

New Approach to Techno-economic Assessment of Power Plants with Carbon Capture and Storage: The Inclusion of Realistic Dispatch Profiles To Calculate Techno-economics of Part Load Operations

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■ INTRODUCTION

Techno-economic assessment of fossil-fueled power plants with (and/or without) carbon capture and storage (CCS) is generally carried out at full load conditions assuming a capacity factor of typically around 85%^{1–3} or even 100%.⁴ This approach allows for straightforward assessment and easy comparison between costing studies but fails to reflect current operating conditions. Nowadays, fossil power plants hardly operate at 85 or 100% of their availability, and this situation is expected to remain or become worse in the future.^{5–8} For example, in 2014, all of the countries included in the European Network of Transmission System Operators for Electricity (ENTSO-E) had an average fossil fuel power plant loading as low as 34% (on the basis of ref 9). In the U.S., in 2011, coal-fired power plants operated at capacity factors of 38–71%.² As a result, the performance indicators reported for power plants with CCS are strongly biased toward optimal dispatch, leading to overestimation of their technical performance¹⁰ and underestimation of their costs.¹¹ Moreover, techno-economic comparisons and/or optimization studies of CCS power under the full load assumption may lead to design and/or technology selections that are only theoretically optimal.

Therefore, the conventional methodology for techno-economic assessment is very limited, and a new approach is necessary. This communication presents an approach for the techno-economic assessment of power plants with and without CCS. The proposed approach is both simple as well as capable of capturing the most important techno-economic considerations of real operating conditions. It builds on existing methods for techno-economic assessment (e.g., ref 1), using the same kinds of performance calculations and indicators [e.g., levelized cost of electricity (LCOE) and specific emission intensity]. More detailed approaches are conceivable but may be too complex and time-consuming for technology selection and initial design.

■ NEW PART LOAD TECHNO-ECONOMIC APPROACH

The key aspect and main difference of the proposed method with respect to conventional approaches is in the assessment of the electricity generated, fuel consumption, and CO₂ emissions based on operating profiles (load versus hours), which are representative of real operation conditions.

The power plant performance should be determined at different operating points ranging from design to minimum load. The number of points is arbitrary and depends upon the

desired accuracy and details of the operating distribution along the year. We suggest to use 4–6 operating points as a start. The overall electricity produced and CO₂ emissions are calculated by multiplying the value at different operating points with the number of operating hours at these loads. For simplicity, the plant performance at part load is calculated at steady state (analogous to Sanchez et al.¹⁰) and can be provided by plant vendors or determined by (off design) simulations.

The mathematical representation of the indicators for the conventional and new approaches are summarized in Table 1.

■ EXAMPLE OF APPLICATION

To illustrate the use of the proposed approach, a simplified example is shown here. A state-of-the-art natural gas combined cycle (NGCC) power plant is selected equipped with post-combustion CO₂ capture technology (MEA). The techno-economic indicators are calculated using both the conventional and part load approaches and are based on the performance reported in Table 2 (in-house modeling results).

The dispatch profiles that were used are reported in Figure 1. The first dispatch profile is hypothetical. In this profile, the plant is idle 2000 h per year and is running the remainder of the year at various operating points (loadings). The second dispatch profile is the real 2015 profile of a recently built Hungarian NGCC representing the current European situation of overcapacity and high operational costs of natural gas (NG) power plants (in comparison to other generators).

Table 3 shows that the CO₂ intensity of the plant without CCS is slightly higher using the part load approach than using the full load approach. This is caused by a significant efficiency drop when operating at part load (up to 8% at 40% MCR). The CO₂ intensity with CCS is similar for the full load and part load scenarios. The lower plant efficiency at part load is balanced by a higher CO₂ capture rate. Differences between both scenarios are more evident when comparing the specific energy consumption per tonne of CO₂ avoided (SPECCA) values. Calculating the SPECCA with the part load approach leads to a value that is 25% higher than calculated with the full load approach.

The economic results also show significant differences between the full load and the part load approaches (Figure 2). Both LCOE and cost of CO₂ avoided (CCA) significantly

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Table 1. Mathematical Representation of Techno-economic Calculations for the Conventional and Part Load Approach

	full load approach	part load techno-economic approach
electricity produced, E_{el} (MWh)	$P_{des} \text{HPY}_{tot}$	$\sum_n^{op=1} P_{op} \text{HPY}_{op}$
where P_{des} and P_{op} are the power outputs at the design or operating point in MW, HPY_{op} is the hours per year that the plant runs at the respective operating point, and HPY_{tot} is the total hours per year that the plant is in operation		
average CO_2 emission intensity, CEI_{av} (kg/MWh)	$3600 \frac{F_{\text{CO}_2,des}}{P_{des}}$	$\frac{(1+\alpha)3600}{\text{HPY}_{tot}} \sum_n^{op=1} \left[\frac{F_{\text{CO}_2,op} \text{HPY}_{op}}{P_{op}} \right]$
where $F_{\text{CO}_2,des}$ and $F_{\text{CO}_2,op}$ are the CO_2 emissions in kg/s at the design or operating point, P_{des} and P_{op} are the power outputs at the design or operating point in MW, HPY_{op} is the hours per year that the plant runs at the respective operating point, HPY_{tot} is the total hours per year that the plant is in operation, excluding the hours that the plant stands idle; it is optional to include a value for the coefficient α representing any additional CO_2 emissions as a result of plant cycling that are not included in the steady-state performance evaluations, which could be retrieved from actual plant emission data		
SPECCA_{av} (GJ/tonne of CO_2)	$3600 \frac{\left(\frac{1}{\eta_{cc,des}} - \frac{1}{\eta_{ref,des}} \right)}{\text{CEI}_{ref,des} - \text{CEI}_{cc,des}}$	$\frac{3600}{\text{HPY}_{tot}} \frac{\sum_n^{op=0} \left[\text{HPY}_{op} \left(\frac{1}{\eta_{cc,op}} - \frac{1}{\eta_{ref,op}} \right) \right]}{\text{CEI}_{ref,av} - \text{CEI}_{cc,av}}$
where η is the net plant efficiency both with (cc) and without (ref) CCS and subscripts des and op refer to conditions at the design and operating points		
levelized cost of electricity (€/MWh)	$\frac{\sum_t \frac{\text{cash flow}_t}{(1+r)^t}}{\sum_t \frac{P_{des} \text{HPY}_{tot}}{(1+r)^t}}$	$\frac{\sum_t \frac{\text{cash flow}_t}{(1+r)^t}}{\sum_t \frac{\sum_n^{op=1} P_{op} \text{HPY}_{op}}{(1+r)^t}}$
where r is the discount rate used to calculate the value of cash flows in year t ; cash flows include investment costs (IC), fixed and variable operation and maintenance costs (FOM and VOM), fuel costs (FC), and restart costs (RC) as follows: $\text{cash flow}_t = [\text{IC} + \text{FOM} + \sum_n^{op=1} (\text{VOM} + \text{FC})_{op} + \text{RC}]_t$		

Table 2. Performance Data of the NGCC (with CCS) Using the Part Load Approach and Compared to the Full Load Approach

parameter	unit	part load approach				full load approach
operating point	% MCR	40	60	80	100	100
Performance w/o CCS						
power output	MW_e	320	480	640	800	800
net efficiency	% LHV	50	53	56	58	58
CO_2 intensity w/o CCS	kg/MWh	426	402	380	367	367
Performance with CCS						
power output	MW_e	262	389	537	697	690
net efficiency	% LHV	41	43	47	50.5	50
CO_2 capture rate	%	95	93	90	85	90
CO_2 intensity w CCS	kg/MWh	26.0	34.7	45.3	63.2	42.6

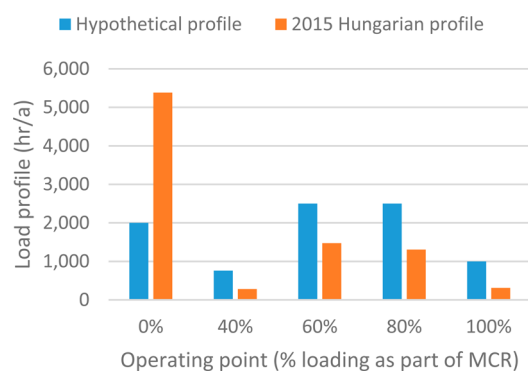


Figure 1. Loading profiles of the NGCC used for part load calculations.

increased when using the part load approach, representing more realistic levelized economics of CCS power in current and future power systems. The results show, for instance, that the

Table 3. Technical Performance Indicators of the NGCC (with CCS) Using the Part Load Approach and Compared to the Results of the Full Load Approach^a

parameter	unit	full load approach	part load hypothetical	part load Hungary 2015
CO_2 intensity w/o CCS	kg/MWh	367	391	392
CO_2 intensity w CCS	kg/MWh	43	42	41
SPECCA	GJ/tonne of CO_2	3.1	3.9	3.9

^aThe values for the part load cases are the weighted average values.

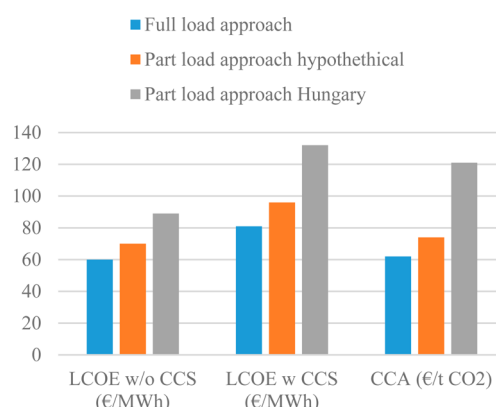


Figure 2. Economic performance indicators of the NGCC (with CCS) using the part load approach and compared to the results of the full load approach. The values for the part load cases are the weighted average values.

LCOE of gas-based power generation with CCS will more likely be above 100 €/MWh than below this value. This inherently also leads to an increase of the cost of CO_2 avoided in the order of 20–100%. The observed differences between the full load and part load approaches showcase the necessity

for including real dispatch profiles when calculating the techno-economic performance of CCS power.

DISCUSSION AND CONCLUDING REMARKS

This communication proposed a new approach to calculate the techno-economic performance of power plants with CCS including part load operation. It builds upon existing techno-economic performance indicators, such as SPECCA, LCOE, and CCA, easing its use by stakeholders. A relevant point of discussion is whether or not LCOE and CCA are the most suitable performance indicators for CCS economics, especially for part load operation. Adversaries of using these indicators note that their use unilaterally averts additional costs of backup power for intermittent renewables to fossil generators.¹² This makes renewables look unrealistically cheap compared to fossil power with CCS. Rather, they propose to look at total power system costs instead or to add the economic benefits of system stability and inertia to the costs of fossil power plants (with CCS), thereby improving the economic picture of fossil-based generation versus renewable generation.¹² We acknowledge that there may be different plausible ways of looking at the performance of fossil power with CCS. We, however, argue that there is merit in introducing a part load approach that uses traditional indicators because these are widely used and well-understood by scientists, industry, and policy makers. Besides, this approach can be very useful when comparing the performance of different carbon capture technologies at more realistic utilization profiles than the currently widely used full load approach. The part load approach is also expected to be useful when optimizing the design of a single carbon capture technology for realistic dispatch situations. Finally, the purpose of this communication was to provide a possible solution that includes the reality of part load dispatch rather than one single solution that fits all situations. It is thus anticipated that this communication will aid to progress the discussion on the techno-economic performance of CCS power, the comparison and selection of carbon capture technologies, and their comparison to other low-carbon generation options.

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Notes

The authors declare no competing financial interest.

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