Life Cycle Analysis of Thermoelectric Power Generation in the United States

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Abstract

The basics of performing a life cycle analysis of thermoelectric power generation are discussed, with three examples of life cycle greenhouse gas (GHG) balances for thermoelectric power generation forms: coal, natural gas, and nuclear. The final section compares multiple electricity generation methods in the United States. Results are presented on the basis of 1 megawatt-hour (MWh) of electricity delivered to the end user. Environmental life cycle results for greenhouse gas (GHG) emissions are presented as carbon dioxide equivalents, based on 100-year global warming potentials (GWPs) established by the 6th Assessment Report from the Intergovernmental Panel on Climate Change in 2021, commonly referred to as AR6 GWP values (IPCC, 2021). Additional details on other environmental life cycle impacts from non-GHG emissions to air, emissions to water, solid waste generation, and land use are available on the Department of Energy,

National Energy Technology Laboratory’s Life Cycle Analysis website: www.netl.doe.gov/LCA.

Keywords:

Carbon capture; Carbon dioxide (CO_2); Coal; Electricity; Greenhouse gases; Life cycle analysis (LCA); Natural gas; Nuclear; Power generation; Thermoelectric

Learning Objectives:

- Understand the key considerations and stages of life cycle analysis
- Explain the effect of CCS technology on global warming potential (GWP) impact
- Understand the difference in GWP across power generation technologies

Identify the best and worst power generation technologies from a life cycle GWP perspective

Introduction

Thermoelectric power provides 78.4% of electricity generation in the United States (EIA, 2023). Thus, evaluating the environmental impacts associated with the operation of these systems is crucial to understanding their role in broader climate change and environmental management strategies. The main thermoelectric sources are coal, natural gas, and nuclear, which have baseload fleet and advanced technology variations. Advanced technology variants include sub-critical pulverized coal (SubPC), supercritical pulverized coal (SCPC), and natural gas combined cycle (NGCC). Despite their technological advancements, these fossil fuel-based power generation technologies are known for being carbon-intensive (UNECE, 2021). To abate these carbon emissions, carbon capture systems can be implemented and achieve between 90%

to 99% capture. Renewable energy technologies represent low-carbon alternatives and include solar PV, solar thermal, wind, hydro, and geothermal. Life cycle analysis (LCA) is a critical framework used to analyze the environmental impacts across the life cycle of a system. This methodology is well suited to evaluating power generation systems because of its comprehensive and flexible system boundaries, ranging from cradle-to-grave, cradle-to-gate, or gate-to-gate analyses. In addition, the LCA framework considers upstream effects, temporal and geographical scales, and a variety of impact categories.

This chapter provides a brief overview of the LCA process and guiding principles, followed by an LCA of thermoelectric power generation. Detailed results for global warming potential (GWP) impacts are given for the advanced technologies to show the contribution of environmental burdens by stage (e.g., fuel extraction and processing, fuel transport, power generation, transmission and distribution) and processes within each stage. The chapter is concluded with a comprehensive comparison of the GWP of thermoelectric plants and renewable energy sources. The boundary of each LCA starts at fuel extraction and ends at the consumer after transmission and distribution, with all results normalized to 1 MWh of electricity.

Life Cycle Analysis Design Considerations for Thermoelectric Power Generation

Life cycle analysis (LCA) is a framework that assesses the comprehensive environmental impacts of a product, system, or service over its lifetime. LCA can be applied to a wide range of products, from the seemingly simple system of producing a paper bag to the large-scale generation of electricity. The life cycle of a product begins with raw material acquisition, includes production and use of a product, and ends with waste disposal and decommissioning activities. Analyses can encompass the entire life cycle of a product (cradle-to-grave), or portions of the life cycle, like raw materials acquisition through production (cradle-to-gate) or a set of processes within (gate-to-gate). It’s important to note that partial LCA results should be used with care because they do not represent a complete life cycle perspective.

LCA provides results that can be used by scientists and stakeholders to make informed decisions. Policy makers use LCA to evaluate consequences of national-level energy policies, researchers use LCA to identify key sources of environmental burdens in a system to justify focused research efforts, and industry uses LCA to identify trade-offs between environmental and economic performance of systems. The purpose of the LCA, as seen by the three stakeholders above, can vary and will affect the design of the energy LCA to be conducted. When selecting LCA results from a previous study to inform decision making, it is important to ensure the purpose meets the current objective. It is equally important when comparing LCA results among studies that different purposes do not impact the ability to compare and interpret the results. To ensure the desired objectives are met, and to allow comparisons to similar studies, analysis is conducted according to the methodology set out in ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a, 2006b). The critical components in LCA are:

1. Goal and scope definition
2. Life cycle inventory (LCI) analysis
3. Life cycle impact assessment (LCIA)
4. Interpretation.

In addition to these key steps, energy based LCA studies must also consider temporal and geographical representativeness.

Goal and Scope Definition

The goal and scope of an LCA are dependent on the audience and the expected level of detail. If the audience is a researcher whose goal is to identify opportunities for improving a process, or a producer whose goal is to compare the environmental performance of two or more options, then a detailed inventory that shows results for each unit process in the model should be in included in the scope. If the audience is a policy maker whose goal is to assess the effect that a new technology could have on national or global emissions, then an analysis in which the boundaries are expanded to account for consequential effects among alternative pathways should be included in the scope. The intended audience for the results will affect the rigor with which an LCA study is performed and the frame of reference from which results are reported. An LCA performed as an internal screening exercise will have different data collection, reporting, and quality assurance standards than a publicly released LCA, where there are specific guidelines provided by ISO 14044 (International Organization for Standardization, 2006b). If an LCA will be directly compared to a previous LCA, then it should use the same methods and approach of the previous LCA. If the goal is to produce a benchmark study from which other studies will follow, the LCA may have a unique scope and level of detail.

The functional unit is the basis of comparison for an LCA and is a key step in the goal and scope phase of an LCA. A life cycle model scales the inputs and outputs of all unit processes to the basis of a functional unit. For a power system LCA, a common functional unit is 1 MWh of electricity delivered to the consumer. The end use of the electricity is omitted from the study boundary when the goal is to compare options that deliver the same service to the user. Including the end use within the boundary would change the purpose of the study, and the definition of the functional unit.

System boundaries determine what processes are included in the LCA, as well as when and where the system operates. Boundary setting can be a straightforward process when, in the case of thermoelectric power generation, a system produces a single product, like electricity. However, when power plants are equipped with carbon dioxide (CO_2) capture technology to reduce greenhouse gas (GHG) emissions to the atmosphere, the destination of the captured CO_2 must be determined to identify the system boundary. If the desired destination is a saline aquifer for permanent geologic storage, then the captured CO_2 is considered a waste product. On the other hand, if the CO_2 is sent to an enhanced oil recovery operation, it is a material flow into another operation and is treated as a co-product. Co-products add complexity to the system boundary of the power plant because it must now account for the disposition and use of the CO_2 as a material flow in another system.

Intentional and clear boundary setting is a critical step in the goal and scope phase of LCA. An example of boundary setting, and its importance, is demonstrated in **Fig. 1**, which shows the boundary for a power generation system. The system boundary as drawn indicates a functional unit of 1 MWh of generated electricity, however, if the transmission and distribution process were included in the system boundary, the functional unit would be 1 MWh of electricity delivered. With the boundary set at the “gate” of the power plant, the product leaving the system is generated electricity. Changing the system boundary has a cascading effect on the functional unit, the life cycle impact results, and potentially, the intended audience. Note that while **Fig. 1** omits electricity transmission and distribution, it is included in **Fig. 2**, which is the basis for the results shown throughout this chapter. <Figure 1 near here>

Life Cycle Inventory Analysis

The life cycle inventory stage of LCA is when relevant data is collected across the entire system, representing all energy and material flows into and out of the system. The inventory provides the ability to evaluate a systems environmental impact and identify areas where improvements can be made. A key component of the inventory stage is data quality. Assessing the quality of inventory data can be done using data quality indicators and scoring with pedigree matrices as outlined in previous guidance (Weidema and Wesnæs, 1996). Data quality scores offer practitioners a way to determine whether additional or alternative data sources are required. In addition, scores can indicate the overall reliability and representativeness of the LCA. Inventory data can range from measured to calculated or modeled data, and can come from sources such as journal articles, government reports, and inventory databases. One example of a comprehensive source for inventory data, is the Federal LCA Commons (Federal LCA Commons, 2023). This collection of life cycle data represents contributions from collaborating agencies such as the National Energy Technology Laboratory (NETL) and the National Renewable Energy Laboratory (NREL).

Life Cycle Impact Assessment and Interpretation

Life cycle impact assessment is the process of taking individual pieces of inventory data and transforming them into life cycle impact results. The results communicate the impacts to human and environmental health by characterizing inventory data according to different impact categories. Characterization factors are used to convert data with different units (e.g., kg methane, kg nitrous oxide) to a common unit (e.g., kg CO_2 equivalents), thus aggregating the inventory data into comprehendible impact results. Impact assessment methods provide an array of characterization factors for several impact categories, such as GWP, acidification potential, and eutrophication potential. Converting and aggregating the life cycle data allows for clear interpretation, which is the final stage of LCA.

The interpretation stage gives a practitioner the opportunity to identify areas in the life cycle, such as specific processes or flows, that are contributing significantly to the environmental burden. This is often done through visualization of the results in a figure or table where individual flow and process contributions can be seen, or a contribution analysis. Interpretation can also include additional analyses, such as sensitivity and uncertainty analysis. Sensitivity analysis helps to measure the impact of varying a specific material or energy flow on the overall result, while uncertainty analysis characterizes the variability of the results.

Temporal Representativeness

Time frames are used to apportion one-time, or periodic burdens, to the functional unit. The burdens from steady-state operations (e.g., coal extraction at a mine, electricity generation at a power plant, or diesel production at a petroleum refinery) are usually on a basis that directly scales with the functional unit, so these processes are unaffected by temporal boundaries. In contrast, construction burdens (e.g., the amount of concrete used for a gas well lining) and periodic maintenance activities (e.g., natural gas well workovers or liquids unloading) need to be normalized to the total production during the study period to express it in terms of the functional unit.

Processes within a life cycle model may have different periods of operation as well. For example, a dedicated energy crop (e.g., biomass in a cofiring configuration) may require 5 years of land preparation and cultivation activities before it can produce its first crop of biomass that can be harvested and combusted in a power plant. To correctly apportion burdens per unit of output, each environmental burden must be normalized to the appropriate time frame. If land preparation occurs once in a crop's life cycle, the associated burdens should be distributed across the total lifetime of the crop. Likewise, assuming cultivation and harvesting are repeated each crop cycle, any burdens should be distributed across the period of the growing and harvesting cycle. The life cycle model then scales these burdens to the functional unit.

Carbon capture and storage (CCS), when added to a thermoelectric power-generating unit, provides another example of how time frames can vary within a life cycle. The 30-year operation of a power plant with carbon capture is a different period than the 100-year injection and monitoring period of a saline aquifer sequestration site, but it would be incorrect from an inventory perspective to cut the injection and monitoring period short just to match the operating life of the power plant. Injection is just one phase in the long-term operation of a saline aquifer sequestration site.

Geographical Representativeness

Geographical boundaries specify the location, or locations, of key components within a supply chain. This is critical when considering the transport distances between points in the supply chain, the origins of electricity and other energy sources used by unit processes, and specification of other parameters that may change depending on geographic region. Geographical boundaries can also serve as the basis for evaluating the extent of interactions among the domestic and global markets of products.

In all LCA studies, transparency is paramount when developing the study design and modeling assumptions used to represent the system or systems of interest. Comparability between LCA study results must be considered before interpreting results and determining the next actions to take. The next sections provide an overview of the LCA performed for three thermoelectric power generation types: coal, natural gas, and nuclear. Coal and natural gas systems include analysis with and without CCS technology. The scope of each LCA is cradle-to-gate, the functional unit is 1 MWh of electricity delivered, and the system boundary considers all environmental impacts upstream of electricity delivered to the end user. The 100-year global warming potential (GWP) characterization factors from the Intergovernmental Panel for Climate Change (IPCC) Sixth Assessment Report (AR6) are used for life cycle impact assessment (IPCC, 2021). Characterization factors are used to convert GHG emissions to a common unit of kg CO_2 equivalents (CO_2e). **Fig. 2** shows a general overview of the power generation systems with and without CCS. <Figure 2 near here>

Coal-Fired Power Generation

Coal has historically played a vital role in commercial power generation. A multitude of advanced coal-based power generation technologies exist each with varying technical specifications and efficiencies. In this analysis, greenfield (i.e., new construction) sub-critical pulverized coal (SubPC) and supercritical pulverized coal (SCPC) are used to characterize advanced coal-based technologies. The SubPC plant without CCS has a steam cycle heat rate of 7,376 Btu/kWh with a net plant efficiency of 38.6% and the SCPC plant without CCS has a steam cycle heat rate of 7,079 Btu/kWh and net plant efficiency of 40.3%. Coupling advanced coal power generation with CCS systems has been presented as a low-carbon option for coal-derived electricity. However, this cannot be inferred solely via traditional reductionist process-based engineering methods. Holistic systems analysis of coal-based power generation that considers all stages of the life cycle (e.g., coal extraction, transportation, combustion, etc.) is necessary for determining key sustainability metrics, such as carbon footprint, and to compare environmental performance across different power generation technologies.

This section compares the GWP and the life cycle GHG emissions profile for electricity production using two coal power generation technologies, SubPC and SCPC, and benchmarks the results against the coal fleet (baseload). SubPC and SCPC technologies are examined without CCS and with CCS using 90%, 95%, and 99% capture rates. Including coal fleet, a total of nine discrete cases are considered. Life cycle inventory data for SubPC and SCPC systems were obtained from previously published reports (Schmitt et al., 2022; Skone et al., 2018a; Skone et al., 2018b). Life cycle inventory data for the coal fleet were obtained from the Federal LCA Commons and NETL's Grid Mix Explorer (NETL, 2020a, 2020b).

This LCA is performed stochastically for the fleet power plants and advanced power plants, capturing uncertainty in the GWP, like use of triangular distributions. For example, upper and lower bounds are set for key parameters in the supply chain, such as methane emissions from coal mining and the coal heating value. This technique provides a robust estimate of the uncertainty in the environmental profile of the evaluated coal power generation technologies.

A comparison of the GWPs for the coal fleet (baseload), SubPC, and SCPC power generation technologies are calculated and provided in **Fig. 3**. These results indicate that the coal fleet (baseload) has the highest GWP of the selected power generation scenarios. Further, the results show a gradual decrease in the GWP of electricity production across SubPC and SCPC systems—primarily due to differences in net efficiency between technologies. CCS scenarios are found to significantly improve the GHG emissions of advanced coal power generation technologies. SubPC technology with CCS using 90%, 95%, and 99% capture rates resulted in a 73.9%, 78.0%, and 81.3% reduction in median GWP relative to the coal fleet (baseload), respectively. Likewise, SCPC technology with CCS using 90%, 95%, and 99% capture rates resulted in a 75.1%, 79.0%, and 82.3% reduction in median GWP, respectively. <Figure 3 near here>

Fig. 4 plots the average contribution of GWP by aggregate stages in the supply chain for advanced coal power generation technologies. These results indicate that coal extraction and power plant operations constitute the largest contributors to GWP in the supply chain. Coal extraction is associated with high upstream GHG emissions and coal combustion during power plant operations result in direct CO_2 emissions. Accordingly, these areas should be targeted for process improvement, as reduction in impacts at these stages has the capacity to significantly increase the environmental performance of coal-based power and electricity generation systems. <Figure 4 near here>

For CCS scenarios, a large fraction of total CO_2 produced during coal combustion is captured on site, transported, and sequestered in a saline aquifer, resulting in lower CO_2 emissions from the power plant. Consequently, advanced coal power generation scenarios utilizing CCS have an improved GWP. Disaggregated overviews of the GWP contributions in the supply chain for SCPC systems without CCS and with CCS at 95% capture rate are provided in **Figs. 5** and **6,** respectively. The contributions from the different life cycle stages are broken down by GHG emissions of interest: CO_2, methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6). These results are compelling and identify CCS as a promising option for reducing the carbon intensity of coal power generation technologies. <Figure 5 and 6 near here>

Natural Gas-Fired Power Generation

Natural gas continues to become an attractive option for power generation as supply becomes more available in some areas of the world (IEA, 2019). An overwhelming majority of the natural gas used for power generation has lower life cycle impacts when compared to coal-fired power generation. The switch to natural gas is further incentivized due to the ability to use existing infrastructure, compared to renewables and other low-carbon technologies where new infrastructure is required. Implementation of carbon capture technology has been slower for natural gas systems when compared to coal due to cost concerns, however, reducing the emissions and environmental impacts of natural gas power generation warrants further investigation (IEA, 2022). Once again, systems analysis is required to determine the environmental performance of natural gas and compare across different power generation technologies.

This section compares the GWP and life cycle GHG emissions profile for electricity production using natural gas combined cycle (NGCC) technology. The NGCC power plant discussed within this chapter has two parallel, advanced F-Class gas-fired combustion turbines, and each combustion turbine is followed by a heat recovery steam generator that produces steam that is fed to a single steam turbine. The NGCC system will be examined without CCS and with CCS using 90%, 95%, and 97% capture rates, for a total of four discrete cases. The NGCC plant without CCS has a steam cycle heat rate of 11,393 Btu/kWh and a net plant efficiency of 53.6%.

Life cycle inventory data were obtained from previously published reports (Rai et al., 2021; Schmitt et al., 2022). <Figure 7 near here>

A comparison of the GWPs and contributions by aggregate stages for the four NGCC cases is provided in **Fig. 7**. These results indicate that the NGCC system without CCS has the highest GWP of the four scenarios. As expected, the addition of CCS significantly reduces the total GWP. NGCC power generation with CCS with 90%, 95%, and 97% capture rates resulted in 65.5%, 69.7%, and 71.3% reductions in GWP respectively, relative to the NGCC case without CCS. Like the findings from the coal systems, these results show that natural gas extraction and power plant operations are the largest contributors to GWP and these stages in the life cycle should be targeted for process improvement to reduce the environmental impacts. **Figs. 8 and 9** show a disaggregated overview of the GWP contributions in the supply chain for NGCC power generation without CCS and with CCS 95%capture rates, respectively. GWP contributions from natural gas extraction and transport are represented by production, gathering, and boosting, processing, transmission, and storage. Overall, as the capture rate increases, the contribution to GWP from natural gas extraction and transport increase, and the total GWP decreases. CCS-equipped plants require energy to capture and compress CO_2, and this energy demand reduces the overall efficiency of the power plant. Although the NGCC systems with CCS have significantly lower CO_2 emissions at the power plant, the upstream emissions are higher because more natural gas is required to generate the same amount of electricity as the NGCC system without CCS. <Figure 8 and 9 near here>

Nuclear Power Generation

The life cycle for nuclear power plants consists of the uranium acquisition and enrichment chain, fuel rod transport, energy conversion facility (i.e., power plant), electricity transmission and distribution (T&D), and end use. The life cycle inventory data used in this analysis can be found in the NETL report, *Role of Alternative Energy Sources*: *Nuclear Technology Assessment*, referred to as the Nuclear TAR (NETL, 2012). **Fig 10** shows the first life cycle stage of this analysis, which accounts for the acquisition of uranium and the transformation of uranium into fuel. This includes the extraction of uranium ore from the earth, processing and enrichment of uranium, and fabrication of uranium fuel rod assemblies. Extraction requires the construction of three types of uranium mines: underground, open pit, and in situ leaching. Construction materials are included within the boundary for all well-known components of uranium mines, conversion facilities, enrichment facilities, and fuel fabrication facilities. Installation and operation material and energy requirements are included for all facilities, as well as transport intermediate to processing facilities. <Figure 10 near here>

Different processes are used to represent the fleet and next-generation power plant operations and construction processes, while they share decommissioning and spent fuel processes. The fleet operation is based on a combination of 2013 fleet burnup rates and electricity generation from EIA data and plant capacity and capacity factors from the Nuclear Regulatory Commission (NRC) (EIA, 2015, 2016; NRC, 2016). Burnup is a measure of the energy provided by the nuclear fuel source, given in units of gigawatt-days (thermal output)/Mg (metric ton) of uranium (GWd-t/Mg U). Because this is a measure of thermal output, an efficiency must be used to convert the thermal output to electricity output. Fleet construction is based on a 1974 study conducted at Oak Ridge National Laboratory. The next-generation operation is based on environmental impact statements from several proposed power plants, and construction is based on a 2005 DOE report (DOE, 2005). Additional details can be found in the Nuclear TAR (NETL, 2012).

Fig. 11 shows the comparison of the nuclear fleet to next generation nuclear power generation. The GWP of the next generation technology is slightly lower compared to the fleet, which is the result of an assumed increase in steam plant efficiency, leading to additional reductions in fuel feed and power plant impacts. There are no direct GHG emissions from power plant operations, however, there are upstream GHG emissions from power plant construction and fuel disposal that are represented by the energy conversion facility contribution. It is important to note that there are criteria air pollutant emissions, water consumption, water emissions, and solid waste flows from the operation of nuclear plants that are outcomes of the LCA but not highlighted in this chapter (NETL, 2012). <Figure 11 near here>

The disaggregated GWP results are shown in **Figs. 12** and **13** for the existing U.S. nuclear fleet and next generation power plants. A discussion of the results follows the descriptions for the life cycle stages. The difference in contributions from uranium extraction and enrichment for fleet and next generation systems is a result of the burnup rates, which determine the fuel demand. A burnup rate of 44.9 GWd-t/Mg U for the fleet system resulted in a higher fuel demand compared to the next generation system with a burnup rate of 48.3 GWd-t/Mg U. Unlike the results for coal and natural gas, electricity T&D represents a significant portion of the total GWP, and the electricity losses during T&D result in additional impacts upstream. <Figure 12 and 13 near here>

Comparison of U.S. Electricity Generation Technologies

Results from the scenarios above are put in the context of a wide array of power generation technologies, both current and advanced in **Fig. 14**, Life cycle inventory data for the natural gas fleet, renewable technologies, and U.S. average electricity mix were obtained from the Federal LCA Commons and NETL's Grid Mix Explorer (NETL, 2020a, 2020b). Coal-fired power generation technologies without CCS result in the highest GWP per unit of electricity delivered, followed by natural gas-fired power plants without CCS. Adding CCS to fossil fuel-fired power generation can significantly reduce the direct CO_2 emissions from a power plant, and thus reduce the GWP. The reduction allows the total GWP for fossil fuel-fired technologies to reach below the 2016 U.S. average electricity mix. However, it is important to acknowledge that this comes at the cost of lower efficiency, increased upstream fuel extraction burdens, and depending on the capture technology, increased upstream impacts from secondary inputs required for capture. Despite the significant reduction in GWP when adding CCS, nuclear and renewable technologies still outcompete fossil fuel power generation when it comes to GWP. <Figure 14 near here>

Conclusion

- After conducting an LCA of thermoelectric power generation, contribution analysis indicated that fuel extraction and fuel combustion stages were the biggest contributors to GWP. Thus, targeting these areas for process improvement should be prioritized. In addition, it was determined that CCS greatly reduces GWP impacts for fossil fuel power plants. *For* subPC and SCPC *plants*, *GWP was decreased by* approximately *74% to 82% from the baseload fleet coal plants* when CCS technology was introduced. Likewise, the CCS NGCC scenarios reduced GWP by 65% to 71% from the baseload fleet natural gas plants. While CCS decreases CO_2 emissions from a power plant, it also reduces overall plant efficiency due to the additional energy that is drawn from the plant to capture and compress the CO_2. This also leads to increased fuel extraction and inherently a higher GWP contribution during the fuel extraction stage, despite a lower overall GWP impact. Furthermore, the introduction of CCS technology may have trade-offs with other non-GWP impact categories. To comprehensively evaluate the environmental burdens of CCS technology, the full host of impact categories should be included in impact assessment. Nuclear power generation does not have direct power plant emissions from combustion like fossil fuel-based power generation, and the majority of its emissions come from uranium extraction and enrichment. This resulted in a significantly lower GWP impact compared to the coal and natural gas thermoelectric power plants. Overall, while fossil fuel generation with CCS is better than the U.S. average grid mix from a life cycle GWP perspective, nuclear and renewable technologies still are still expected to emit less GHGs than fossil fuel technologiess and represent low carbon alternatives to conventional power generation.

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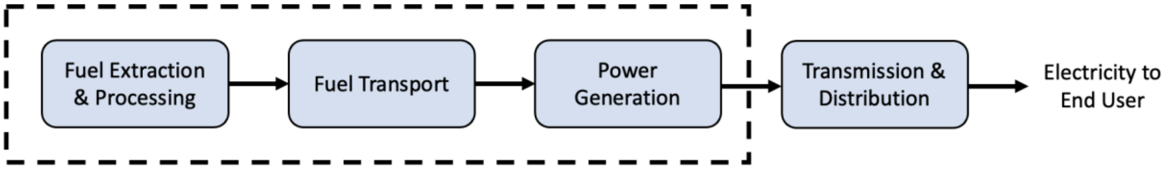

Fig. 1 Simplified boundaries for electricity production.

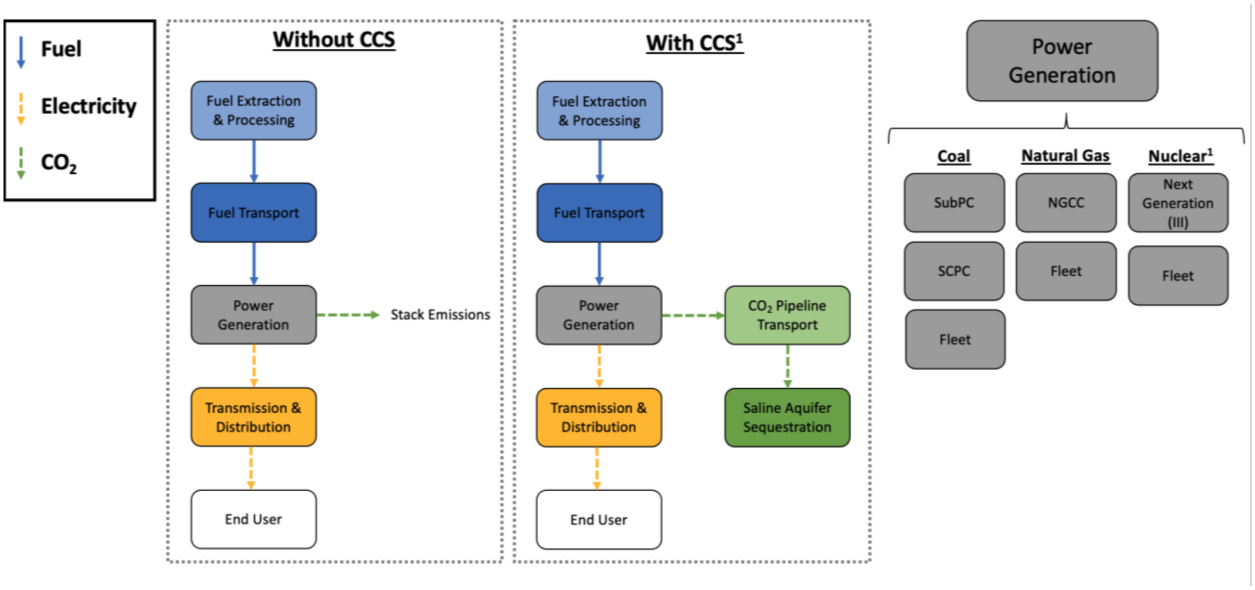

Fig. 2 Scenario analysis of coal, natural gas, and nuclear power generation. 1: Nuclear power generation analysis does not include a CCS scenario.

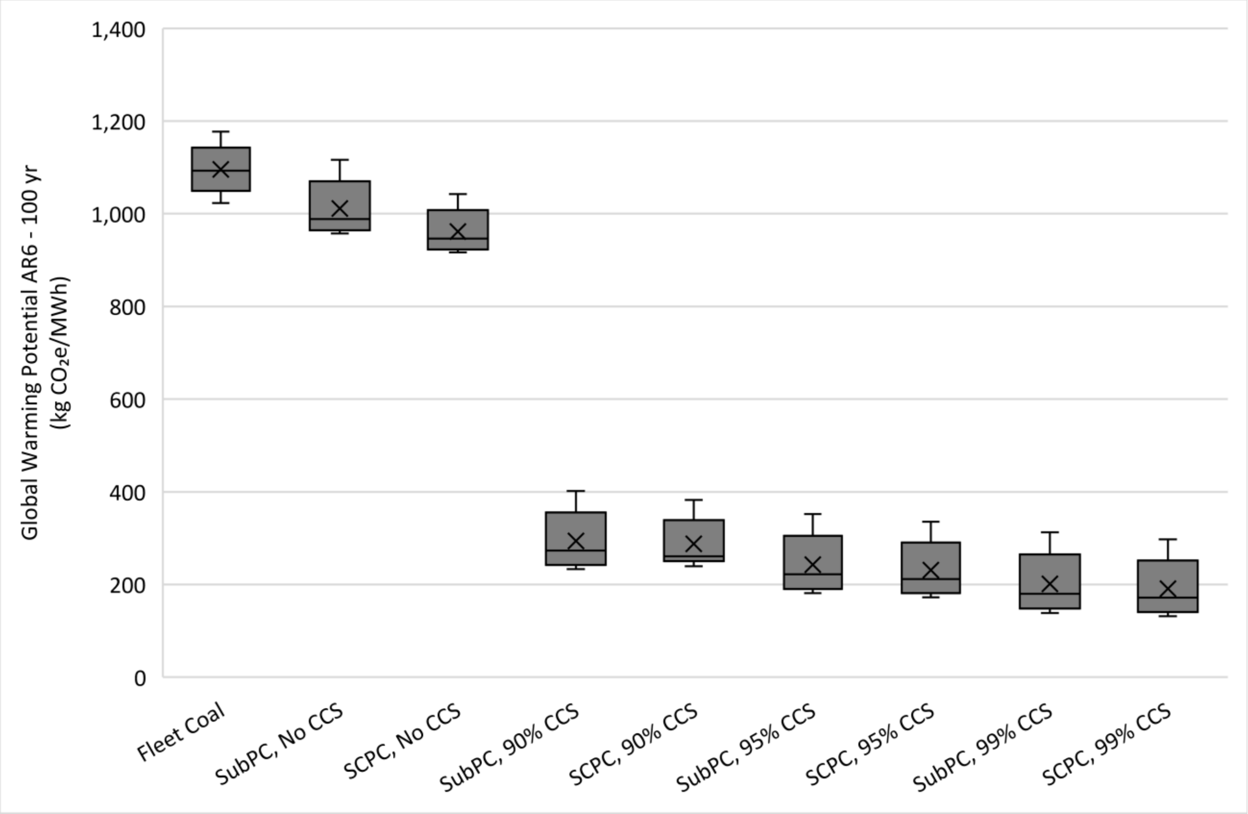

Fig. 3 Comparison of GWP for advanced coal power generation technologies, with or without CCS with varying capture rates. The results are benchmarked against the coal fleet (baseload).

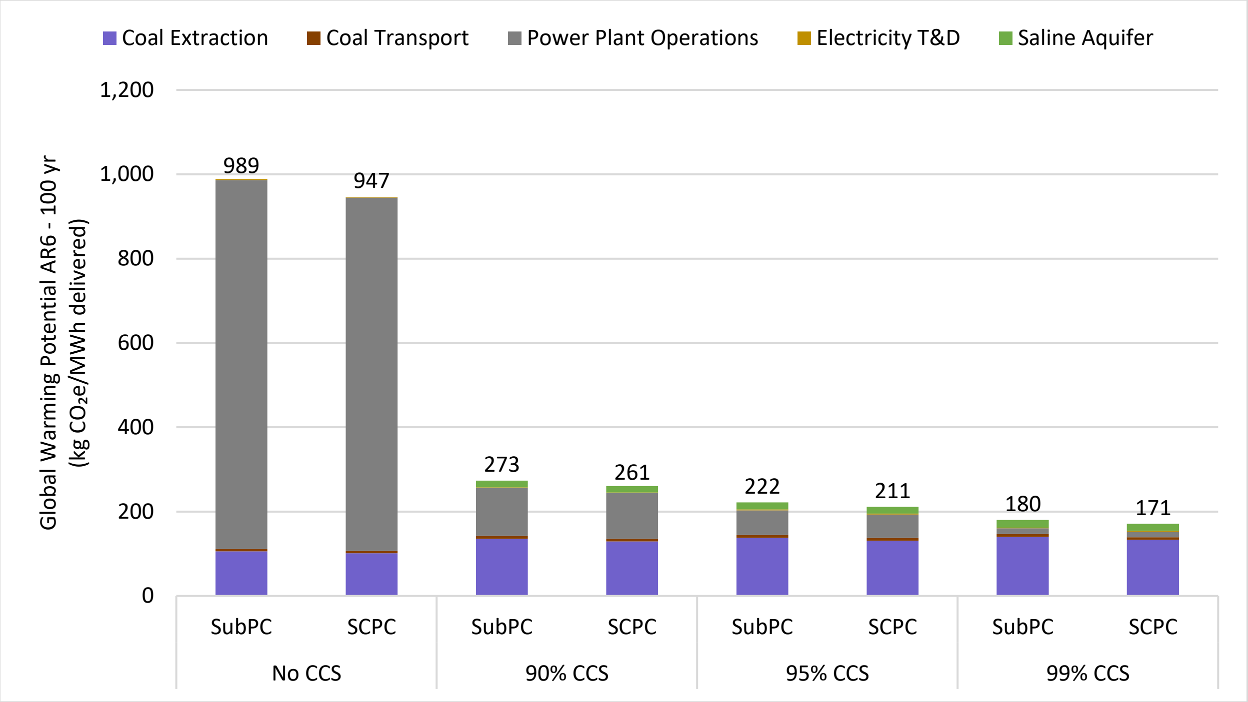

Fig. 4 Average contribution to GWP by aggregate stages in the supply chain for advanced coal power generation technologies.

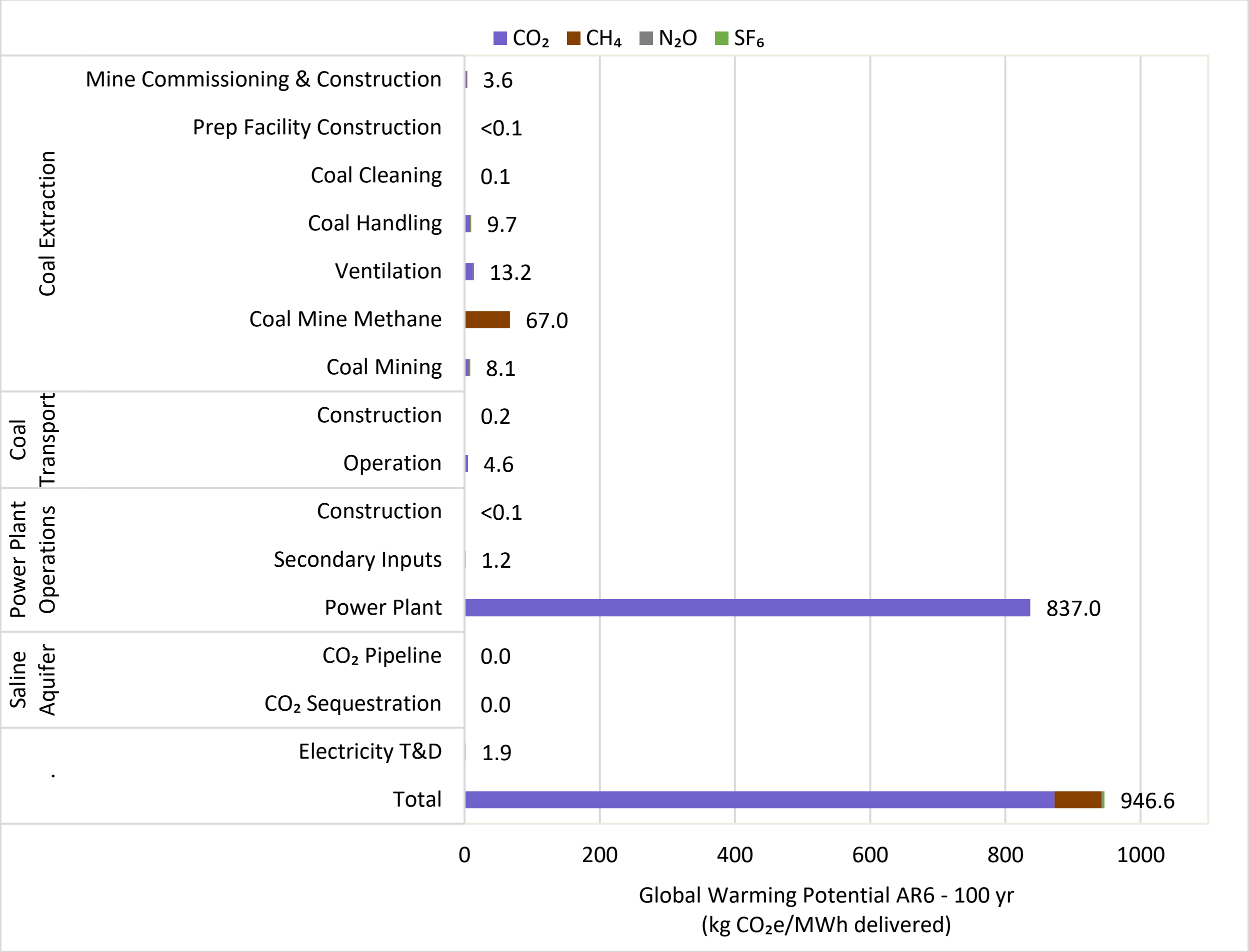

Fig. 5 Average contribution to GWP by disaggregate stages in the supply chain for SCPC power generation without CCS.

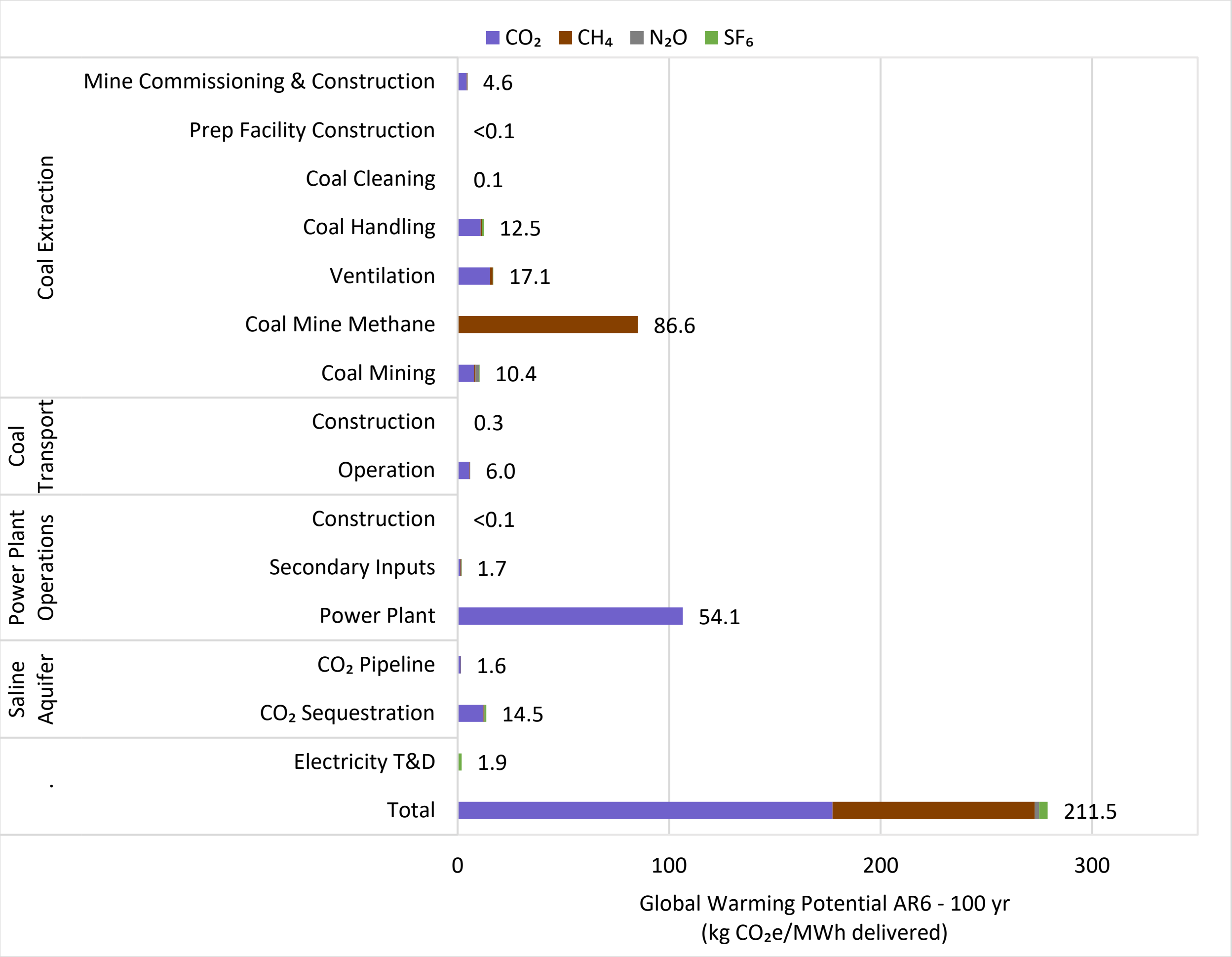

Fig. 6 Average contribution to GWP by disaggregate stages in the supply chain for SCPC power generation with 95% CCS.

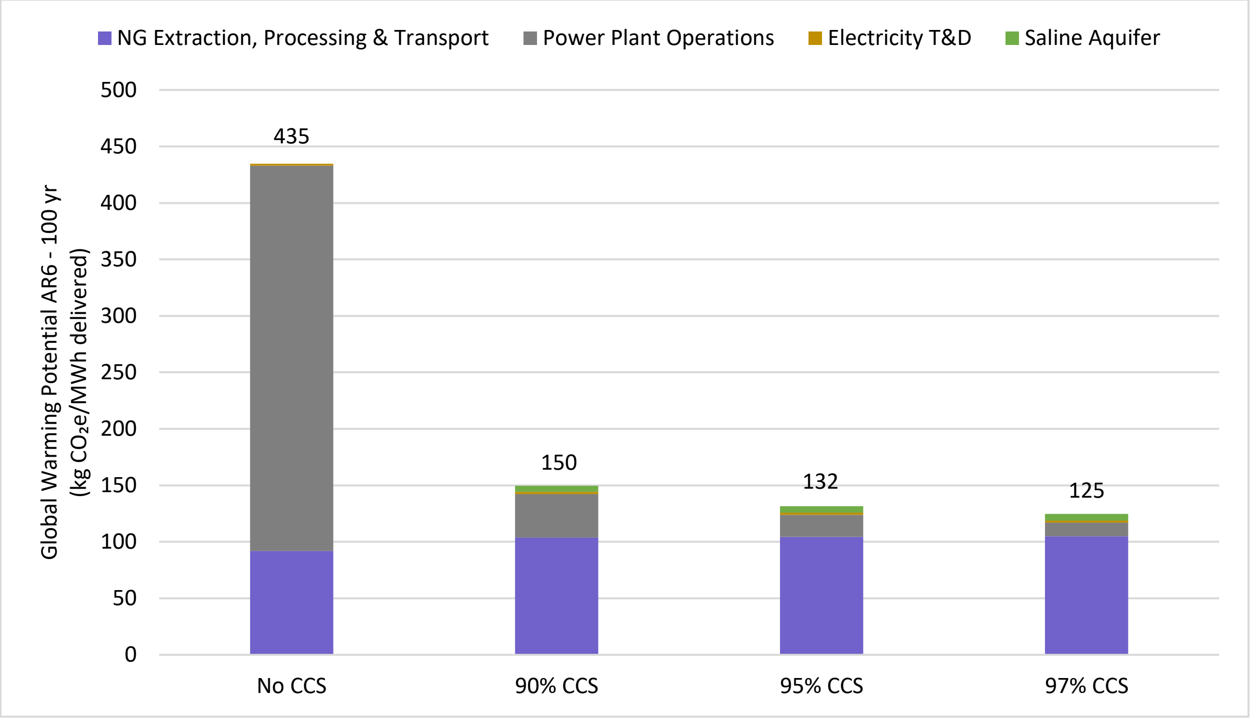

Fig. 7 Average contribution to GWP by aggregate stages in the supply chain for natural gas combined cycle generation technology.

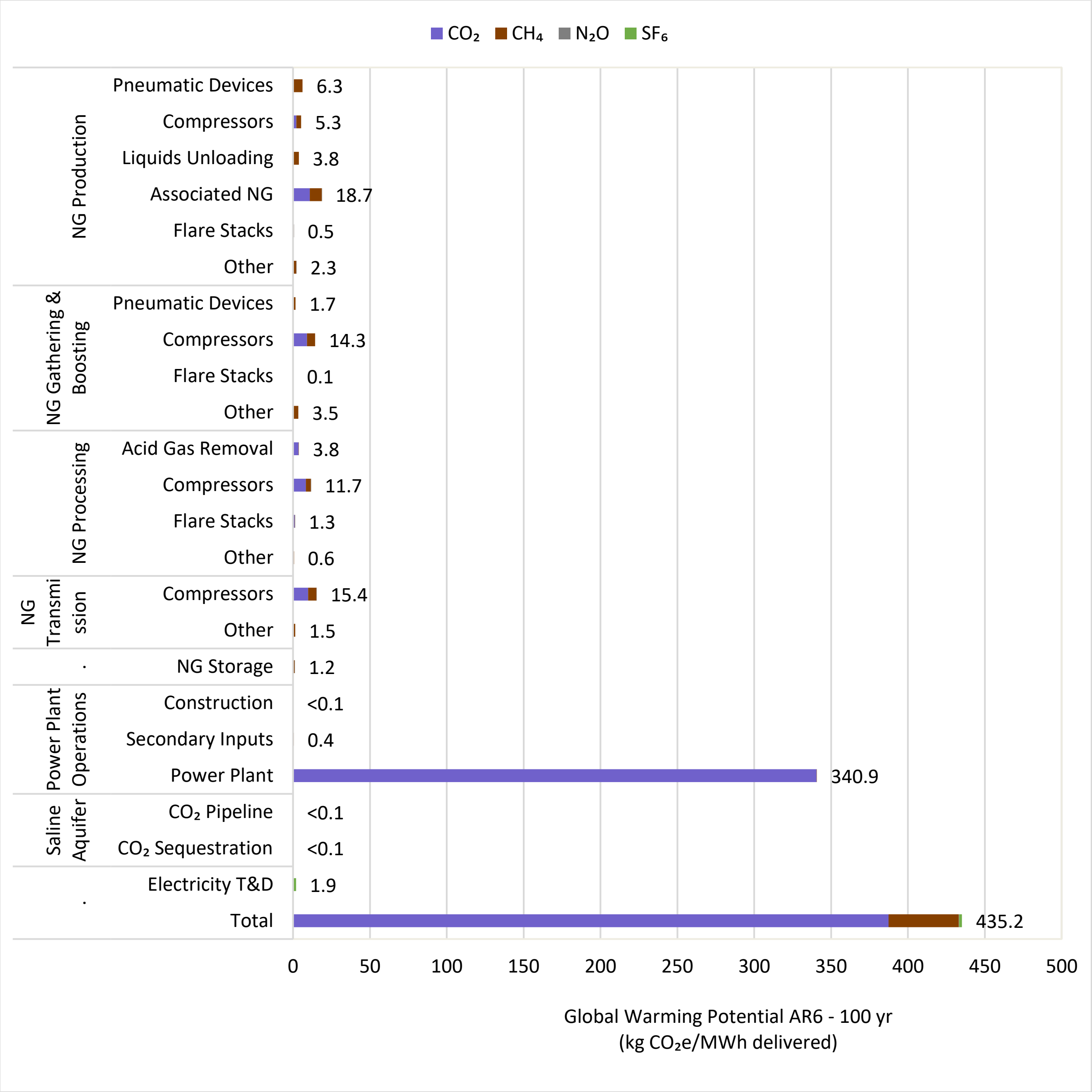

Fig. 8 Average contribution to GWP by disaggregate stages in the supply chain for NGCC power generation without CCS.

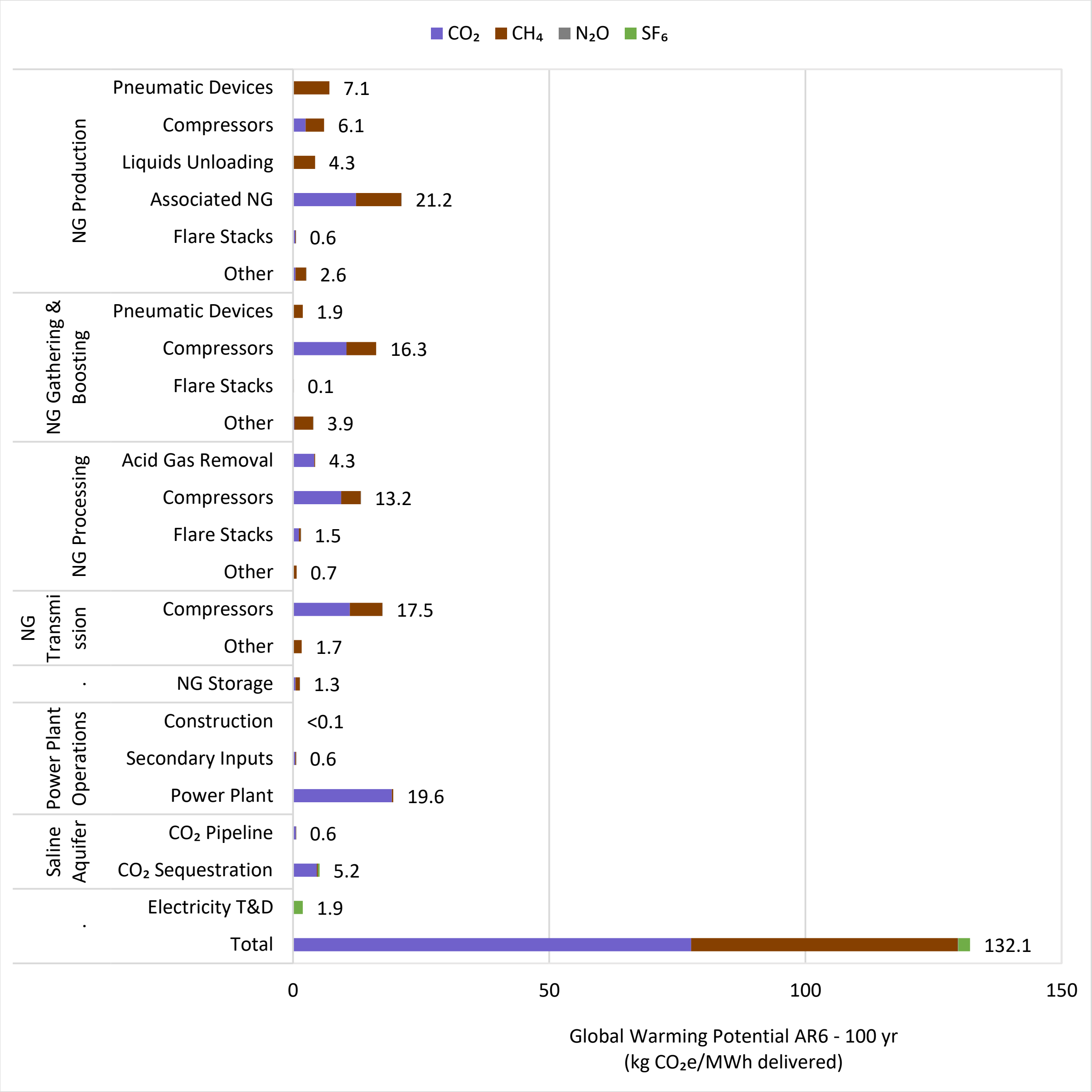

Fig. 9 Average contribution to GWP by disaggregate stages in the supply chain for NGCC power generation with 95% CCS.

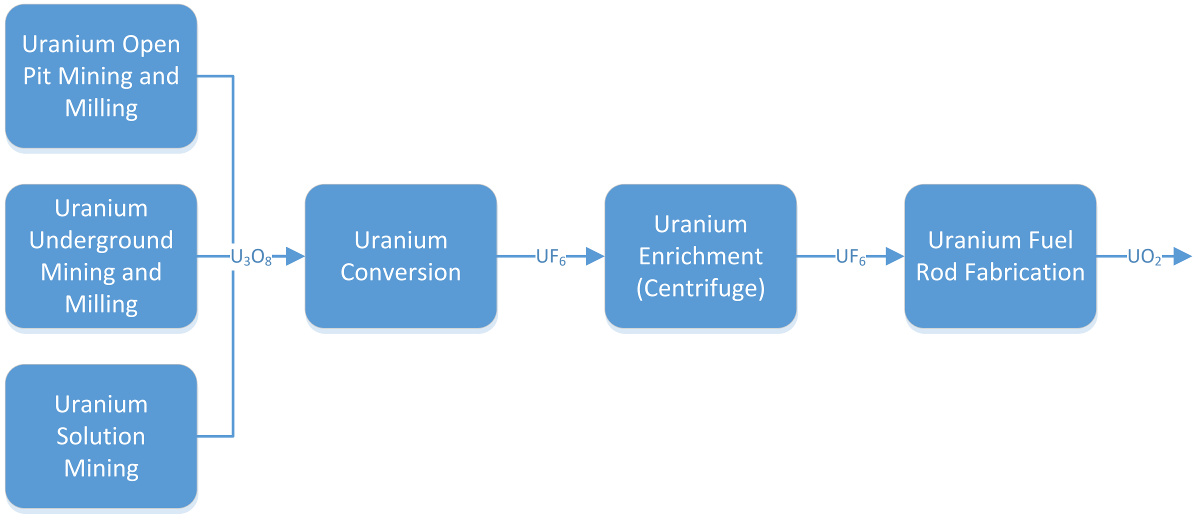

Fig. 10 Uranium enrichment supply chain.

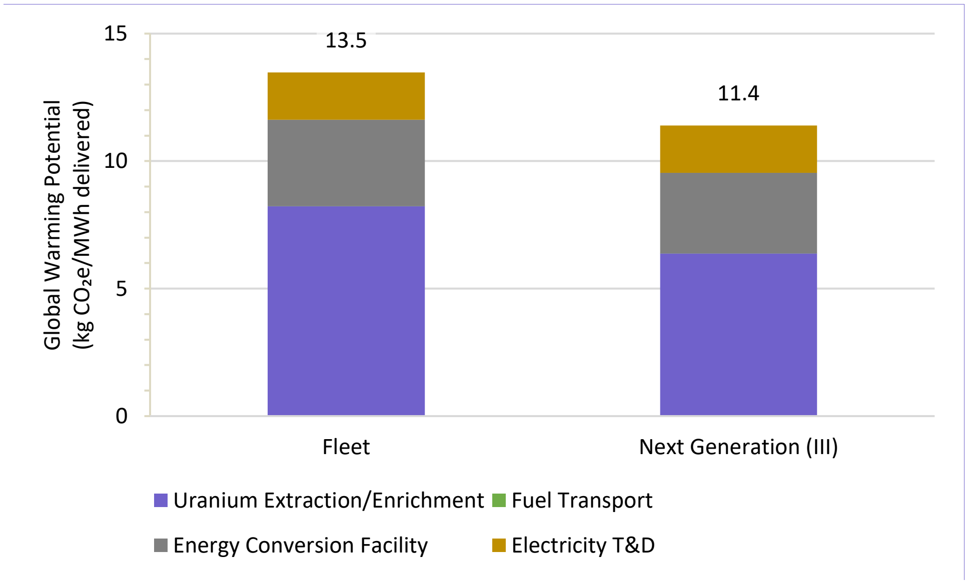

Fig. 11 Average contribution to GWP by aggregate stages in the supply chain for nuclear power generation technology

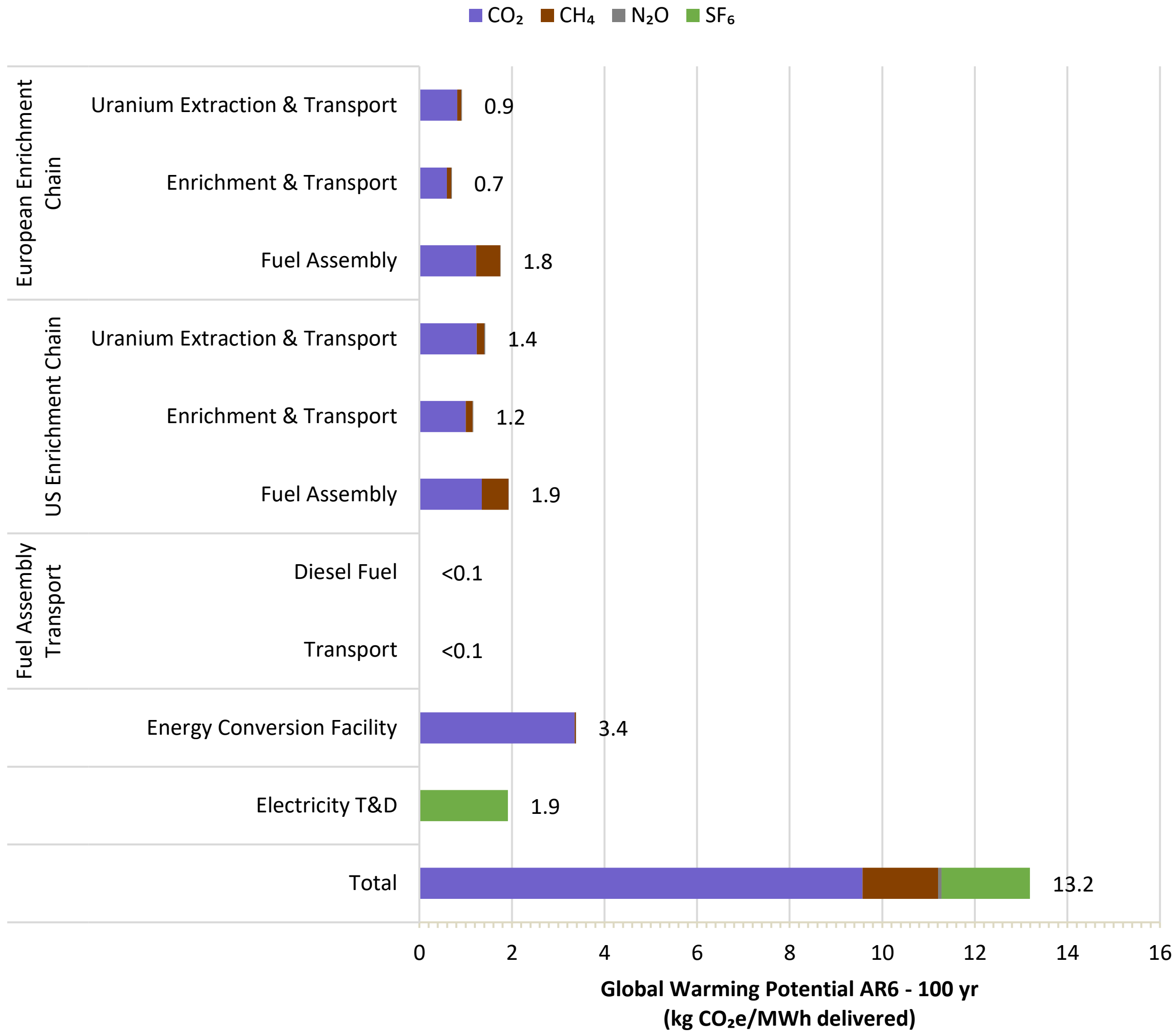

Fig. 12 Average contribution to GWP by disaggregate stages in the supply chain for nuclear fleet power generation.

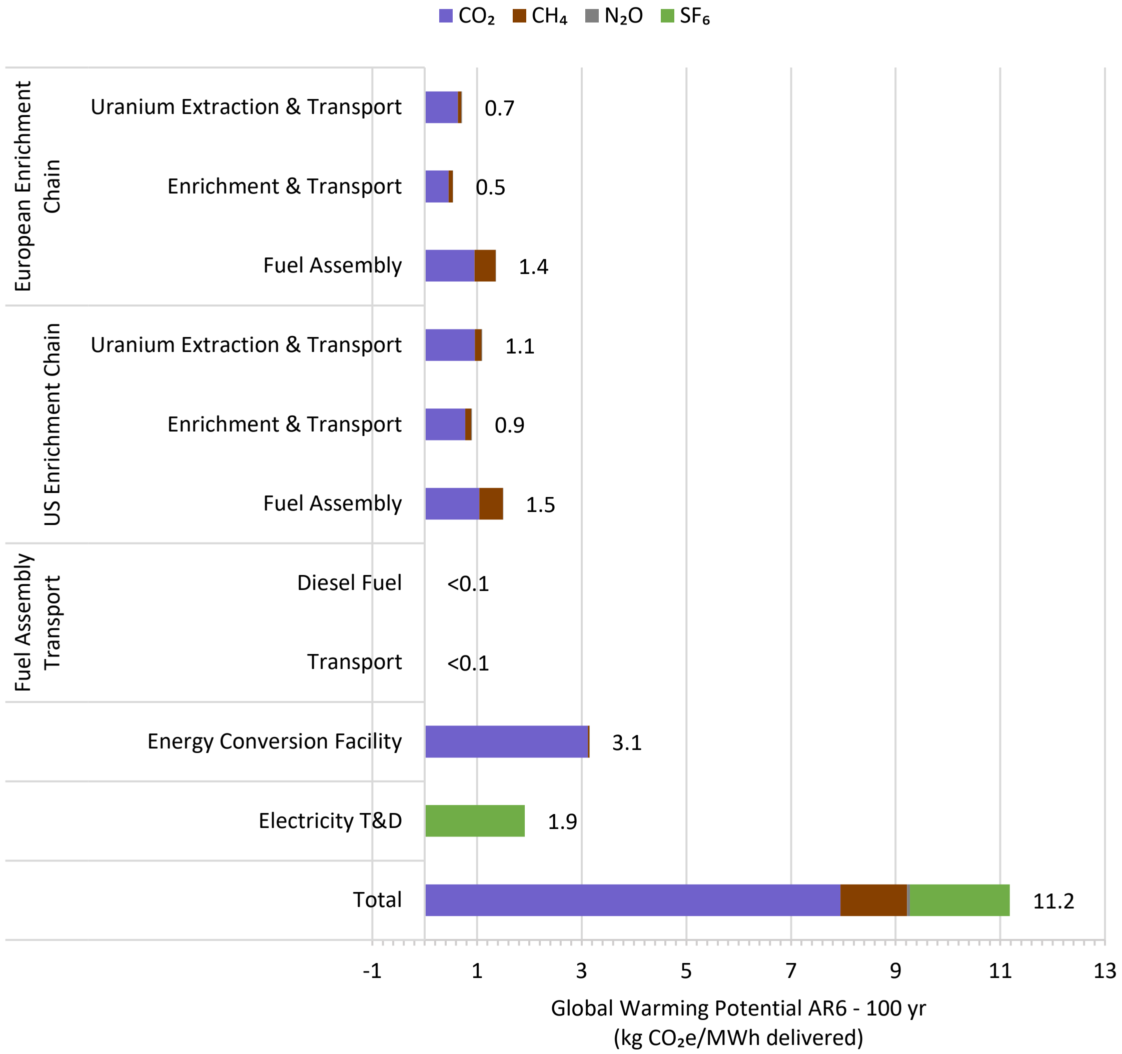

Fig. 13 Average contribution to GWP by disaggregate stages in the supply chain for next generation nuclear power generation.

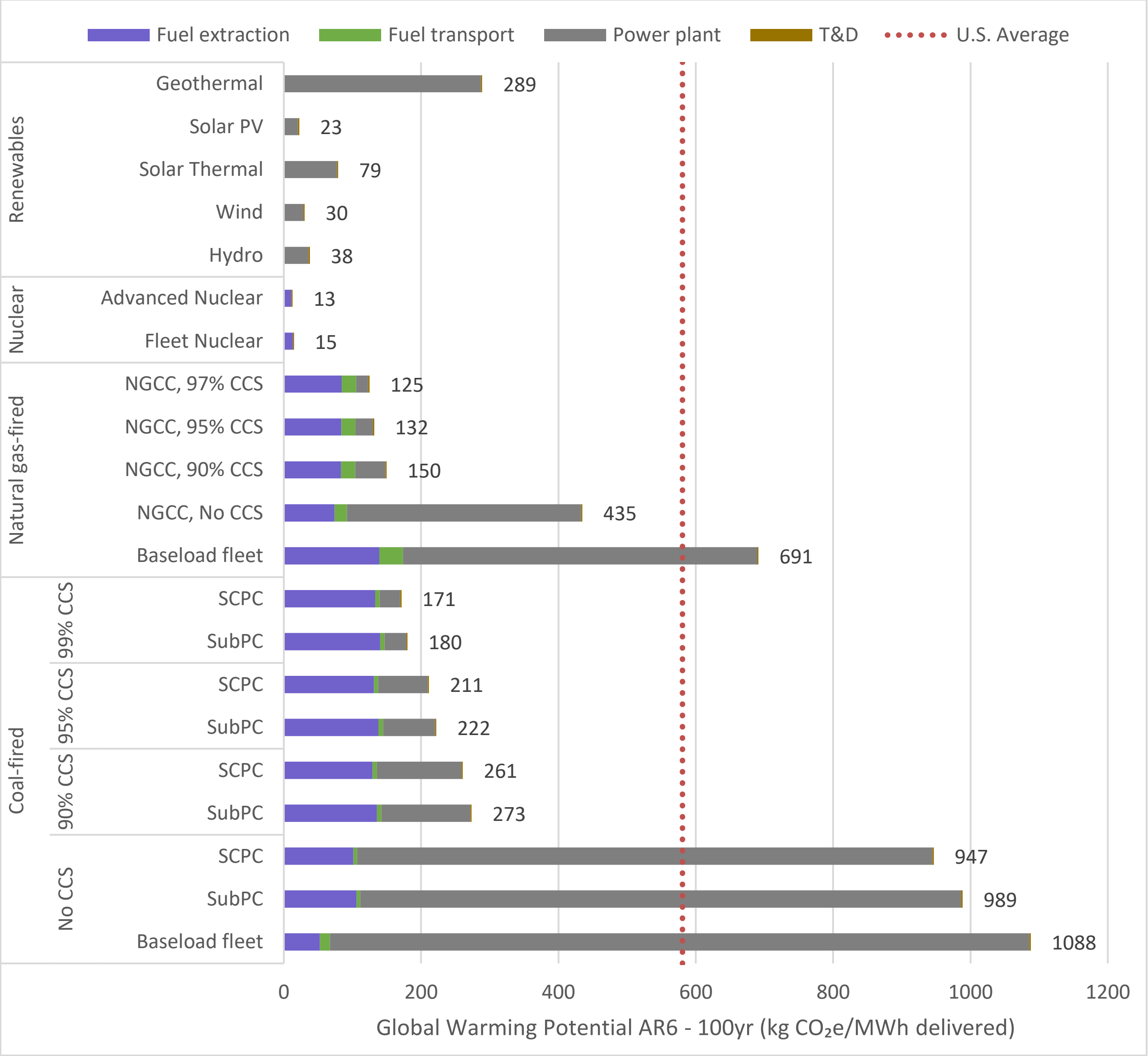

Fig. 14 Average contribution to GWP by aggregate stages in the supply chain for different power generation technologies. Red dotted line represents the GWP for 2016 U.S. average electricity production.