SCOPING STUDY ON OPERATING FLEXIBILITY OF POWER PLANTS WITH CO_2 CAPTURE

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IEA GHG OVERVIEW

Background

IEA GHG has undertaken several studies on power plants with CCS which include assessment of operation at steady state full load. An important aspect which has not been considered in detail is operability, which includes the ability to change the power output in response to changes in power demand, to be able to accommodate changes in ambient conditions, fuel compositions etc., to be easily started-up and shut-down and to be able to accommodate equipment failures in a safe manner.

Operability of fossil fuel power plants is likely to become more important in future as more renewable power systems with variable outputs and more nuclear plants, which are relatively inflexible, are built to reduce CO_2 emissions. The operability of power plants with CCS could have a major impact on the extent to which CCS will be used in future and it could also be a significant factor in the choice of the optimum CO_2 capture technology. However, little information on the operability of power plants with CCS is currently available.

IEA GHG has employed the University of Waterloo in Canada to undertake an initial scoping study on CCS plant operability which provides the following:

- A review of operability drivers and issues within electricity systems
- A review of literature on operability of power plants with CCS
- Discussion of techniques for the detailed assessment of the operability of power plants with CCS
- Discussion of the trade-off between operability and cost
- A proposed scope of a detailed study, including an estimate of the amount of effort required

Results and Discussion

Operability drivers and issues within electricity systems

Much of a power generator's need for operability results from control actions taken by electricity system operators, in particular due to variations in electricity demand. Other factors such as changing ambient conditions and fuel analyses can also be significant. To provide background to the discussion of CCS power plant operability, this report discusses the main drivers for power plant operability within present and future electricity systems and the resulting operability issues for power plants.

Literature on operability of power plants with CCS

To date there is little mention of the operability of power plants with CCS in the literature. Of the three different CO_2 capture approaches: post-combustion, pre-combustion and oxy-combustion, operability of oxy-combustion has received the most attention. Extensive gaps exist in the consideration of the important operability issues of power plants with CCS and it is not possible to comment on the relative operabilities of the three capture options. Some further work may be being undertaken by CCS process licensors and utilities but such work is not in the public domain. There is a need for a public domain, impartial analysis of the operability of the leading CO_2 capture technologies which would be available to other researchers, potential customers of CCS technologies and policy makers. Undertaking impartial technical analyses is one of the main roles of IEA GHG.

Techniques for the detailed assessment of the operability of power plants with CCS

Techniques are available for the assessment of flexibility, controllability and start-up and shutdown issues. The technical discussion of these techniques included in this review will provide a basis for a more detailed study on CCS plant operability. In anticipation that commercially-available process simulation software will be used to perform the studies, four applications that have been featured in the literature on power plants with CCS have been identified and their capabilities investigated. Of these four: AspenPlus®, Unisim (formerlyHYSIS), gPROMS and Pro Treat, all but the latter appear to be well suited to the investigations that are proposed.

Trade-off between operability and cost

Improving the operability of a process may result in higher costs. It is important to understand the trade-off between costs and benefits of improved operability. While costs are relatively simple to assess, estimating the benefits is significantly more difficult and to do so with reasonable accuracy requires the simulation of the overall electricity system. Future electricity systems may be substantially different from current systems and will vary between countries, so the application of CCS power plants in a range of systems should be assessed.

Proposed scope of a detailed study

The scope of a study that would assess the operability of CCS power plant more deeply is proposed. The four main areas of the study, which would be undertaken sequentially, are:

Flexibility:	The focus is on steady-state performance of the power plants with CO_2 capture at a variety of conditions
Controllability:	The scope is expanded such that dynamic performance of the processes is considered in the face of set-point changes and disturbances
Start-up/shutdown:	At this level, the dynamic performance of the processes in the special cases of start-up and shutdown are also included in the analysis
Operability trade-offs:	Information garnered from the above studies is used to enable the benefits of operability to be assessed

The study would cover examples of the three leading CO_2 capture processes, namely post-combustion, pre-combustion and oxy-combustion capture. The effort required for the proposed study is estimated to be 4-11 man-years. The uncertainty depends mainly on model development and the capabilities of the investigators undertaking the work.

Major Conclusions and Recommendations

Operability is an important consideration for power plants operators and it is likely to become even more so in future due to the increased use of renewable energy sources with low-CO_2 emissions. It could be a significant factor in the choice of the optimum CO_2 capture technology and it may also affect the extent to which CCS will be used in future.

There is currently little published work on operability of power plants with CCS.

The amount of effort required for detailed analysis of the operability of power plants with CCS would be substantially greater than that of IEA GHG's other technical studies. For such a study to go ahead addition funding would be needed, for example from any IEA GHG Members and Sponsors that are especially interested in this subject.

IEA GHG will organise a workshop to discuss CCS plant operability. This will involve researchers working on modelling and design of CCS plants and modelling of future electricity systems. This may lead to IEA GHG setting up a network of researchers on this subject and organising technical studies.

University of
Waterloo

Scoping Study On Operating Flexibility of Power Plants With CO_2 Capture

prepared for

International Energy Agency Greenhouse Gas R&D Programme

by

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Contents

List of Tables

List of Figures

1 Introduction

1.1 Study objectives

The IEA GHG (International Energy Agency Greenhouse Gas R&D Programme) has devoted considerable resources toward the study of power plants with CCS (Carbon Capture and Storage). However, past studies have only considered the steady-state performance of these processes; the *operability* has, to date, been ignored. Given that operating flexibility may be the deciding factor in terms of:

- the overall adoption of CCS as a CO_2 mitigation strategy and
- the choice of the optimum CO_2 capture technology,

and that little information on the operating flexibility of power plants with CCS is currently available, the IEA GHG believes that a detailed evaluation of the three leading CO_2 capture technologies (*i.e.*, post-, pre-, and oxy-combustion), for both coal and natural gas, is in order. This study, representing a first step toward meeting that goal, has as objectives to:

- determine the existing state of knowledge,
- identify the information gaps that exist,
- suggest approaches to secure the missing information, and
- estimate the effort required to fulfill the above objectives.

1.2 Definition of operability

Operability is the ability of a process to operate satisfactorily under conditions different than the nominal design conditions.[1] To declare a process “operable”, four criteria must be met:

1. The process must be *flexible*. That is, the process must be able to operate in an acceptable manner over a range of steady-state conditions.
2. The process must be *controllable*. That is, it must both be able to recover from process disturbances and move to new set-points in a measured and timely fashion.
3. The process must be able to be (easily) started-up and shut-down.
4. The process must accommodate equipment failures in a safe manner.

In this study, the emphasis is on the first two criteria with minor consideration given to start-up and shutdown and none with respect to the last criterion.

1.3 Outline of report

Operability becomes an issue when processes are required to adapt to changing conditions. In Section 2, aspects of current electricity systems that necessitate operability are described. In addition, characteristics of future electricity systems that have operability implications are also presented.

The treatment of operability as it relates specifically to power plants with CCS begins in Section 3 with a review of the existing relevant literature. This is followed by a discussion in Section 4 of approaches for quantifying process operability and then by the presentation of a methodology for performing operability cost/benefit analysis in Section 5.

Finally, recommendations for the scope of a detailed study are given in Section 6.

2 Operability within today's electricity systems

Electricity systems consist of generators and loads, connected via a transmission system, under the coordination of a system operator. Electricity systems are designed to safely and reliably provide consumers with electricity, on demand, in an economically efficient manner. As conditions within electricity systems change, the expectation is that generators' operation will adapt to compensate. This section begins by presenting 'drivers' for operability within present-day electricity systems and speculates as to what new drivers will present themselves in the future.

Contemplation of the drivers for operability within the electricity system leads to the identification of several essential points to consider when evaluating the operability of existing or proposed power plants. Presentation of these operability issues is given next.

Finally, this section concludes with a summary of how existing non-fossil fuel power plants and those fossil-fired plants without CCS fare in the face of the operability issues relevant in today's electricity systems.

2.1 Operability drivers

With respect to present-day electricity systems, much of the generators' need for operability results from control actions taken by system operators.

- Electricity systems are, for the most part, demand driven. The almost continuously *varying demand* requires near simultaneous adjustment of generators' output as large-scale storage of electric energy is infeasible.

- Through a process called *unit commitment*, system operators select the states that generators are to assume in future time periods. The typical unit commitment problem will cover a single day subdivided into 24 one-hour time intervals. Up to four different states are considered:

  Cold shutdown: the unit is completely shutdown

  Warm shutdown: the unit is shutdown but the generator is kept 'warm'

  Unit synchronized, no load: the generator frequency is synchronous with that of the grid but power is not being injected

  Unit in operation: the generator is injecting power to the grid

- Solving the unit commitment problem requires an estimate of each generator's capability[1] and of total electricity demand for each future time interval. As part of the unit commitment, *reserve capacity* — extra generation capability beyond the anticipated requirement — is committed:

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[1] *Capability* is the maximum amount of power that a generator is able to deliver at a given moment in time.

  - to accommodate unexpected changes in generator capability,
  - to account for uncertainty in the demand or price forecast,
  - to provide some protection in the case of an unexpected equipment failure
  - *etc*.

  Note that different classes of reserves exist distinguished by the speed with which the reserve capacity can be brought online. For example, the rules for the Ontario Electricity Market identify 10-minute and 30-minute operating reserves.

- Immediately prior to a dispatch interval, system operators are charged with determining the *optimal power flow*. Solving a load flow problem consists of finding a reasonable set of voltages, phase angles, and power flows given the electricity demand, the generators in operation, and the characteristics of the transmission system. In practice, many different feasible load flows exist and the optimal power flow is the load flow which optimizes the performance metric of interest. Some examples are:
  - generation cost
  - pollutant emissions
  - combined cost and security
  - minimum load shedding
- Occasionally, the transmission line capacity is insufficient for the most economic electricity dispatch. This condition is referred to as *congestion*. One method of relieving congestion is for system operators to re-dispatch generation. That is, to provide a new set of power output instructions such that congestion is alleviated.
- Many loads require a well-controlled frequency to run properly and, thus, *frequency control* is an important function of system operators. Frequency changes occur whenever the supply and demand of electricity are not in balance. If system operators need to increase power output, a new dispatch instruction is given to the marginal generators which typically have ten minutes to respond.

In other cases, generator owners require flexibility and controllability to respond to their own unique challenges.

- The heat input characteristic of a generator can be dependent upon *seasonal variations* which affect things like ambient temperature and cooling water temperature. By illustration, according to data collected at the U.S. National Oceanic and Atmospheric Administration's Buffalo office, water in Lake Erie, the source of Nanticoke Generating Station's cooling water, varies between 0.6°C and 23°C.[2] Assuming a steam temperature of 538°C (main steam temperature of Nanticoke), the Carnot cycle efficiency goes from a maximum of 66% to a minimum of 63% — a substantial difference.

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[2] Measured at a depth of 9m.

- In the face of *fuel-price volatility*, a generator owner might be inclined to substitute fuels in an effort to minimize generation costs. For example, the Lennox Generating Station, located on the eastern shore of Lake Ontario, fires natural gas most of the year but switches to fuel oil residues during the winter when demand of natural gas for space heating causes its price to jump.

- *Fuel heterogeneity* at power plants using, for example, coal or municipal waste as a primary energy source, if uncontrolled, can lead to sub-optimal and even unsafe power generation.

Deregulation, energy security, climate change, and demand side management are the dominant forces guiding the evolution of electricity systems. Thus, in the future, new and different operability drivers will become manifest.

- In a *deregulated electricity system*, market-based mechanisms are used to determine the generators and loads that are active in any time period and to arrange ancillary services. In theory, deregulation creates additional revenue streams for nimble generator companies to exploit.

- An increasing share of generating capacity may be *non-dispatchable* (*e.g.*, solar, wind, run-of-the-river hydroelectric, tidal). In the absence of new energy storage, greater reserves will be required to manage the uncertain power availability from these generators.

- A push towards *energy self-sufficiency* encourages the use of domestically produced and, perhaps, alternative fuels (*e.g.*, biomass) either as a replacement or a supplement for imported fuels.[3]

- *Regulation of* CO_2 *emissions* will become pervasive; CO_2 emission caps (whether hard caps or intensity based) and/or carbon taxes will spread to more countries as will areas participating in CO_2 emission trading regimes.

- *Nuclear power* will experience a resurgence as it is capable of producing electricity without emitting CO_2 while also being dispatchable. Nuclear generators, though, are ill-suited to frequent load changes.

- Hydrogen is gaining appeal as an energy carrier and a *hydrogen economy* could present an opportunity for power plants with co-generation potential.

- There may be more interest in *combined heat and power* plants. These plants allow for greater overall plant efficiency by making use of waste heat from power generation. These plants may be less flexible than plants that produce only electricity or only heat.

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[3] One could also argue that energy self-sufficiency is a driver toward wind and solar power.

- Providing generation capacity for demand ‘spikes’ is a costly proposition and *peak shaving* would delay the need for new capacity by increasing the capacity utilization of existing stock. One way of achieving timely reductions in electricity demand is by increasing the number of interruptible loads in the electricity system.
- “Smart” meter deployment enables the implementation of another peak shaving initiative. These electricity meters capture both the time and quantity of electricity consumed and their broad deployment allows *time-of-use* pricing to be implemented. Consumers are charged the market price of electricity (or a time-sensitive tariff) — a price that changes to reflect the ease of matching supply to demand in any given time period. Presumably, allowing consumers to ‘feel’ the true price will allow more efficient use of the resource.

2.2 Operability issues

Given the aforementioned operability drivers in present and future electricity systems, the following operability issues emerge. An exhaustive discussion of each issue is beyond the scope of this report but, that being said, for each issue, examples of questions that fall within its domain and the motivating operability drivers are presented.

2.2.1 Flexibility issues[4]

1. Part-load operation.

   Can the generator operate at part-load? What is the minimum load? What is the maximum load (which may exceed the nameplate rating)?

   Drivers: *frequency control, reserve capacity, non-dispatchable, nuclear power, combined heat and power*

2. Support for standby modes.

   Can the generator be placed on standby (*i.e.*, warm shutdown)? A generator on standby has a net power output of zero but can begin producing power more quickly than if it were completely shutdown. However, maintaining this advanced state of readiness incurs additional expenses that may not be fully recoverable.

   Drivers: *unit commitment, reserve capacity, non-dispatchable, nuclear power, combined heat and power*

3. Changing ambient conditions.

   Can the generator accommodate changes in ambient conditions (*e.g.*, ambient air temperature, temperature of cooling water source, wind speed, *etc.*)?

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[4] *Flexibility* refers to a generator’s ability to operate in an acceptable manner over a range of steady-state conditions.

Drivers: *seasonal variations, combined heat and power*

4. Variable fuel inputs.

   Can the power plant, in whole or in part, make use of different fuels? Can the power plant accommodate the changing properties of heterogeneous fuels (*e.g.*, coal, municipal waste)?

   Driver: *fuel price volatility, energy self-sufficiency*

5. Variable CO_2 capture rates.

   Can the emission rate of CO_2 vary independently of the plant load? If so, what are the minimum and maximum rates of CO_2 capture? Can the power plant operate without capturing CO_2?

   Drivers: *optimal power flow, congestion, unit commitment, reserve capacity, frequency control, non-dispatchable, regulation of* CO_2 *emissions*

6. Unsynchronized hydrogen and electricity production.

   Can a pre-combustion plant divert a portion of its hydrogen production away from electricity production — either to be stored for later electricity production or sold into the hydrogen economy? For that matter, can hydrogen be purchased from the hydrogen economy in lieu of being produced on site?

   Drivers: *congestion, unit commitment, frequency control, hydrogen economy*

7. Unsynchronized hot water/steam and electricity production.

   Can a combined heat and power plant change gross electricity and/or heat output independent of the other?

   Drivers: *congestion, unit commitment, frequency control, combined heat and power*

8. Variable CO_2 transmission and well injection.

   Can the CO_2 transmission system and well injection accommodate different flow rates of CO_2?

   Drivers: *regulation of* CO_2 *emissions, peak shaving, time-of-use pricing*

2.2.2 Controllability issues[5]

1. Ramp rate.

   How quickly can a generator respond to a change in set-point?

   Drivers: *congestion, frequency control, non-dispatchable, nuclear power, combined heat and power*

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[5] *Controllability* refers to a generator's ability to recover from process disturbances and move to new set-points in a measured and timely fashion

2. Variable CO_2 capture rates.

   How quickly can the CO_2 emission rate be varied?

   Drivers: *optimal power flow, congestion, unit commitment, reserve capacity, frequency control, non-dispatchable, regulation of* CO_2 *emissions*

3. Variable CO_2 transmission and well injection.

   How quickly can the CO_2 transmission system and well injection accommodate different CO_2 flow rates?

   Drivers: *regulation of* CO_2 *emissions, peak shaving, time-of-use pricing*

4. Resiliency.

   How well can the process recover from disturbances?

   Drivers: *fuel variability, changing ambient conditions*

2.2.3 Issues related to start-up/shutdown

1. Generator start-up and shutdown.

   After being shutdown, how long must a generator wait until it can be restarted? How long does it take for a generator to come online after being in cold shutdown? Warm shutdown? Synchronized, no-load state? And, how long does it take for a plant that is running to be shutdown?

   Drivers: *congestion, unit commitment, reserve capacity, non-dispatchable, nuclear power, combined heat and power*

2. Start-up and shutdown of CO_2 capture plant.

   Is it possible to start-up and/or shutdown the CO_2 capture-part of the plant without requiring simultaneous start-up and/or shutdown of the generator? If so, how long does start-up and shutdown take?

   Drivers: *congestion, reserve capacity, non-dispatchable, regulation of* CO_2 *emissions*

2.3 Summary of operability of existing power plants

Existing power plants are grouped in the following categories:

1. Wind
2. Solar (thermal)[6]

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[6] Most likely configuration is a solar concentrator with a thermal fluid or steam driving a turbine.

3. Solar (photovoltaic)
4. Hydroelectric (with storage)
5. Hydroelectric (run-of-the-river)
6. Nuclear
7. PC (Pulverized Coal)
8. Natural gas/oil (thermal)
9. Natural gas/oil (SCGT (Simple-Cycle Gas Turbine))
10. NGCC (Natural Gas Combined Cycle)
11. IGCC (Integrated Gasification Combined Cycle)
12. Diesel[7]

From the point of view of flexibility with respect to existing power plants, there are four key issues that need to be considered: part-load operation, support for standby modes, changing ambient conditions, and variable fuel inputs.[8] An analysis of the power plants with respect to these flexibility issues is given in Table 1.

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[7] Diesel generators, burning either oil or gas, are typically used in remote communities or to provide emergency backup. This category is listed for completeness sake but it is felt that diesel's niche role in the power generation sub-sector is reason to preclude it from further consideration.

[8] The other flexibility issues — variable CO_2 capture rates, unsynchronized hydrogen and electricity production, unsynchronized hot water/steam and electricity production, and variable CO_2 transmission and well injection — are omitted as they are not relevant to power plants in *existing* electricity systems; significant CO_2 capture from power plants has yet to be implemented and the hydrogen economy has yet to rear its head.

Table 1: Flexibility issues of existing power plants

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
Wind	• power output is continuously variable from 0–100% of rated capacity • wind speed, u, must exceed a minimum threshold (about 3.5–5 m/s) for power output [2, 3, 4, 5] • exists an upper-end cut-out speed where the system turns the turbine out of the wind or brakes	• No.	• power output, P, affected by changes in wind speed; $P = f\left(u^3\right)$ • At most, small to modest affect on power output with changing ambient air temperature. $\rho \propto 1/T$ and relationship between power output and air density is likely $P = f\left(\rho^3\right)$	• No.
Solar (thermal)	• power output is continuously variable from 0–100% of rated capacity • correct thermal fluid temperature and pressure thresholds must be met in order for power output to be possible	• supports warm shutdown and synchronized, no-load states	• power generation is dependent upon intensity of incident sunlight although thermal inertia delays the onset and dampens the effect of variations in electrical output caused by intensity changes	• a solar thermal installation could use an alternative source of energy to supplement (or replace) solar energy but this would suggest suboptimal siting of the solar thermal generator

continued. . .

Table 1: Flexibility issues of existing power plants *continued…*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
Solar (photovoltaic)	• power output is continuously variable from 0–100% of rated capacity • there exists a threshold intensity below which no power is generated	• No.	• no light (*e.g.*, at night), no power output • clouds, smog, *etc*. are an issue as power output is directly proportional to light intensity but the extent of the influence depends upon collector type (*e.g.*, standard or concentrating cell) and whether or not the array is designed for diffuse light	• No.
Nuclear	• limited possibility for part-load operation if incorporated into design • base-load steam temperature and pressure is relatively low and, hence, part-load operation is particularly inefficient • changing loads introduces change into a heavily safety system-loaded design which increases the risk of transients that might cause units to trip	• No.	• changing cold sink temperatures affect the achievable condenser vacuum which, in turn affects the overall efficiency (by about 1–2%) and the unit capability • the effect is more pronounced for sites with cooling towers as opposed to lake bottom cooling	• No.

continued…

Table 1: Flexibility issues of existing power plants *continued…*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
Hydroelectric (w/ storage)	• power output is continuously variable from 0–100% of rated capacity subject to cavitation prevention • no threshold flowrate required for power generation; open the gates, close the breakers and electricity will flow	• No.	• gross head can experience large seasonal fluctuations and power output is a function of head and flowrate. Generators capabilities', particularly those with low head, will fluctuate in accordance with these changes.	• No.
Hydroelectric (run-of-the-river)	• power output is continuously variable from 0–100% of rated capacity • no threshold flowrate required for power generation; open the gates, close the breakers and electricity will flow	• No.	• inlet volumetric flowrate can experience large seasonal fluctuations and power output is a function of head and flowrate. Generator output will fluctuate in accordance with these changes.	• No.

continued…

Table 1: Flexibility issues of existing power plants *continued…*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
PC	• power output is continuously variable over the interval $[P_{min}, P_{max}]$ • turn-down to between 20–25% using just coal is possible [6, 2] • auxiliary fuel may be used at low loads to support unstable burners [7, p 1132] • minimum load is a function of steam cycle efficiency, impacts on steam turbine and boiler components, controllability, cost of shutdown/startup, *etc*. • $P_{max} > P_{base}$ (*i.e.*, it is possible to exceed the base-load power output albeit not for extended periods of time)	• supports warm shutdown and synchronized, no-load states	• changes in the temperature of cooling water will have a modest effect on plant power output • changes in air density may limit capacity because of fan limits • wet and frozen coal will have a small effect on power plant output (the main impact is on process stability) due to reduced pulverizing	• significant capability to burn different coals although lower quality coals will incur an efficiency penalty • it is possible to co-fire biomass (perhaps up to 20%) with minor equipment modifications • petcoke can be co-fired with coal depending upon the petcoke type (*e.g.*, fluid, sponge, *etc*.), the original properties of the liquid fuel (*e.g.*, fuel source determines increases in SO_2, SO_3, NO_x that are experienced), and cost

continued…

Table 1: Flexibility issues of existing power plants *continued...*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
Natural gas (thermal)	• power output is continuously variable over the interval $[P_{min}, P_{max}]$ • minimum power output is between 10–25% on a continuous basis but it can be less depending upon steam turbine, boiler design acceptable life expenditures, and cost (very inefficient at low loads and natural gas is expensive)	• supports warm shutdown and synchronized, no-load states	• changing cold sink temperatures will have a modest effect on the power output • to a lesser extent, thermal efficiency depends upon the ambient air temperature	• generally possible for a light fuel oil or a liquid or gaseous fuel derived from biomass to be used but radiant and convective characteristics may be different and hence heat transfer surfaces need checking and sometimes modification

continued...

Table 1: Flexibility issues of existing power plants *continued…*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
Natural gas (SCGT)	• power output is continuously variable over the interval $[P_{min}, P_{max}]$ • minimum power is theoretically between 20–30% but, in practice, $P_{\min} = 70\% \pm 10\%$ for efficiency and emission reasons • various means are available for temporarily increasing peak output but at the cost of gas turbine parts life and maintenance cost	• no, it is not possible to isolate combustion from power generation	• thermal efficiency depends upon ambient temperature; typical lapse rates (*i.e.*, rate of power reduction versus ambient temperature) are 22% and 12% for aeroderivative and frame SCGT's, respectively, from 15°C to 32°C [8] • high ambient temperatures result in a reduction of maximum power output [8] • inlet air cooling and humidification is done to offset the impact of increasing air temperature on the efficiency of the Brayton cycle	• can use syngas, biofuel, and also oil (in the latter case, considerations at the design stage would have been required) • hydrogen-rich fuels (*i.e.*, natural gas) provide the greatest capacity and efficiency; switching to, for example, residual oil would result in capacity and efficiency reductions of about 10% [9]

continued…

Table 1: Flexibility issues of existing power plants *continued…*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
NGCC	• power output is continuously variable over the interval $[P_{min}, P_{max}]$ • exhaust from the gas turbine can bypass the HRSG (Heat Recovery Steam Generator) [9, p 4] • The turndown ratio depends upon the ratio of power between the gas turbine and the steam turbine (*e.g.*, 1x1, 2x1, 3x1). For a 1x1, performance is similar to SCGT. That is, power output could be as low as 20–25% but usually kept at 50+% due to efficiency and emissions. NO_x and CO rise a lot as load is decreased below 50–65% for most units. • significant efficiency drop at minimum load compared to base-load operation (perhaps about 40% [9]) • various means are available for temporarily increasing peak output by between 3–10% but at the cost of gas turbine parts life and maintenance cost	• the exhaust from the gas turbine could be vented which would keep the gas turbine and, maybe the steam turbine, warm • steam turbine supports warm shutdown; support for synchronized, no-load is possible if steam turbine does not share shaft with gas turbine	• thermal efficiency, on a percentage basis, is affected less than for SCGT because bottoming cycle makes up for the loss of power generation from the gas turbine • still a signficant impact on power output with changing ambient temperature: abuot 0.5% reduction in capability for every 1°C increase in temperature [9] • thermal efficiency takes a hit due to changing lake temperatures (if that is the cooling water supply) but this is almost insignificant relative to the drop experienced by changing air temperatures and/or if cooling towers are the cold sinks in the bottoming cycle.	• can use syngas, biofuel, and also oil (in the latter case, considerations at the design stage would have been required) • hydrogen-rich fuels (*i.e.*, natural gas) provide the greatest capacity and efficiency; switching to, for example, residual oil would result in capacity and efficiency reductions of about 10% [9] • dual-fuelling is also possible (*i.e.*, supplemental firing downstream of the gas turbine to increase the amount and quality of steam production)

continued…

Table 1: Flexibility issues of existing power plants *continued. . .*

	Flexibility issues			
	Part-load operation	Support for standby modes	Changing ambient conditions	Variable fuel inputs
IGCC	• power output is continuously variable over the interval $[P_{min}, P_{max}]$ • part-load capability is poor relative to that of a PC plant — likely a minimum of 50%	• as with NGCC, the exhaust from the turbine could be vented which would keep the gas turbine and, maybe the steam turbine, warm	• thermal efficiency change resulting from deviations in ambient air temperature would have a major affect • power output is essentially constant with respect to changing ambient air temperature [10] • thermal efficiency of the bottoming cycle would be modestly impacted by changing cold sink temperatures • wet and frozen coal will have a small effect on power plant output (the main impact is on process stability) due to reduced pulverizing	• possible to use different coals but would experience a major de-rate for switching from bituminous to sub-bituminous, for example • issues with co-firing moderate to high amounts of biomass due to changing slagging characteristics • GE units have dual-fuel capabilities; either configured for syngas/natural gas or syngas/liquid [10]

With respect to controllability and start-up/shutdown, the power plants belong to one of four categories as depicted in Figure 1. The relevant controllability issues are the ramp rate of the units and the speed with which they can be started-up and shutdown.

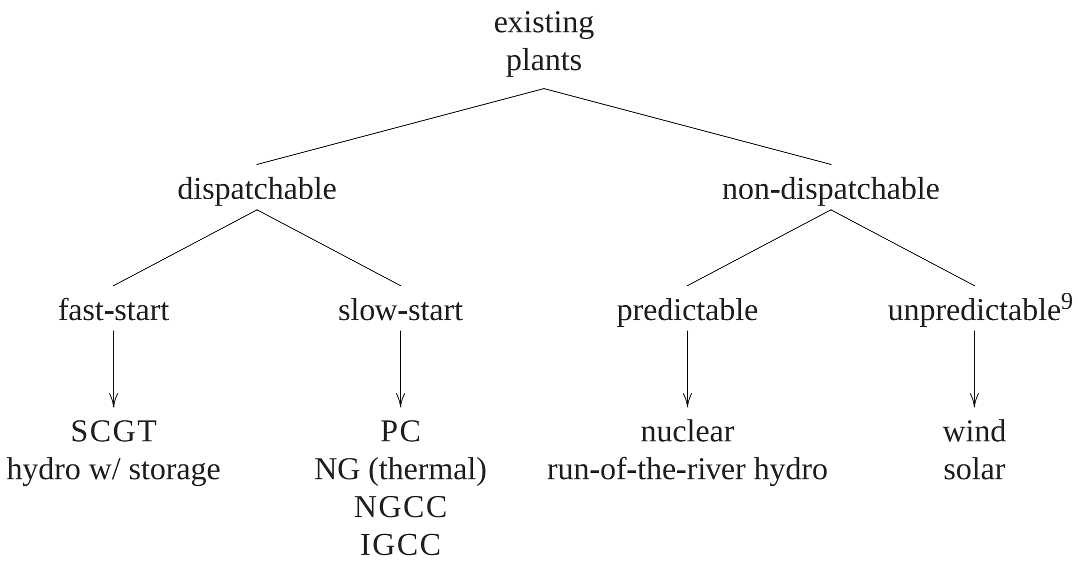


Figure 1: Classification of existing power plants with respect to controllability and start-up/shutdown characteristics

Dispatchable, fast-start:

- power plants are able to respond very quickly — defined to be in under ten minutes — to dispatch instructions from the system operator
- can reach base-load conditions from a cold start within this same ten minute time-frame [8]
- historically, each shutdown/start-up cycle adversely impacts SCGT life but newest units don't suffer from this [8]

Dispatchable, slow-start:

- within their control range, these plants can respond to dispatch instructions very quickly (*i.e.*, good load-following ability)
- can only provide reserve power if currently in operation or in synchronized, no-load state

---

[9] Whether wind and solar are correctly classified as predictable or unpredictable is debatable. Wind and solar are predictable on a broad energy basis but have unpredictable, rapid fluctuations over a wide load range from one dispatch interval to the next. In the context of controllability, it is this later behaviour which is most relevant and, hence, they are deemed *unpredictable* for this study.

- start-up time measured in hours [9]; shutdown can technically be very quick but it is preferable it if were not[10]

Non-dispatchable, predictable:

- limited ability to control power output
  - in the case of nuclear, power output is deliberately kept constant over dispatch interval
  - in the case of run-of-the-river hydroelectric, it might be possible to reduce power output by causing part of the flow to circumvent the turbine but, in general, power output is subject to the vagaries of the water flow
- power output is known with almost complete certainty over unit commitment planning horizon
- with respect to start-up and shutdown, these power plants are essentially always on[11]

Non-dispatchable, unpredictable:

- on-demand changes in power output (except for eliminating output completely) are not possible
- unpredictable, rapid fluctuations over a wide range from one dispatch interval to the next
- significant uncertainty with respect to power output over unit commitment planning horizon
- the fluctuations in power output from these sources has to be mitigated by other technologies which causes fuel and emissions impacts that are not usually accounted for
- the concepts of start-up and shutdown are not applicable

---

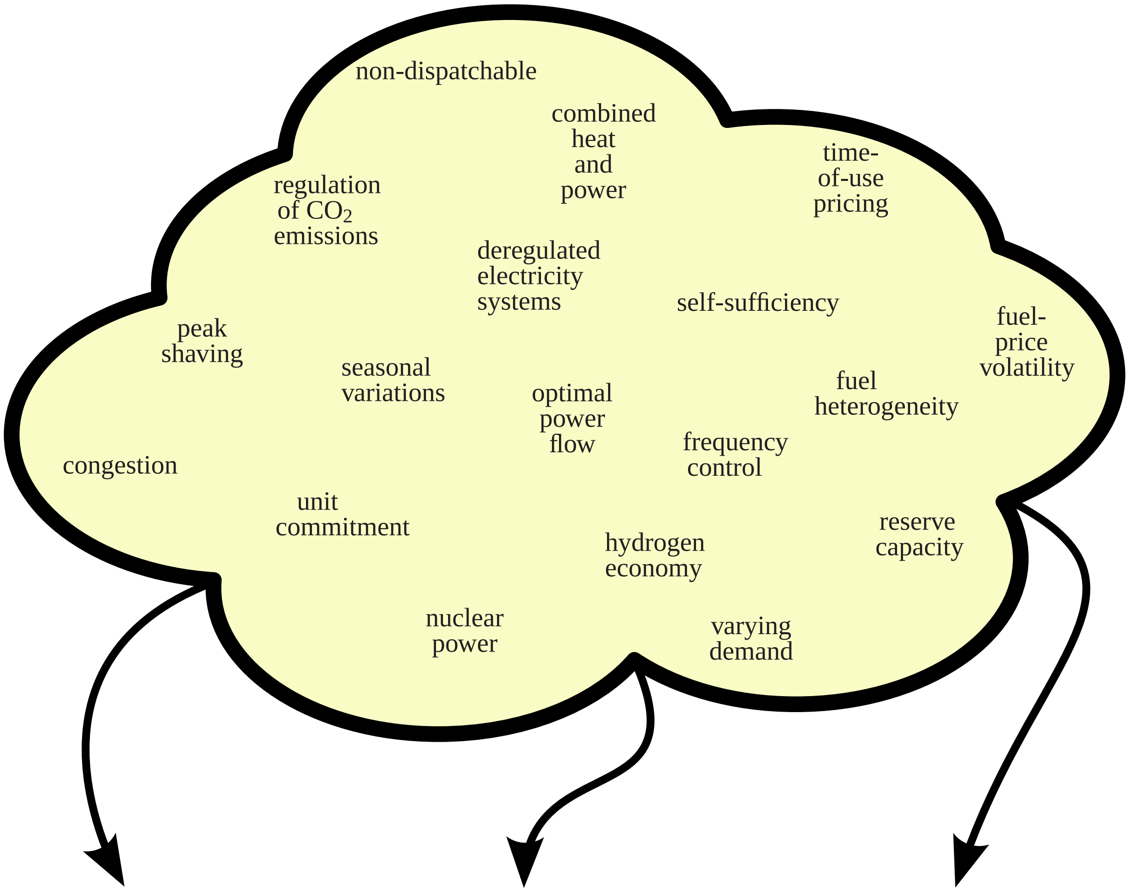
[10] Multi-shaft NGCC's can start the gas turbine independent of the steam turbine thereby achieving up to 65% power output within 15–25 minutes[9, p 27]

[11] The start-up and shutdown processes for nuclear power plants are difficult to justify economically and technically and, therefore, not initiated unless necessary (*e.g.*, for scheduled maintenance, emergencies).

2.4 Closing remarks

In this section, drivers for operability in electricity systems are introduced. In present-day electricity systems, operability enables system operators to orchestrate the safe and reliable delivery of electricity and allows generator owners to respond to changes in weather, fuel properties, and market conditions. And, while important today, with the apparent increasing popularity of deregulation and demand-side management techniques and growing concerns with respect to energy security and climate change, operability within electricity systems is likely to become even more important as time goes on. These operability *drivers* lead to the identification of several *issues* against which potential new entrants (*i.e.*, power plants with CCS) into the electricity should be vetted. For reference purposes, these drivers and issues are given in Figure 2.

The review of existing power plants with respect to flexibility, controllability, and start-up/shutdown revealed that, overwhelmingly, generators each vary in their ability to cope with off-design conditions. And, when coupled with other information regarding, for example, the relative cost of generation and the emissions intensity of these different forms of power generation, it is painfully evident that the reliable operation of the system requires a ‘basket’ of power generation technologies.



Flexibility issues

1. Part-load operation.
2. Support for standby modes.
3. Changing ambient conditions.
4. Variable fuel inputs.
5. Variable CO_2 capture rates.
6. Unsynchronized hydrogen and electricity production.
7. Unsynchronized hot water/steam and electricity production.
8. Variable CO_2 transmission and well injection.

Controllability issues

1. Ramp rate.
2. Variable CO_2 capture rates.
3. Variable CO_2 transmission and well injection.
4. Resiliency.

Start-up/shutdown issues

1. Generator start-up and shutdown.
2. Start-up and shutdown of CO_2 capture plant.

Figure 2: Summary of operability drivers and issues

3 Review of literature on operability of power plants with CCS

Although many papers in the open literature discuss power plants with CO_2 capture, only a small percentage of the published reports speak to the operability of these processes. In most cases, reference to operability is only in passing:

- Patrick Mönckert, *et al.* [11] discuss their experiences operating a 0.5 MW_{th} oxy-coal combustion pilot plant. A start-up procedure is described but, admittedly, it won't scale-up.

  Issue touched upon: *start-up/shutdown*

- Vijay Sethi, *et al.* [12] report the results from a study comparing air-fired combustion with oxy-combustion of lignite, sub-bituminous, and bituminous coals using a test rig. Flexibility was not of particular interest to these researchers but their experiment does show that it is possible for the same equipment to operate in both air-fired and O_2/CO_2-firing modes.

  Issue touched upon: *variable fuel inputs*

- Graeme Sweeney [13] briefly describes the "The Stanwell Project", a proposed 200 MW_e IGCC being built alongside an existing 1400 MW_e PC power plant in northeastern Australia. The IGCC will have both capture and non-capture modes with efficiencies of 34% and 40%, respectively.

  Issue touched upon: *variable CO_2 capture rates*

- Kvamsdal, *et al.* [14] qualitatively compare different CO_2 capture processes in terms of maturity and operational challenges. The authors touch on the ability to start-up, shutdown, and control CO_2 capture process only to say that all capture processes save amine absorption would have non-trivial operational challenges.

  Issue touched upon: *start-up/shutdown*

- Sanden, *et al.* [15] describe Just Catch™: a project whose aim is to dramatically reduce the capital and operating costs of amine-based post-combustion capture. A design objective is to allow the power plant to operate even when the capture process is not available.

  Issue touched upon: *variable CO_2 capture rates*

- Kourosh Zanganeh and Ahmed Shafeen [16] propose a paradigm shift with respect to the design of oxy-combustion power plants: intentional egress of air into the cycle instead of attempting to eliminate (minimize) its infiltration. They examined the sensitivity of parasitic energy consumption and flue gas composition to varying amounts of "air leakage".

Issue touched upon: *variable CO_2 capture rates*

- Varagani *et al.* [17] report their results from experiments conducted using a 1.5 MW_{th} pilot-scale oxy-combustion boiler. One of the experiments conducted was to observe the impacts resulting from substituting air for O_2 in the boiler.

  Issue touched upon: *variable CO_2 capture rates*

- Sekkappan *et al.* [18] discuss the results of techno-economic studies of oxy-fuel combustion using three different coals: South African bituminous, German lignite, and Greek lignite. They state that, for oxy-combustion, start-up will use air firing with emissions being released to the atmosphere and a controlled switch-over to O_2/CO_2-recycle combustion at some later time.

  Issue touched upon: *start-up/shutdown*

- Sarofim [19] discusses the state-of-the-art with respect to oxy-combustion. He surmises that in times of need, net power output could be increased by:

  1. Venting a fraction of the flue gas.

     The fraction of the flue gas that is vented does not have to be compressed thereby increasing the net power output. In this fashion, up to 8% of the original electrical output of the plant could be restored.

  2. Substituting air for O_2.

     Using air instead of O_2 would reduce the energy consumption of the ASU (Air Separation Unit). In this fashion, up to 16% of the original electrical output of the plant could be restored.

  Issue touched upon: *variable CO_2 capture rates*

- Knudsen *et al.*[20] report on their experiences operating a 1 t/h amine-based post-combustion pilot plant. As their initial attempt to assess the operation of the pilot plant under off-design conditions, the inlet flue gas flowrate is reduced to 25% of its design value while keeping the L/G ratio in the absorber constant. It was observed that the recovery rate stayed the same and that specific recovery energy increases with decreasing flue gas flowrate.

  Issue touched upon: *part-load operation*

- Arienti *et al.*[21] examine the cost and performance of the co-generation of hydrogen and electricity using IGCC technology with CCS. As part of the study, it is demonstrated that the ratio of hydrogen to electricty production can vary from 1.3:1 to 3.1:1 while operating the plant at full load and recovering 85% of the CO_2.

  Issue touched upon: *unsynchronized hydrogen and electricity production*

Only a handful of research groups are explicitly investigating the operability of power plants with CO_2 capture. Two of these groups are focused on oxy-combustion:

- Yamada *et al.* [22] use a dynamic simulation of a 1000 MW_e oxy-combustion power plant to simulate plant start-up and examine its part-load and base-load operation.
  - The base-load, steady-state design calls for five ASU's. Due to significant ASU start-up costs, an optimization study at 60% of base-load revealed that it is more economical to keep all the units running rather than, for example, having three ASU's running at 100% of capacity with the other two shut-off.
  - Power output set-point is ramped from 600 to 1000 MW_e at a rate of 1.8 MW/min (3% of 600 MW_e). About 20 minutes is required to achieve the new steady-state.
  - The authors show a start-up procedure that takes about 10 hours to reach 600 MW_e from "light off" conditions.

  Issues considered: *part-load operation, ramp rate, start-up/shutdown*

- Lars Imsland [23] considers the controllability of oxy-fuel combustion using dynamic models. He reaches two relevant conclusions:
  - FGR (Flue Gas Recycle) is open-loop unstable and control is thus required. Changes in fuel and oxygen input resulting from changes in load must be offset by changes in CO_2 output. If more fuel is introduced, more recycle will be necessary to control the temperature in the furnace.
  - Relative to air-fired combustion, oxy-fuel combustion, with its FGR, will be "slower".

  Elsewhere, Imsland *et al.* compare the set-point tracking of oxy-methane combustion under PID-control and MPC (Model Predictive Control) [24]. In so doing, the outline for the development of simplified dynamic model of an oxy-methane combustion process is given.

  Issues considered: *part-load operation, variable CO_2 capture rates*

The other two groups are considering post-combustion capture using amines:

- Alie *et al.* [25] describe the electricity system generation cost reduction that is realized when coal-fired power plants with CO_2 capture have flexibility with respect to the CO_2 recovery rate. More generally, the paper proposes a methodology for assessing this and other CO_2 mitigation options.

  Issue considered: *variable CO_2 capture rates*

- Chalmers and Gibbins [26, 27] consider the flexibility of a coal-fired power plant with CO_2 capture using amine absorption. They examine the sensitivity of power output and thermal efficiency to load changes in each of the following four modes of operation:

1. no CO_2 capture
2. 85% recovery of CO_2 capture
3. 85% recovery of CO_2 capture but without solvent regeneration (rich solvent storage)
4. 85% recovery of CO_2 capture with regeneration of previously stored rich solvent (twice the nominal CO_2 production)

Issue considered: *variable CO_2 capture rates*

Conclusions drawn from the literature review:

- The operability of power plants with CO_2 capture is generally not considered when said processes are being designed or when these designs are being evaluated.
- Of the three different CO_2 capture approaches, oxy-combustion operability has received the most attention with post-combustion based on amine-absorption having received some and no mention having been found relating to the operability of pre-combustion capture.
- Extensive gaps exist in the consideration of the important operability issues with respect to power plants with CCS. No definitive assessment of the operability of the individual technologies is available and it certainly is not possible to comment on the relative operabilities of post-, pre-, or oxy-combustion capture.
- The gaps in the understanding of the operability of power plants with CCS is presented in Tables 2 through 4.

Table 2: Summary of information availability on flexibility of power plants with CCS

	Power generation process		
	Post-combustion	Pre-combustion	Oxy-combustion
1. Part-load operation	• ability to operate at off-design flue gas flow rates has been demonstrated in a pilot plant • no information regarding minimum load or maximum load	• no information available	• simulation of off-design performance has been carried out • no explicit investigation into the minimum or maximum loads yet undertaken
2. Support for standby modes	• no information available	• no information available	• no information available
3. Changing ambient conditions	• no information available	• no information available	• no information available
4. Variable fuel inputs	• no information available	• no information available	• the feasibility of using different ranks of coal has been demonstrated using a test facility
5. Variable CO_2 capture rates	• several designs that allow for operating the power plant without capturing CO_2 have been proposed	• a design that allows for operating the power plant without capturing CO_2 has been proposed	• the performance benefit of reducing or ceasing CO_2 capture has been discussed

continued…

Table 2: Summary of information availability on flexibility of power plants with CCS *continued...*

	Power generation process		
	Post-combustion	Pre-combustion	Oxy-combustion
6. Unsynchronized hydrogen and electricity production	• N/A	• varying the ratio of hydrogen to net electricity output at full load has been simulated	• N/A
7. Unsynchronized hot water/steam and electricity production	• no information available	• no information available	• no information available
8. Variable CO_2 transmission and well injection	• no information available	• no information available	• no information available

Table 3: Summary of information availability on controllability of power plants with CCS

	Power generation process		
	Post-combustion	Pre-combustion	Oxy-combustion
1. Ramp rate	- no information available	- no information available	- using dynamic simulation, the feasibility of increasing power at a rate of 3%/min has been demonstrated
2. Variable CO_2 capture rates	- no information available	- no information available	- no information available
3. Variable CO_2 transmission and well injection	- no information available	- no information available	- no information available
4. Resiliency	- no information available	- no information available	- no information available

Table 4: Summary of information availability on start-up/shutdown of power plants with CCS

	Power generation process		
	Post-combustion	Pre-combustion	Oxy-combustion
1. Generator start-up and shutdown	• thought to be trivial • no procedure available nor any indication as to length of time required	• no information available	• start-up procedures using air-firing are proposed • an estimate of the time required to start-up from cold shutdown is available
2. Start-up and shutdown of CO_2 capture plant	• no information available	• no information available	• no information available

4 Techniques for the detailed assessment of the operability of power plans with CCS

The objective of this section is to discuss techniques for the detailed assessment of the operability of power plants with CCS with a focus on filling the information gaps that exist (see Tables 2 through 4). The assessment of the three different operability criteria of interest in this study — flexibility, controllability, and start-up/shutdown — are each presented separately.

4.1 Evaluation of flexibility

When one proposes to evaluate the flexibility of power plants with CCS, two different kinds of investigations are suggested. On the one hand, the objective is to determine if process operation is feasible given the anticipated operating conditions. For example, can the power plant accommodate the changes in ambient air temperature, temperature of cooling water, *etc*. that are to be expected in a particular location? Can the power plant switch from burning a brown coal to a sub-bituminous one?

On the other hand, one seeks to quantify the amount of flexibility inherent in a power plant design. For example, if part-load operation of the power plant with CCS is possible then what is the minimum possible power output? Or, what is the maximum quantity of hydrogen an IGCC can divert from electricity production?

Biegler *et al.* refer to these two different kinds of analysis as the *flexibility test problem* and the *flexibility index problem*, respectively.[1] What follows is a statement of each problem's objective, the basic problem formulation, and suggestions as to how this theory can be applied to the case of power plants with CCS. The section concludes with a survey of process simulation software potentially well suited toward flexibility analysis.

4.1.1 Flexibility test problem

The objective of the *flexibility test problem* is to determine if a particular design is flexible given a specified amount of uncertainty in some of the variables. It is useful to differentiate between two different classes of sub-problems: *multi-period evaluation* and *evaluation under uncertainty*.

Multi-period evaluation is concerned with assessing whether a design is capable of operating under various specified conditions in a sequence of time periods. That is:

$$\begin{array}{ll}
\text{find} & \mathbf{z}^1, \mathbf{z}^2, \ldots, \mathbf{z}^N \\
\text{s.t.}^{12} & h_i\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k, t^k\right) = 0 \quad \forall\; p = 1,2,\ldots,N;\; i = 1,2,\ldots,m \\
 & g_j\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k, t^k\right) \leq 0 \quad \forall\; p = 1,2,\ldots,N;\; j = 1,2,\ldots,r \\
 & r\left(\mathbf{d}, \mathbf{z}^1, \mathbf{z}^2, \ldots, \mathbf{z}^N, \mathbf{x}^1, \mathbf{x}^2, \ldots, \mathbf{x}^N, \theta^1, \theta^2, \ldots, \theta^N, t^1, t^2, \ldots, t^N\right) \leq 0
\end{array} \tag{1}$$

---

[12] s.t. = subject to

EXAMPLE 4.1

An analyst with the system operator seeks to determine whether there is sufficient capacity to meet the projected demand in some future 24-hour time period. As it turns out, this determination hinges upon whether or not a nominally 500 $\mathrm{MW_e}$ coal-fired generator unit with post-combustion CO_2 capture using MEA (monoethanolamine)[13] can deliver a specified amount of power E^k for each of the 24 time periods, k. The analysis is complicated by the fact that there is an upper limit on the daily total CO_2 emissions from this power plant. Then, using the formulation in (1), the problem amounts to:

$$
\begin{array}{rlll}
\text{find} & x^1_{\mathrm{CO_2}}, x^2_{\mathrm{CO_2}}, \ldots, x^N_{\mathrm{CO_2}} & & (\text{rate of } \mathrm{CO_2} \text{ recovery in every time period}) \\
\text{s.t.} & h_i(\ldots) = 0 & & (\text{heat and material balance in each period is satisfied}) \\
 & g_j(\ldots) \leq 0 & & (\text{power output in each period is} \geq 450\ \mathrm{MW_e}) \\
 & r(\ldots) \leq 0 & & (\text{total } \mathrm{CO_2} \text{ emissions} \leq \text{emissions cap})
\end{array}
$$

In the previous example, the net electricity output of the power plant in each time period, E^k, is the uncertain parameter for which flexibility is being assessed (θ^k in (1)).

Evaluation under uncertainty is concerned with assessing whether a design is capable of tolerating a specified amount of uncertainty in some of the process parameters. Thus,

$$
\forall\, k \in T \left\{
\begin{array}{lll}
\text{find} & \mathbf{z}^k & \\
\text{s.t.} & h_i\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right) = 0 & \forall\ i = 1, 2, \ldots, m \\
 & g_j\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right) \leq 0 & \forall\ j = 1, 2, \ldots, r
\end{array}
\right. \tag{2}
$$

where $T = \left\{\theta \,\middle|\, \theta^L \leq \theta \leq \theta^U \right\}$.

EXAMPLE 4.2

The nominally 500 $\mathrm{MW_e}$ coal-fired generator unit with post-combustion CO_2 capture using MEA described in [28] is situated on the north shore of Lake Ontario from which the power plant draws its cooling water. Over the course of the year, the lake temperature typically varies between 0.6℃ and 23℃. With the unit at base-load, the CO_2 capture plant operating at the design recovery of 85%, and an assumed cooling water temperature of 12℃, a net electric output of 344 $\mathrm{MW_e}$ for the plant was calculated. In commenting on the study, a plant engineer expresses interest in knowing if the 344 $\mathrm{MW_e}$ power output is achievable over the full range of expected lake temperatures. Using the formulation in (2) as a basis, the problem amounts to:

$$
\begin{array}{c} \text{for all possible} \\ \text{lake temperatures } T_k \end{array}
\left\{
\begin{array}{lll}
\text{find} & HI^k, x^k_{\mathrm{CO_2}} & \\
\text{s.t.} & h_i(\ldots) = 0 & (\text{heat and material balance satisfied}) \\
 & g_j(\ldots) \leq 0 & (\text{power output} = 344\ \mathrm{MW_e})
\end{array}
\right.
$$

---

[13] A detailed description of an Aspen Plus® model of such a power plant can be found in [28].

In the previous example, the different possible lake temperatures are the uncertain parameters. Note that there are an infinite number of possible temperatures as T varies continuously over the interval $[0.6°\mathrm{C}, 23°\mathrm{C}]$. In this case, though, finding feasible values for HI and x_{CO_2} at the temperature extremes (*i.e.*, 0.6°C and 23°C) would probably be sufficient.

4.1.2 Flexibility index problem

The objective of the *flexibility index problem* is to measure the amount of flexibility that is present. For a given design, the feasible uncertain parameter space can be expressed as:

$$R = \left\{ \theta \,\middle|\, \left[\exists\, \mathbf{z} \,\middle|\, \begin{array}{ll} h_i\left(\mathbf{d}, \mathbf{z}^k, \mathbf{z}, \theta\right) = 0 & \forall\, i = 1, 2, \ldots, m \\ g_j\left(\mathbf{d}, \mathbf{z}^k, \mathbf{z}, \theta\right) \leq 0 & \forall\, j = 1, 2, \ldots, r \end{array} \right] \right\} \qquad (3)$$

The *flexibility index problem* basically seeks to characterize R.

EXAMPLE 4.3

The generator company hires a consultant to help it devise a bidding strategy for its coal-fired power with CCS; the unit is based upon a design evaluated in [28]. The consultant, having read the study, is aware that 64% of the steam flow is extracted from the IP/LP crossover and fed to the stripper reboiler in order to achieve the design recovery of 85%. While this is a substantial reduction in CO_2 emissions, the consultant suspects that it might be possible to further reduce CO_2 emissions at times of need at the expense of an additional de-rating of the power plant. Conversely, when supplementary power is desired, the CO_2 recovery rate could be lowered. The consultant muses to itself, "To what extent can the power plant with CCS deviate from its design recovery rate while operating at base load?" Assuming that the CO_2 recovery is solely a function of the fraction of steam extracted, x_{steam}, the problem amounts to characterizing R where:

$$R = \left\{ \begin{array}{c} \text{all} \\ \text{possible } \mathrm{CO}_2 \\ \text{recoveries} \end{array} \,\middle|\, \left[\exists\, x_{\mathrm{CO}_2} \,\middle|\, \begin{array}{ll} h_i(\ldots) = 0 & \text{(heat and material balance satisfied)} \\ g_j(\ldots) \leq 0 & (x_{steam}\text{within upper and lower limits} \end{array} \right] \right\}$$

4.1.3 Assessing flexibility of power plants with CCS

As stated at the beginning of Section 4.1, depending upon the flexibility issue being considered, either the *flexibility test problem* or the *flexibility index problem* type analysis will be indicated. Table 5 lists the flexibility issues from Section 2.2.1, the corresponding uncertain parameters, and an indication as to whether the 'test' or 'index' problems are indicated.[14] What follows, then, is a detailed discussion of how the ‘test’- and ‘index’-type analyses could proceed.

The specifics of a flexibility assessment will vary with the process (*i.e.*, pre-, post-, or oxy-combustion), the fuel (*i.e.*, natural gas or coal), and the flexibility issue being considered. That being said, prior to performing the flexibility analysis itself, the following preliminary tasks are required:

1. Design the process (*i.e.*, select/size major equipment): $\mathbf{d}$
2. Develop process model (*i.e.*, heat and material balance): h_i
3. Specify the process operating constraints: g_j
4. Identify the control variables: $\mathbf{z}$
5. Define upper and lower bounds for the control variables: $\mathbf{z}^{\min}, \mathbf{z}^{\max}$

Table 5: Examples of uncertain parameters associated with different flexibility issues

Flexibility issue		Uncertain parameters	Problem type
1.	Part-load operation	E and/or $\dot{m}_{fuel}$	index
2.	Changing ambient conditions	$T_{air}, T_{water}, P_{air}, RH_{air}, u_{wind},$ [15] q_{water}	test
3.	Variable fuel inputs	x_f, HV[16]	test
4.	Variable CO_2 capture rates	$\dot{m}^{cap}_{CO_2}$	index
5.	Unsynchronized hydrogen and electricity production	$\dot{m}_{H_2}$[17]	index
6.	Unsynchronized hot water, steam, and electricity production	$\dot{m}_{water}, \dot{m}_{steam}$[18]	index
7.	Variable CO_2 transmission and well injection	$\dot{m}^{cap}_{CO_2}, \dot{m}^{well}_{CO_2}$[19]	index

---

[14] Recall that flexibility is important because it is anticipated that the process is to operate at conditions other than the nominal design conditions. The so-called *uncertain parameters* in (1), (2), and (3) are the process inputs that, collectively, define the off-design conditions the process faces.

[15] Like with net power plant output, it might be true that, if the CO_2 capture process is in operation, $\dot{m}^{cap,\min}_{CO_2} > 0$.

[16] Recognizes changes in fuel characteristics due to fuel heterogeneity and changing feed-stocks.

[17] $\dot{m}_{H_2}$ is net the hydrogen used internally for power generation.

[18] $\dot{m}_{steam}$ is the net steam exported from the power plant; it excludes auxiliary steam consumption like, for example, for CO_2 capture process.

[19] Two considerations: it is assumed that all of the CO_2 captured is pipelined and, in order for $\dot{m}^{cap}_{CO_2} \neq \dot{m}^{well}_{CO_2}$, a mechanism for temporary CO_2 storage or decompression and venting must exist.

Analyzing 'test'-type issues As indicated in Table 5, there are two flexibility issues which lend themselves to the *flexibility test problem* type analysis and, more specifically, *evaluation under uncertainty*: changing ambient conditions and variable fuel inputs.

Preliminary to the actual analysis, the uncertain parameter space, T, must be defined. First, the domain of each uncertain parameter is specified.

- For discrete variables, each member of the parameter domain needs to be explicitly declared (*e.g.*, $HV_{coal_1}, HV_{coal_2}, \ldots$).
- For continuous parameters, the parameter domain can be inferred by specifying the parameter's lower and upper bounds (*e.g.*, $0.6℃ \leq T_{water} \leq 23℃$).

T then consists of the hyper-space defined by the combination of the uncertain parameters.

Then, for every member of T, find a value of $\mathbf{z}$ that satisfies the heat and material balance and the process constraints (*i.e.*, h_i and g_j, respectively). This can be difficult when the uncertain parameter space is infinite or near-infinite is size. It then becomes computationally challenging to examine every member of T. Some workarounds for this problem are discussed below.

1. Discretize the domain of the continuous variables.
2. Only examine the vertices of the uncertain parameter space.

   The *critical points* are particular combinations of the uncertain parameter values for which the process is most infeasible. If the process can operate feasibly at these worst-case conditions then it necessarily must be able to operate feasibly over the entire uncertain parameter space. In general, it is not possible to identify these critical points *a priori*. However, if the constraints $h_i\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right)$ and $g_j\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right)$ define a convex region then the critical points must be found at the vertices of the polyhedron defined by the upper and lower bounds of the uncertain parameters.[29]
3. Only allow one uncertain parameter to vary at a time with the other parameters fixed at their nominal values.
4. Reformulate the *flexibility test problem* as an MINLP (Mixed-Interger Non-Linear

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Programming) problem (see Appendix A for the complete derivation):

$$
\begin{aligned}
\chi(\mathbf{d}) = \quad & \max_{\substack{\theta, \mathbf{z}, u \\ \lambda_i, \gamma_j}} \quad u \\
& \text{s.t.} \quad \sum_{i=1}^{m} \lambda_i \frac{\partial}{\partial \mathbf{z}} h_i(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) + \sum_{j=1}^{r} \gamma_j \frac{\partial}{\partial \mathbf{z}} g_j(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) = 0 \\
& \qquad \sum_{j=1}^{r} \gamma_j = 0 \\
& \qquad \gamma_j \left[g_j(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) - u \right] = 0 \\
& \qquad \theta \in T, \ \gamma_j \geq 0 \ \forall \ j = 1, 2, \ldots, r
\end{aligned}
$$

If $\chi \leq 0$, then the design is flexible.

Up until now, it has been assumed that the values that uncertain parameters can take are independent of each other. Thus, the uncertain parameter space resulting from uncertain parameters θ_1 and θ_2 shown in Figure 3.

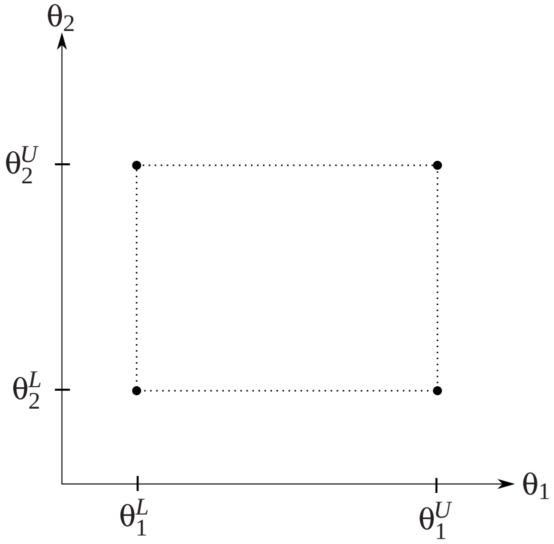

Figure 3: Uncertain parameter space when parameters independent.

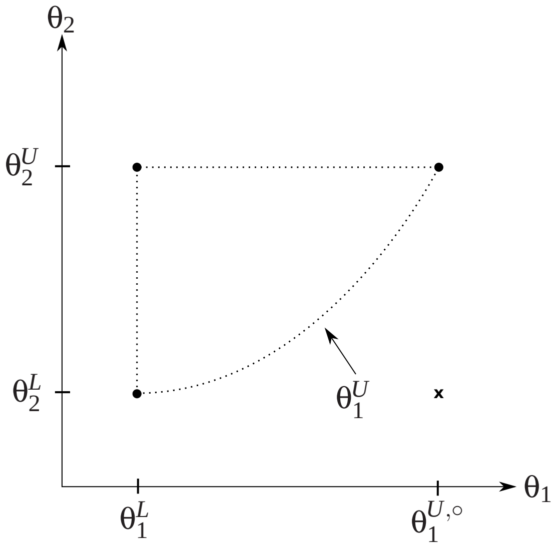

Figure 4: Uncertain parameter space when parameters dependent.

There are instances, though, where the lower and/or upper limits of one uncertain parameter may depend upon the value of another. For example, the upper limit on the amount of CO_2 captured depends upon the heat input to the boiler. The uncertain parameter space resulting when $\theta_1^U = f(\theta_2))$ is illustrated in Figure 4. In this case, extra care must be taken when defining T that infeasible combinations of the uncertain parameters are excluded.

Analyzing 'index' type issues As indicated in Table 5, there are several flexibility issues which lend themselves to the *flexibility index problem* type analysis: part-load operation, variable CO_2 capture rates, unsynchronized hydrogen and electricity production, unsynchronized hot water, steam, and electricity production, and variable CO_2 transmission and well injection.

Several methods for "characterizing" R are proposed below.

1. Map the feasible uncertain parameter space. In cases where uncertain parameters are continuous, the domain will have to first be discretized in order to make the search tractable.

2. Only allow one uncertain parameter to vary at a time with the other parameters fixed at their nominal values. For each uncertain parameter, then, the *flexibility index problem* reduces to finding the minimum and maximum feasible values of the uncertain parameter. That is, finding

$$\begin{aligned} \theta^L = \ & \min_{\mathbf{z},\theta} \quad \theta \\ & \text{s.t.} \quad h_i(\mathbf{d},\mathbf{z},\mathbf{x},\theta) = 0 \quad \forall\, i = 1,2,\ldots,m \\ & \qquad\ \ g_j(\mathbf{d},\mathbf{z},\mathbf{x},\theta) \le 0 \quad \forall\, j = 1,2,\ldots,r \end{aligned}$$

   and

$$\begin{aligned} \theta^U = \ & \max_{\mathbf{z},\theta} \quad \theta \\ & \text{s.t.} \quad h_i(\mathbf{d},\mathbf{z},\mathbf{x},\theta) = 0 \quad \forall\, i = 1,2,\ldots,m \\ & \qquad\ \ g_j(\mathbf{d},\mathbf{z},\mathbf{x},\theta) \le 0 \quad \forall\, j = 1,2,\ldots,r \end{aligned}$$

3. Use the "depth" of the largest hyper-rectangle that can be inscribed in R as the *flexibility index*.[30, 31] Using this approach, the *flexibility index problem* can be expressed as:

$$\begin{aligned} & \max_{\delta} \quad \delta \\ & \text{s.t.} \quad \chi(d) \le 0 \\ & \qquad\ \ T(\delta) = \left\{\theta \,\middle|\, \theta^\circ - \delta(\Delta\theta)^- \le \theta \le \theta^\circ + \delta(\Delta\theta)^+ \right\} \\ & \qquad\ \ \delta \ge 0 \end{aligned}$$

   where

$$\chi(d) = \max_{\theta \in T(\delta)} \quad \psi(\mathbf{d},\theta)$$

   and

$$\begin{aligned} \psi(\mathbf{d},\theta) = \ & \min_{\mathbf{z},u} \quad u \\ & \text{s.t.} \quad h_i(\mathbf{d},\mathbf{z},\mathbf{x},\theta) = 0 \quad \forall\, i = 1,2,\ldots,m \\ & \qquad\ \ g_j(\mathbf{d},\mathbf{z},\mathbf{x},\theta) \le u \quad \forall\, j = 1,2,\ldots,r \end{aligned}$$

   For any particular value of the flexibility index, δ, one would have to check that the process operation is feasible (*i.e.*, $\chi \le 0$) over all uncertain parameters $\theta \in T(\delta)$. Since $T(\delta) = \left\{\theta \,\middle|\, \theta^\circ - \delta(\Delta\theta)^- \le \theta \le \theta^\circ + \delta(\Delta\theta)^+ \right\}$ can be very large or infinite, establishing that $\chi(d) \le 0$ can be a significant computational challenge. Several alternatives to a full evaluation exist:

(a) Discretize the domain of the uncertain parameters θ so that $T(\delta)$ has a finite number of members.

(b) Only allow one uncertain parameter to vary at a time with the other parameters either fixed at their nominal values or becoming control variables. This is akin to the trivial case shown above.

(c) Only examine the vertices of the hyper-rectangle $T(\delta)$ (requires that the constraints $h_i\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right)$ and $g^j\left(\mathbf{d}, \mathbf{z}^k, \mathbf{x}^k, \theta^k\right)$ define a convex region to be valid).

(d) It is also possible, under certain conditions, to reformulate the *flexibility index problem* as an MINLP.[30]

It should be noted that δ, as calculated above, will not be a completely objective measure of flexibility as:

- the hyper-rectangle is centred at θ°.
- the relative dimensions of the hyper-rectangle are fixed by the values of $(\Delta\theta)^-$ and $(\Delta\theta)^+$.

The selection of values for θ°, $(\Delta\theta)^-$, and $(\Delta\theta)^+$ is somewhat subjective.

4.2 Evaluation of controllability

The assessment of power plants with CCS with respect to controllability is concerned with the dynamic performance of these process in the face of changing conditions: can the process recover from process disturbances and new set-points in a measured and timely fashion?

As discussed by Luyben *et al.* [32], achieving acceptable plant controllability requires engagement across the entire “spectrum of process control”:

1. *Control hardware and infrastructure:* selection of sensors and control valves.
2. *Controller tuning:* determine the tuning constants for controllers in the plant.
3. *Controller algorithms and DCS configuration:* deciding on the type of controllers (*e.g.*, PID), assigning input and output variables, specifying alarms, configuring displays, *etc*.
4. *Control system structure:* deciding what variables to control and to manipulate and how these should be paired.
5. *Process design:* design of the process.

This section is strictly concerned with the *assessment* of controllability; it is assumed that the distributed control system has already been synthesized. Two methods for assessing the controllability are considered — frequency analysis and simulation approach. What follows is a review of each method and a suggestion of how controllability analysis of power plants with CCS could proceed.

4.2.1 Frequency response approach

Frequency response approach allows one to study the response of the system to sinusoids of all frequencies. In the discussion that follows, reference will be made to the system represented by the block diagram in Figure 5 the response for which is given by:

$$y(s) = y^*(s)\frac{G_c(s)G_v(s)G_p(s)}{1+G_s(s)G_c(s)G_v(s)G_p(s)} + d\frac{G_d(s)}{1+G_s(s)G_c(s)G_v(s)G_p(s)} \tag{4}$$

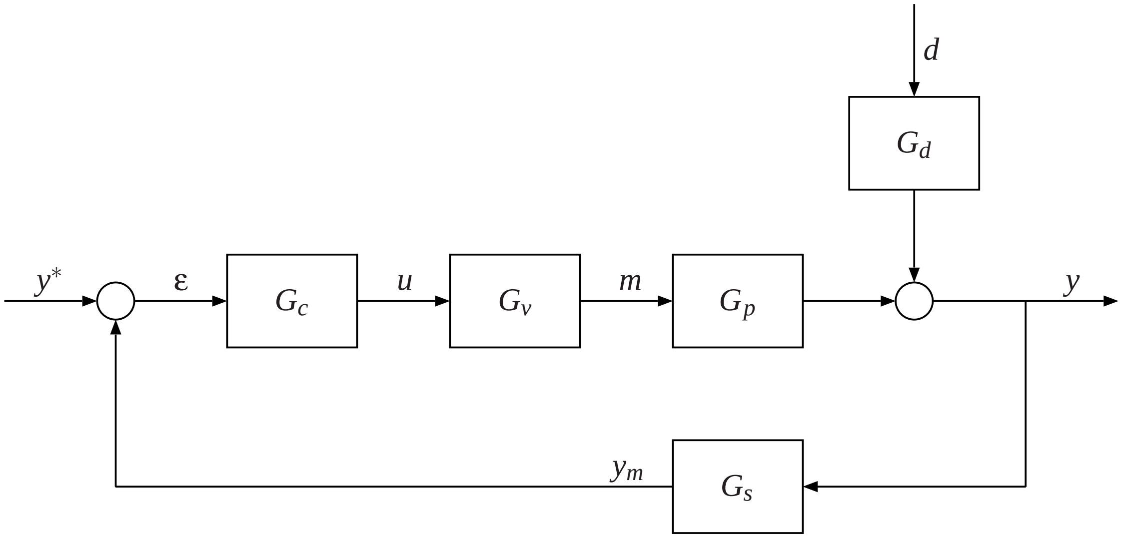

Figure 5: Block diagram for closed-loop process with feedback control

Recall that the frequency response of a system can be obtained directly from the transfer function by substituting $\hat{\imath}\omega$ for s wherever it appears. The frequency response is normally presented in the form of a Bode diagram: a log-log plot and a semi-log plot of amplitude ratio, *AR*, and phase lag, ϕ, versus frequency, ω, respectively.[33, p 314]

Open-loop analysis The open-loop transfer function, $G_{OL}(s)$, is defined as:

$$G_{OL}(s) = G_s(s)G_c(s)G_v(s)G_p(s)$$

and the corresponding frequency response is:

$$G_{OL}(\hat{\imath}\omega) = G_s(\hat{\imath}\omega)G_c(\hat{\imath}\omega)G_v(\hat{\imath}\omega)G_p(\hat{\imath}\omega)$$

Analysis of Bode diagram of the open loop-response is typically used to yield the following insights:

- Assuming there is a single critical frequency, the Bode diagram can be used to assess system stability. The *Bode stability criterion* states that the process is unstable if *AR* is greater than unity at the critical frequency.

- Calculate the gain margin, GM

$$GM = \frac{1}{AR_c}$$

  where AR_c is the amplitude ratio at the critical frequency. The gain margin is the amount by which the system gain can be increased before the system becomes unstable. Typically, a *gain margin* > 2 is required.

- Calculate the phase margin, PM.

$$PM = 180 + \phi_g$$

  where ϕ_g is the open-loop phase where $AR_{OL} = 1$. The phase margin indicates how much lag can be added to the system before the system becomes unstable. Normally, *phase margin* $> 30^\circ$ is required.

Closed-loop analysis The system response to a change in set-point (assuming no disturbances, *i.e.*, $d = 0$ in Equation 4) is given by:

$$\frac{y(s)}{y^*(s)} = \frac{G_c(s)G_v(s)G_p(s)}{1 + G_s(s)G_c(s)G_v(s)G_p(s)}$$

Analysis of Bode diagram of the open loop-response is typically used to yield the following insights:

- An amplitude ratio of unity as $\omega \to 0$ indicates no steady-state offset.
- An amplitude ratio close to unity over a wide range of frequencies indicates rapid approach to new steady-state after set-point change.
- The peak amplitude ratio should not < 1.25.
- A large bandwidth — the frequency at which the amplitude ratio $= 0.707$ — indicates a relatively fast response with a short rise time. It is the range of frequencies over which effective control is possible.

The system response to a disturbance (assuming no change in set-point, *i.e.*, $y^* = 0$ in Equation 4 is given by:

$$\frac{y(s)}{d(s)} = \frac{G_d(s)}{1 + G_s(s)G_c(s)G_v(s)G_p(s)}$$

A small amplitude ratio over the entire range of frequencies is desirable as this indicates little deviation from the set-point.

4.2.2 Simulation approach

The *simulation approach* consists of observing the dynamic response of a process to changes in set-point and disturbances. It is called the "simulation" approach but, theoretically, nothing precludes the same analysis being conducted using the actual plant or a reduced-scale version of it. The general procedure is to:

1. Specify the input.

   This requires identifying the variable whose value is to change and specifying how it is to change. Examples of input signals are step-changes, impulses, ramps, sinusoids, random values, and actual plant data.

2. Feed the input into the process and observe the performance.

   The time-domain response of the controlled variable is of principal interest. That being said, the effect of the input on the controller output is also monitored; unnecessary, rapid fluctuations in the controller output can adversely affect the final control element and should be avoided. In the case where the input is a step-change, below are listed metrics that are used to characterize the dynamic performance of the process.[20]

   Rise time: time it takes for the output to reach 90% of its final value

   Settling time: time after which output remains within 5% of its final value

   Overshoot: ratio of the peak value to the final value (should be < 1.2)

   Decay ratio: ratio of the first and second peaks (should be < 0.3)

   Steady-state offset: difference between the final value and the set-point (should be ≈ 0)

   Total variation: ratio of total variation and overall change at steady-state (should be ≈ 1

   The rise time and settling time are indicators of the *speed* of the response and overshoot, decay ratio, steady-state offset, and total variation speak to its *quality*. The **squared root of $\mathbf{ISE}$** seems to give a reasonable trade-off between the the speed and quality of the response and be used as an index with which to compare different dynamic responses.[34]

Another potential index of controllability is the **operating window**: the range of feasible steady-state values of process variables that the specified design can achieve.[35] When it comes to determining the *operating window*, two approaches are commonly used:

1. keeping the disturbances fixed at zero, the controlled variables are varied in order to identify the range of possible set points

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[20] The 'rule-of-thumb' performance criteria stated below are taken from [34, p 29].

2. keeping the set-point constant, vary the disturbance variables in order to elucidate the range of disturbance that can be compensated (*i.e.*, for which the controlled variables can be maintained at constant set points)

4.2.3 Assessing controllability of power plants with CCS

The specifics of the controllability assessment may vary with the process (*i.e.*, pre-, post-, or oxy-combustion), the fuel (*i.e.*, natural gas or coal), and the controllability issue being considered. As with flexibility analysis, it makes sense to start by considering the variables within the system that are subject to change. Table 6 lists the controllability issues outlined in Section 2.2.2, examples of variables representing set-points/disturbances of concern, and the type of analysis suggested.

Table 6: Examples of set-points and disturbance variables associated with different controllability issues

Controllability issue	Controlled variable/disturbance	Preferred analysis
1. Ramp rate	E	simulation
2. Variable CO_2 capture rates	$\dot{m}^{cap}_{CO_2}$	simulation
3. Variable CO_2 transmission and well injection	$\dot{m}^{cap}_{CO_2}, \dot{m}^{well}_{CO_2}$	simulation
4. Resiliency	$T_{air}, T_{water}, P_{air}, RH_{air}, u_{wind}, q_{water}$	frequency

Depending upon the controllability issue being considered, one is either interested in assessing the set-point tracking performance of the system or its disturbance rejection ability. Prior to performing the controllability analysis itself, the following preliminary tasks are required:

1. Design the process and the control system. The entire “spectrum of process control”, as given at the beginning of Section 4.2, should be considered.

2. Develop a dynamic model of the process.

3. Evaluate the flexibility of process. Feasible, state-state operation at the off-design conditions should be confirmed prior to analyzing the controllability of the process to and from these off-design states.

4. Specify the process operating constraints. This should include acceptable tolerances on the controlled variables and the input to the final control element.

Disturbance rejection The variables in Table 6 associated with *resiliency* are examples of disturbances that may affect the operation of a power plant with CCS. Here, it is felt that frequency response approach might offer some advantages over the simulation approach:

1. More so than changes in set-point, disturbances are cyclical in nature and of varying periodicity.
2. Unlike the simulation approach, the frequency response approach does not require the detailed characterization of the disturbances. This is important as all possible disturbances are usually not known *a priori*. The frequency response approach provides some insight into how the system will respond to upsets that were initially unanticipated.

   That being said, important disturbances should be investigated explicitly using the simulation approach. In particular, the system response to the worst-case disturbance(s) should be considered using this method. This is the approach that Imsland [24, 23] used as part of their evaluation of the dynamic performance of oxy-fired NGCC.

Certain caveats apply when using the frequency response approach as outlined above:

- It is applicable to linear systems with linear control control algorithms.
- The open-loop and closed-loop transfer functions are needed.

Therefore, depending upon what is at one's disposal, it might be necessary to develop reduced-order, linear variants of 'exact' models or to derive linear models of the system's response from simulation or plant data. While the resultant models will not be as accurate, experience has shown that these simple models are often 'good enough' for examining dynamic system performance.[33]

Set-point tracking There are three controllability issues which involve changes in set-point: ramp rate, variable CO_2 capture rates, and variable CO_2 transmission and well injection. In the initial discussion of controllability issues in Section 2.2.2, the emphasis is on the speed with which transitions to new operating states can be achieved. As such, the simulation approach is perhaps better suited for assessing the set-point tracking performance of a system:

- There is no uncertainty regarding the identity of the input variables.
- Information is usually available regarding the desired plant flexibility and so it is straightforward to devise the appropriate input signals.
- Because the analysis is performed in the time-domain, the results of the analysis are of more immediate interest to the process engineer.

It is the simulation approach that Yamada *et al.* [22] used in their investigation of the set-point tracking ability of an oxy-combustion:

- The rate of fuel input is adjusted to control the power plant load. The rate of oxygen input is adjusted to maintain a constant ratio of excess air.
- As a first step, the feasible operation at the lower bound, midpoint, and upper bound of the operating range is confirmed.
- Then, with the plant in steady-state at its lower bound, the load set point is increased at a rate of 3%/min until the upper bound is reached.

4.3 Start-up/shutdown

The major challenge with respect to evaluating the start-up and shutdown of a power plant with CCS is the synthesis of the start-up and shutdown procedure. For the purposes, it is assumed that such a procedure is available. Once the procedure is known, its evaluation requires the use of dynamic models to simulate to process as it transitions from one state to the next. An example of this approach for an oxy-combustion power plant is discussed by Yamada *et al.* [22].

Some issues to consider:

- Most process flowsheets exclude units and streams whose usage is confined to start-up and/or shut-down.
- Associated with the previous bullet, start-up and shutdown procedures may have process control implications that again aren't present under normal operation and these will have to be accommodated.
- With respect to determining the speed with which a process can be turned on and off, there are potentially constraints that cannot be deduced from examining a process flowsheet or performing a process simulation.

4.4 Tools for evaluating flexibility of power plants with CCS

Most of the research into the design of power plants with CCS is enabled using commercially-available process simulation software. The assessment of operability of said plants would be facilitated by leveraging the existing expertise that exists in this area. Table 7 lists software that has been mentioned in the power plant with CCS literature reviewed for this work. Given these citations and in-house experience with various process simulation tools, the following four applications were selected for consideration:

- Aspen Plus®

- UniSim Design
- gPROMS
- ProTreat

Table 7: Software used for simulating power plants with CCS

Process	Software	Reference
pre-combustion	Aspen Plus®	general discussion [36]
	Aspen Plus®	no specific mention of capture [37]
	Aspen Plus®	capture and no-capture steady-state simulation at nominal conditions [38]
	Aspen Plus®	process model of ASU [38]
	HYSYS	process model of ASU [38]
	Aspen Plus®	80% recovery of CO_2 [39]
	Aspen Dynamics	details available in NETL report that is not public; IGCC not equipped with capture [37]
oxy-combustion	Aspen Plus®	steady-state simulation at nominal conditions [40]
	HYSYS	sensitivity to air infiltration studied [16]
	gPROMS	dynamic simulation of process (controller modelled in MATLAB) [24]
post-combustion	ProTreat	90% CO_2 recovery from an NGCC using MEA [41]
	Aspen Custom Modeler	equilibrium stage models of different *Stripper* configurations [42]
	Aspen Plus®	steady-state simulation with 85% CO_2 recovery [43]
miscellaneous	HYSYS	process model of ASU [38]
	gPROMS	process model of amine absorber [44]

In order to get a detailed understanding of the capabilities of each software package, the documentation of each application was thoroughly reviewed and each licensor was approached. The information gathering process was guided by the following set of questions:

1. Who developed the technology underlying the application?
2. Who is the current licensor?
3. What are the licensing costs?
4. Is the software in active development? What is the current version?

5. What computing platforms does the software run on (*i.e.*, CPU architecture, OS)?
6. Which solution modes (*i.e.*, SM (Sequential Modular) and EO (Equation Oriented)) does the software support?
7. Does the software support both steady-state and dynamic models?
8. Are there reports of the software having been used for steady-state and dynamic simulations of pre-, post-, and oxy-combustion processes?
9. Does the software natively support the following:
   (a) rate-based column model
   (b) amine property methods and/or models
   (c) combustion reactions
   (d) non-conventional solids (*e.g.*, coal)
10. Is the software extensible (*i.e.*, can a user specify custom UOM (Unit Operation Model)'s)?
11. Does the software accommodate integer variables during optimization?

4.4.1 Review of Aspen Plus®(AspenTech)

`http://www.aspentech.com/products/aspen-plus.cfm`

1. *Who developed the technology underlying the application?* The core of Aspen Plus® was developed at MIT as part of the Advanced System for Process Engineering project. AspenTech was founded in 1981 with the objective of commercializing this technology.
2. *Who is the current licensor?* Aspen Plus® is licensed by AspenTech.
3. *What are the licensing costs?* Inquiries regarding licensing costs for Aspen Plus® were not acknowledged.
4. *Is the software in active development? What is the current version?* The software is currently in active development. The current version is 2006.5 and was released in February 2008.
5. *What computing platforms does the software run on (i.e., CPU architecture, OS)?* Windows 2000 Professional (SP4), Windows XP Professional (SP2), Windows 2000 Server (SP4), Windows Server 2003 (SP1), Windows Vista (Business Edition).

6. *Which solution modes (i.e.,* SM *and* EO*) does the software support?* Aspen Plus® supports both SM and EO solution modes.

   Does Aspen Dynamics use SM, EO*, or both?* Aspen Dynamics uses the EO approach. In actuality, Aspen Dynamics is a set of UOM's built upon Aspen Custom Modeler.

   Is ***RateSep™***[21] *supported in Aspen Dynamics?* **RateSep™** is not supported in Aspen Dynamics. Aspen Dynamics is compatible with the following Aspen Plus® column models: PetroFrac, RadFrac, and Extract.

7. *Does the software support both steady-state and dynamic models?* The base Aspen Plus® package is a steady-state simulation environment. With Aspen Dynamics, an extension to Aspen Plus®, dynamic simulation and optimization of chemical processes is possible.

8. *Are there reports of the software having been used for steady-state and dynamic simulations of pre-, post-, and oxy-combustion processes?* Descriptions of steady-state process models of pre-combustion [39], post-combustion [28], and oxy-fuel combustion [45] can be found in the literature.

9. *Does the software natively support:*

   (a) *rate-based column model?* The base Aspen Plus® package contains column model based on equilibrium stages. Rate-based column model is offered via the **RateSep™** extension.

   Is ***RateSep™*** *supported in* EO *mode?* **RateSep™** is supported in EO mode since Aspen Plus® 2006.

   (b) *amine property methods and/or models?* Aspen Plus® has been able to effectively model amine-H_2O-MEA VLE (Vapour-Liquid Equilibrium) since at least version 11.1.[28] The newest version contains improved parameters for amine systems based upon work performed at the University of Texas (Austin).

   (c) *combustion reactions?* Aspen Plus® includes reaction UOM's based upon stoichiometry, yield, free-energy minimization, *etc*.

   (d) *non-conventional solids (e.g., coal)?* Coal is specified using proximate, ultimate, and sulphur analyses. Tutorials for converting coal into conventional components accompanies the software.

10. *Is the software extensible (i.e., can a user specify custom* UOM*'s)?* User models developed in a high-level language (*e.g.*, FORTRAN, C), Aspen Custom Modeler, or that are CAPE-OPEN compliant can be used with Aspen Plus®. Additionally, dynamic models that are included with Aspen Dynamics can be modified using Aspen Custom Modeler.

    Is a separate license required for Aspen Custom Modeler? Aspen Plus®, **RateSep™**, Aspen Dynamics, and Aspen Custom Modeler are all licensed individually.

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[21] **RateSep™** is a column model that uses a rate-based approach to calculate mass-transfer.

11. *Does the software accommodate integer variables during optimization?* Aspen Plus® comes with an extended SLP (Sequential Linear Programming) solver for use in EO mode. This allows MILP (Mixed-Interger Linear Programming) and MINLP problems to be solved.[46]

4.4.2 Review of UniSim Design (formerly HYSYS, Honeywell)

`http://hpsweb.honeywell.com/Cultures/en-US/Products/ControlApplications/simulation/UniSimDesign/default.htm`

1. *Who developed the technology underlying the application?* In the late 1970's professors from University of Calgary's Department of Chemical and Petroleum Engineering partnered with Hyprotech, then a start-up, to spearhead the development of process simulation tools. (`http://www.ucalgary.ca/community/research/hyprotech`) Thus, HYSYS was born.

2. *Who is the current licensor?* UniSim Design is licensed by Honeywell. The following sequence of events led to Honeywell's acquisition of the technology:

    - In May of 2002, AspenTech purchased Hyprotech which was then a subsidiary of AEA Technology (`http://www.aspentech.com/publication_files/pr5-10-02.htm`)
    - A year later, on August 7, 2003, the FTC alleged that AspenTech's acquisition of Hyprotech was in violation of the Clayton act (*i.e.*, anticompetitive).
    - On July 14, 2004 the FTC ordered AspenTech to divest itself of the HYSYS intellectual property. (`http://www.ftc.gov/opa/2004/07/aspen.shtm`)
    - On December 23, 2004, as part of their compliance with this order, Honeywell purchased the HYSYS intellectual property from AspenTech. Honeywell rebranded this software as UniSim.

    Aspen retains the right to use the HYSYS brand and currently licenses software under this moniker that is developed independently from Honeywell's offering.

3. *What are the licensing costs?* Academic licensing is \$600 USD for UniSim Design and this includes dynamic capabilities. The options required for simulating post-combustion capture with amines (either Amines or OLI Electrolyte) are not typically available with the academic license.

    Commercial licensing is about \$40000 or \$50000 depending upon whether the Amines option or OLI Electrolyte option, respectively, is selected. The price increases by \$8000 USD or \$16000 USD if network, as opposed to standalone, licensing is selected.

4. *Is the software in active development? What is the current version?* The software is currently in active development. The current version is R380 and was released April 2008.

5. *What computing platforms does the software run on (i.e., CPU architecture, OS)?* UniSim Design is available on Window 2000 (SP4), Server 2003, XP, and Vista.

6. Which solution modes (*i.e.*, SM and EO) does the software support? UniSim Design, in steady-state mode, is an EO, event-driven system. This means that simulation is automatically updated to reflect user input as it is provided.[47]

   In dynamic mode, information is not processed with every change; integration must be explicitly activated. Pressure and flow are calculated simultaneously over the entire flowsheet; composition and energy balances are calculated using an SM approach.[48, p 1-43]

7. *Does the software support both steady-state and dynamic models?* UniSim Design offers an integrated steady-state and dynamic modelling environment.

8. *Are there reports of the software having been used for steady-state and dynamic simulations of pre-, post-, and oxy-combustion processes?* Description of the use of HYSYS for steady-state simulation of post-combustion capture using MEA and oxy-combustion is present in the literature.[45]

9. *Does the software natively support the following:*

   (a) *rate-based column model?*

   A non-equilibrium stage model based on “stage efficiency” is used to simulate the performance of absorbers and strippers.[49, p C-4] Note that this non-equilibrium approach is only used when the amines package has been invoked and the calculations are restricted to tray-type columns.[50]

   There is also an OLI rate-based column that can be used with the OLI thermodynamic package for electrolyte modelling in UniSim Design. It provides the same functionality as **RateFrac™** and **RateSep™**.[50]

   (b) *amine property methods and/or models?* The thermodynamic packages developed for DB Robinson and Associates’ amine plant simulator, AMSIM, is available as an option for UniSim Design.[49][22]

   UniSim Design also has an interface for OLI Systems Inc.’s technology and component databanks for for aqueous electrolyte systems.

   (c) *combustion reactions?* There are five types of reactions that be modelled in UniSim Design: conversion, equilibrium, heterogeneous catalytic, kinetic, and simple rate.[49]

   (d) *non-conventional solids (e.g., coal)?* For representing coals in UniSim design, one would create a “Hypothetical group” and specify the corresponding coal analysis, heat of combustion, and heat of formation.[49]

   UniSim Design incorporates solid characterization technology imported from SPS.[47]

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[22] It is only suitable for H_2S and CO_2 loadings less than unity.

10. *Is the software extensible (i.e., can a user specify custom* UOM*'s)?* UniSim Design allows for custom unit operations, property packages, and kinetic reactions.[51, p 1-2] Interfaces for Visual Basic and C++ are provided. The latter provides compiled libraries developed using any programming language to be linked to a UniSim Design simulation.

    UniSim Design also supports reading Aspen HYSYS 2006 and older data files and can write Aspen HYSYS 2006 files.

11. *Does the software accommodate integer variables during optimization?* UniSim Design allows binary variables to be defined in "selection optimization".[50, p 13-24]

4.4.3 Review of gPROMS (Process Systems Enterprise, Ltd.)

`http://www.psenterprise.com/gproms/index.html`

1. *Who developed the technology underlying the application?* gPROMS was developed by the Centre for Process Systems Engineering at Imperial College London.

2. *Who is the current licensor?* gPROMS is licensed by Process Systems Enterprise, Ltd.. At launch, this spin-off company acquired rights to all technology that had been developed by the Centre for Process Systems Engineering since 1990. It is completely self-funded.

3. *What are the licensing costs?* Process Systems Enterprise, Ltd. was not willing to provide specific information regarding licensing costs for gPROMS. To quote, "pricing is aligned to the market average and volume discounts apply for multiple licenses."

4. *Is the software in active development? What is the current version?* The software is currently in active development. The latest version is 3.1 and was released April 23, 2008.

5. *What computing platforms does the software run on (i.e., CPU architecture, OS)?* Windows 2000 (SP1), Windows XP (SP1), 32-bit and 64-bit GNU/Linux.

6. *Which solution modes (i.e.,* SM *and* EO*) does the software support?* gPROMS uses an equation-oriented representation.

7. *Does the software support both steady-state and dynamic models?* gPROMS supports both steady-state and dynamic simulation, parameter estimation, optimization, and experiment design.

8. *Are there reports of the software having been used for steady-state and dynamic simulations of pre-, post-, and oxy-combustion processes?* gPROMS has been used for the simulation of oxy-combustion.[24]

9. *Does the software natively support the following:*
    (a) *rate-based column model?* Within gPROMS's Advanced Model Library are components for non-equilibrium modelling of gas-liquid contactors.
    (b) *amine property methods and/or models?* gPROMS contains the requisite physical properties package needed to accurately model CO_2 recovery from flue gas using amines.[52]
    (c) *combustion reactions?* gPROMS has been used for the simulation of oxy-combustion.[24]
    (d) *non-conventional solids (e.g., coal)?* While gPROMS does have solids handling capabilities, it is not clear if it possess specific features to represent coal.

10. *Is the software extensible (i.e., can a user specify custom* UOM*'s)?* The key protocols used by gPROMS are published thus enabling users to embedded custom software within gPROMS or *vice versa*.

    gPROMS also supports industry-standard interfaces:

    - gO:Simulink and gO:MATLAB are used for embedding gPROMS models into Simulink and MATLAB, respectively.
    - go:CAPE-OPEN allows gPROMS to be used alongside CAPE-OPEN compliant software (*e.g.*, Aspen Plus®, PRO/II).

    gPROMS models are expressed within a proprietary modelling language and are accessible to the user. Existing models can be modified and new models can be created.

11. *Does the software accommodate integer variables during optimization?* gPROMS supports integer optimization in both steady-state and dynamic simulations. There is also support for discontinuous constraints in steady-state mode.

4.4.4 Review of ProTreat (Optimized Gas Treating, Inc.)

`http://www.ogtrt.com`

1. *Who developed the technology underlying the application?* The technology appears to have been originally developed by Ralph Weiland who was a Professor of Chemical Engineering at the Clarkson University from 1980–1989.

    Siva Sivasubramanian joined Optimized Gas Treating, Inc. in 2002. Notable is that he received his PhD from Clarkson University (he appears to have been a graduate student of Ross Taylor, one of the creators of ChemSep) and his fourteen years at AspenTech where he was the architect of RateFrac.

2. *Who is the current licensor?* ProTreat is licensed by Optimized Gas Treating, Inc. Optimized Gas Treating, Inc. was created in 1992 for the purpose of the marketing and sales of a Windows application for simulating gas removal with aqueous amine solvents.

3. *What are the licensing costs?* Currently licensing runs $6000 USD for a year. Academic users need only pay 10% of the license value which is thus currently $600 USD.

4. *Is the software in active development? What is the current version?* The software is currently in active development. The latest version is 3.10 and was released 2007-10-22.

5. *What computing platforms does the software run on (i.e., CPU architecture, OS)?* ProTreat runs on Windows 95, 98, 2000, NT, ME, XP.

6. *Which solution modes (i.e.,* SM *and* EO*) does the software support?* ProTreat uses the SM approach for solving flowsheets.

7. *Does the software support both steady-state and dynamic models?* ProTreat is not set up for dynamic simulations.

8. *Are there reports of the software having been used for steady-state and dynamic simulations of pre-, post-, and oxy-combustion processes?* ProTreat has been used for simulating post-combustion capture [41].

9. *Does the software natively support the following:*
   (a) *rate-based column model?* ProTreat includes mass transfer-based column models.
   (b) *amine property methods and/or models?* ProTreat supports amines — separately or as two- and three-amine blends — and piperazine. It also accounts for the effect of heat-stable salt formation.
   (c) *combustion reactions?* ProTreat does not include any reactor reactor models and thus would not be able to simulate fossil fuel combustion.
   (d) *non-conventional solids (e.g., coal)?* ProTreat cannot accommodate solid components.

10. *Is the software extensible (i.e., can a user specify custom* UOM*'s)?* Users themselves cannot incorporate custom UOM's however Optimized Gas Treating is open to receiving user requests for adding UOM's.

11. *Does the software accommodate integer variables during optimization?* ProTreat cannot accommodate integer variables.

In brief, of the four process modelling environments considered, all but ProTreat appear to be good candidates for the assessment of operability for the CO_2 capture schemes of interest in this study.

5 Assessing the trade-offs between operability and cost

Assessing the trade-off between operability and cost is not as simple as one might initially believe. While the costs are relatively simple to sort out, estimating the benefits requires significantly more effort. In this section, an approach for capturing the benefits of changes made to an electricity system is outlined. A proposal made by Chalmers and Gibbins to enhance the operability of post-combustion CO_2 capture [27] provides the context.

To guarantee the correct assessment of the merits of mutually-exclusive investment decisions requires using an incremental approach.[53] Briefly:

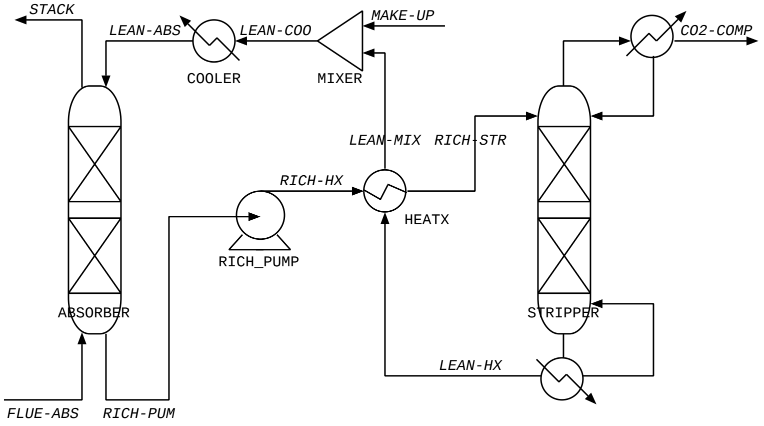
- The incremental benefit of the 1st option — the *challenger* — as compared to the default action (could be 'do nothing') is measured against the incremental cost.
- If the net incremental benefit is positive, then the 1st option is *accepted* (*i.e.*, becomes the new base-case). Otherwise, the 1st option is *discarded*.
- The 2nd option is compared incrementally with the base-case and a decision to accept or reject the 2nd option is made.
- The process step is repeated until all investment options have been considered.

The standard approach in techno-economic studies of post-combustion CO_2 capture using amine solvents is to design the process such that the solvent is immediately regenerated after absorbing CO_2. A corresponding process flowsheet is shown in Figure 6(a). One of the strategies proposed by Chalmers and Gibbins [27] for increasing the operability of post-combustion CO_2 capture with amine solvents is to introduce intermediate reservoirs for 'rich' and 'lean' solvent. This would allow the energy penalty associated with regenerating the solvent to be incurred at some later time. The corresponding process flowsheet is shown in Figure 6(b). The question is, "Does this plant modification make economic sense?"

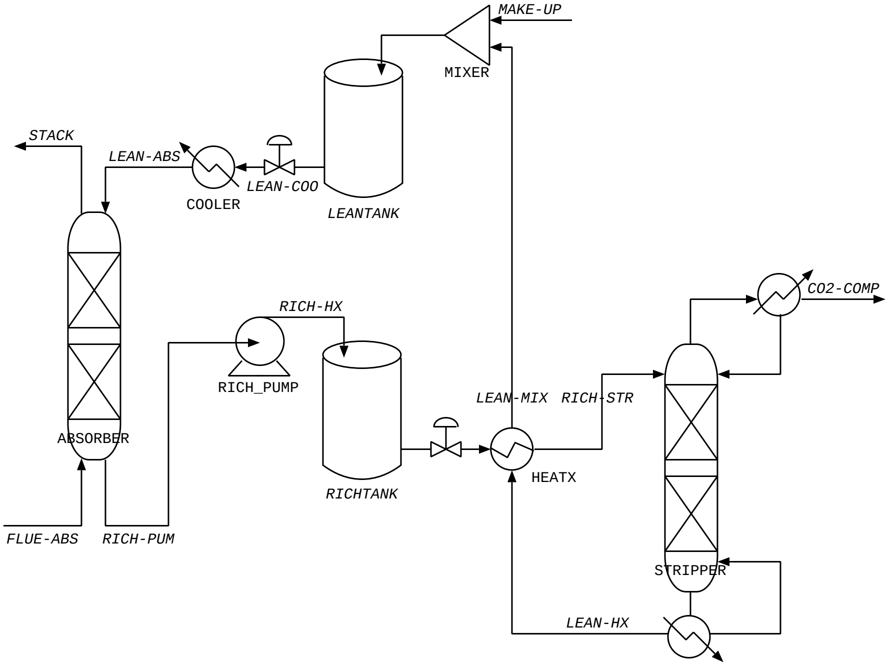
For the purpose of the economic assessment, the base-case is the power plant with fixed CO_2 recovery at 85% and continuous solvent regeneration. The challenger is a power plant that, during periods of peak demand, recovers 85% of the CO_2 but stores the rich solvent in lieu of regenerating it. Then, at some future off-peak period, the power plant continues to recover 85% of the CO_2 from the flue gas but the solvent regeneration occurs at 150% of the nominal rate.

The incremental cost is the difference between the capital cost of the two options. Here, it is the cost of the intermediate storage tanks — at least one each for 'rich' and 'lean' solvent — and for oversizing the stripper that are most important.

The incremental benefit is the difference in the operating income between the base-case and the challenger. As a first approximation, it is assumed that the operating costs and revenues of the two plants are the same when both are recovering 85% of the CO_2 in the flue gas and immediately regenerating the 'rich' solvent. Thus, only revenues and



(a) Base-case flowsheet



(b) Base-case flowsheet

Figure 6: Process flowsheets for post-combustion capture using amine solvents

costs in the the peak and off-peak intervals need to be considered. For the base case, the operating income, OI_b, is given by:

$$OI_b = t_p E_{b,p} \left(\rho_{b,p} - C_{b,p}\right) + t_{op} E_{b,op} \left(\rho_{b,op} - C_{b,op}\right) \tag{5}$$

For the case with intermediate solvent storage:

1. During peak periods, rich solvent is stored for time t_p, allowing for ΔE^+ additional power to be sold at price $\rho_{s,p}$. The cost of electricity in this mode is $C_{s,p} < C_{b,p}$.
2. During off-peak periods, 50% more solvent is regenerated for time t_{op}. Power output is decreased by ΔE^-. Power produced in this period is sold at a price $\rho_{s,op}$ and the cost of electricity is $C_{s,op} > C_{b,op}$.

The operating income, in this scenario, OI_s, is given by:

$$OI_s = t_p \left(E_{s,p} + \Delta E^+\right) \left(\rho_{s,p} - C_{s,p}\right) + t_{op} \left(E_{s,op} - \Delta E^-\right) \left(\rho_{s,op} - C_{s,op}\right) \tag{6}$$

The length of the off-peak period,t_{op}, is such that all of the extra solvent that is stored during peak periods is regenerated. The incremental benefit is determined by calculating the difference $OI_b - OI_s$. However, reasonable values for E, ρ, and C in Equations 5 and 6 are not so easy to determine:

1. In an electricity system, the quantity of power sold by a generator depends in a complicated manner on, among things:
    - hourly electricity demand
    - generator's marginal generation cost relative to all other generators
    - CO_2 emissions limit or, equivalently, the CO_2 emissions tax
    - CO_2 emissions intensity of the generator relative to that of all other generators
    - generator's technical operating characteristics (*e.g.*, ramping capability)
    - generator's proximity to load centres
    - transmission line capacities
2. Generation cost is a function of electric power output. So, difficulty in determining E makes finding C equally as elusive a target.
3. In deregulated markets, the price that generators receive for their electricity in any future time period is not known *a priori* and is difficult to predict even over the short term.

As there are no electricity systems containing power plants with CCS, there is no real-world experience to draw upon, no 'rules-of-thumb' to apply. A methodology has been proposed in response to the challenge of assessing the benefit of novel CCS technologies in the context of power generation.[25] The central feature of this approach is the simulation of the electricity system of interest. That is,

- Generators are dispatched such that sufficient electricity is produced in each time interval to satisfy the demand in the most economic fashion.
- At the same time, CO_2 emission limits are respected or CO_2 emission taxes are imposed, as the case may be.
- Utilization of CO_2 capture technology is driven by endogenous economic and operability considerations.

A proposed algorithm for the new methodology is given below:

1. Model the existing electricity system; an electricity system consists of electricity generators and loads connected via a transmission network that produce electricity under the direction of a system operator. Figure 7 contains a schematic of a simple electricity system. It features:
    - Two generators (G_1 and G_5).
      The operating characteristics of each generator are specified: efficiency, CO_2 emissions intensity, minimum and maximum power output, ramp rate, *etc*.
    - Four loads (L_2, L_3, L_4, L_6).
      At a minimum, the demand of each load, as a function of time, is specified.
    - Seven transmission lines (T_{12}, T_{16}, T_{23}, T_{26}, T_{34}, T_{45}, T_{56}).
      Again, at a minimum, the maximum capacity of each line is specified. Depending upon the model used for power flow, other information (*e.g.*, line length, electrical properties) would be needed.

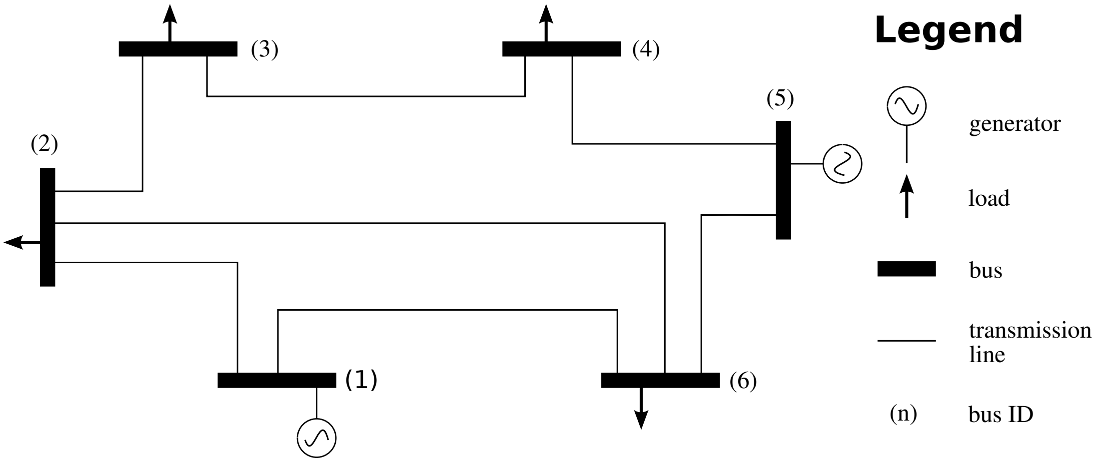


Figure 7: Simple electricity system bus diagram

2. Simulate the base-case operation of the electricity system with CO_2 mitigation enforced through either a limit on CO_2 emissions or the imposition of a CO_2 emissions tax. Once the simulation is complete, all the requisite information for calculating OI_b is available.

3. Implement the new scenario. For the example considered above, the operating characteristics of the generator with CCS would be modified to reflect the addition of the solvent storage tanks and the oversized stripper.

4. Simulate the operation of the electricity system under the new configuration and calculate OI_s.

5. With OI_b and OI_s now known, the incremental benefit of the additional investment can be determined and the challenger thus accepted or discarded.

6 Proposed scope of detailed study

The objective of the proposed study would be to assess the performance of power plants with CO_2 capture under conditions different than the nominal design conditions. Off-design conditions result from variability with respect to:

- plant load (including standby, startup, and shutdown)
- CO_2 recovery
- hydrogen, hot water, and steam generation (were applicable)
- fuel
- ambient conditions

The three leading CO_2 capture processes — post-combustion, pre-combustion, and oxy-combustion — with coal and natural gas as a fuel source should be considered.

What does an “assessment” of the power plants with CO_2 capture entail? Assuming all the processes meet or exceed requirements for safety, the study, as envisioned, would ascertain the relative economic benefit of the different mitigation technologies.

A complete cost/benefit analysis may not be compatible with the needs and resources of the IEA GHG R&D Programme. To that end, a range of options is suggested and is depicted in Figure 8.

The four major areas of study are:

Flexibility The focus is steady-state performance of the power plants with CO_2 capture at a variety of conditions.

Controllability The scope is expanded such that dynamic performance of the processes is considered in the face of set-point changes and disturbances.

Start-up/shutdown At this level, the dynamic performance of the processes in the special cases of start-up and shutdown are also included in the analysis.

Operability trade-offs Finally, the information garnered at the inner levels is used to enable the ‘benefits’ of operability to be assessed thus enabling the relative economic benefit of the different mitigation technologies to be assessed.

As is to be expected, as one extends outward from the centre of the onion, more detailed information regarding the operability of the different power plants is obtained but at the expense of additional effort and cost.

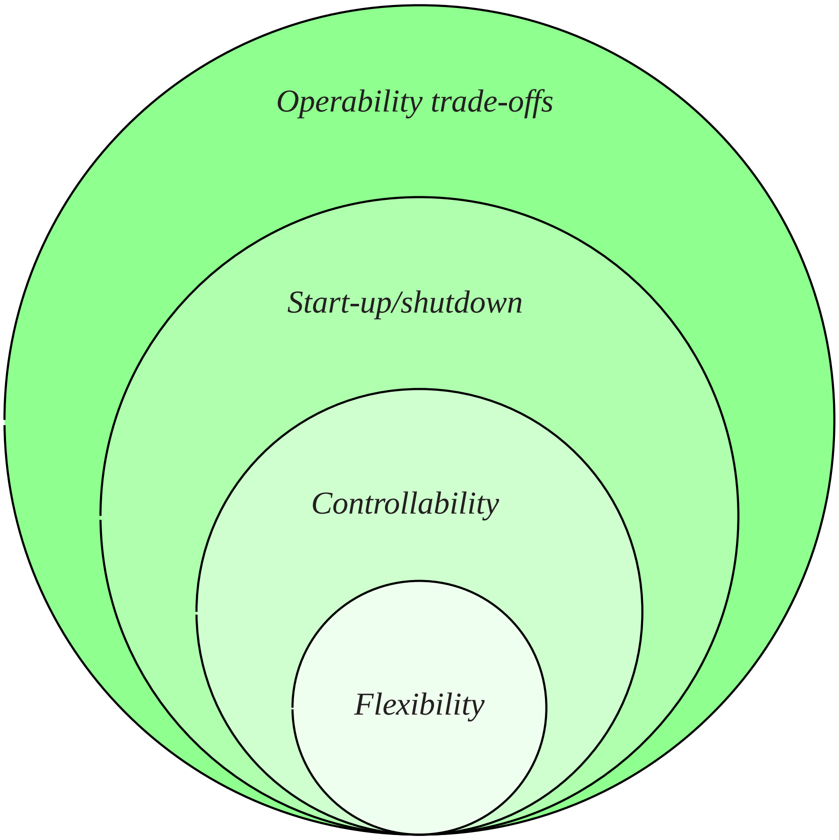


Figure 8: Onion diagram for power plant with CO_2 capture operability study

6.1 Flexibility

Here, the objective is to quantify the ability of power plants with CO_2 capture to operate in an acceptable manner over a range of steady-state conditions. The following major tasks are proposed:

1. Literature review.

    - Summary of steady-state modelling of power plants with CO_2 capture.

    Estimated effort: 2–4 months

2. Development of steady-state models.

    - Includes sizing and/or performance of all major pieces of equipment
    - Process operating constraints need to be identified (*e.g.*, approach to entrainment flooding in stripper $\leq 80\%$)

    Estimated effort: 2–12 months *per process* (*i.e.*, post-, pre-, and oxy-combustion)

    - low-end of range assumes that an existing process model is adapted for flexibility analysis
    - high-end of range assumes that process model must be developed from scratch

3. Flexibility analysis.

    - With respect to changing ambient conditions and variable fuel inputs, demonstrate feasible operation over the expected domain of uncertain parameters (*i.e.*, flexibility test problem).
    - For other variables (*i.e.*, plant load, CO_2 recovery, *etc.*), quantify the amount of flexibility.
    - Another important performance metric for a power plant is the cost of electricity:

      $$\frac{FC \cdot FCF + FOM}{C^{fuel} \cdot 8760 \cdot E} + VOM + \frac{FC}{HV} \cdot HR \tag{7}$$

      While the first term is a function of the plant design (which is fixed in this study), the last two terms are a function of the operation of the process. The sum of the last two terms is an important indicator of the *cost* of operability and should be recorded.

    Estimated effort: 3–6 months

4. Recommendations for improving flexibility.

    As a follow-up to the flexibility analysis of the base design, recommendations for improving flexibility via, for example, process flowsheet changes, should be made.

    Estimated effort: 1–2 months

6.2 Controllability

Here, the additional objective is to quantify the ability of power plants with CO_2 capture to recover from process disturbances and to move to new set-points in a measured and timely fashion. The following additional tasks are proposed:

1. Literature review.

   - Summary of dynamic modelling of power plants with and without CO_2 capture.

   Estimated effort: 1–2 months

2. Development of dynamic models.

   - Development of dynamic process models can be accelerated by leveraging steady-state models developed within inner level.
   - Control systems need not be “perfect” or “optimal” as the overall controllability depends mostly on the process design.

   Estimated effort: 3–12 months *per process* (*i.e.*, post-, pre-, and oxy-combustion)
   - time reported assumes dynamic models are adapted from existing dynamic models reported in the literature or steady-state models developed during evaluation of flexibility

3. Controllability analysis.

   - Examine the disturbance rejection ability of the different CO_2 capture processes.
     - Important disturbances that all processes need to be assessed against include fuel composition and ambient conditions
     - There are important disturbances that are process specific and these too should be assessed (*e.g.*, downstream oxygen purity in oxy-combustion).
     - Many different control performance metrics exist: integral error, maximum deviation of controlled variable, decay ratio, rise time, *etc*.
   - With respect to changes in the set-point of plant load, CO_2 recovery, *etc*., a key performance metric is the speed with the controlled variable moves from one steady-state condition to another.

   Estimated effort: 3–6 months

4. Recommendations for improving controllability.

   As a follow-up to the controllability analysis of the base design, recommendations for improving controllability via, for example:

  - advanced control
  - process flowsheet modifications
  - process redesign (*i.e.*, different equipment selections, unit sizing, *etc*.)

should be made.

Estimated effort: 1–2 months

6.3 Start-up/shutdown

Here, the additional objective is to quantify the operational requirements with respect to plant start-up and shutdown. The following additional tasks are proposed:

- Literature review.
  - Summarize the potential impacts that start-up and shutdown have on power plants with and without CO_2 capture. These impacts will likely include:
    - operating costs
    - maintenance frequency
    - plant life

  Estimated effort: 1–2 months

- Extension of dynamic process models.
  - Incorporate streams and units associated with start-up and shutdown to the dynamic models developed in the previous level. (*e.g.*, PC plants use natural gas for start-up and to enhance flame stability at low loads.)
  - Devise start-up and shutdown sequences.

  Estimated effort: 2–4 months *per process* (*i.e.*, post-, pre-, and oxy-combustion)

- Start-up/shutdown analysis.
  - Important performance metrics include:
    - time to start-up/shutdown
    - cost of start-up/shutdown
    - minimum-up and -down times.

  Estimated effort: 2–4 months

6.4 Operability trade-offs

Here, the additional objective is to simulate the performance of the power plants with CO_2 capture within an electricity system. The following additional major tasks are proposed:

- Literature review.
  - Summarize methodology used for estimating economics of CO_2 capture processes.

  Estimated effort: 2–6 months

- Develop electricity system simulation model incorporating power plants with CO_2 capture.
  - Summarize the electricity system being used for the case study.
    - Electricity system has four components:
      1. Generators
      2. Loads
      3. Transmission system
      4. Operator
  - Develop reduced-order models of the power plants with CO_2 capture.[23]
  - Synthesize schedule of electricity demand, changing ambient conditions, fuel variability, CO_2 price, *etc.*.

  Estimated effort: 4–8 months

- Simulate operation of electricity system.
  - A separate electricity system simulation is required for each CO_2 mitigation technology being investigated.

  Estimated effort: 3–6 months

- Perform the cost/benefit analysis.
  - Estimate the capital and *FOM* costs for the different capture process.
  - Using the data from the electricity system simulation, calculate the *CoE* (Cost of Electricity) (see (7)) and the *CCA* (Cost of CO_2 Avoided).

  Estimated effort: 1–2 months

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[23] Electricity system scheduling is normally cast as LP (Linear Programming) or NLP (Non-Linear Programming) programming problems and it is currently not feasible to solve these problems with detailed process models imbedded inside. Thus, the need for reduced-order models.

6.5 Comments regarding proposed detailed operability study

Assessing the operability of power plants with CCS is an ambitious agenda. That being said, there is nothing that precludes such an investigation from being undertaken and it is believed that the results of such a study would be very useful.

One specific concern is that the proprietary nature of some CO_2 capture technologies could pose a barrier to performing operability analysis. It is the opinion of the authors that no such barrier exists. The fundamentals of post-, pre-, and oxy-combustion processes are understood well enough that the development of process models suitable for the proposed analysis is possible without access to proprietary information.

Out of necessity, the estimates of effort required to complete many of the tasks is quite broad. Most of the uncertainty in the estimates is related to model development and, specifically, to the capabilities of the investigator(s) undertaking the work. Once the appropriate models have been developed, analysis of operability requires only modest effort.

Table 8 summarizes the effort involved in traversing each layer of the 'onion'. The column labelled *Effort* is obtained by summing the estimates for the individual tasks given in Sections 6.1 through 6.4. *Time* is an estimate of the the calendar time required to complete each area of study. It is obtained by assuming that development of post-, pre-, and oxy-combustion process models is performed concurrently. That being said, it might be possible to further parallelize the work and, therefore, the estimates in this last column are probably conservative.

Table 8: Summary of effort required for detailed operability study

Area of Study	Effort man-months	Time months
Flexibility	12–48	8–24
Controllability	14–46	8–22
Start-up/shutdown	9–18	5–10
Operability trade-offs	10–22	10–22
Total	45–134	31–78

The outputs from the detailed study are expected to include suggestions (*e.g.*, flowsheet changes, equipment modifications) for improving the flexibility and controllability of power plants with CCS. It is thought that the assessment of these new scenarios could be performed relatively quickly by reusing models and systems from the detailed study. An estimate of the time required for the analysis of these 'step-off' cases is given in Table 9.

Table 9: Summary of effort required for supplemental analyses

Task	Time weeks
Model development	1–4
Flexibility	1–3
Controllability	1–3
Start-up/shutdown	1–2
Operability trade-offs	2–6
Total	6–18

7 Conclusion

Modern and future electricity systems require their constituent generators to be operable if the systems are to meet their customers' expectations. If power plants with CCS are to be introduced within these systems then the operability of these plants must first to be assessed.

To date, there is little mention of the operability of power plants with CCS in the literature. A few researchers have begun to think about the operability of these processes in a determined fashion but there is much more that is unknown rather than is known. Therefore, the IEA GHG R&D Programme's belief that the evaluation of leading CO_2 capture technologies with respect to operability should be undertaken is well-founded.

Techniques are available for the assessment of flexibility, controllability, and start-up/shutdown issues. These techniques are a combination of theoretical methodologies and experience based approaches. In anticipation that commercially-available process simulation software will be used to perform the studies, four applications that have been featured in the power plant with CCS literature have been identified and their capabilities investigated. Of these four — Aspen Plus®, HYSYS, gPROMS, and ProTreat — all but the latter appear to be well suited to the investigations that are proposed.

The general feeling is that "the more operability, the better". However, it is equally understood that improving the performance of a process at off-design conditions comes at a cost. It is important to understand, then, where the operability cost-benefit trade-off lies. It is suggested that to do so with reasonable accuracy requires the simulation of the electricity system within which the increased operability is proposed. The key benefit of this approach is that it endogenizes many of the variables that are difficult to predict in electricity systems for which no real-world experience exists (*i.e.*, there is no real-world experience with power plants with CCS).

Finally, the report concludes by providing the scope for a study that would delve into the operability of power plants with CCS more deeply. Understanding that such a complete, detailed analysis might be beyond the means of the IEA GHG R&D Programme, a layered approach is synthesized. The areas to be considered in their proposed order are:

1. Flexibility
2. Operability
3. Start-up/shutdown
4. Operability trade-offs

As one proceeds through the different layers, the output from the previous level feeds into the next; deeper insight into plant operability is obtained but at the expense of additional cost and effort. In total, it is estimated that the entire project would take a minimum of 4 person-years worth of effort and 2.5 years to complete.

A Reformulation of *flexibility test problem* as an MINLP problem

Reformulate the *flexibility test problem* as an optimization problem:

1. Calculate χ where:

$$\chi(\mathbf{d}) = \max_{\theta \in T} \psi(\mathbf{d}, \theta) \tag{8}$$

   and

$$\begin{aligned} \psi(\mathbf{d}, \theta) = \min_{\mathbf{z}, u} \quad & u \\ \text{s.t.} \quad & h_i(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) = 0 \quad \forall\, i = 1, 2, \ldots, m \\ & g_j(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) \leq u \quad \forall\, j = 1, 2, \ldots, r \end{aligned} \tag{9}$$

2. If $\chi \leq 0$ then the design is flexible.

If each square sub-matrix of dimension $(n_z \times n_z)$ of the partial derivatives of the constraints g_j, $j = 1, 2, \ldots, r$ with respect to the control $\mathbf{z}$:

$$\left(\frac{\partial g_1}{\partial z}, \frac{\partial g_2}{\partial z}, \ldots, \frac{\partial g_r}{\partial z}\right), \; r \geq n_z + 1$$

is of full rank, then the number of active constraints in the optimal solution is equal to $n_z + 1$.[54, p 680] Therefore, for a given θ, ψ can be determined by solving a system of $n_z + 1$ equations (*i.e.*, $g_j(\mathbf{d}, \mathbf{z}, \theta) = u \; \forall\, j \in J_A$) and $n_z + 1$ unknowns (*i.e.*, $\mathbf{z}$ and u).

The KKT (Karush-Kuhn-Tucker) conditions of (9) are:

$$\begin{aligned} \sum_{i=1}^{m} \lambda_i \frac{\partial}{\partial \mathbf{z}} h_i(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) + \sum_{j=1}^{r} \gamma_j \frac{\partial}{\partial \mathbf{z}} g_j(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) &= 0 \\ \sum_{j=1}^{r} \gamma_j &= 0 \\ \gamma_j \left[g_j(\mathbf{d}, \mathbf{z}, \mathbf{x}, \theta) - u \right] &= 0 \\ \gamma_j &\geq 0, \; \forall\, j = 1, 2, \ldots, r \end{aligned}$$

Whenever there are $n_z + 1$ active constraints, ψ is given by solving the KKT conditions for u. Therefore, the two-level optimization problem found above is given by the following MINLP:

$$\begin{array}{rcll}
\chi(\mathbf{d}) = & \max\limits_{\substack{\theta,\mathbf{z},u\\ \lambda_i,\gamma_j}} & u & \\
& \text{s.t.} & \displaystyle\sum_{i=1}^{m}\lambda_i\frac{\partial}{\partial\mathbf{z}}h_i(\mathbf{d},\mathbf{z},\mathbf{x},\theta)+\sum_{j=1}^{r}\gamma_j\frac{\partial}{\partial\mathbf{z}}g_j(\mathbf{d},\mathbf{z},\mathbf{x},\theta) & = 0\\
& & \displaystyle\sum_{j=1}^{r}\gamma_j & = 0\\
& & \gamma_j\left[g_j(\mathbf{d},\mathbf{z},\mathbf{x},\theta)-u\right] & = 0\\
& & \theta\in T,\ \gamma_j\geq 0\ \forall\ j=1,2,\ldots,r &
\end{array}$$

Again, if $\chi \leq 0$, then the design is flexible.

List of Symbols

Variables

C	cost of electricity
ΔE	change in electric power output
$\mathbf{d}$	vector of design variables
E	electric power output
g	inequality constraint
HI	heat input to the boiler
h	equality constraint
$\dot{m}$	mass flow rate
ρ	price of electricity
OI	operating income
P	pressure
q	volumetric flow rate
RH	relative humidity
r	multi-period constraint
T	temperature
t	length of time period
θ	vector of uncertain parameters
x	fraction
$\mathbf{x}$	vector of state variables
$\mathbf{z}$	vector of control variables

Superscripts

$+$	denotes an increase
$-$	denotes a decrease
$\circ$	pertaining to initial value
cap	pertaining to capture

k	index of uncertain parameter states
L	pertaining to lower bound
U	pertaining to upper bound
$well$	pertaining to injection

Subscripts

air	pertaining to air
b	pertaining to base-case
$\mathrm{CO_2}$	pertaining to carbon dioxide
f	index of fuel constituents
i	index of equality constraints
j	index of inequality constraints
k	index of time periods
op	pertaining to off-peak
p	pertaining to peak
s	pertaining to storage
$water$	pertaining to water
$wind$	pertaining to wind

Sets

J_A	set of indices of the active constraints
m	number of equality constraints
N	number of time periods
R	set of feasible values of the uncertain parameters
r	number of inequality constraints
T	uncertain parameter space

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