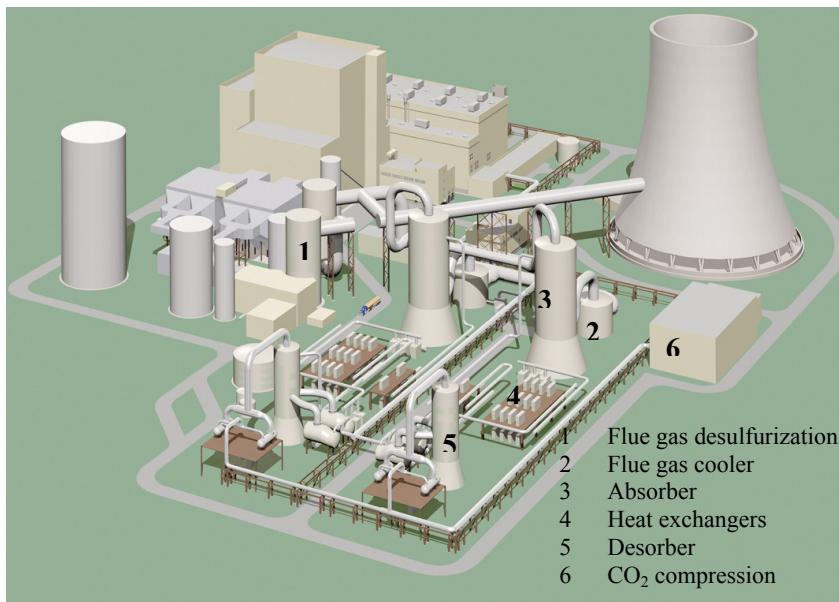


Figure 1: Indicative layout for a steam power plant with retrofitted CO<sub>2</sub> capture and compression

### 3. Capture-ready measures

#### 3.1 Definition

The definition of the capture process and the appropriate integration measures enable the determination of necessary capture-ready features, which allow for a later retrofit of a power plant with a CO<sub>2</sub> capture unit. In most markets, future new-built steam power plants need to be ready for incorporation of a carbon capture plant at a later date, i.e. “capture ready”. “Capture-readiness” objectives are:

- Enable or ease later integration of a carbon capture plant,
- Avoid lock-ins that exclude or hinder use of future capture developments,

- Remove aspects that make retrofit of capture plant impossible,
- Minimize capture ready pre-investments in order to avoid stranded assets.

This results mainly in space and access for additional equipment and auxiliaries, necessary energy supplies and provisions for cooling requirements.

### **3.2 Capture-ready power plant**

Relevant power plant areas with various impacts on readiness for a later retrofit of a CO<sub>2</sub> capture plant are:

- Rearrangement of components in the plant layout and sufficient space for the capture plant as well as CO<sub>2</sub> compressor set according to technological requirements
- Enough space in the steam turbine building for future modifications on steam turbine, routing of large piping as well as space for installations for low-grade heat utilization (e.g. from CO<sub>2</sub> compressor intercoolers)
- Possibility to adapt steam turbine to requirements of future capture plant
- Readiness of flue gas system for incorporation of additional or modified blower, additional or enlarged desulfurization plant and tie-in for the capture plant
- Possibility to extend cooling system for additional waste heat loads and preparation for additional circulating water pump
- Preparation of electric auxiliary power supply and cable routing for enlargement
- Preparation for enlargement of raw water intake and treatment/demineralization as well as provisions for waste water disposal

Steam power plants that include these concepts in their capture-ready design will consequently be able to incorporate, at a later date, a wide range of possible post-combustion carbon capture processes.

## **4. Upgrade of upstream flue gas cleaning equipment for CO<sub>2</sub> capture**

### **4.1 Requirements**

In order to employ the most efficient post-combustion CO<sub>2</sub> technology, consideration must be given to improving today's air pollutant capture efficiency. Current EU regulations require emission levels of 20 mg/m<sup>3</sup> filterable particulate and 200 mg/m<sup>3</sup> SO<sub>x</sub>. These flue gas levels entering the post-combustion CO<sub>2</sub> capture system may result in reduced CO<sub>2</sub> capture

efficiencies and increased reagent usage. The current optimized emission targets to minimize the impact on CO<sub>2</sub> capture may be as low as 10 mg/m<sup>3</sup> filterable particulate and 5 mg/m<sup>3</sup> SO<sub>2</sub>. This means SO<sub>2</sub> removal levels in excess of 99.5% are required. In addition to particulate matter and SO<sub>2</sub>, mercury and other heavy metals such as lead may also have an impact on the CO<sub>2</sub> capture process and thus will require removal from the flue gas stream.

Electrostatic Precipitators for particulate control and Open Spray Towers for SO<sub>2</sub> control are current State of the Art for EU air pollution control, beside NO<sub>x</sub> removal. There is currently no legislative requirement for mercury control. The majority of the plants in Europe employing these air pollution components will have a difficult challenge to improve the flue gas cleaning efficiency to meet the more stringent requirements. It is nevertheless conceivable that improvements to the existing air pollution control equipment components are possible. This, however, will require a plant by plant evaluation. The plant size as well as condition and size of the existing equipment, footprint restrictions, ability to install necessary new equipment upgrades and the impacts on balance of plant components are several typical parameters that will affect the ability to utilize post-combustion CO<sub>2</sub> capture.

Siemens Environmental Systems and Services (SESS) is a global leader in the supply of air pollution equipment. They have supplied air pollution control equipment for new and existing facilities for nearly 100 years. They have been involved in FEED (front-end engineering design) and pilot studies to help incorporate the lowered emission requirements of post-combustion CO<sub>2</sub> capture. They understand the challenges of upgrading existing components and retrofitting more efficient equipment into existing plants. In addition, they have been a leader in supplying the quality air pollution control equipment that is required in today's marketplace.

In different geographical areas today, new air pollution control equipment must meet more restrictive standards both as a requirement to permit and build new coal fired plants and in anticipation of future post-combustion CO<sub>2</sub> capture.

Table 1 presents some of the emission and removal levels which have been recently requested from SESS.

Parameter	Units	Recent AQCS
SO <sub>2</sub>	% Removal	95 - 99
SO <sub>2</sub>	mg/Nm <sup>3</sup>	<100
SO <sub>3</sub>	mg/Nm <sup>3</sup>	<5
PM	mg/Nm <sup>3</sup>	13.5
HCL	mg/Nm <sup>3</sup>	1.5
HCL	% Removal	98 – 99% +
HF	mg/Nm <sup>3</sup>	0.35
Mercury	ug/Nm <sup>3</sup> wet	0.4
Lead	mg/Nm <sup>3</sup> wet	1.2

Table 1: Recent Air Pollution Control Removal Requirements

#### 4.2 Upgrade of flue gas cleaning system for CCS requirements

In order to meet these future restrictive requirements, upgrades to the existing air pollution control systems will be mandatory. It is likely that the addition of highly efficient air pollution control equipment devices such as a Fabric Filter for improved particulate control, an Activated Carbon Injection System for mercury control, a Wet Flue Gas Desulfurization (WFGD) system with improved mass transfer devices such as Siemens Dual Flow Trays, and a Wet Electrostatic Precipitator for additional particulate and sulfuric acid control will need to be incorporated. These components are in use and proven in today's utility marketplace. In addition, it is likely that other balance of plant components will need to be evaluated. These include ash handling, WFGD system byproduct quantity, waste water treatment, induced draft fans, etc.

Siemens Water Treatment is one of the leaders in the treatment of WFGD waste water having supplied multiple systems. Incorporation of any post-combustion CO<sub>2</sub> technology will likely result in an increase in the quantity and a minimization of the components of the waste water stream discharged from the facility. Siemens Water Treatment can provide valuable insight with the integration of the complete system.

## **5. CO<sub>2</sub> compressor design for CCS application**

### **5.1 Requirements for CO<sub>2</sub> compressors**

Compression of CO<sub>2</sub> differs from most fluid compression tasks due to high molecular weight, highly compressible behavior and the presence of the so-called critical point. At the critical point the difference between the liquid and gaseous fluid phase disappears. During the compression process the CO<sub>2</sub> volume reduction is tremendous, resulting in large impeller diameter at the first and very small impeller diameter at the last stage. The carbon capture and storage (CCS) application for power plants leads to an economic CO<sub>2</sub> transport via pipelines at supercritical pressure levels. Pressure losses and sufficient pipeline distances taken into account require compressor discharge pressures in the range of 200 bar.

Customer requirements for CO<sub>2</sub> compressors are high efficiency, wide performance maps and superb reliability of the machine including facilities and drive. Therefore Siemens offers an integral gear-type compressor as the preferred solution for CO<sub>2</sub> compression from its portfolio, covering gear-type compressors as well as single shaft machines. Siemens' experience in the development, design and manufacturing of gear-type compressors for more than 60 years and its ongoing R&D activities are the basis for its excellent technical expertise in turbo-machinery technology.

### **5.2 Technical solution**

A gear-type compressor may be equipped with up to 4 pinion shafts arranged around a bull gear leading to a maximum of 8 process stages. Every pinion shaft runs at its dedicated circumferential velocity, leading to optimized impeller velocity. In combination with an axial inlet and latest computationally optimized impeller geometries polytropic stage efficiencies of up to 90 % are accessible. Recooling the fluid after every process stage is easily feasible and lowers the average compression temperature. This kind of isothermal compression is the most efficient one and gives maximum benefit to the customer. The gear-type compressor can be driven by electrical motor, steam turbine or gas turbine.

Due to the special characteristics of supercritical CO<sub>2</sub>, the difference between a pump and a compressor for the compression task disappears and becomes a mere question of density rather than phase. Siemens offers a CCS compression module which contains an intercooled gear-type compressor, a dedicated cooler for changing the CO<sub>2</sub> fluid density into the liquid

range and a pump or high-density compressor for the last compression step including drive and all electrical controls. Along with the high flow density, special design focus must be given to rotor dynamics, rotor stability and bearing load. With this combined package, high desired outlet pressure up to 250 – 300 bar can be obtained; for CCS applications in the power plant market this approach seems to be very attractive. To strengthen and extend the knowledge about CO<sub>2</sub> behavior and CCS compression requirements, the CO<sub>2</sub> compressor development is coordinated with the CO<sub>2</sub> capture process development and the optimization of power plant integration. Furthermore, Siemens is involved in European R&D projects and in close co-operation with well-known utility companies.

### 5.3 Heat recovery

The latest step of CO<sub>2</sub> compression integration into the power plant is the intercooler heat recovery (see Figure 2).

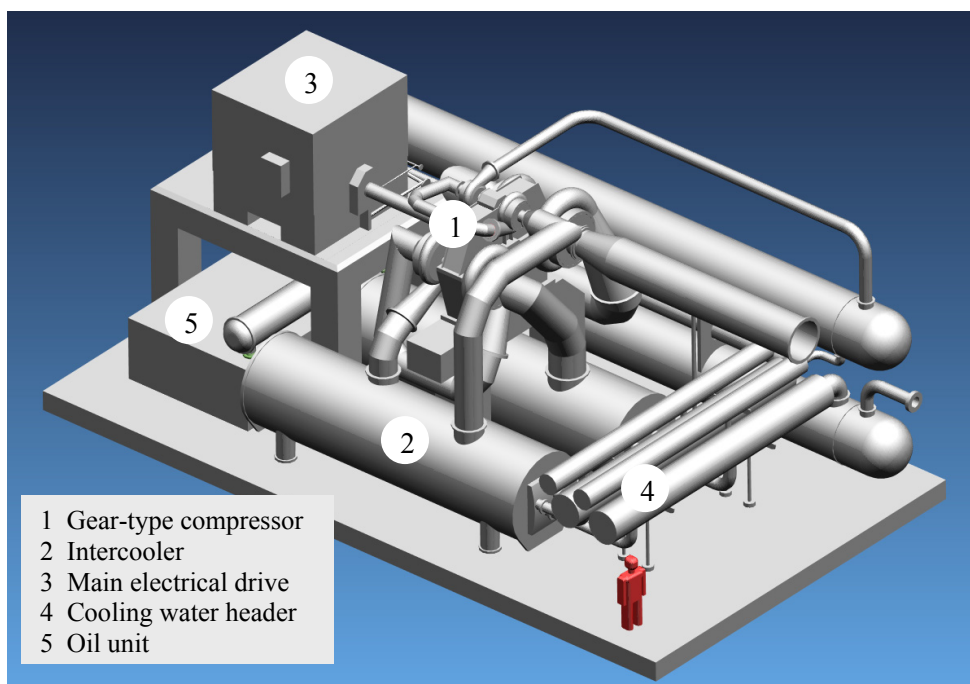


Figure 2: Gear-type compressor module for heat recovery

The unused heat, which is normally dissipated in the cooling system, will be recovered in heat exchangers designed for this purpose and supply the power plant with energy. Therefore a certain temperature level must be reached in the heat exchangers for generating useful heat, resulting in a new compressor intercooler concept. This disadvantage of having a higher average compression temperature ratio by leaving the ideal process of isothermal compression will be overcompensated by the advantage of heat recovery and power optimization into the

plant. This heat recovery has a tremendous impact on the compressor design, rotor dynamics and material selection.

## 6. Improved configuration of Siemens CO<sub>2</sub> capture process

An important lever for lowering the capture costs is the application of an advanced capture process scheme, i.e. to optimize the configuration of absorber and desorber and utilize suitable process improvements for lowering the energy demand for regeneration of the solvent. Therefore, the Siemens development focuses on the determination of an optimum capture process configuration considering the given boundary conditions and interfaces from the underlying power generation process.

During process development, approx. 50 different improvement options of the flow scheme were identified and rated according to qualitative criteria. Out of these 50 options, about 30 promising process variants were selected and calculated using the simulation model. The operating conditions of each process scheme were optimized. The results were ranked regarding energy consumption, investment and operation costs. In a further step, combinations of the most promising process variants were evaluated. As a preliminary result, the energy consumption of the process was – based on a value of 3.5 GJ/ton of separated CO<sub>2</sub> [1] – decreased by 30%. At the same time, costs per ton of CO<sub>2</sub> avoided were decreased by about 15% using the advanced process configuration. Figure 3 shows the standard process configuration, to which several improvements have been added that decrease the energy demand. The improvements characterizing this advanced process configuration are indicated as a gray box.

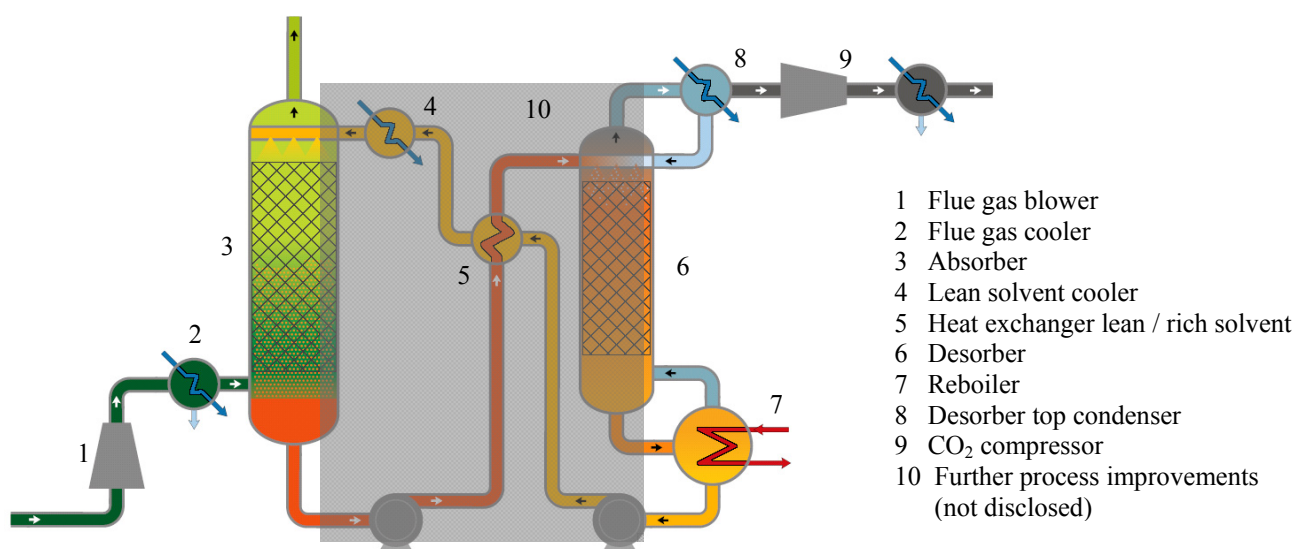


Figure 3: Standard process configuration with several improvements (indicated as a gray box)

## 7. Optimized power plant integration

The amounts of required media (steam, electricity, cooling water) are interdependent and additionally depend on the considered capture process variant. An integrated evaluation and optimization of the complete system incorporating the power plant and the capture unit is thus necessary. Each process part (power generation, CO<sub>2</sub> capture, CO<sub>2</sub> compressor) requires different modeling tools, which are implemented and optimized for the corresponding simulation tasks. The evaluation and optimization of the entire system can be done by aligning the interface values between the different simulation models. In this work, evaluation functions are derived to avoid numerous iterations between all tools. The evaluation criteria quantify the impact of single interface streams on the power output and efficiency. For example, the influence towards power plant efficiency of the required reboiler steam temperature or of the reachable temperature level for the low-temperature waste heat from the CO<sub>2</sub> capture process can be described as a characteristic function that can be used as an input for modeling different variants of the capture unit. Figure 4 gives a simplified overview of the main interfaces for heat integration and auxiliary power within a power plant with CO<sub>2</sub> capture.

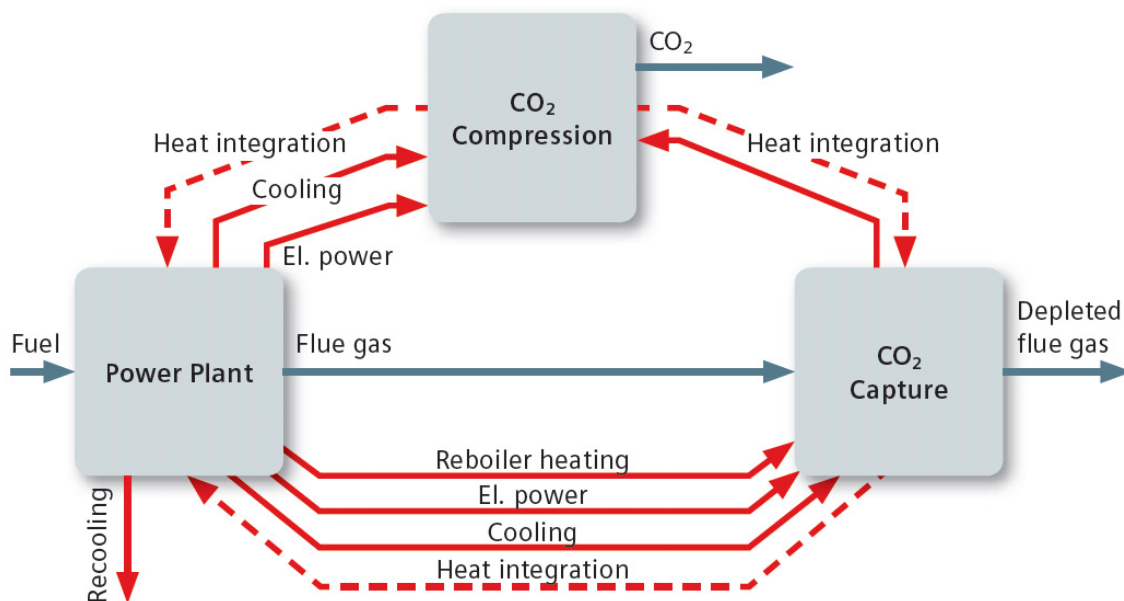


Figure 4: Simplified overview of main interfaces within a power plant with CO<sub>2</sub> capture

Compared to the reference case without capture, performance calculations for a power plant (hard coal, 800 MW<sub>gross</sub> class steam power plant, net efficiency 45.7 % (LHV) without CCS) with the optimized Siemens CO<sub>2</sub> capture process show an efficiency drop as low as approx. 9 %-pts including CO<sub>2</sub> compression. Beside the capture process optimization itself, the

considered variants also feature low-temperature heat integration between the power plant and the CO<sub>2</sub> compressor as well as appropriate steam desuperheating for further reduction of efficiency drop.

## **8. Conclusions**

The CO<sub>2</sub> capture process cannot be fully optimized without considering its integration into the power plant and the adaptation of existing process units to the new requirements defined by the CO<sub>2</sub> capture process. Siemens coordinates the in-house development and improvement of CCS-relevant technologies such as upgraded flue gas desulfurization, CO<sub>2</sub> compression, low-grade steam extraction from the steam turbine, CO<sub>2</sub> capture process and capture-ready plant layout in order to optimally integrate the capture process into the power plant and achieve maximum plant efficiency.

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