IEA GHG WORKSHOP ON OPERATING FLEXIBILITY OF POWER PLANTS WITH CCS

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INTERNATIONAL ENERGY AGENCY

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DISCLAIMER AND ACKNOWLEDGEMENTS

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by IEAGHG as a record of the events of that workshop.

The workshop was organised by IEAGHG in co-operation with Imperial College London. The organisers acknowledge the financial support and hospitality provided by the Imperial College Centre for Carbon Capture and Storage (IC4S) and the UK CCS Community Network.

The principal organisers of the workshop were:

- John Davison, IEA Greenhouse Gas R&D Programme
- Hannah Chalmers, Imperial College London
- Jon Gibbins, University of Edinburgh, previously Imperial College London
- Victoria Harding, Imperial College London

The author of the workshop report is Hannah Chalmers.

The report was sent to the other workshop organisers and presenters for review prior to publication. Reviews were received from the following presenters:

- Andy Brown, Progressive Energy
- Michael Maloney, Doosan Babcock
- Vince White, Air Products

The report should be cited in literature as follows:

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IEAGHG OVERVIEW

In 2008 the IEA Greenhouse Gas R&D Programme (IEAGHG) carried out a study to review the current state of knowledge on operating flexibility of power plants with CCS and suggest possible future activities that could be undertaken by IEAGHG. During discussions at their 34th meeting, IEAGHG's Executive Committee decided that the best way forward would be to organise a workshop on this subject and then decide whether to undertake any technical studies or other activities.

IEAGHG organised a workshop on the operating flexibility of power plants with CCS in London on the 11th and 12th November 2009. The workshop was organised in collaboration with Imperial College London, who also hosted the meeting. The aims of the workshop were to discuss the state of knowledge on CCS plant flexibility, build contacts between people working in this emerging field of CCS research and identify important issues and the needs for further work. About 50 participants from 12 different countries attended the workshop.

Invited speakers made presentations on the operating requirements for CCS plants in future electricity systems, modelling and operating experience of pre-combustion, post combustion and oxy-combustion capture plants and flexibility of CO_2 transport and storage. Discussion sessions were held at the end of each set of subject presentations and at the end of the workshop, with active contributions from a large number of participants. The presentations and discussions, including areas where further work is needed, are summarised in this workshop report.

Participants were asked to complete a questionnaire at the end of the workshop to provide general feedback and to enable them to indicate whether they thought further meetings of CCS flexibility should be held and if so how they should be organised. The people who responded unanimously agreed that further discussions should be held and most people suggested a face-to-face meeting within 6 months to 1 year. About half of the participants thought that the discussions should take place within existing meetings such as IEAGHG's post combustion and oxy-combustion capture networks and GHGT conferences and the other half thought that IEAGHG should set up a new network on CCS flexibility.

Proposals for possible future meetings and studies on CCS plant flexibility will be discussed at IEAGHG's next Executive Committee meeting in March 2010.

IEA GHG Workshop on Operating Flexibility of Power Plants with CCS

Hannah Chalmers, Imperial College London[1]

1. Introduction

This report provides an overview of presentations and discussions from a workshop on operating flexibility of power plants with CCS hosted by the IEA Greenhouse Gas R&D Programme with Imperial College London on 11-12 November 2009. Around 50 individuals attended the meeting, who are listed in Appendix A.

The agenda of the meeting is given in Appendix B. The meeting began with an introduction (section 2) followed by a series of presentations exploring electricity system requirements for CCS operation (section 3). The impact of CO_2 transport and storage system characteristics on operating options for power plant operation was then explored (section 4). Following an overview of CCS plant flexibility modelling (section 5), each of the families of CO_2 capture technology closest to commercial deployment at power plants was reviewed (sections 6-8). The meeting then concluded with an open discussion that asked meeting participants to reflect on key emerging themes and potential priorities for future work (section 9). This final discussion was complemented by a feedback questionnaire that was completed by around 2/5 of the meeting participants (section 10). A copy of the questionnaire is given in Appendix C.

This document does not intend to given an exhaustive account of all points made by each speaker. Instead, it aims to complement the record of the meeting provided by the presentations by summarising key themes raised and providing a rapporteur's report of the discussions following the presentations. All of the presentations that can be made available are included in Appendix D. Although this report was circulated to speakers for comments before publication, they do not necessarily endorse its contents.

2. Workshop introduction and context

Presentation 1) Introduction, John Davison, IEA Greenhouse Gas R&D Programme

The workshop opened with a brief presentation from John Davison of the IEA Greenhouse Gas R&D Programme (IEA GHG). He introduced the aims and activities of IEA GHG and then outlined the motivation for convening the workshop. In particular, he noted that although power plant flexibility with CCS is seen as increasingly important by several stakeholder groups, there is little information available in the public domain. The core aims of the workshop were, therefore, to:

- Review the flexibility requirements for CCS;
- Discuss the state of knowledge on CCS plant operating flexibility;
- Build contacts between people working in the field; and
- Identify key issues and the need for further work.

[1] Since the meeting and drafting of this report, the author has moved from Imperial College London to the Institute for Energy Systems at the University of Edinburgh. Contact details: Hannah.Chalmers@ed.ac.uk; +44(0)7888 801020.

3. Electricity systems and CCS operating requirements

Presentations:

2) Value of Flexible Operation of Advanced Coal Plants with CCS, Tom Wilson, Electric Power Research Institute

3) The Need for Flexibility in Power Plants with CCS, John Davison, IEA Greenhouse Gas R&D Programme

4) The Impact of Intermittency, James Cox, Pöyry Energy Consulting

5) Grid and Process Modeling of Flexible Post-Combustion CO_2 Capture, Stuart Cohen, The University of Texas at Austin

This series of presentations highlighted a complex range of considerations that could impact on CCS operating requirements in different electricity systems, including demand patterns, fuel prices and the composition of the existing fleet. Some speakers also noted the importance of considering the provision of electricity network support (ancillary) services, as well as electrical energy, if a complete understanding of both the requirements for and value of flexible operation of power plants is to be obtained. A recurring theme was the need to understand the impact of large-scale decarbonisation in electricity systems. This could have significant implications for both the role that power plants with CCS might play in the electricity system and the economic viability of some flexible operating modes. For example, it can be expected that as CO_2 prices increase, modes of flexible operation that would require bypass of CO_2 capture will become increasingly unattractive.

The discussion following the presentations expanded a number of themes introduced by the speakers. The importance of regulations in determining if and how flexible operation of CO_2 capture might be used was identified in this and later sessions. There is significant uncertainty in this area since many jurisdictions are still developing packages of measures to reduce greenhouse gas emissions and, at the time of the meeting, the future direction of any co-ordinated international action to reduce greenhouse gas emissions was unclear. The role of Government is expected to be particularly important for early CCS projects where it is likely that significant contributions of public money will be required for successful financing (and this support is beginning to be delivered in several countries). It was noted that it is important to distinguish between flexibility in power plant output and varying the amount of CO_2 captured. Some argued that variable rates of capture were likely to be unacceptable to regulators. It was also noted, however, that there are precedents for trading in some cases. For example, SO_2 permit trading in the US is allowed. Although there are relatively small volumes of trading, this mechanism has proved to be important for 'keeping the lights on' during periods when very limited supply is available to meet electricity demand, as well as providing some degree of electricity price control.

Another theme for discussion was the impact of different assumptions about which technologies are deployed at a large-scale within electricity (and related energy) systems. Many of these comments were related to presentations focussing on the potential for high volumes of renewables with intermittent (or variable) output to significantly change the operating requirements for other plants in the system, including power plants with CCS. The potential to use electric vehicles, electricity storage and interconnection to offset renewable intermittency were all raised. Although these approaches may help to make the operating environment less challenging for power plants with CCS, it was suggested that none of these could be guaranteed to remove the need for flexible operation of power plants with CCS at this stage. For example, several different operating profiles could be possible for electric vehicle charging and the potential to use vehicle batteries as storage within the electricity network is not yet fully understood.

The very significant increase in peak electricity prices that was indicated in modelling of the UK and Irish systems with high contributions from intermittent renewables reported by James Cox was also explored in more detail. The main consideration here is likely to be that electricity price formation in competitive markets appears to change when the capacity factor[2] in the network decreases to around 10% or less, at least for the examples considered in the analysis reported at this workshop. The number of periods with a capacity factor less than 10% is likely to be reduced in systems with significant contributions from intermittent generators, with an associated increase in peak prices during these periods. Although they are likely to be less important, other factors that can increase running costs such as changes in the number of start-ups and shutdowns and any decreases in plant efficiency associated with off-design operation to provide back-up within the electricity system should also be considered for a full understanding of electricity price changes under different scenarios to be understood.

4. CO_2 transport and storage

Presentations:

6) Incorporating Transportation into a Flexible CCS Network, Julia Race, Newcastle University

7) CCS Operating Flexibility Experience from In Salah, Jonathan Forsyth, BP Alternative Energy International

Although CO_2 transport is not new in some contexts, it is important to understand differences between current experience and the much larger transport networks that are expected for CCS deployment. While some CO_2 may be transported by ship, the focus in this workshop was on CO_2 pipelines. These pipelines typically transport CO_2 in the dense phase, which requires both CO_2 pressure and temperature to be maintained at sufficiently high levels, using booster stations where necessary. The quality of CO_2 that is transported (i.e. whether impurities are present and, if so, what they are and at what level) could have a significant impact on what temperature and pressure will need to be maintained to ensure single phase flow[3]. A broad range of factors need to be taken into account in determining how the potential impacts of impurities might affect power plant operation with CO_2 capture such as cost of CO_2 purification before entering the pipeline, pipeline material constraints and environmental considerations, including at the storage site. A number of situations for transient analysis of pipelines that need to be considered for a full understanding of interactions between CO_2 transport and other aspects of CCS systems were also noted. These include start-up/shut-down, linepack/depacking, load following, upset conditions and blowdown.

Experience at In Salah suggests that CO_2 storage will be flexible enough to handle any likely changes in CO_2 flow rates, except that there will be a system peak capacity. Peak capacity can be increased with expenditure to increase capacity in transport/injection systems, if the formation being used for storage is able to accept additional CO_2. This does indicate, however, that any modes of flexible operation at power plants that might lead to increased throughput must be carefully specified and communicated to storage (and pipeline) system operators. It is also possible that some excess capacity will be available during 'normal' operations as a deliberate measure to ensure sufficient storage capacity is available during upsets. Additionally, seasonal variation is a normal operating consideration for companies producing hydrocarbons (e.g. changes in natural gas production to reflect demand in European heating markets).

[2] In this discussion, capacity factor = (total capacity currently available to operate/current demand)– 100%

[3] It is technically feasible to transport two-phase flow, but most pipelines are designed for a fluid that is single phase.

Much of the discussion following the initial presentations focussed on exploring some relatively detailed questions brought up by the introductory overviews. For pipelines, the sensitivity of the distance between stations where CO_2 is repressurised to keep it in the dense phase was explored. Even very small amounts of impurity could make a significant difference, but it should also be possible to offset the effects of impurities by increasing the pressure that CO_2 is compressed to before entering the pipeline system. Further work is needed both to validate equations of state for CO_2 with impurities and to understand trade-offs between different operating approaches that can be considered to maintain single phase flow in transport systems, even if significant levels of impurity are present. The potential impacts of water in pipelines were also raised. Drying specifications are expected to be an important component of requirements for CO_2 entering pipeline systems. This also suggests a commercial question of whether or not pipeline operators may be willing to accept out-of-specification CO_2 for a premium price that is able to cover associated costs. No problems have been observed for the pipelines in-service at In Salah.

For CO_2 storage flexibility, the speed of response for wells at In Salah receiving CO_2 was discussed and is generally expected to be sufficiently quick that it would not constrain flexible operation of power plants with CO_2 capture. When a well is started, CO_2 injection begins by opening the relevant valve. The predictability of CO_2 storage was also explored in more detail. It is generally expected that operators will improve their ability to predict the behaviour of storage sites as they gather operating data, in addition to information gathered to allow a reasonable understanding of the storage formation to be developed before CO_2 injection begins. Modelling suggests that variations in flow rate should not generally affect ultimate storage capacity in a particular formation, but further work may be required to improve understanding in this area.

5. Overview of CCS plant flexibility modelling

Presentation 8) Overview of CCS plant flexibility modelling, Colin Alie

This presentation used a case study example to explore motivation and methods that can be used to assess the impact of CCS on plant flexibility. A three step process considering modelling of a generating unit with CCS, simulation of the electricity system and analysis of results was outlined. For the example considered, benefits for operating flexibility could be quantified but the need to undertake sensitivity analysis and further work to improve understanding of dynamic performance was noted. One initial conclusion was that operating flexibility appeared to shift capacity from providing electricity in energy markets to contributing to reserve markets providing support (ancillary) services in electricity networks. It is, therefore, likely that additional metrics that are able to account for plant income being obtained from multiple revenue streams will be required. The discussion following the presentation explored what measures could be considered. Suggestions included return on investment and net present value. From an electric utility perspective, it was noted that a broad range of factors would be considered within any investment decision-making process, including those already identified but also considerations such as capital expenditure, long run costs of electricity production and potential ranges in costs for different scenarios of the future. The potential importance of understanding trade-offs between steady-state efficiency and transient performance in further work was also highlighted.

6. Pre combustion capture plant

Presentations:

9) IGCC with CCS, Designs and Experience, Rosa Maria Domenichini, Foster Wheeler

10) Analysis of Flexibility Options for Electricity Generating Projects with Pre-combustion Capture of CO_2, Andy Brown, Progressive Energy

The presentations in the pre-combustion session included information on the dynamic modelling and operating experience of IGCC plants and methods of achieving operating flexibility. The speakers noted that a range of different definitions of flexibility for power plants with CCS can be used. These can arise for a number of reasons including systematic differences between technologies and alternative perspectives on which modes of flexible operation might be economically attractive to plant operators. The importance of respecting any regulatory requirements to maintain high levels of CO_2 capture was again highlighted. It was also suggested that gaining operating experience with initial integrated gasification combined cycle (IGCC) plants deployed with CO_2 capture would be a crucial step in determining what options for flexible operation might be technically feasible and worthwhile in the future, because reliable chemical process plant is best operated under relatively steady state conditions.

Although it is expected that IGCC plants can provide some degree of operational flexibility, the commercial case is less clear. A range of possibilities were presented by the speakers. The analysis reported by Andy Brown considered several options, including a range of polygeneration schemes in which additional products are produced during times of low electricity demand. Only diurnal storage of syngas or hydrogen was expected to be sufficiently valuable to be worth further investigation, if a customer for additional hydrogen production could be identified. The sensitivity of results to price assumptions and site-specific factors was, however, noted. Both speakers also addressed concerns related to the ability of IGCC plants to provide sufficiently fast response to meet electricity network connection requirements, using the case of the UK. The UK requires more rapid response from power plants than other systems, partly due to typical demand profiles and also since it has a relatively small installed electricity generating capacity and a weak or pre-filled interconnection to the European grid. It is expected, however, that these requirements can be met, possibly with recourse to natural gas supplementary firing, fuel mixing or innovative process nuances.

7. Oxy-fuel plants

Presentations:

11) Study of the Process & Operation of Oxyfuel Power Plant, Shunichiro Ueno, IHI Corporation

12) Oxyfuel Combustion Technology, Michael Maloney, Doosan Babcock Energy

13) ASU and CO_2 Processing Units for Oxyfuel CO_2 Capture Plants, Vince White, Air Products

The presentations in the oxy-fuel session included results from simulation studies of oxy-fuel power plants and discussion of further work that is expected to improve understanding of options that are likely to be available for operators of these plants as this CO_2 capture approach is scaled up. Simulation studies have not indicated any 'show-stoppers' for start-up, shutdown and transient operation of oxy-fuel power plants, but further work is required to validate these results in real projects. Designs for oxy-fuel plants that are closest to commercial deployment make some significant use of technology that has been developed for the operating requirements of other markets, such as air separation units (ASUs) and CO_2 compressors. It is, therefore, expected that the operating flexibility of oxy-fuel plants will evolve to meet power market requirements as vendors are approached by real potential customers that are able to explain their needs.

Much of the discussion following the presentations focussed on exploring performance and operating options for ASUs and CO_2 compression. One concern that is frequently raised in discussions of oxy-fuel plant flexibility is the likely start-up time for ASUs. Vendors can consider a number of options to allow more rapid start-up where this is a priority for a customer. ASU start-up from ambient temperatures requires the building up of a liquid inventory and cooling of metal within the system. For relatively short shutdowns (up to a whole weekend) liquid could be retained in the system providing a 'stand-by' mode. Although some evaporation would be expected, this would retain temperatures allowing a much more rapid start-up. It should also be possible to increase the capacity of critical components for building up the liquid inventory. It might also be possible to relax restrictions in temperature gradient that constrain the rate at which an ASU plant can be cooled down if customer interest provides motivation for undertaking appropriate design work. The use of interim storage of liquid oxygen to improve ASU ramp rates is also being considered.

Part load operation of oxy-fuel plants has also received very little attention. For example, as with other CO_2 capture options, efficient turndown of CO_2 compressors with electric drives should be possible for approximately 70-100% of design throughput for current typical designs. If throughput is reduced below 70% then some flow can be recycled so the plant can continue to operate, but with extra power required per unit CO_2 captured. No problems are expected with maintaining output pressure at part load, as long as recycling of CO_2 is used, where necessary, to ensure that compressor throughput is within the manufacturer's allowable operating range. It should also be noted that most power plant applications will require multiple trains of CO_2 compression, providing multiple operating options at part load.

Both CO_2 purity and oxygen purity in an oxy-fuel context were also discussed in this session. Concerns have been raised about the purity of CO_2 produced by oxy-fuel plants, but vendors are developing solutions for cost-effective removal of any significant impurities before CO_2 enters the transport system. The purity of oxygen produced by ASUs is of interest since times for start-up and load change are typically related to reaching relatively high oxygen purity, as is typically required in other applications. For oxy-fuel power plants, it is possible that lower purity oxygen will be adequate for combustion as long as the CO_2 compression and purification system is designed to handle the resulting changes in gas to be processed (possibly with some trade-offs in the level of CO_2 captured at the time). Further work is required to understand the implications of this potential change in ASU operating requirements for overall flexibility of oxy-fuel power plants.

Another aspect of oxy-fuel plant design which is currently under discussion is the potential to avoid the installation of specific measures for reducing some conventional pollutant emissions (e.g. flue gas desulphurisation and selective catalytic reduction) that are increasingly common at current pulverised coal-fired power plants, since these pollutants are expected to be removed within the CO_2 compression and processing unit at an oxy-fuel plant. Although it seems likely that this will be possible for normal operations, it will also be necessary to determine what measures for control of these pollutants might be necessary during start-up, shutdown and any periods where the plant operator switches to air-firing. It is likely that local environmental regulations will have a significant impact on decisions related to this aspect of system design. It was noted, for example, that there is a precedent in Europe for allowing start-up without flue gas desulphurisation. This is justified since coal-fired plants starting-up on oil may not fully combust the fuel initially. It is, therefore, necessary to bypass the flue gas desulphurisation unit to avoid significantly longer outages that would result from any uncombusted oil reaching the flue gas desulphurisation unit.

8. Post combustion capture plants

Presentations:
14) Experience with the CASTOR/CESAR Pilot Plant, Jacob Nygaard Knudsen and Jørgen Nørklit Jensen, DONG Energy Power
15) Steam Turbines for Operating and Future-proof Upgrading Flexibility, Mathieu Lucquiaud and others, Imperial College London
16) Modelling of Post Combustion Capture Plant Flexibility, Hanne Kvamsdal, SINTEF
17) Operability of Power Plants with CCS: Earlier and Ongoing Projects at NTNU Department of Engineering Cybernetics and SINTEF Applied Cybernetics, Finn Are Michelsen and others, NTNU and SINTEF

The post combustion capture presentations, with discussion following each individual presentation, included industrial and academic perspectives on post combustion capture plant modelling and operation. One key area for further work identified in this session was availability of data for model validation. Although some relevant results have been obtained at pilot plants, there is typically limited data available in the public domain. For pilot plants operating at real power plants, including the CASTOR/CESAR unit discussed in the first presentation in this session, there are also some constraints on which operating options can be included in test runs since it is typically necessary to prioritise the ongoing commercial power generating operations.

A number of valuable insights have, however, been gained from experience with the CASTOR/CESAR pilot plant and many of these have been reported in the literature, including within the Greenhouse Gas Control Technologies conference series. Variations in liquid to gas ratio in the unit are possible by varying the solvent flow rate. It is also possible to change the flue gas flowrate to the absorber, although controlling both flowrate and CO_2 concentration in the gas simultaneously is generally not possible at an operating power plant, typically with reducing CO_2 content at lower loads. The response time of this pilot unit has generally been quick, but it should be noted that this is expected to depend on the retention time of the solvent in the system. Different response times may, therefore, be encountered in commercial plants. For scale-up activities, a key concern is the uncertain cost involved.

The second presentation in this session focussed on steam turbines for flexible operation and upgrading as post-combustion capture solvents develop. A range of topics were covered including the potential for oversizing key components to allow additional electricity export during some modes of flexible operation and the use of a floating pressure turbine system to allow maximum flexibility for upgrading plants to use improved solvents in the future. It is expected that relatively small variations in capital cost would be observed between many of the options presented, although one option that involves a clutched low pressure turbine could have higher upfront costs than the other options, which are expected to add no more than 1% to the plant capital cost. The potential for operating efficiency losses for an additional valve that is likely to be built in for low pressure turbine control in some cases also needs to be considered. Further work to improve understanding of CO_2 compression systems receiving variable flows of CO_2 might also be necessary.

For provision of some ancillary services[4] relatively fast response is required, so two different approaches to using voluntary bypass[5] at a post-combustion capture plant were discussed. In one case, steam is returned to the power cycle allowing additional electrical output to be generated (assuming sufficient turbine and generator capacity is available – as would be the case for many retrofits, but may not be the case for plants operating with CO_2 capture from day 1). In this first case, it is assumed that auxiliary power use in the CO_2 capture unit and for CO_2 compression is also avoided. In the second case, steam is also returned to the power cycle allowing full low pressure turbine output to be delivered, but auxiliary power is still used. This second case represents a situation where the power plant operator chooses to reduce the steady-state efficiency to improve transient response, which may allow them to generate additional revenue by providing support (ancillary) services within the electricity network. The potential to use interim storage of rich solvent to shift the capture energy penalty was also introduced[5]. For maximum short-run flexibility with this approach, it will be necessary to oversize the system downstream of the absorber, although some use of solvent storage is likely to be possible without that additional investment. It was noted that the requirement for oversizing could extend to transport and storage systems, although this would depend on how any future transport network is operated.

The second half of this session discussed past, ongoing and future work at SINTEF and NTNU. This included dynamic modelling of amine absorption from a chemical engineering-led perspective and work drawing on existing expertise in cybernetics. The overall aim of this latter work is to develop a systematic procedure for integrated process and control design that can improve both design and operation. It will, of course, be necessary for strategies developed using these procedures to be implemented in real tests, including adaptation to any physical limits in these systems that are not identified in the initial desk-based work. Complementary work in the BIGCO2 project is also focussing on a modelling approach that is suitable for identifying and testing control philosophies. Mass transfer and kinetics are expected to be the most important consideration for absorber modelling, with changes in viscosity included using correlations available in the literature. As already noted, availability of data for validation is one significant challenge for this work. SINTEF are planning to build their own pilot unit that should help to provide data, in addition to involvement in other projects such as CESAR.

9. Wrap-up discussion

One topic that was not covered in detail in this workshop was the flexibility of baseline power plants without CO_2 capture. In particular, for pulverised coal-fired power plants the general trend of increasing steam temperatures has led to changes in standard boiler designs. In older designs, a steam drum was included in the boiler and was able to provide very fast response (although only for very limited periods of

[4] Ancillary services are support services provided within electricity networks to help ensure security and quality of electricity provision. A broad range of services are required, including response/reserve services to help to ensure that supply and demand of electricity are matched over timescales ranging from seconds to minutes and hours.

[5] During voluntary bypass, the capture rate is deliberately reduced. This avoids some or all of the energy penalty associated with CO_2 capture, but obviously leads to an increase in CO_2 emissions from that plant during the period when the capture rate is reduced. Interim storage of solvent that is 'rich' in CO_2 could also be used to avoid some energy penalty during peak periods, but without extra CO_2 emissions. When solvent is stored, it must be regenerated later so the energy penalty is shifted, rather than avoided, and additional capital expenditure would also be required.

time) as a support service in the electricity network. There has been some concern about the ability of supercritical coal-fired power plants to provide similar response. Although operators in continental Europe are comfortable with operating supercritical units, including meeting requirements for providing support services, there are outstanding concerns in other jurisdictions. For example, as discussed by the speakers in the pre combustion capture session at this workshop, the UK has particularly stringent rules for fast response that power plants must be able to provide to be allowed to connect to the electricity network. In this context, the potential to use CO_2 capture to improve plant flexibility by providing additional operating options for supplying support services to the electricity network could be valuable.

There was also some general discussion about the importance of considering flexible operation within initial commercial-scale demonstration projects. Although it is expected that the primary purpose of these projects will be proving CCS on power plants at this scale, it is likely that any information that could be gathered on plant flexibility would be valuable. For example, for electric utilities improving understanding of flexibility of power plants with CCS could be a key component of quantifying commercial risk associated with these projects. The importance of demonstrating a portfolio of technologies that are likely to have a range of different characteristics is also a key concern in this context. It was suggested, however, that a clear distinction is made between large pilot projects that would not be required to operate flexibly and commercial projects that would be expected to respond to normal business requirements including flexible operation, where appropriate.

The policy implications associated with considering power plant flexibility with CCS were also revisited in this final session. It was suggested that flexibility should not be considered as a key issue currently since it is necessary to successfully finance, construct, operate and maintain initial commercial-scale pilot/demonstration projects before fully commercial projects are deployed. It was also observed, however, that there is a near-complete absence of information in this area that is suitable to inform policy and that decisions that may be made in the near-term future could be difficult to reverse once they are established. Although flexible operation has been relatively unimportant within discussions determining policy until now (e.g. at European level the focus has been on regulations for CO_2 storage that are not intended to address this area), it seems likely that ensuring that robust information is available as policy-makers and others continue to develop regulations and incentive packages for CCS could be critical. Otherwise, it is possible that policy-makers will introduce measures that constrain plant operation inadvertently, with related unintended negative consequences, including for the costs of installing and operating CCS at power plants and wider operating costs for the electricity system as a whole.

Related to this discussion, it was also noted that including flexibility of CCS in economic assessments could identify sources of added value that allow progress on CCS projects that would not be feasible without these additional revenue streams. Some concerns were expressed that any operating modes that led to a reduction in operating hours would be detrimental to plant economic performance. It is also essential to carry out realistic assessment of the balance between costs and benefits associated with any additional investment that would be required to make different operating modes available (e.g. oversizing or adding units to allow interim storage of post combustion capture solvents, liquid oxygen, syngas or hydrogen). Alongside this it is very likely, however, that changes in electricity and energy systems are going to be implemented in response to concerns about the risk of dangerous climate change. As discussed in section 2, in many jurisdictions this is leading to significant increases in the use of intermittent (or variable) output renewable energy sources. It can be argued that plants that are able to provide back-up to complement renewable generation should attract significant revenue streams, but for fossil-fired power plants with CCS to play this role it will be important to demonstrate and deploy systems that have sufficient operating flexibility as soon as possible.

Looking to the future, one important consideration could be improving understanding of different perspectives on power plant operating requirements and actions to reduce greenhouse gas emissions in different jurisdictions. Many speakers at this workshop used the UK as a case study example. It is expected that similarities and differences will be observed in other jurisdictions and these should be explored. The importance and value of bringing together different viewpoints, including a range of technical disciplines was noted. For example, the contributions made by experts in CO_2 transport and storage during this workshop were seen as particularly valuable. It was noted that areas of further work suggested by the presentation on CO_2 transport were validation of equations of state for modelling CO_2 with impurities[6] and transient modelling of pipelines. The importance of ensuring that potential operators are involved early was also highlighted, since this particular stakeholder group is keen to understand the potential impacts of emerging technologies on their businesses as soon as possible. Other useful contributors to future discussions could include electricity network operators and CO_2 compressor manufacturers.

10. Feedback questionnaire

To complement discussions at the workshop, a feedback questionnaire was circulated to participants and is included in Appendix C. 20 responses were received from a total meeting attendance of around 50. All of the questionnaire respondents indicated that they would like further discussions on CCS flexibility. The vast majority suggested physical meetings with a preference for a further meeting/event to be arranged in 6 months to 1 year (rather than more than 1 year or less than 6 months). Almost half of the respondents suggested that meetings should be held approximately annually, but several suggested that it would be best to arrange meetings every 6 months to 1 year. 10 respondents preferred including flexibility sessions within existing series of meetings and 9 respondents recommended organising a new IEA GHG network on flexibility. One respondent suggested that a network should be formed and flexibility sessions should also be included in existing meetings.

A number of respondents provided useful feedback on potential topics that could be added in future discussions. One area where further work was suggested was in improving understanding of what future energy systems might look like and the implications this could have for power plants with CCS. Both technical and commercial arrangements for the development of new electricity systems as a whole and particular technologies operating within them need to be considered. Implications for including energy storage in electricity system analysis were also highlighted as a potential topic for further consideration in the future.

Respondents suggested that more detailed analysis on both economic and engineering aspects of flexibility should be considered for inclusion at future workshops, although this would probably require longer presentations and potentially a longer meeting. It was noted that one theme emerging from presentations addressing individual CO_2 capture technologies was the potential role for short-term reversible storage in

[6] Some work is now being funded in this area and IEA GHG has been tracking developments in the area of CO_2 purity, most recently with a working group meeting held in conjunction with the first oxy-fuel combustion conference in Cottbus earlier this year. See http://www.co2captureandstorage.info/networks/CO2_Quality.htm

each system (e.g. hydrogen, oxygen, rich and lean solvent) and it could be useful to compare these options in more detail. Other suggestions included paying particular attention to potential roles for dynamic modelling and broadening the scope to consider more novel technologies that are less close to commercial deployment, where sufficient information is available to begin to undertake analysis of the impacts that these technologies could have on power plant operation. The inclusion of further work on CO_2 quality was also proposed, possibly including discussion related to guidelines that some stakeholders expect will be developed relatively soon.

The importance of considering the whole CCS chain from fuel production through capture and transport to storage was highlighted. The inclusion of perspectives on CO_2 transport and storage within this workshop was welcomed and it was suggested that this element could be expanded in the future. For example, it might be useful to invite a presentation on experience gained from operating the pipeline used in the Weyburn project[7]. There was also a broader wish to see more input on experience gained at pilot/demo plants, as well as more international perspectives on if and how power plants with CCS might be operated in the future from the perspective of organisations that would run and regulate them.

There were several comments related to improving links between the academic and industry knowledge represented at the workshop and the policy/regulatory community. This included suggestions for including Government representatives in future workshops and asking policy-makers to present on their understanding of flexibility options for power plants with CCS. It was noted that discussion in this area could cover a broad range of considerations including how the market could be organised to deliver CCS and revisiting/expanding some of the early discussions in this workshop on the potential impacts of increasing electricity supply from intermittent (or variable) sources within the electricity/energy system. The importance of ensuring that any work in this area takes full account of how both initial investment and operating costs are recovered was noted. One respondent, however, suggested that it would be helpful to limit the discussion of the global political scene at future workshops to allow time for more focussed technical topics.

Although many of the respondents commented on the good mix of participants attending this workshop, a number of suggestions were made to expand the range of perspectives present in the future. In addition to direct involvement of policy-makers already noted, it was suggested that electricity network operators and regulators should be invited to future workshops. Insights from original equipment manufacturers for key items that were not considered at this workshop were also highlighted as potentially valuable for the future. Particular examples given were CO_2 compressors and steam turbines. The inclusion of developing country participants and environmental non-governmental organisations was also recommended. It was also noted that other international CCS organisations such as CSLF, GCCSI and the CCS team at IEA headquarters in Paris could make useful contributions.

11. Conclusions

This report has presented a rapporteur's perspective on presentations and discussions at a workshop on power plant operating flexibility with CCS which was hosted by IEA GHG with Imperial College London on 11th-12th November 2009. Responses to a post-meeting feedback questionnaire on the potential for future

[7] See http://www.ptrc.ca/weyburn_overview.php for an overview of this project

meetings in this area are also included. The workshop did not give a definition of 'operating flexibility' and a number of different interpretations were used. One theme raised towards the beginning of the workshop that is likely to be relevant whatever definition is used, is the importance of understanding the nature of future electricity systems. Technical, commercial and policy/regulatory considerations must all be taken into account in establishing what changes compared to current systems could mean for requirements and value of operating flexibility for power plants with CCS.

Operating experience at In Salah suggests that CO_2 storage activities should not be a limiting factor for CCS system flexibility. Although CO_2 transport by pipeline is not new, it was recommended that further work is undertaken to improve understanding of interactions between power/capture plants and CO_2 transport systems. A number of factors will need to be considered in determining how it is best to handle trade-offs, including in determining CO_2 quality/purity specifications and managing transient operations including start-up, shutdown and load following (where power plant output is adjusted to take account of changes in electricity demand).

In the sessions on different CO_2 capture technologies a range of relatively detailed technical points were identified and discussed. A significant knowledge base is being built up in modelling activities, but it is critical that this is complemented by relevant pilot/demonstration activity. Determining if and how data can be shared for model validation is an important challenge that requires careful consideration. Some potentially important topics, such as CO_2 compression and challenges for providing sufficient flexibility in operation using power plants without CO_2 capture, received limited attention in this workshop but were noted as areas that could be considered in more detail at future meetings. It should also be noted, however, that many technology vendors are still in the early stages of adapting products to potential operating requirements for power plants with CCS, so improvements in operating flexibility can be expected if these are likely to be sufficiently valuable to customers. For example, both of the presenters in the pre combustion session noted that approaches to providing fast response with IGCC plants had been identified by their organisations when they had been faced with a commercial need to meet this requirement.

The post-meeting feedback questionnaire suggested significant interest in further face-to-face meetings on the topic of power plant operating flexibility with CCS, but it is not clear whether this would be best pursued through a new IEA GHG network or incorporation of this topic into existing meetings (or both). There was also a significant unanswered question on whether operating flexibility should be seen as a key issue for initial commercial-scale plants. Although investors would prefer to avoid situations that require flexible operation, many of the workshop participants suggested that expected developments in electricity systems are likely to make some form of flexible operation of power plants with CCS effectively mandatory. Establishing a robust understanding of different potential plant performance characteristics and the implications of flexible operation from a commercial perspective as soon as possible, therefore, seems to be a high priority for some stakeholders including electric utilities. In this context, developing and disseminating a reliable knowledge base to inform ongoing formulation of relevant policy and regulations could also be essential. Contributors to the workshop wrap-up discussion noted that once regulators have implemented frameworks these are typically notoriously difficult to revise. One priority for the short to medium term could, therefore, be to ensure that sufficient understanding of power plant flexibility with CCS is developed and disseminated to ensure that unintended consequences that restrict operating options for power plants with CCS are identified and avoided in draft regulations before they become law, where appropriate.

Appendix A Workshop attendees (arranged alphabetically by organisation)

Participant	Organisation
Christophe Clays	Air Liquide
Alain Guillard	Air Liquide
Fred Lockwood	Air Liquide
Paul Higginbotham	Air Products
Vince White	Air Products
Jonathan Forsyth	BP Alternative Energy International
Adekola Lawal	Cranfield University
Giuseppina Di Lorenzo	Cranfield University
Meihong Wang	Cranfield University
Colin Alie	CSIRO
Jørgen Nørklit Jensen	DONG Energy Power
Michael Maloney	Doosan Babcock Energy
Nick Booth	E.On Engineering
Robin Irons	E.On Engineering
Tom Wilson	Electric Power Research Institute
Harsh Pershad	Element Energy
Gerald Kinger	EVN AG
Rosa Domenichini	Foster Wheeler Italiana
Ulrich Liebenthal	Hamburg University of Technology
Sebastian Linnenburg	Hamburg University of Technology
Peter Fletcher	Honeywell Advanced Solutions
Deborah Adams	IEA Clean Coal Centre
John Kessels	IEA Clean Coal Centre
John Davison	IEA GHG
Michael Haines	IEA GHG
Shunichiro Ueno	IHI Europe
Hannah Chalmers	Imperial College London
Olivia Errey	Imperial College London
Jon Gibbins	Imperial College London
Mathieu Lucquiaud	Imperial College London
Vangelis Tzimas	Institute of Energy (European Commission)
John Griffiths	Jacobs Engineering
Mohan Karmarkar	Jacobs Engineering
Maria Eugina Monux Sanz	Jacobs Engineering
Anna Rattray	Jacobs Engineering
Makoto Akai	National Institute of Advanced Science and Technology (AIST, Japan)
Konrad Eichhorn Colombo	Norwegian University of Science and Technology
James Cox	Pöyry Energy Consulting
Andy Brown	Progressive Energy
Peter Stephenson	RWE npower
Hanne Marie Kvamsdal	SINTEF
Finn Are Michelsen	SINTEF
Jihong Wang	University of Birmingham
Julia Race	University of Newcastle
Stuart Cohen	University of Texas at Austin
David Steen	UOP NV

Appendix B Meeting Agenda

Day 1: 11th November

Lunch and registration	12.15-13.30
1. **Welcome and introduction** – IEA GHG and Imperial College	13.30-13.40
2. **Electricity systems and CCS operating requirements** **Chair – John Kessels, IEA Clean Coal Centre, UK**	13.40-15.00
Power plant and CCS flexibility – Tom Wilson, EPRI, USA	
The need for flexibility in power plants with CCS – John Davison, IEA GHG, UK	
Electricity systems operation – James Cox, Poyry, UK	
Grid and Process Modeling of Flexible Post-Combustion CO_2 Capture – Stuart Cohen, University of Texas, USA	
Question and answer session	15.00-15.15
Coffee/Tea break	15.15-15.45
3. **CO_2 transport and storage** **Chair – Mike Haines, IEA GHG, UK**	15.45-16.25
CO_2 transport – Julia Race, Newcastle University, UK	
CO_2 storage – Jonathan Forsyth, BP, UK	
Q&A	16.25-16.40
4. **Overview of CCS plant flexibility modelling** – Colin Alie, CSIRO, Australia	16.40-17.05
5. **Pre combustion capture plant** **Chair – John Griffiths, Jacobs Engineering, UK**	17.05-17.45
IGCC with CCS, designs and experience – Rosa Maria Domenichini, Foster Wheeler, Italy	
Flexibility of gasification plants with CCS – Andy Brown, Progressive Energy, UK	
Q&A	17.45-18.00

Day 2: 12th November

Arrival	08.30-09.00
6. **Oxy-fuel plants**	09.00-10.00
Chair – Peter Stephenson, RWE npower, UK	
Operation of oxy-fuel power plant	
– Shunichiro Ueno, IHI, Japan	
Oxy-fuel boilers and ancillaries	
– Michael Maloney, Doosan Babcock, UK	
ASU and CO_2 processing	
– Vince White, Air Products, UK	
Q&A	10.00-10.15
Coffee/Tea break	10.15-10.45
7. **Post combustion capture plants**	10.45-12.05
Chair – Jon Gibbins, Imperial College London, UK	
Experience with the CASTOR/CESAR pilot plant	
– Jørgen Nørklit Jensen, DONG Energy, Denmark	
Steam plant design for operational and upgrading flexibility	
– Mathieu Lucquiaud, Imperial College London, UK	
Modelling of post combustion capture plant flexibility	
– Hanne Kvamsdal, SINTEF, Norway	
Plant control and optimisation	
– Finn Are Michelsen, SINTEF, Norway	
Q&A	12.05-12.20
8. **Discussion and priorities for future research**	12.20-12.35
Chair – John Davison, IEA GHG, UK	
9. **Close of meeting**	12.35-12.40
Lunch	12.40-13.45

Appendix C Feedback questionnaire

WORKSHOP ON OPERATING FLEXIBILITY OF POWER PLANTS WITH CCS

Imperial College, London, UK
11th – 12th November 2009

FEEDBACK

1. Did you find this meeting useful? Why or why not?

2. Would you like further discussions on CCS flexibility? (Please tick chosen options)

☐ No further discussions
☐ Yes, organise a new IEA GHG Network on CCS flexibility
☐ Yes, include flexibility sessions in existing series of meetings,
e.g. GHGT and IEA GHG's existing oxy-combustion and
post combustion capture network/conference meetings
☐ Yes, ask organisations other than IEA GHG to arrange the meetings
If so, please suggest other possible organisation(s)

3. If you would like further discussions, how would you like them to be organised?

☐ Physical meetings
☐ Web-based meetings
☐ E-mail discussion group/ message board etc
☐ Other (please give details)

4. When would you like a further meeting/event to be arranged?

☐ Not at all
☐ Within the next 6 months
☐ 6 months - 1 year
☐ More than 1 year

5. If regular meetings/events were arranged, how frequently would you like them to occur?

☐ Not at all
☐ More frequently than once every 6 months
☐ Every 6 months - 1 year
☐ Approximately annually
☐ More than 1 year between events

6. Do you have any preferences for time/location of meetings?

7. Are there any topics not covered by this workshop that you would like to be included in future discussions?

8. Are there any topics that you would like to be excluded from the scope of future discussions?

9. Do you have any comments regarding the type of participants at this workshop (e.g. industry, academic, other / seniority within organisations / level of previous experience) and any improvements that could be made in the future?

10. Any other comments/thoughts?

11. If you would like us to contact you to discuss your feedback from this meeting in more detail, please provide your name and preferred contact details here.

Thank for providing this feedback. Key messages will be included in the meeting report.

Appendix D Presentation slides

The presentation slides that are available are included in this Appendix. They can also be downloaded in pdf format from http://www.co2captureandstorage.info/techworkshops/Flexibility.html.

IEA Greenhouse Gas R&D Programme

Workshop on Operating Flexibility of Power Plants with CCS

Introduction

John Davison

IEA Greenhouse Gas R&D Programme

IEA Greenhouse Gas R&D Programme

- A collaborative research programme which started in 1991
- Aim is to:

Provide its members with impartial information on the role that technology can play in reducing greenhouse gas emissions

- Based in the UK
- Main focus has been on CCS
- Funding approx £2 million/year (US$3 million/year)

Members and Sponsors of IEA GHG

IEA GHG Activities

- Studies (>100)
- Communications
- Facilitating and focussing R&D activities
- R&D networks
  - CO_2 storage
    - Risk Assessment, Well Bore Integrity, Monitoring
  - CO_2 capture
    - Post combustion and Oxy-combustion
    - High temperature solids looping

Why a Workshop on CCS Flexibility?

- Operating flexibility of CCS plants is important
- For utilities
  - Flexibility has practical and economic advantages
  - It could affect the choice of CCS technology
- For policy makers
  - It could affect the extent to which CCS can be used
- There is little information on CCS plant flexibility

Aims of the Workshop

- Review the flexibility requirements for CCS
- Discuss the state of knowledge on CCS plant operating flexibility
- Build contacts between people working in the field
- Identify key issues and the need for further work

Agenda

- Day :1 Wednesday
  - Electricity systems and CCS operating requirements
  - CO_2 transport and storage
  - Overview of CCS plant flexibility modelling
  - Pre-combustion capture plants
- Day 2: Thursday
  - Oxy-combustion capture plants
  - Post combustion capture plants
  - Discussion and priorities for further work

Where to go from here?

- A report of the meeting will be distributed
  - Presentation slides will be included
- Questionnaire
  - Do we want any further meetings?
  - If so, how should they be organised?
  - What topics should be included?
  - Please leave paper copies here or respond to the e-mail questionnaire

Thanks

- Thanks to Imperial College Centre for Carbon Capture and Storage for providing the room
- The UK CCS Community network for sponsoring the dinner
- Imperial College staff, especially Hannah Chalmers Victoria Harding and Jon Gibbins for helping to organise the workshop

ELECTRIC POWER RESEARCH INSTITUTE

Value of Flexible Operation of Advanced Coal Plants with CCS

Tom Wilson (twilson@epri.com)
Sr. Program Manager
Global Climate

Workshop on Operating Flexibility of Power Plants with CCS

Imperial College, London
11 November 2009

Background

- Emerging literature on flexible operation of coal with CCS (e.g., Gibbins, Chalmers, et al.)
  - Appears technically feasible – though many engineering questions remain
  - Little analysis of the potential economic benefits
    - May differ significantly by region
    - Will include economic benefits that are hard to measure
  - Little discussion of political viability
- EPRI's CoalFleet for Tomorrow program undertook an economic "scoping" analysis in 2007:
  - Rough estimate of the economic value of flexibility over time in several US regions
- Updating and extending analyses in 2009-2010

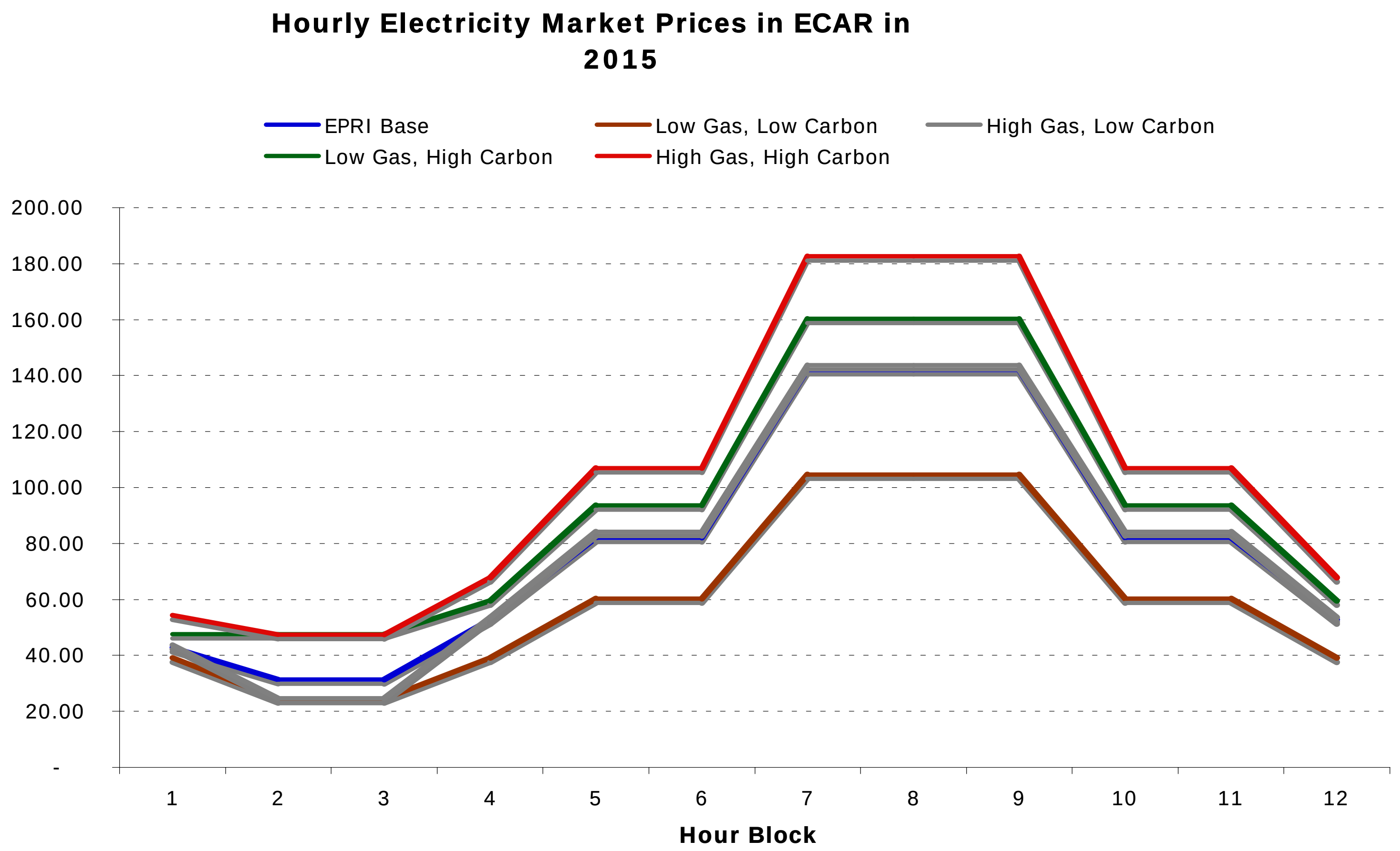
Why Consider Flexible Operation of Advanced Coal w/ CCS?

- Technical Requirements
  - What if CO_2 compression fails or pipeline does not accept CO_2?
- Operational Value
  - Advanced coal with CCS is more like a chemical plant than a conventional power plant
    - Distinct intermediate products produced for use in other processes
    - Components operating in parallel rather than in series
    - Integration

And …

Why Consider Flexible Operation of Advanced Coal w/ CCS? (continued)

- Economic reasons
  - Regaining capacity at peak hours



Examples: Consider Two Types of Flexibility for an IGCC Plant with CCS

- Free Venting
  - When electricity price is high and CO_2 price is low, CCS is halted to produce more electricity from reduced auxiliary loads
  - No capital investment is required to alter the plant so this always makes money
- Oversize Air Separation Unit
  - Additional investment required, so you may win or lose

Analysis Assumptions – Free Venting

556 MW IGCC Plant

	CCS Operation	Freely Venting
Heat Rate (Btu/kWh)	10,505	9,505
CO2 Emissions (ton/MWh)	.10	.94
Auxiliary Loads (MW)	189	146
Output Gain (MW)		43

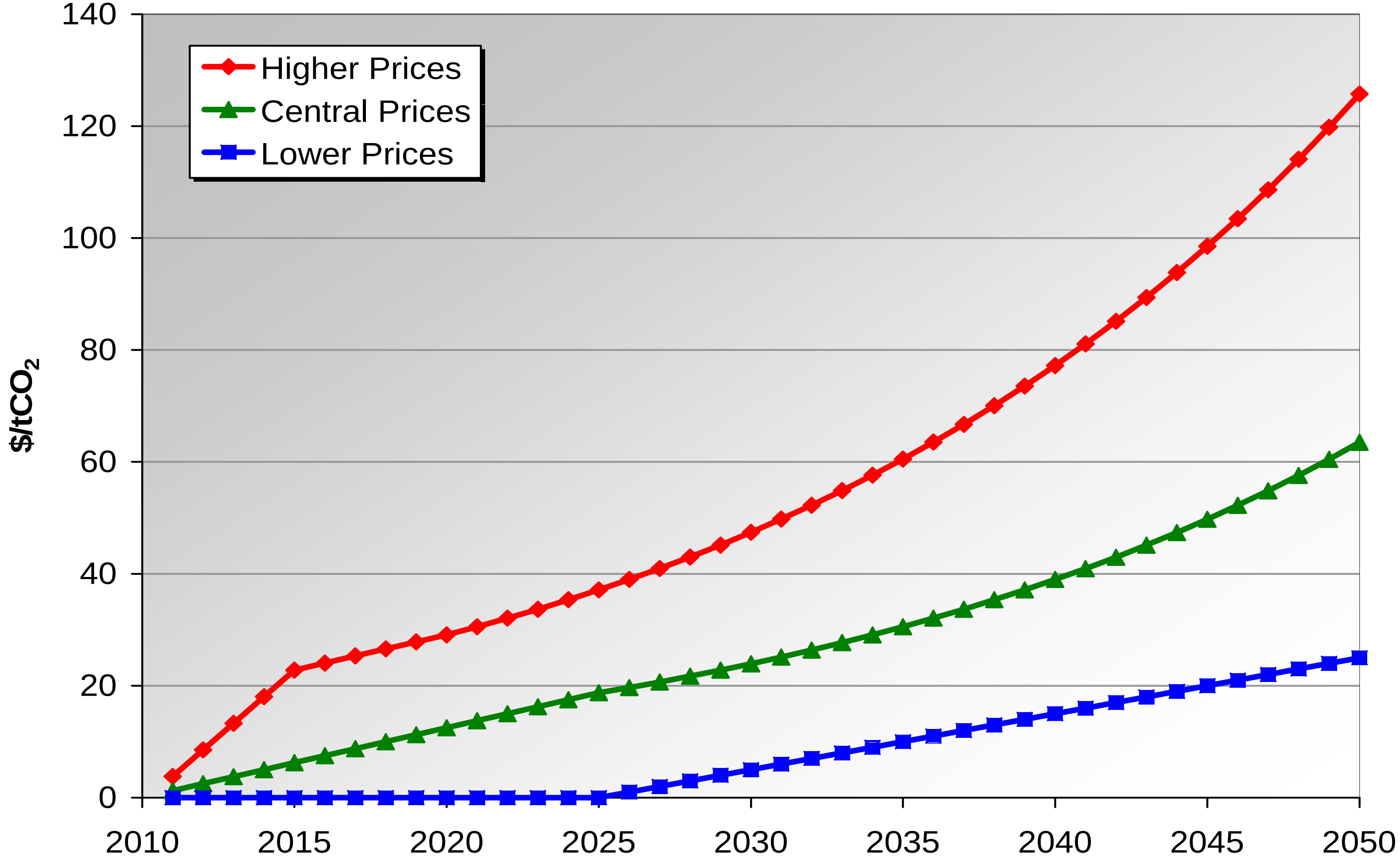
Also, assumes that policy framework allows you to vent

Analysis Approach

- To calculate the added cash flow we estimate electricity price and CO_2 value for every hour of the year
- CO_2 is vented if it increases cash flow for that hour
- The yearly value is the sum of the hourly values

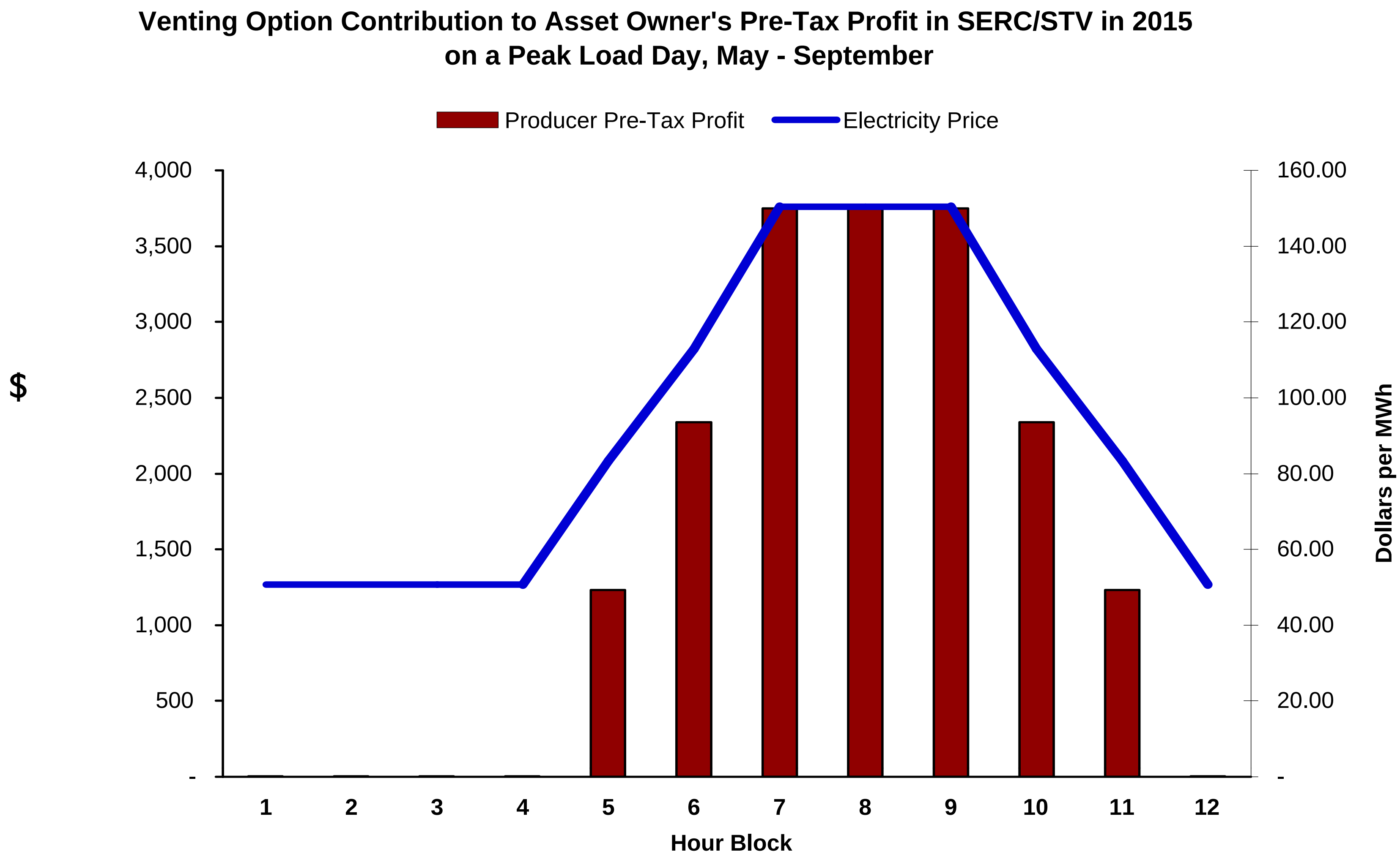
Simulations of electricity markets utilized a multi-region US electric sector model, NESSIE

Evaluated Value Across Three CO_2 Emission Allowances Price Scenarios *(EPRI Report 1011769)*



Note: This was 2007; the higher path would be viewed as low cost under current legislative proposals

Free Venting Allows Additional Revenue with Additional Cost of Paying for CO_2 Emissions



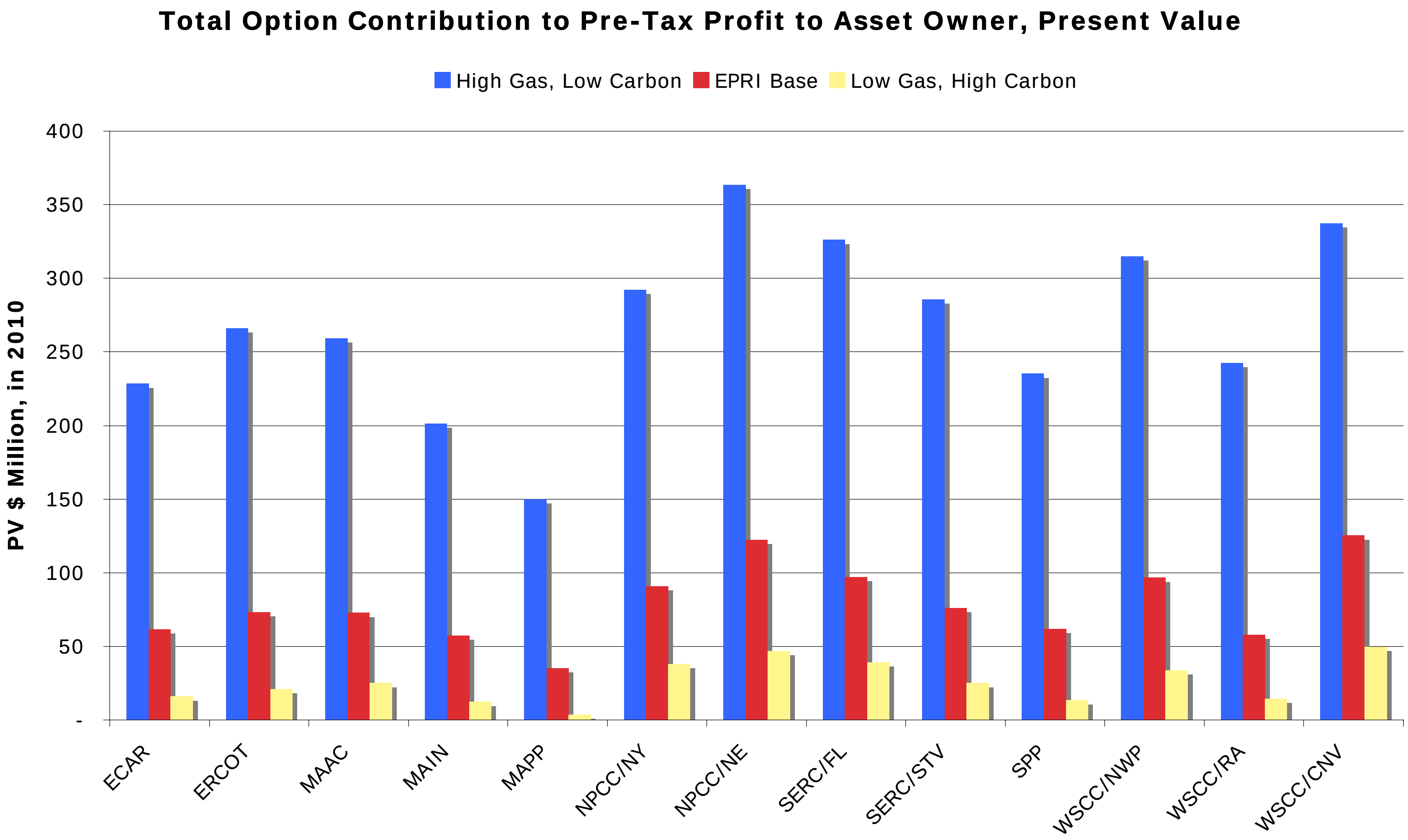
Venting Option Impact in the Southeast (SERC/TVS)

Producer Profit (PV in 2010)	
Net Profit ($ Million)	44.7
Net Profit ($ per kW)	80.4
Customer Cost (PV $ Million in 2010)	
Rate Savings due to Avoided Capacity	29.6
Taxpayer Receipts (PV $ Million in 2010)	
Net Taxpayer Receipts	19.6
Total Social Impact (PV $ Million in 2010)	**93.8**

Sensitivity of Value to CO_2 and Gas Prices

	High Gas, Low Carbon	EPRI Base	Low Gas, High Carbon
Producer Profit (PV in 2010)			
Net Profit ($ Million)	164.7	44.7	13.6
Net Profit ($ per kW)	296.2	80.4	24.5
Customer Cost (PV $ Million in 2010)			
Rate Savings due to Avoided Capacity	29.6	29.6	29.6
Taxpayer Receipts (PV $ Million in 2010)			
Net Taxpayer Receipts	84.2	19.6	2.8
Total Social Impact (PV $ Million in 2010)	**278.4**	**93.8**	**46.0**

Value of Option to Vent Varies by Region



2^{nd} Example of Flexibility: Oversized Air Separation Unit (ASU)

- Oversize the ASU by one third and provide storage for six hours of air products
  - Run ASU and overproduce at periods of low electric prices
  - Shut down ASU when electric prices are high, use stored air products, and sell production from reduced aux power loads into grid

Analysis Parameters for ASU Oversizing

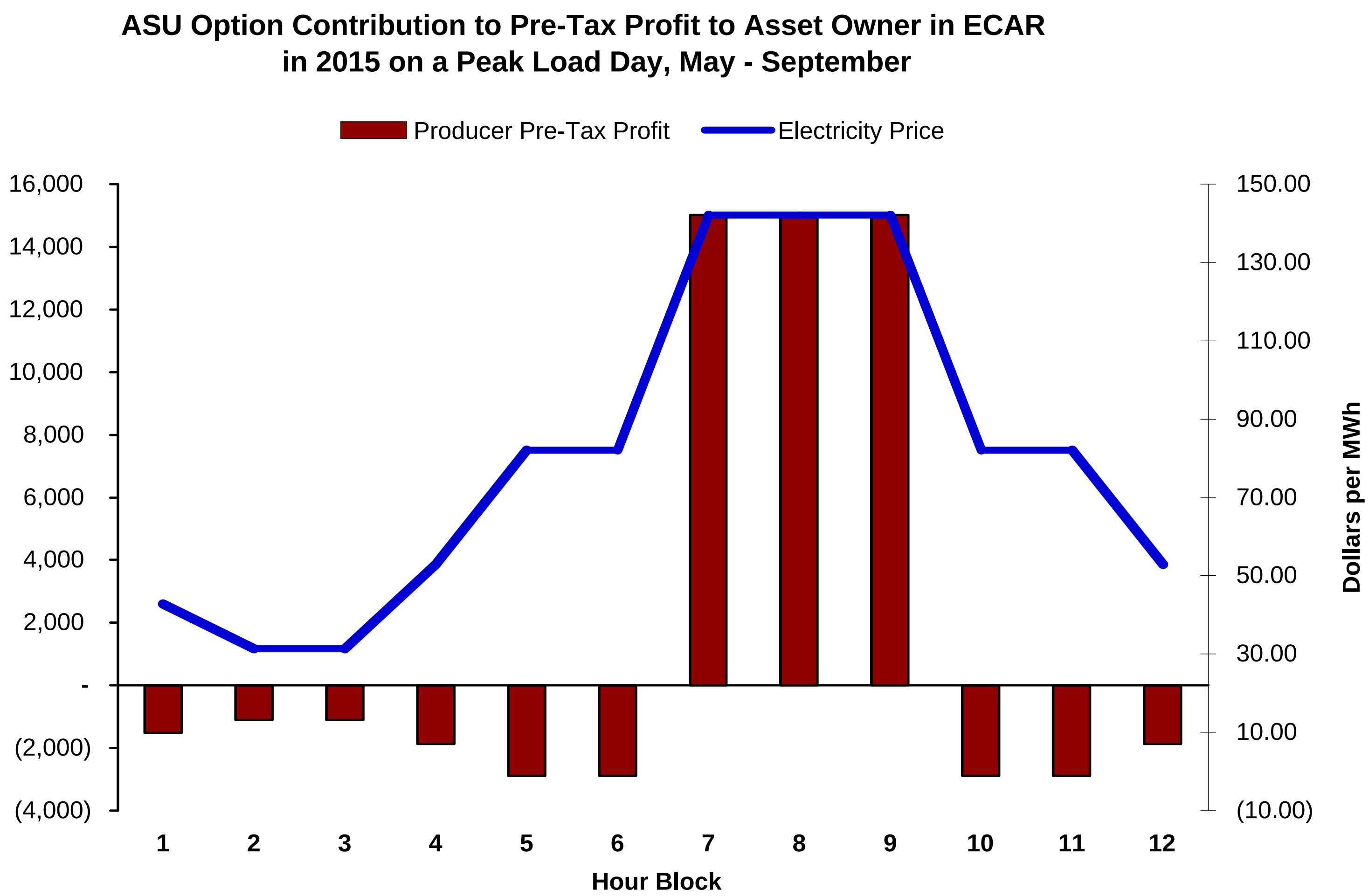
	Normal Operation	Larger ASU On	Larger ASU Off
Auxiliary Loads, MW	120	160	0
Gain in Output, MW		-40	120

Cost of ASU Expansion: 1/3 of Normal ASU Cost

Analysis Approach

- Need the price profile for each day in the year
- Find the highest six hours in the day and shut down the ASU during those hours
- The yearly cash flow value is the sum of the hourly values over the year

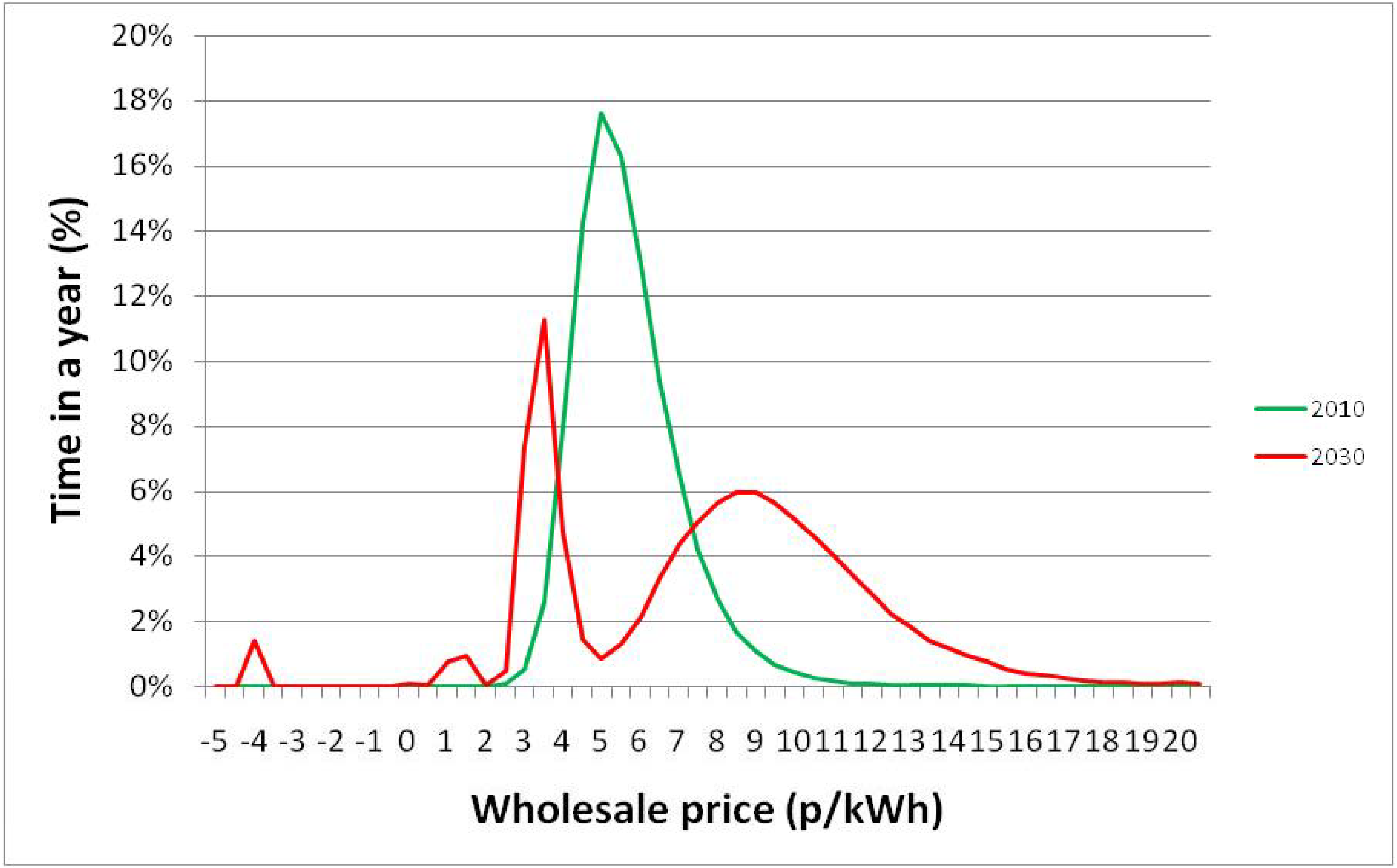
Calculating the Daily Cash Flow



ASU Option Impact in the Midwest (ECAR)

Producer Profit (PV in 2010)	
Net Profit ($ Million)	-51.0
Net Profit ($ per kW)	-91.8
Customer Cost (PV $ Million in 2010)	
Rate Savings due to Avoided Capacity	83.2
Taxpayer Receipts (PV $ Million in 2010)	
Net Taxpayer Receipts	-18.1
Total Social Impact (PV $ Million in 2010)	**14.0**

Value Likely Greater in a Low-Carbon System: E.g., UK Electric Prices in a Low-Carbon World?



Source: Redpoint modelling for Committee on Climate Change

Value Could Be Greater in When CO2 Price Volatility Considered

Source: IETA

Concluding Thoughts

- Both examples – venting and oversizing the ASU – potentially have positive social value even with simple analysis approach
  - Caveat: No detailed engineering done
  - Caveat: Did not consider ancillary services value and other possible value
  - Need more detailed analysis (stochastic, real options) to get better estimates
- Flexibility value depends on owner characteristics – region, electricity prices, need for peaking/quick replacement of intermittent generation
- Venting from a PC will provide more value because the capacity gain is greater than for IGCC
  - Capture technology advances reduce the energy penalty and the option value of flexibility
- Flexible operation will likely be a key issue for advanced coal with CCS
  - Operational reasons
    - If you have to have flexibility and can't vent … how do best implement it?
  - Possibly economic reasons – too early to tell how valuable it might be

IEA Greenhouse Gas R&D Programme

The Need for Flexibility in Power Plants with CCS

John Davison

IEA Greenhouse Gas R&D Programme

Workshop on operating flexibility of power plants with CCS

Imperial College, London, 11th-12th November 2009

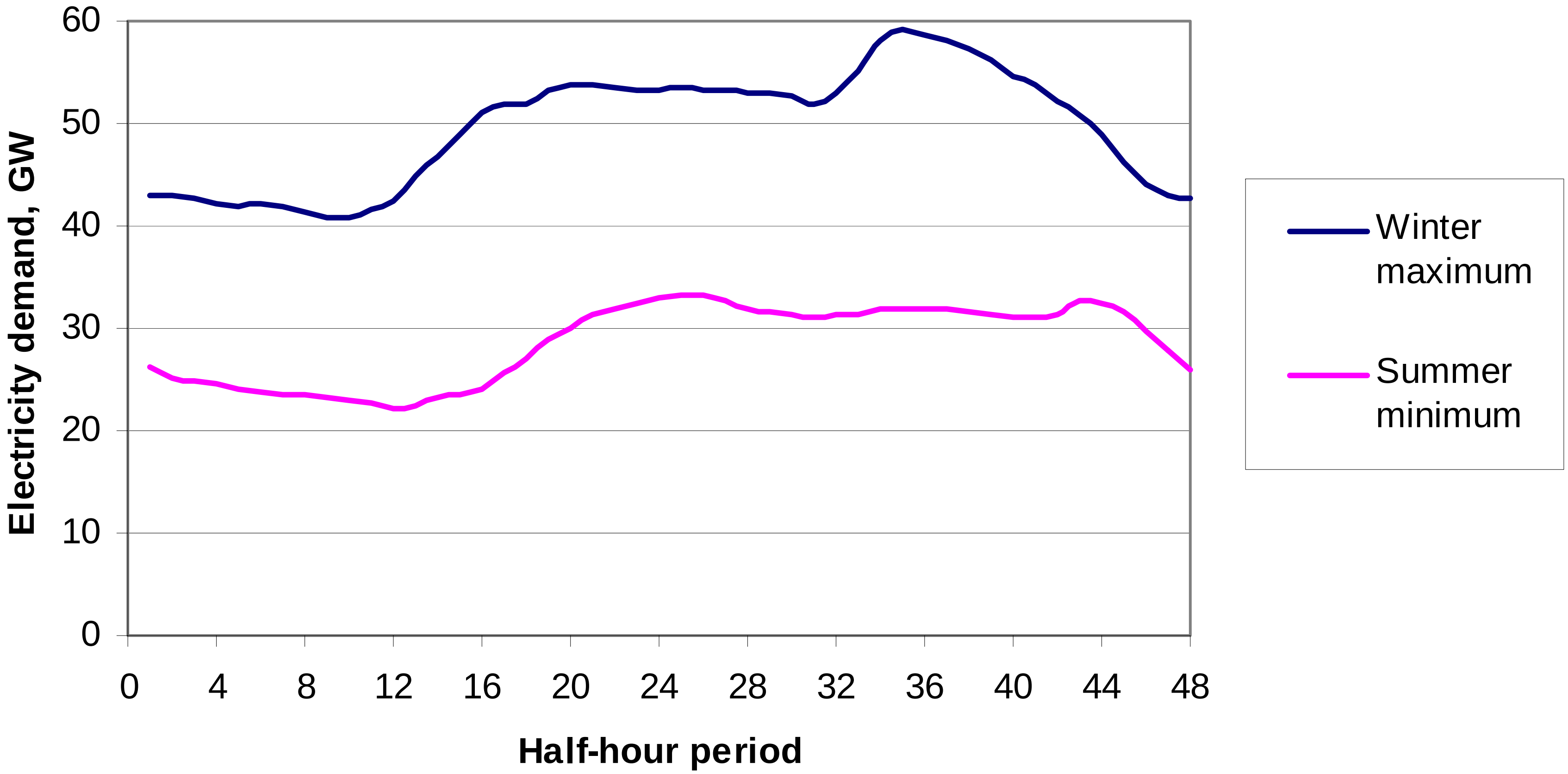
Outline of the Presentation

How flexible will CCS plants need to be?

- Variability in electricity demand
- By how much will CO_2 emissions need to be reduced
- Characteristics of the other generation technologies that will be used to reduce CO_2 emissions

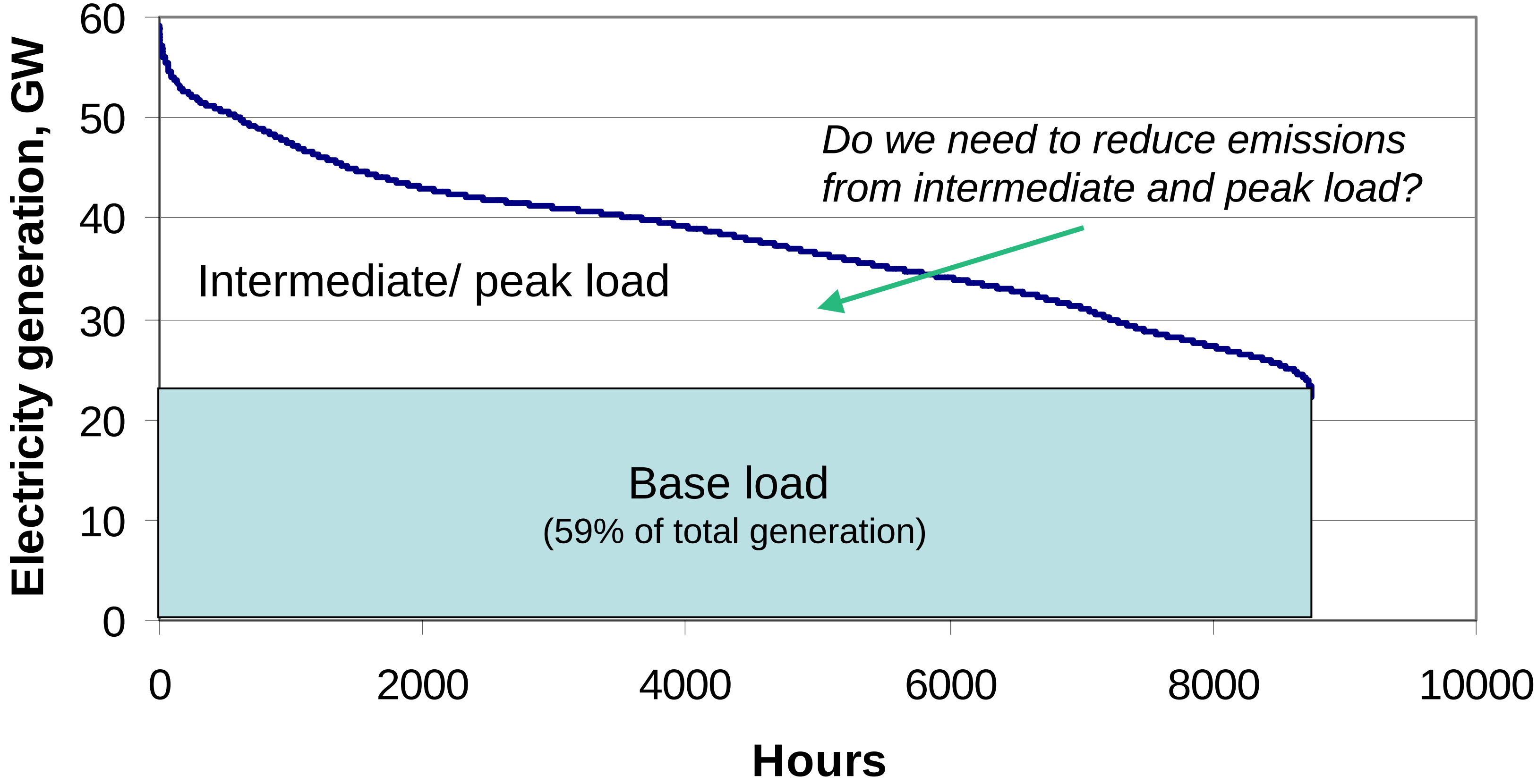
Can we avoid the need for CCS plant flexibility?

Electricity Demand



UK, 2008-9

Electricity generation



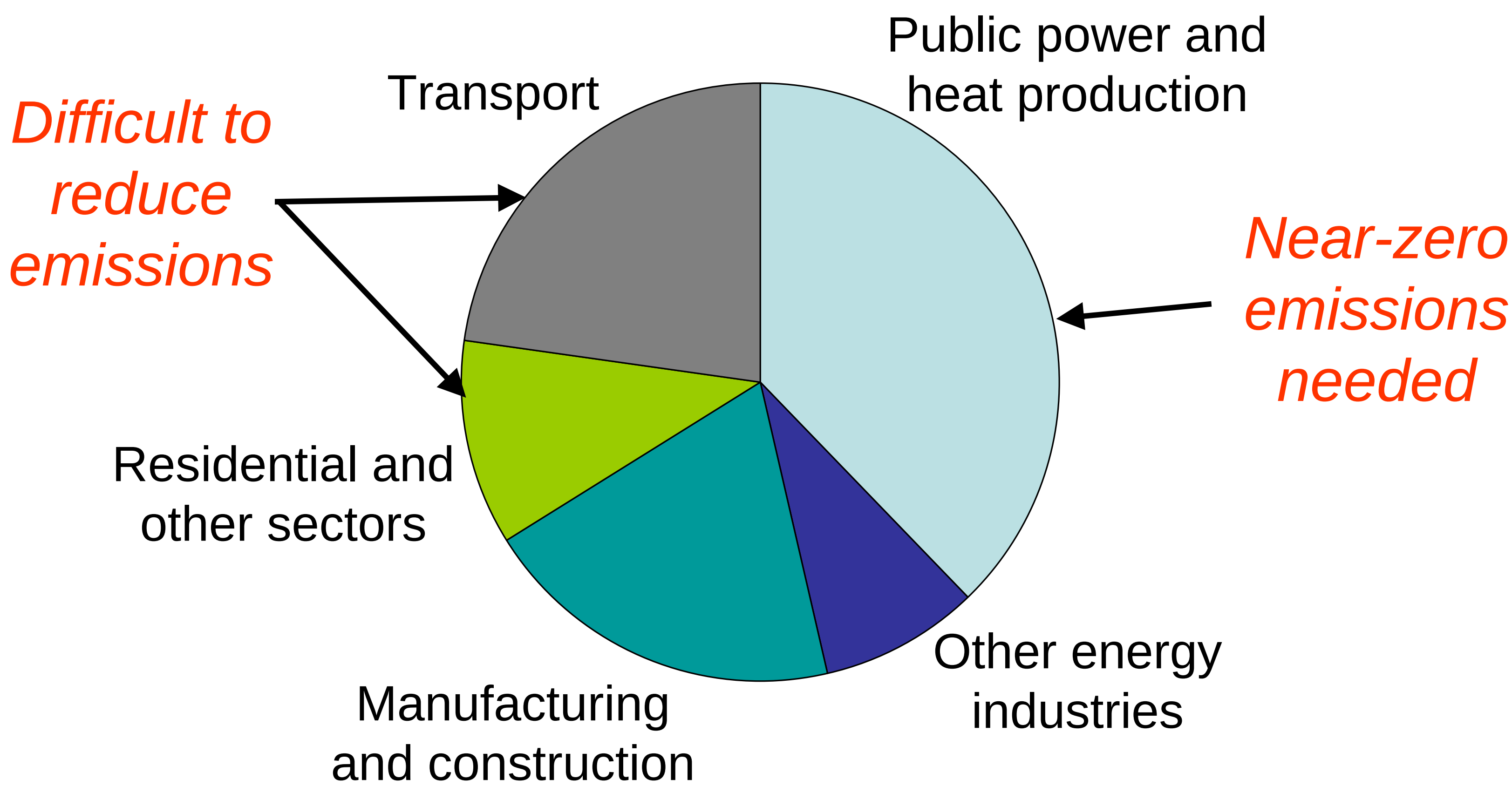
Data source: UK, 2008-9

The Need for Deep Reductions in Emissions

G8 meeting, L'Aquila, Italy 2009:

- "The G8 countries have committed to reduce their greenhouse gas emissions by 80% or more by 2050 with reference to 1990 or more recent years."
- "G8 countries committed to undertake significant comparable mid-term reductions, coherent with the long term objectives."

CO_2 Emissions



IEA 2007 data, excludes land-use change

Techniques for Emission Reduction

- Energy efficiency improvements
- Land-use changes
- Changing to lower carbon fuels (coal to gas)
- Renewable energy
- Nuclear
- CCS

Impact of Renewable and Nuclear Energy

- Large increases in renewables are expected
  - EU's Renewable Energy Directive commits to 20% of overall energy from renewable sources by 2020.
  - For electricity a greater fraction may be required
    - E.g. ~35% in the UK
  - Wind, solar, tides etc have variable outputs
- Use of nuclear is expected to increase in some countries, decrease in others
  - Nuclear plants are relatively inflexible

Impact of Renewable and Nuclear Energy

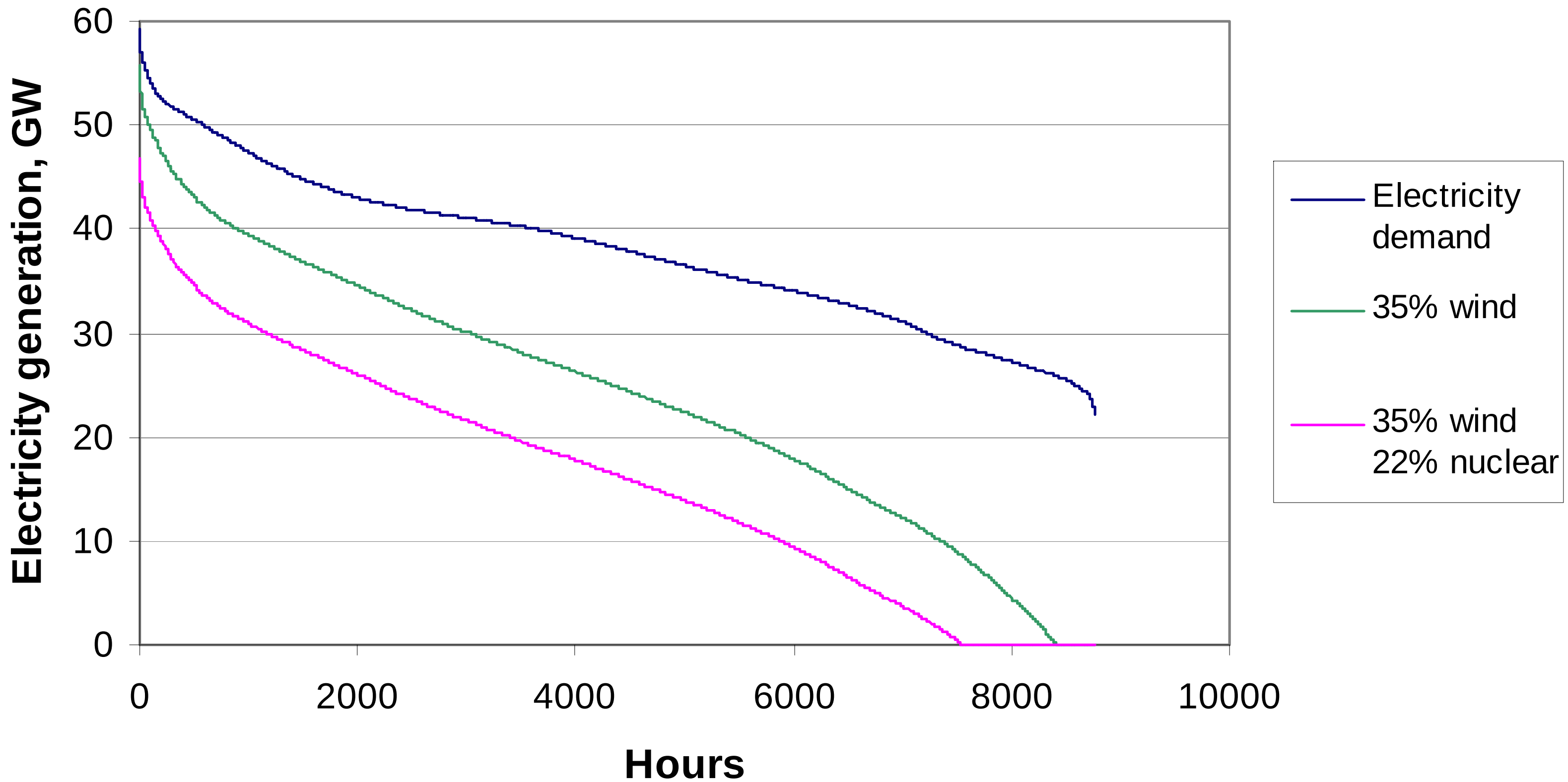
Marginal operating cost merit order

- Wind / solar etc
- Nuclear
- Fossil fuels with CCS / Biomass
- Fossil fuels without CCS

Low marginal cost, operate whenever available

Higher marginal cost, operate at lower load factor

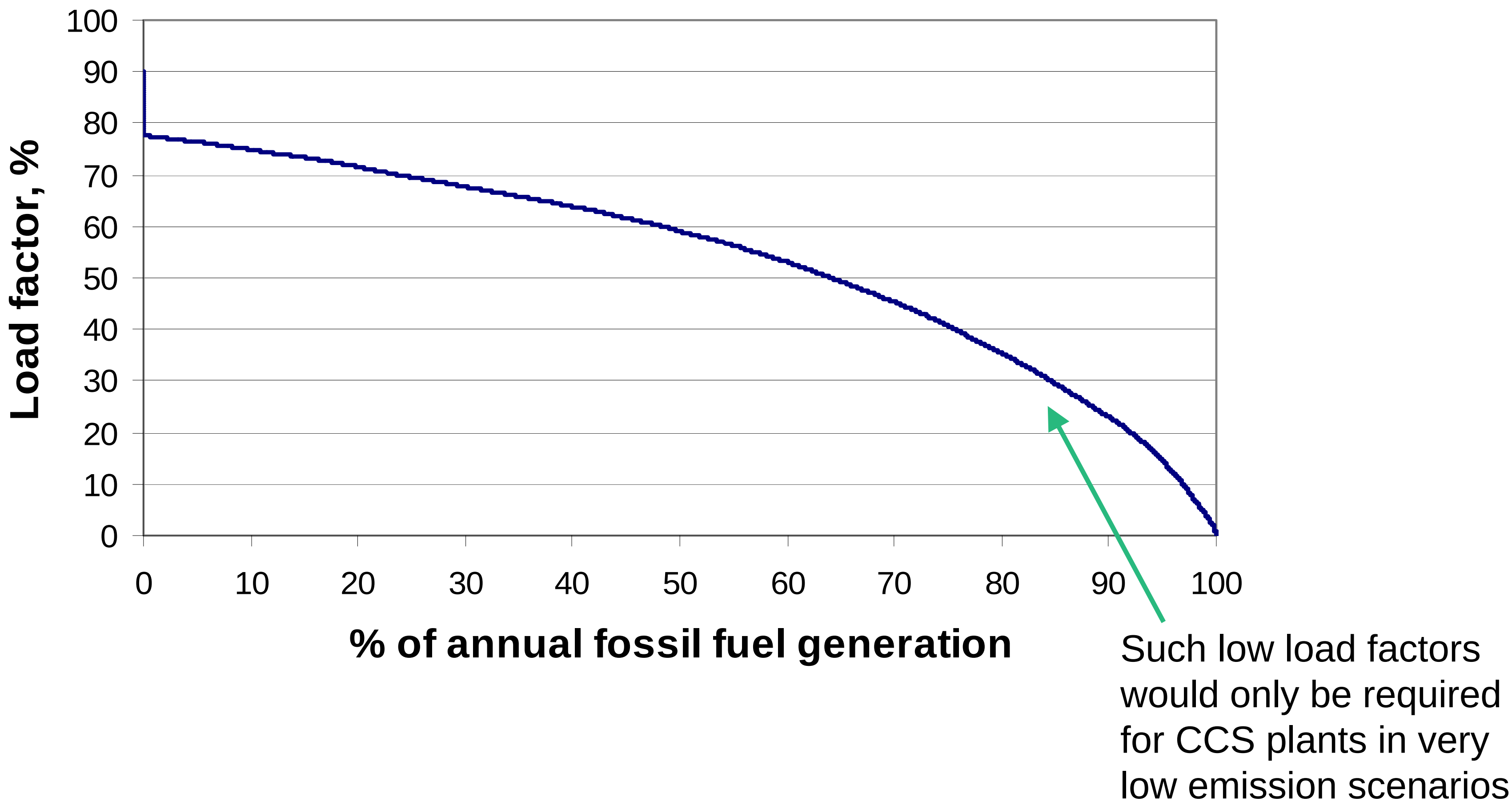
Fossil Fuel Power Generation



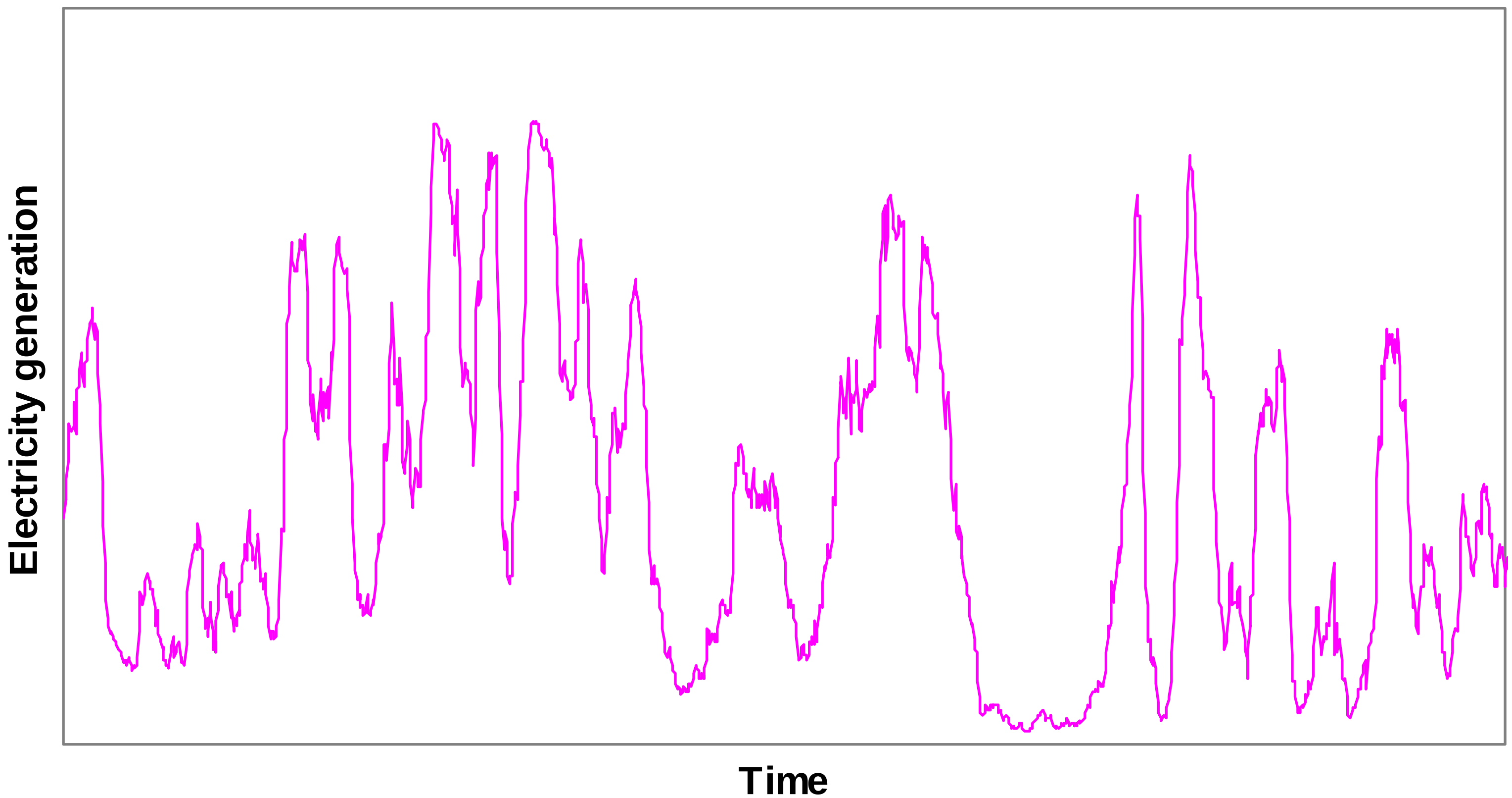
Data sources: UK power demand 2008-9
Wind energy scaled from current UK output

Fossil Fuel Plant Load Factors

35% wind, 22% inflexible nuclear generation

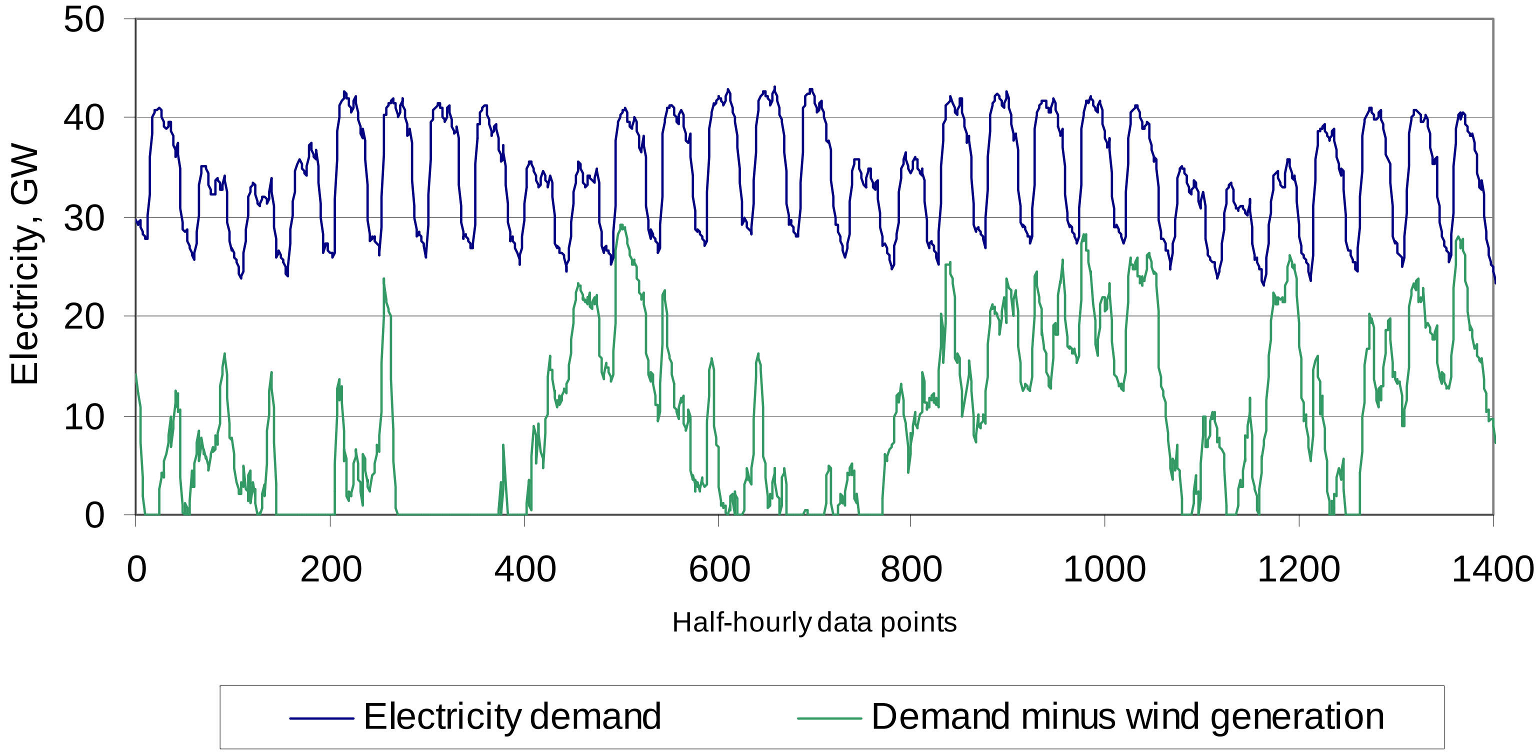


Variability of Wind Generation



HV grid connected wind in the UK, May 2009

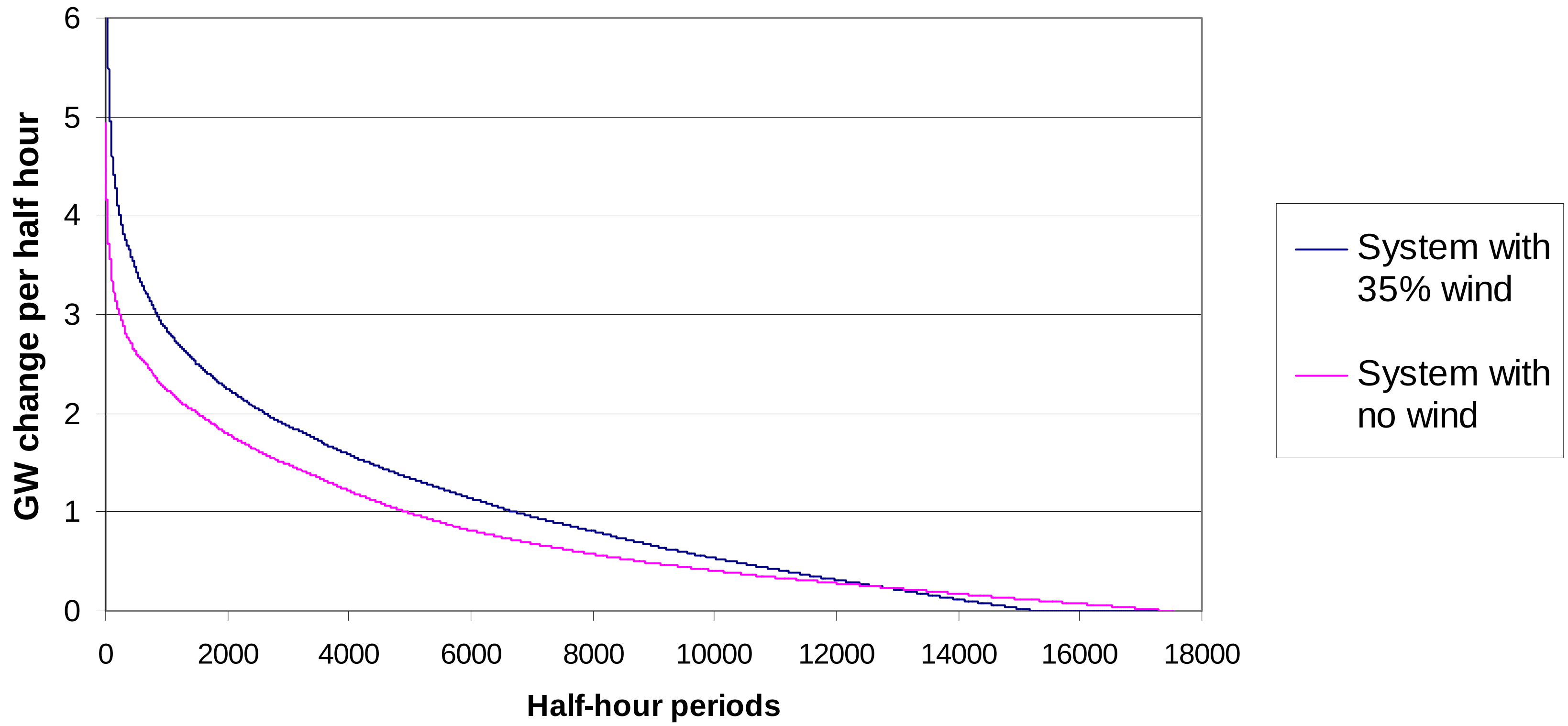
Electricity Supply from Non-Wind Plant



Basis: UK, May 2009, wind scaled to 35% of total generation

Rate of Change of Load

Impact of wind generation on fossil fuel power plants



Basis: UK power demand (maximum 59GW)
22% of generation from ‘inflexible’ plants
Wind output scaled from current system output

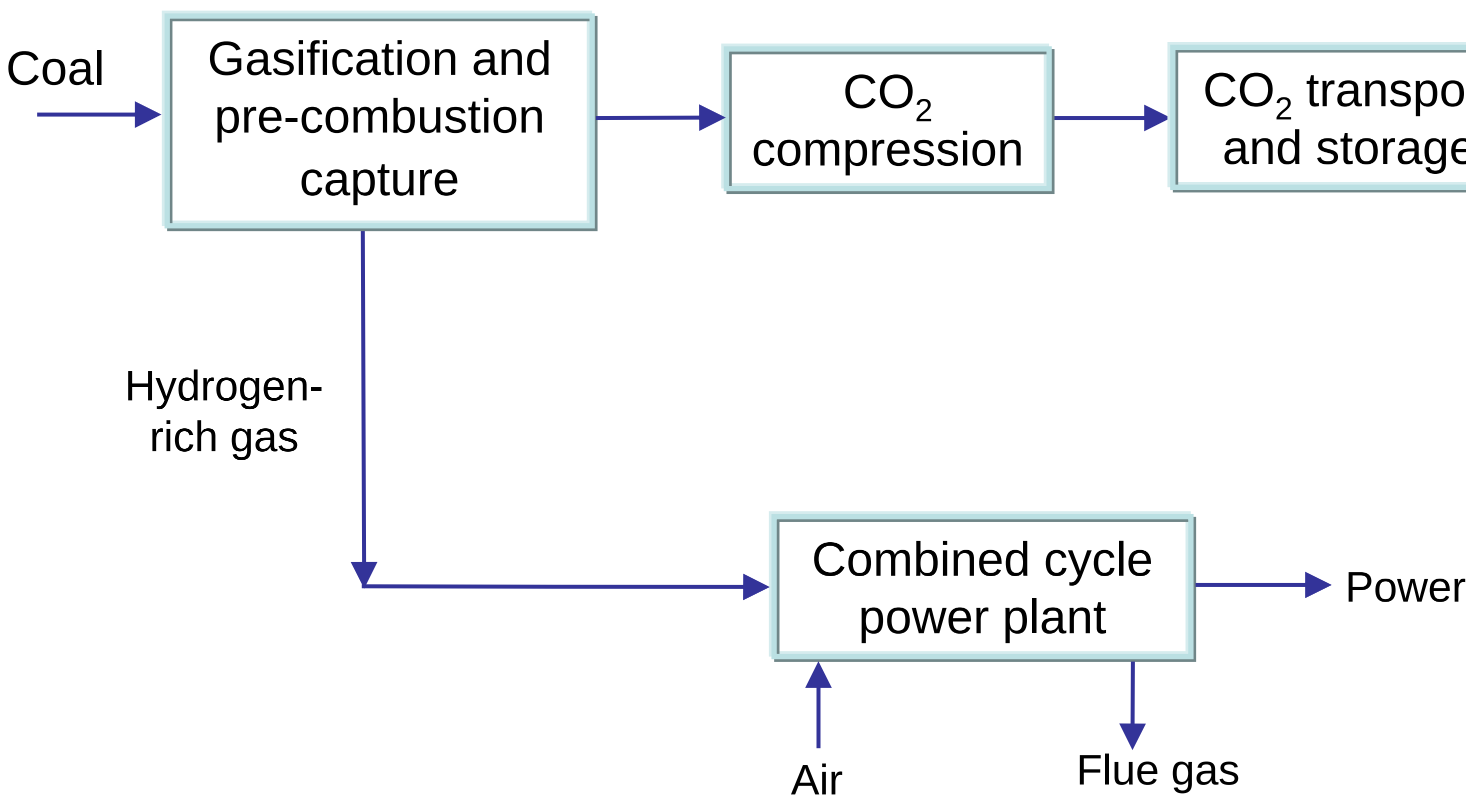
Economic Implications

- CCS plants are capital intensive
- Operation at low load factors increases costs
- This may not be a significant problem
  - There is limited competition to CCS for intermediate load generation with low-CO_2 emissions
    - Hydro and biomass have major resource constraints
  - Prices of intermediate load power will be higher in a carbon-constrained world

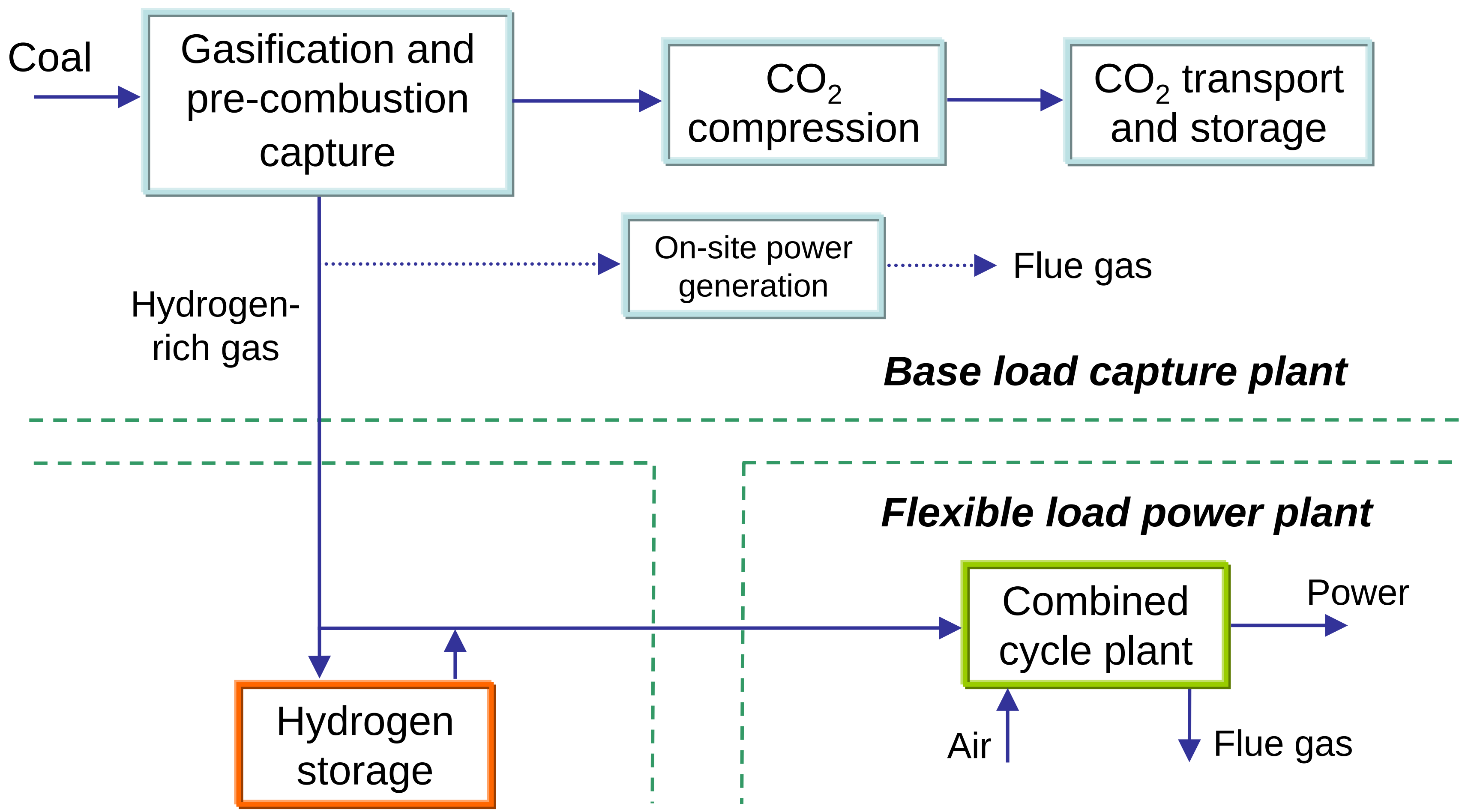
Can the Need for Flexibility be Avoided?

- Smart grids, load shifting etc to smooth demand
- Electricity storage
  - Pumped hydro, compressed air storage, flow batteries etc
  - Electrolysis to produce hydrogen – an expensive option
- Include energy storage in CCS processes
  - Solvent storage in post combustion capture (short term)
  - Oxygen storage in IGCC and oxy-combustion (short term)
  - Hydrogen storage in gasification combined cycles (short and long term)

Integrated Gasification Combined Cycle



Gasification Combined Cycle with H_2 Storage



Gasification Combined Cycle with H_2 Storage

- Gasification, capture and storage can operate at base load – no need for flexibility
- Only the combined cycle plant has to operate flexibly
- High utilisation of capital investment
- Underground hydrogen storage is proven technology, e.g. in salt caverns in Texas and UK
- Small cost and efficiency penalties for non-integrated base load plants
- Large cost advantage for intermediate load plants
- 99% CO_2 capture is possible

Conclusions

- CCS flexibility requirements depend on external factors:
  - Variability of electricity demand
  - The overall GHG abatement requirement
  - The amount of wind and nuclear in the system
  - Developments in electricity system load management
- Some CCS plants will be able to operate at base load if there is a modest CO_2 abatement requirement, little wind and nuclear or high load management
- Most CCS plants will probably have to operate flexibly
- Including energy storage in some CCS processes can be an effective way to reduce the need for flexible operation

The impact of intermittency

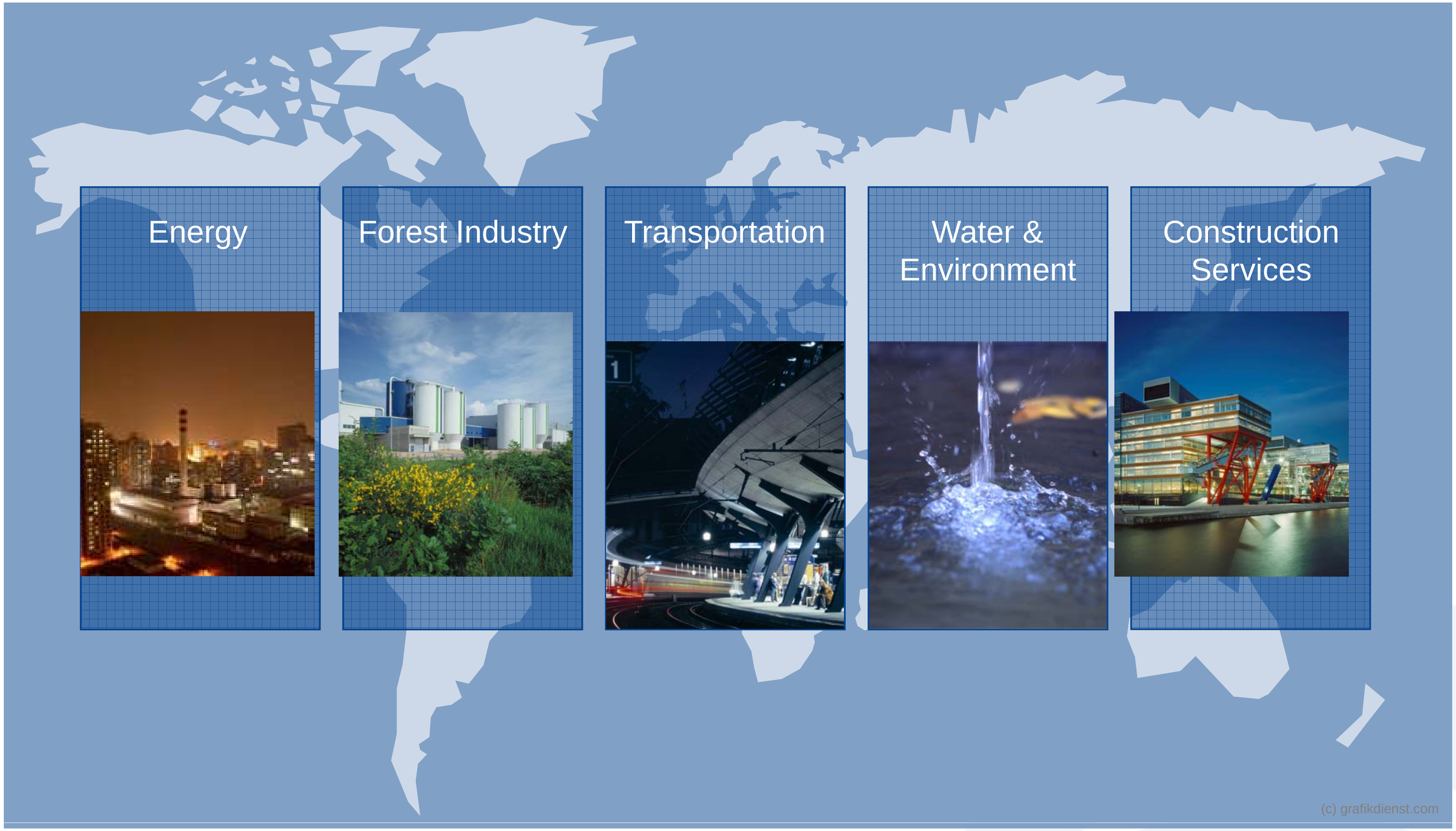
A presentation to IEA GHG/ Imperial College

11 November 2009

Agenda

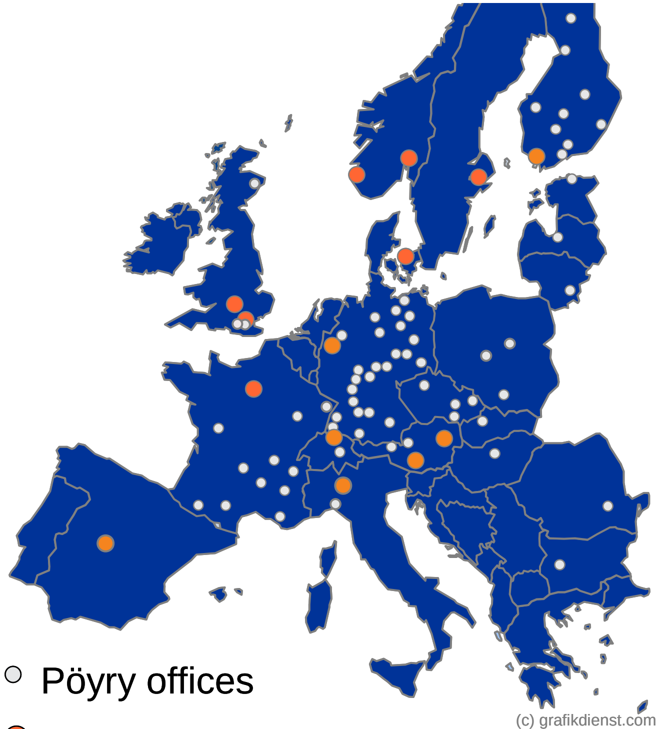
1. About Pöyry
2. Introduction to study
3. Thoughts on an intermittent world

Pöyry Plc – global consulting and engineering company



PÖYRY

Pöyry Energy Consulting



○ Pöyry offices

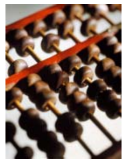
● Pöyry Energy Consulting offices

Over 250 energy market experts in 15 offices across Europe:

- Copenhagen
- London
- Moscow
- Paris
- Vienna
- Düsseldorf
- Madrid
- Oslo
- Stockholm
- Villach
- Helsinki
- Milan
- Oxford
- Stavanger
- Zurich

Strategy

Business Operation



Valuation & Financing

Sustainability

PÖYRY

Agenda

1. About Pöyry
2. Overview of study
3. Thoughts on an intermittent world

Study objectives

'How could the impact of intermittent generation, required to meet targets for renewables and decarbonisation of generation, affect the wholesale energy markets in GB and Ireland?'

Specific areas of investigation

- Market prices
- Plant operation
- New thermal generation
- Wind revenue
- Reserve and response
- Interconnection and transmission
- Market arrangements
- Security of supply

Study summary

Overview

- Almost £1m budget
- Nov 2008 – May 2009
- 5 Workstreams
- 4 Steering Group meetings
- 2 major presentations
- Final report

Sophisticated computer modelling…

- 2.8 million wind records
- Each model run generates 50 million records, 840,000 prices and a 1.5GB database
- A total of 150GB of data generated from the study

Study membership

6 Founders

- Centrica
- DONG
- EirGrid
- ESB/I
- National Grid
- RES

10 Members

- Bord na Mona
- Committee on Climate Change
- DECC
- Bord Gais
- RWE
- EDF Energy
- Premier Power
- Scottish Power
- CER/NIAUR
- Premier Power
- SWS Energy

- 4 government bodies
- 3 grid operators
- 4 established players/ incumbents
- 2 wind power operators
- 3 new entrants

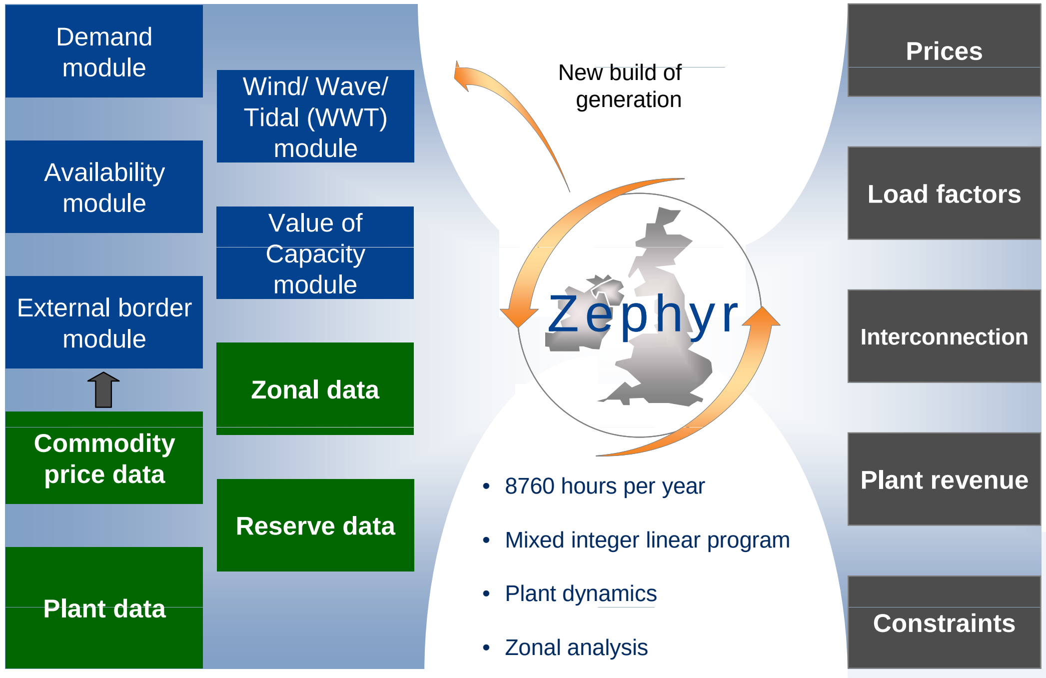
Summary of modelling

Zephyr has been designed specifically to answer the key questions about how intermittency could affect the GB wholesale market

Principles

- Detailed underlying wind data
  – Hourly data for 8 years for 36 sites
- History as basis
  – Wind, availability and demand
  – 8 historical simulations for each future year
- Zonal analysis
- Value of capacity
- System security standard

Platform



PÖYRY

Agenda

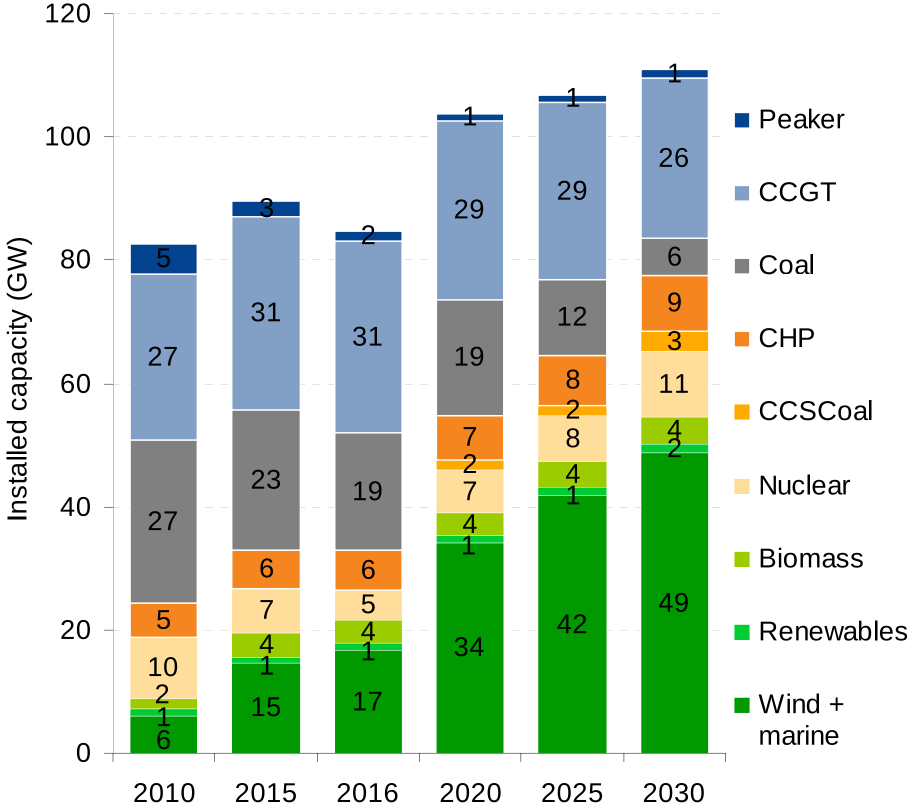
1. Introduction to study
2. Overview of study
3. Thoughts on an intermittent world

PÖYRY

Summary of ‘Core scenario’

The study was focused around a Core scenario. It does not represent a base case but instead provides a ‘stress-test’ with a high percentage of generation from renewables.

Installed capacity assumptions in GB



Fuel and demand assumptions

- Demand was assumed to grow at around 0.4% p.a.

- Oil price ~$70/bbl
- Coal price ~$70/tonne
- Carbon price ~€37/tCO_2

- New build of CCGT and coal is market determined

- New build of renewables, nuclear and coal CCS is ‘non-market determined’

PÖYRY

The study assumed wind generation build patterns across the UK and the ROI

Hourly historical wind speed data for each region was used to simulate wind generation

Installed capacity by region: 2020

GB Capacity: 32.7GW

SEM Capacity: 6.1GW

Installed capacity by region: 2030

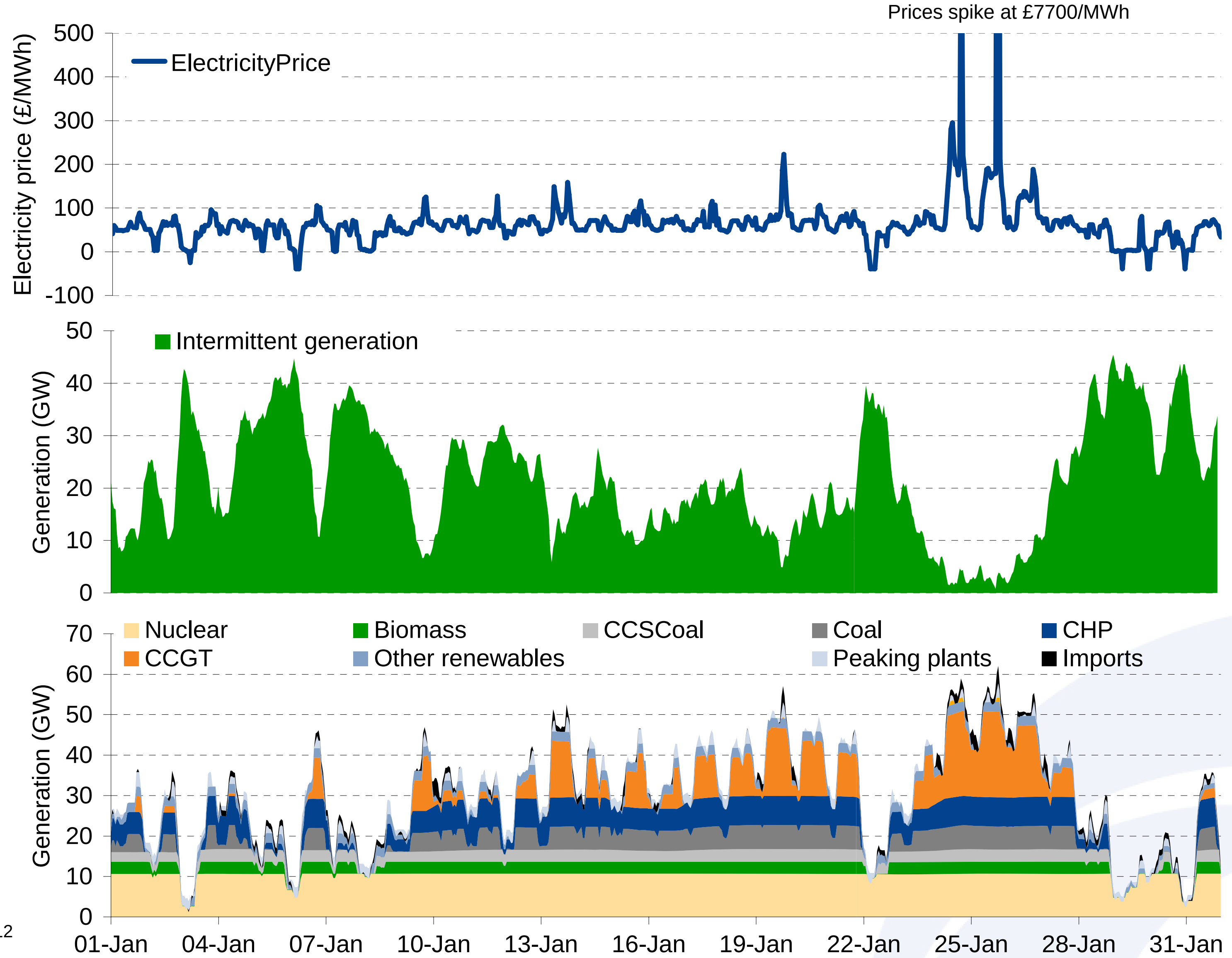
GB Capacity: 43.1GW

SEM Capacity: 7.9GW

Installed capacity (MW): 1000 5000 8000

January 2030 (based on 2000 data)

The model allows highly detailed simulations of future years based on historical weather data. The example below shows January 2030 based on actual wind data from 2000

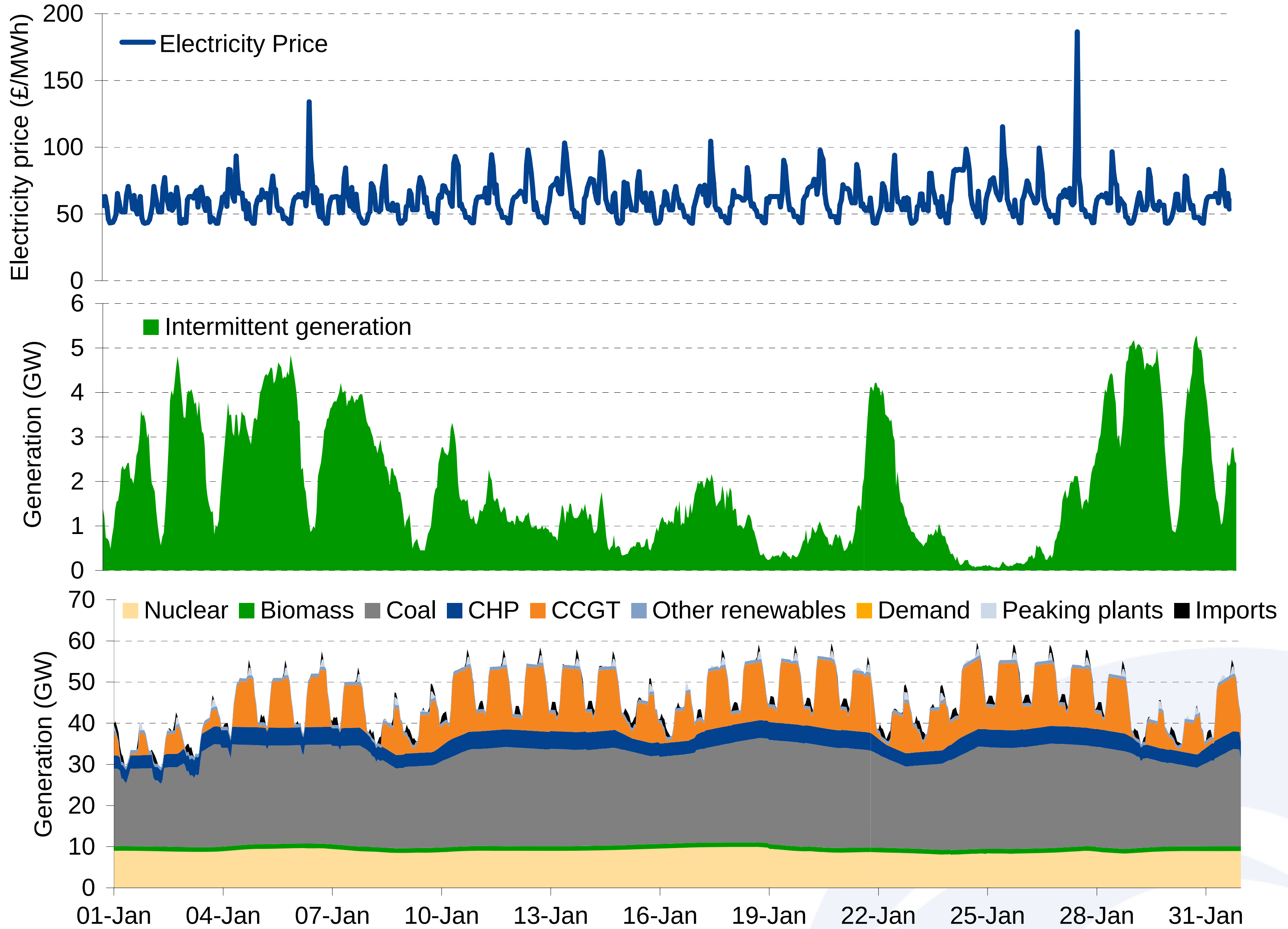


Prices may become highly volatile, and driven increasingly by wind generation

Wind generation is very variable, leading to periods of very high generation, and periods of very low generation

Thermal plant will have to operate in a different manner, with lower load factors and higher risk

GB – January 2010 (based on year 2000)



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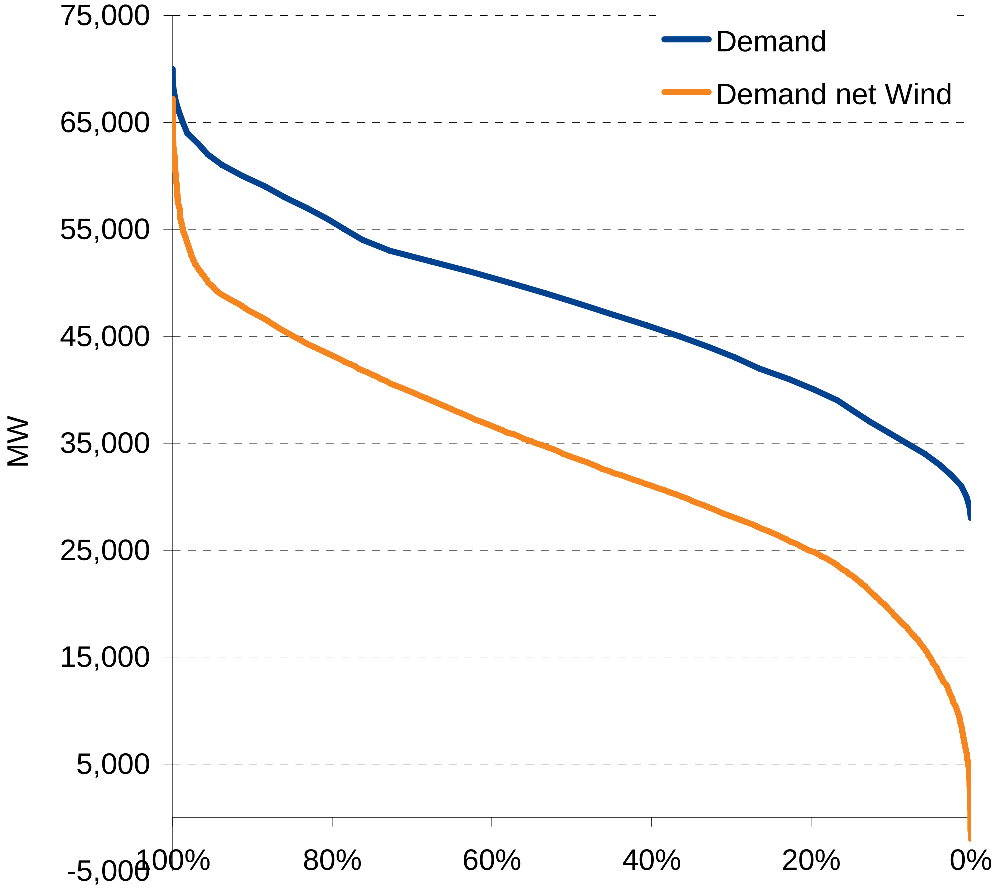
Understanding the 'demand net wind'

Operating space for thermal plant will decrease

Demand and demand net wind duration curve for GB in 2030

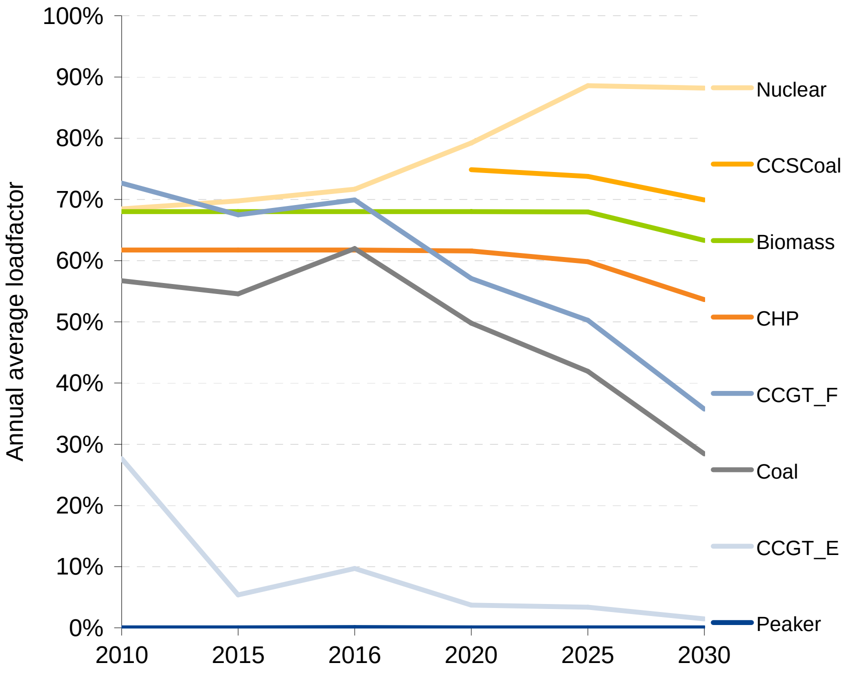


- At present, there is a continuous requirement of around 30GW
- In the core scenario demand net wind varies between 0-65GW
- Less need for base load generation

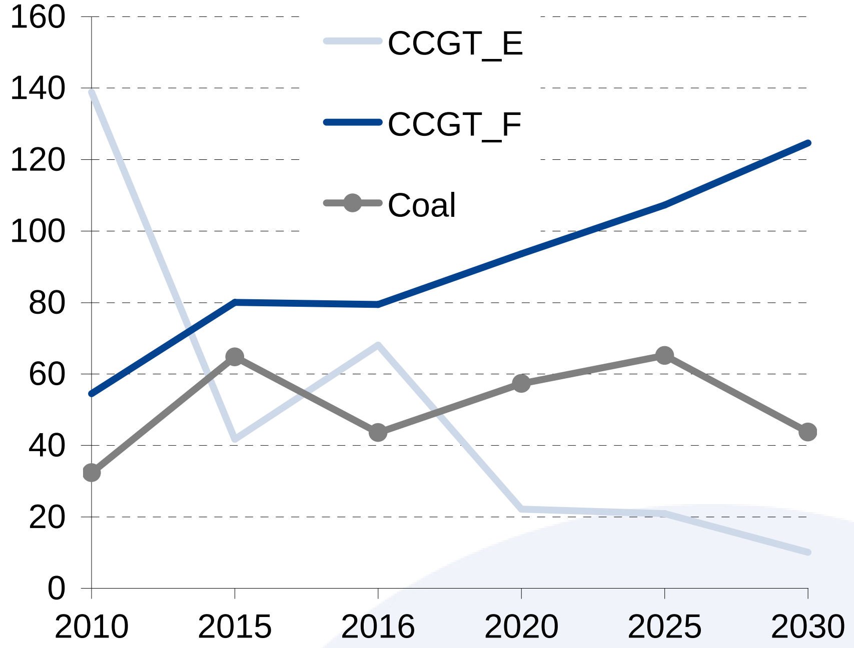
Plant operation profiles will change radically

Not only will thermal plant load factors be squeezed by intermittent and baseload generation, but operating regimes will change

Load factor by plant type – GB



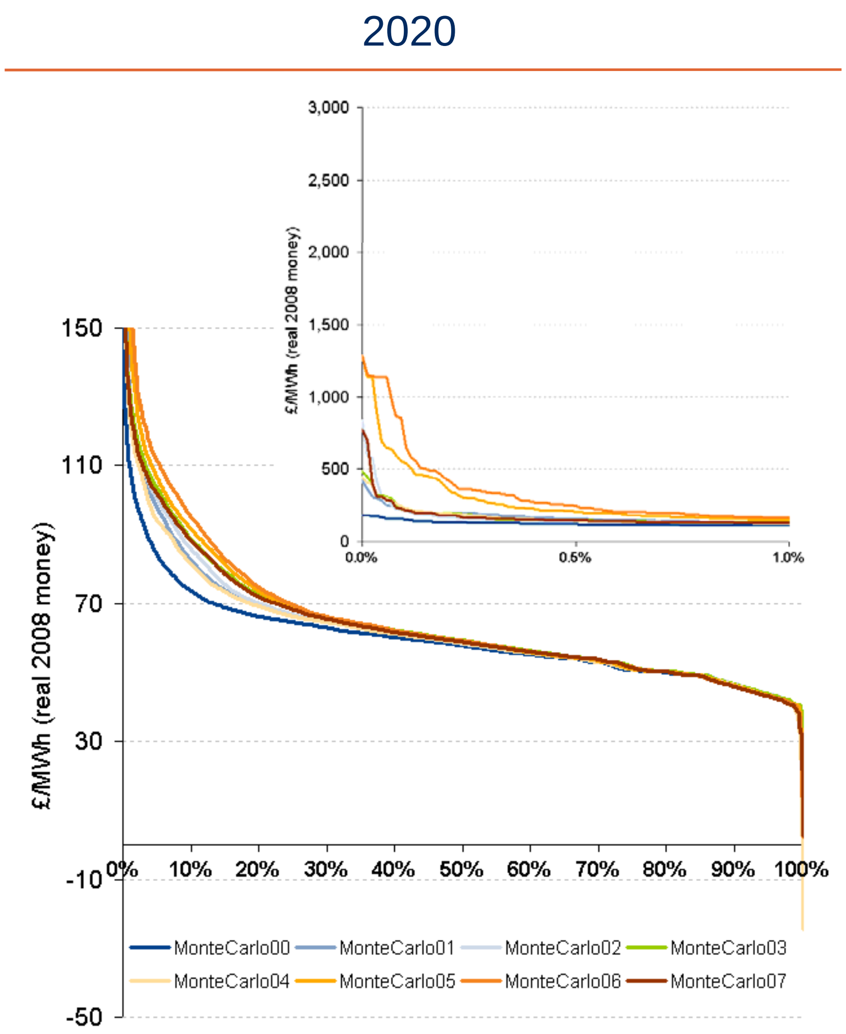
Starts per year

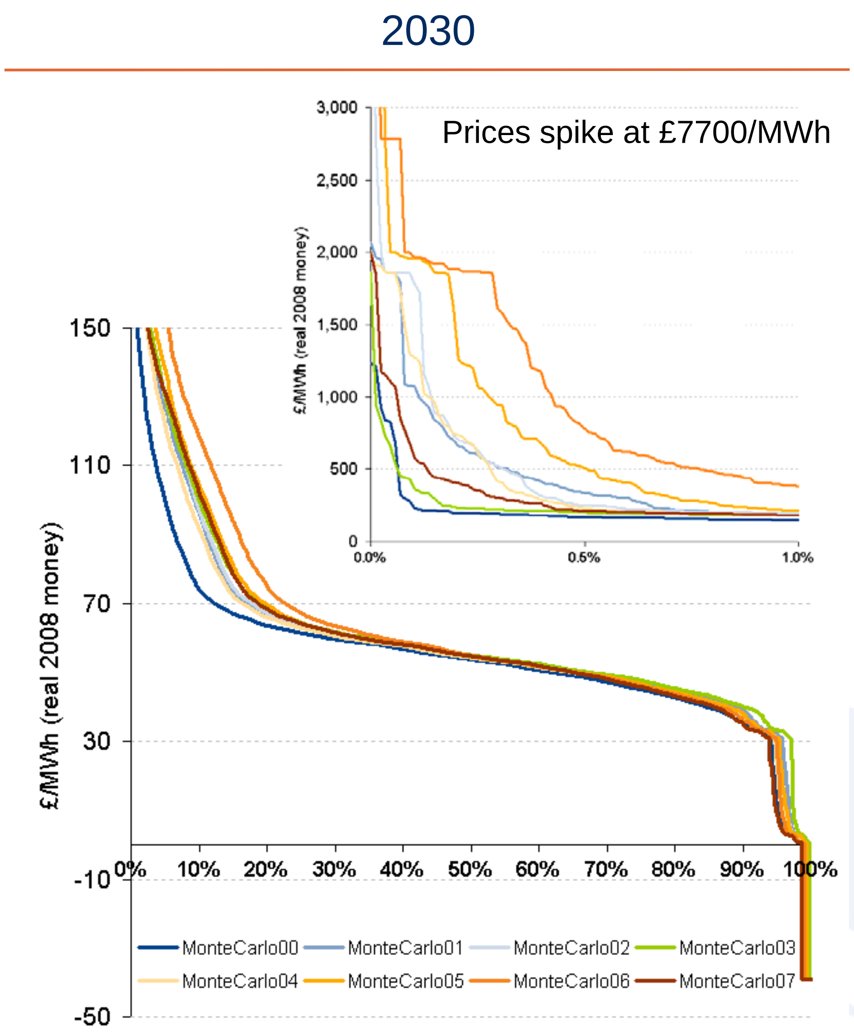


Data from Core scenario

Sensitivity of prices year on year

If security of supply is maintained, prices will become very peaky – with prices over £7000/MWh and less than zero by 2030

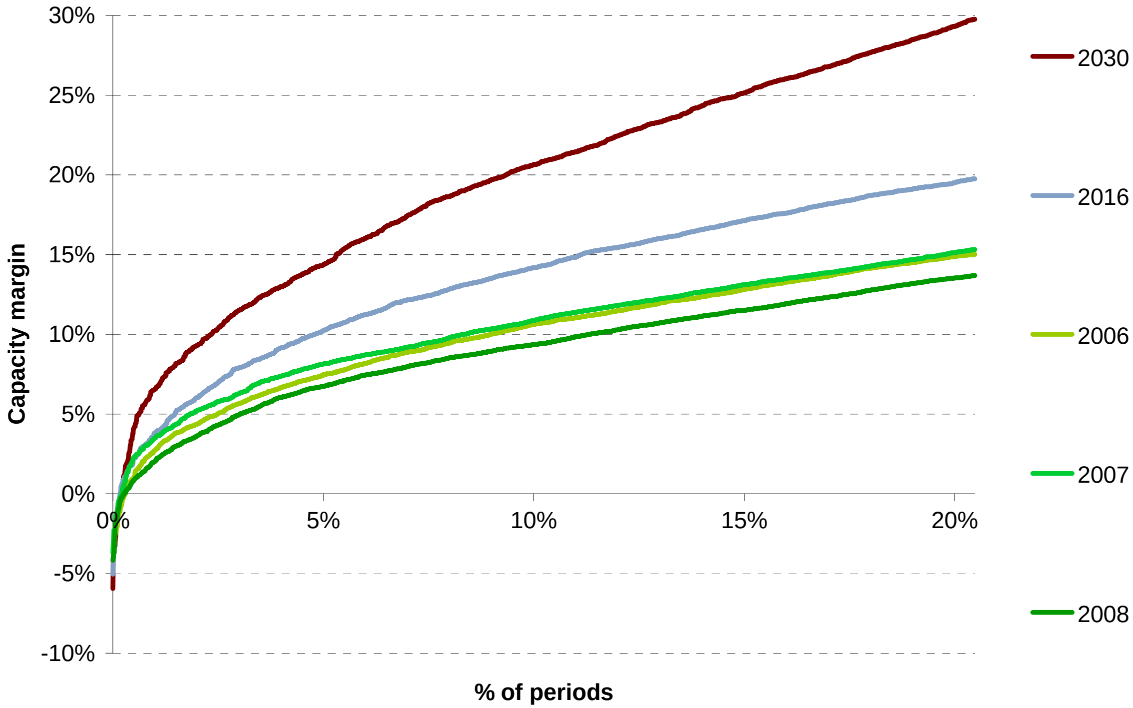




GB faces an investment conundrum

Earning the returns below will become increasingly difficult, as the scarcity value has to be captured in a smaller number of hours

Capacity margins in GB



- LCPD and (possibly) the IED will retire old mid-merit and peaking generation
- With a continuation of BETTA, the capture of capacity revenue will become more difficult
- Differences in outcomes between a BETTA and SEM market are stark

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Summary

- A high wind world will look very different to currently

- The thermal system will flex in response to the wind
- Extremes will become more important
- Spiky prices
- Uncertainty and risk
- Changing operating patterns
- Investment conundrum in GB

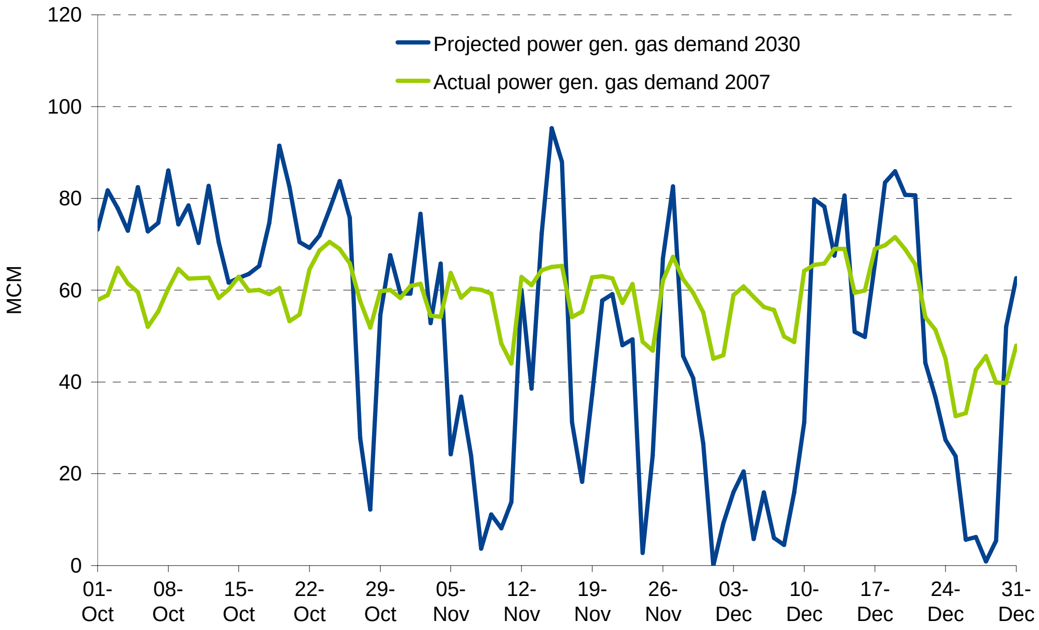
- Is CCS well suited to this environment?

- Potential effect on gas network?

Gas intermittency project

A multi-client gas intermittency project began in September, investigating the implications on the gas network

Daily gas demand



Areas of investigation

- Market and investment
- Value of storage and flexibility
- System operation
- Regulation

PÖYRY

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Grid and Process Modeling of Flexible Post-Combustion CO_2 Capture

Stuart Cohen
EPA STAR Fellow, Ph.D. Student
Thermal/Fluids Systems Division, Department of Mechanical Engineering
The University of Texas at Austin

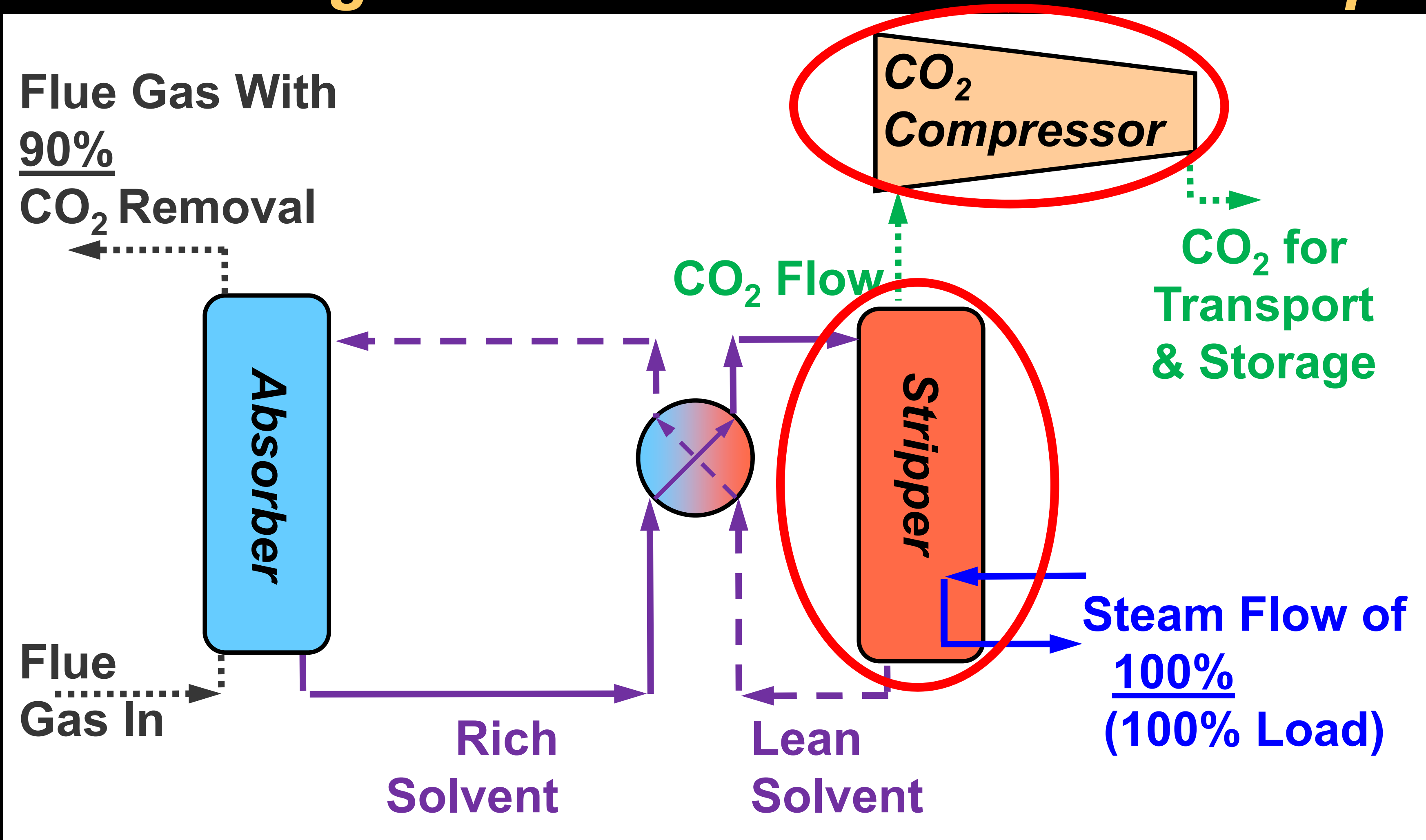
Workshop on Operating Flexibility of Power Plants with CCS

November 11, 2009

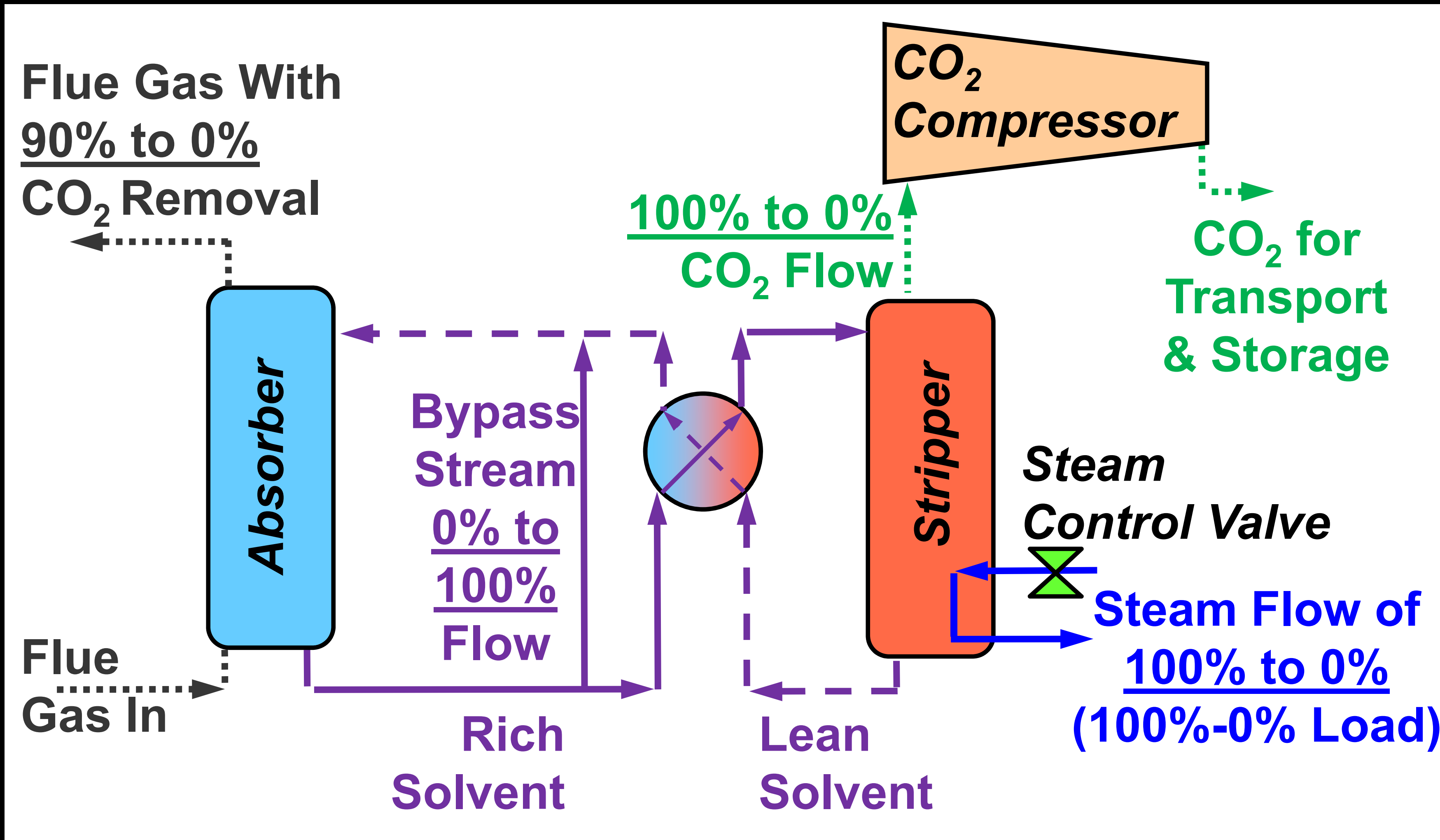
Outline

- Flexible post-combustion absorption/stripping
- Flexibility in response to hourly electricity demand and price variations
  - Multi-year analysis
- Dynamic process modeling

CO_2 Absorption/Stripping & CO_2 Compression Uses a Large Fraction of Power Plant Output



Instead, Could Vary Steam Rate and Stripper Solvent Rate for Flexible Operation



A Thermo-economic Grid Model is Created to Examine Flexible CO_2 Capture in Response to Hourly Electricity Market Variations

INPUTS

Hourly electricity demand for day to decade-long periods

CO_2 and fuel prices

Plant performance & economic parameters

1st order dispatch & electricity market model

OUTPUTS

Hourly generation for each plant

Market electricity price

Operating profits

CO_2 emissions

Flexible CO_2 capture utilization

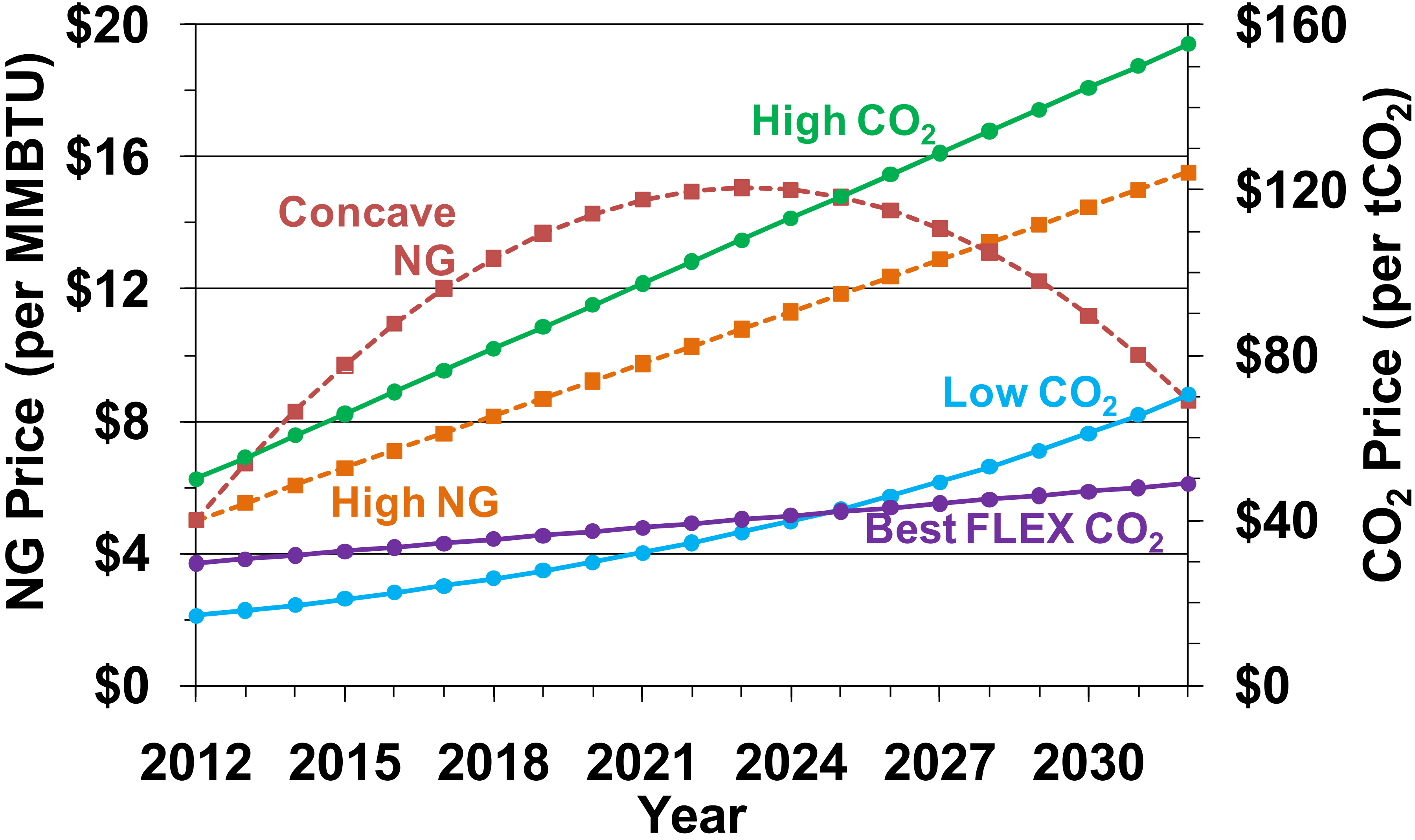
The Dynamic Model Considers Several Electric Grid Scenarios

Scenario	CO_2 Capture Installed?	Flexible CO_2 Capture Operation?	CO_2 Capture at Partial-Load When?
BAU (no capture)	No	n/a	n/a
CCS Base (inflexible capture)	Yes	No	*Never*
FLEX Op Costs	Yes	Yes	*When operating costs are less at partial-capture load*
FLEX Profit	Yes	Yes	*When operating profits are greater at partial-capture load*

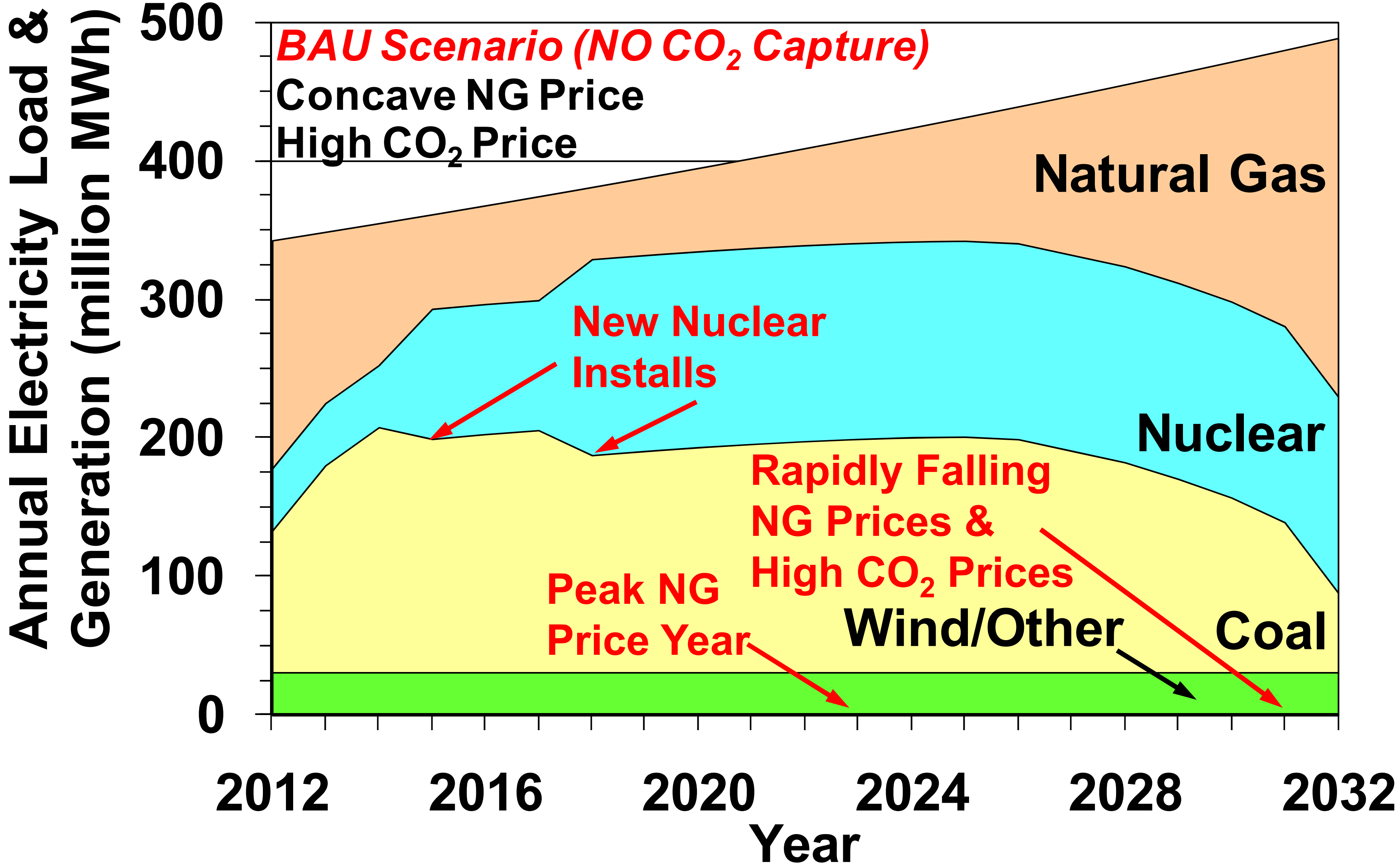
The Model Has Recently Been Adapted for Multi-Year Analysis of Dynamic Grid Behavior in ERCOT (TX grid)

- 8 of 15 current and all new ERCOT pulverized coal-based plants are considered for CO_2 capture
- For flexible CO_2 capture scenarios
  - Choose between 20% and 100% load
  - Energy use per tCO_2 nearly the same at each operating point, but greater emissions at 20% load (venting)
- Electricity demand increases 1.8%/yr
- Current grid planning documents used to estimate future ERCOT power plant fleet
  - 2 large nuclear installations in 2015, 2018

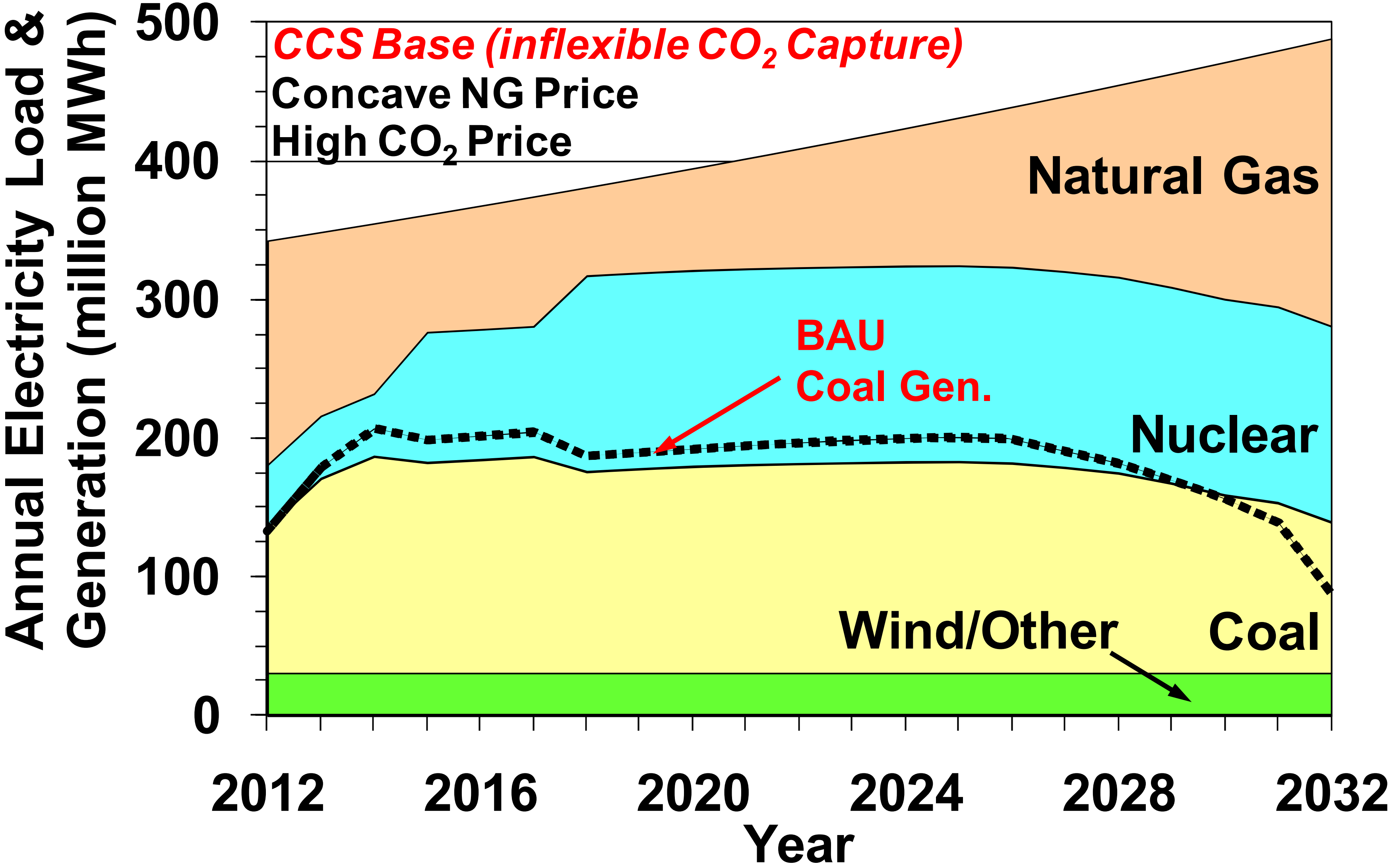
Several Gas/CO_2 Price Paths are Used to Investigate a Variety of Market Scenarios



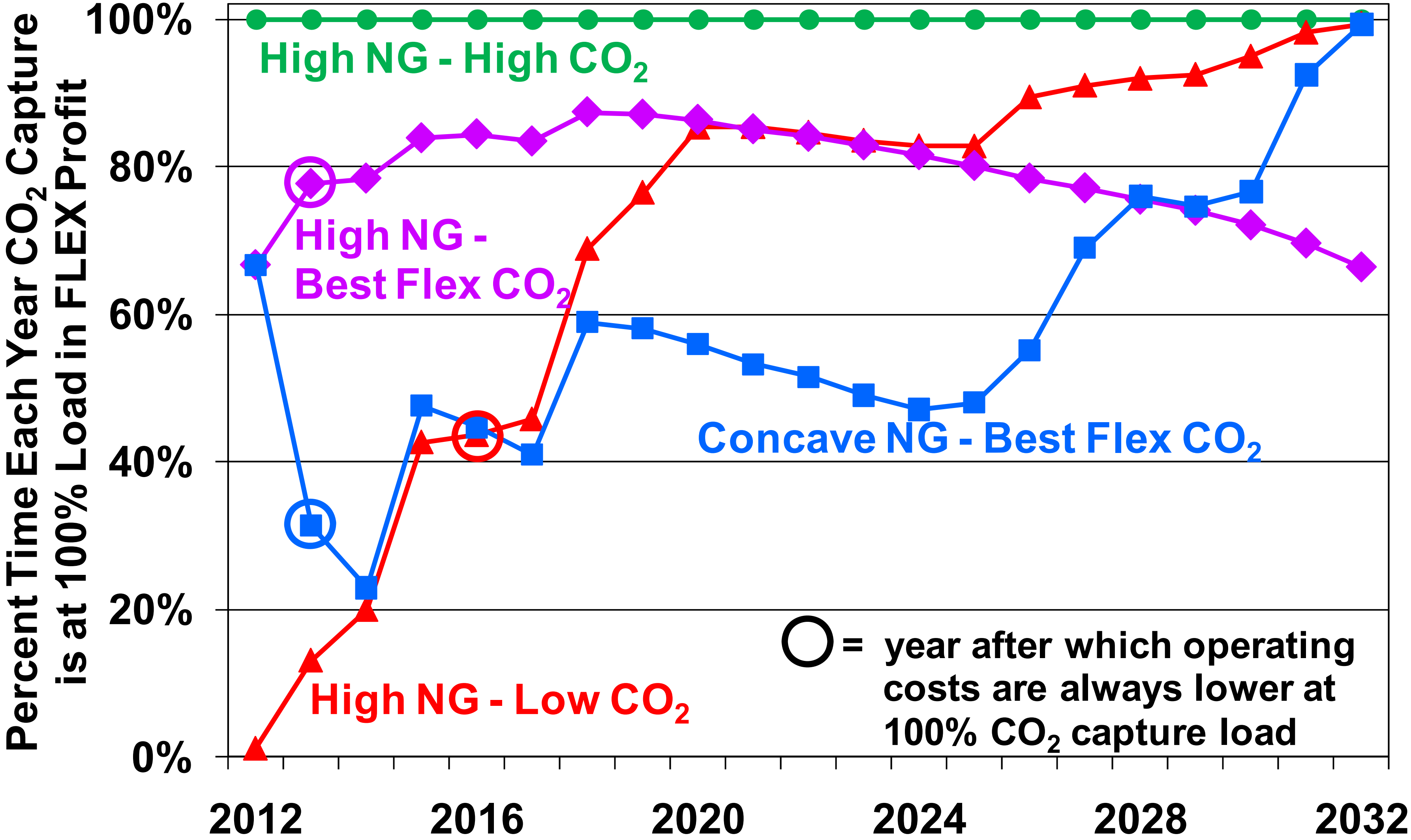
Coal-Based Generation Drops Substantially with High CO_2 and Low NG Prices



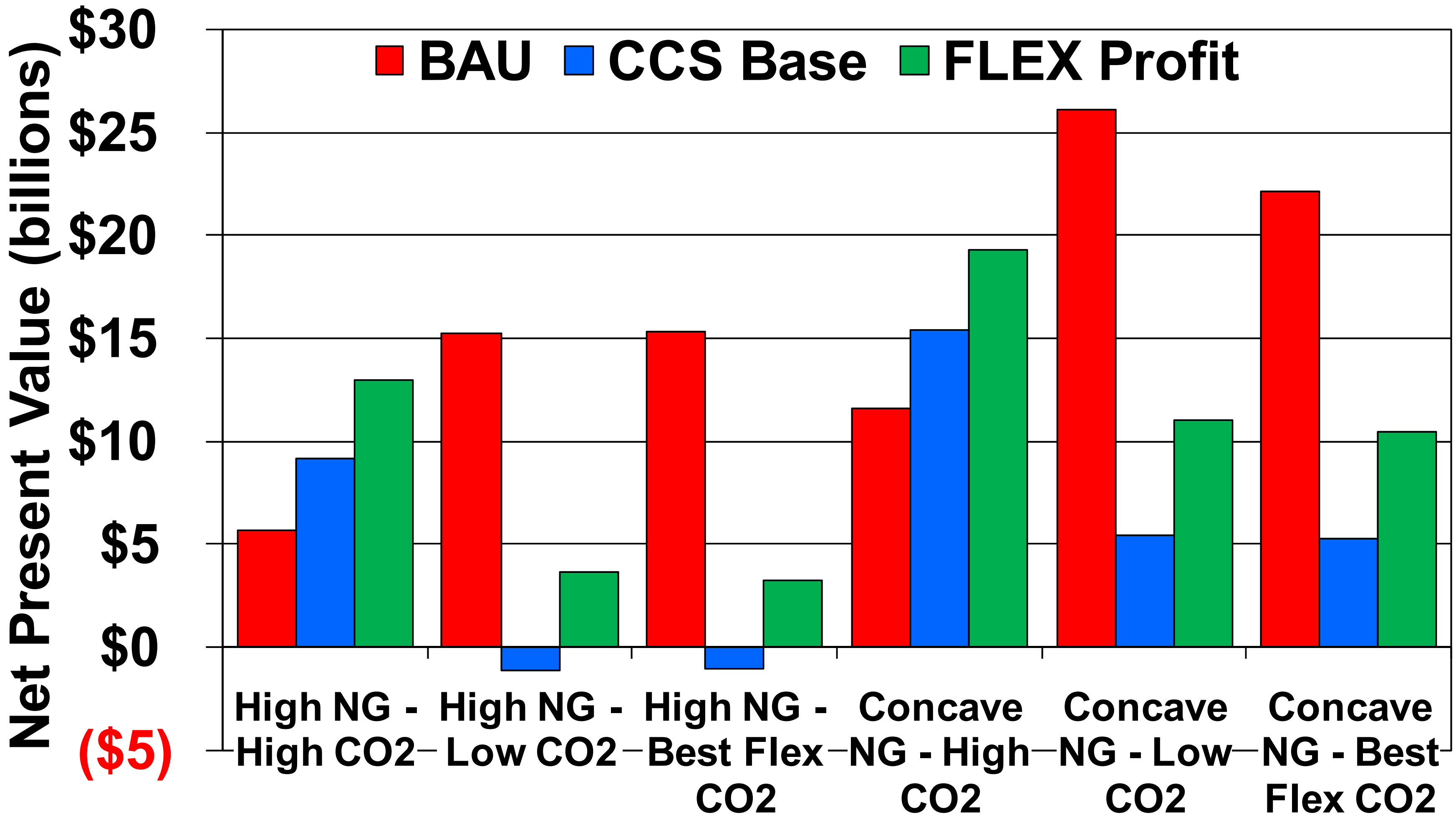
CO_2 Capture Allows Greater Coal-Based Generation in Later Years



Utilization of Flexible CO_2 Capture is Highly Dependent on Fuel and CO_2 Prices



Flexibility Greatly Improves Lifetime NPV Across Capture Plants with $3000/kW Replacement Capacity Cost

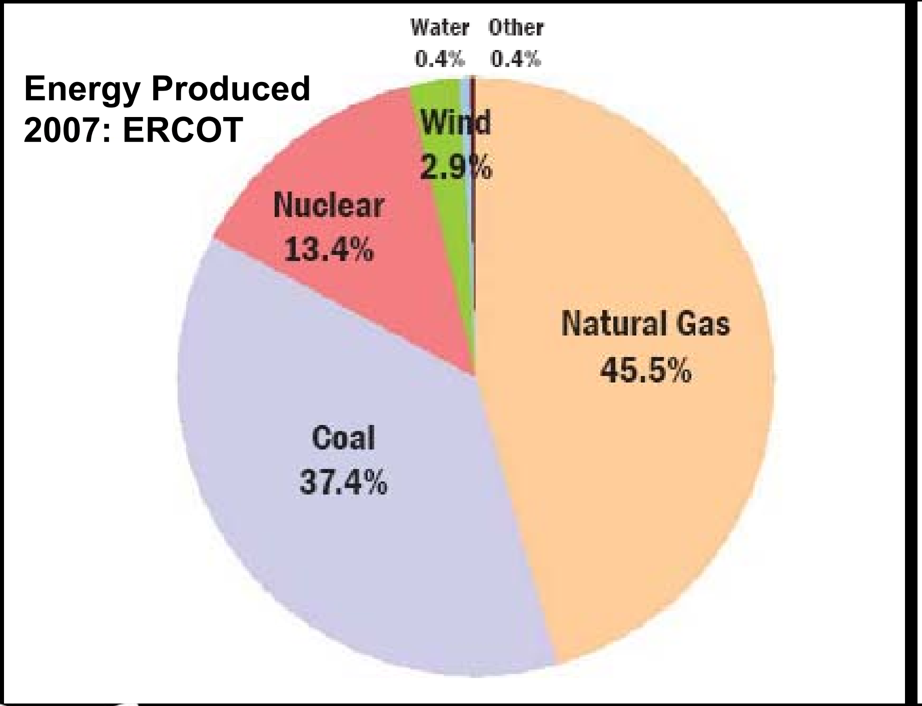


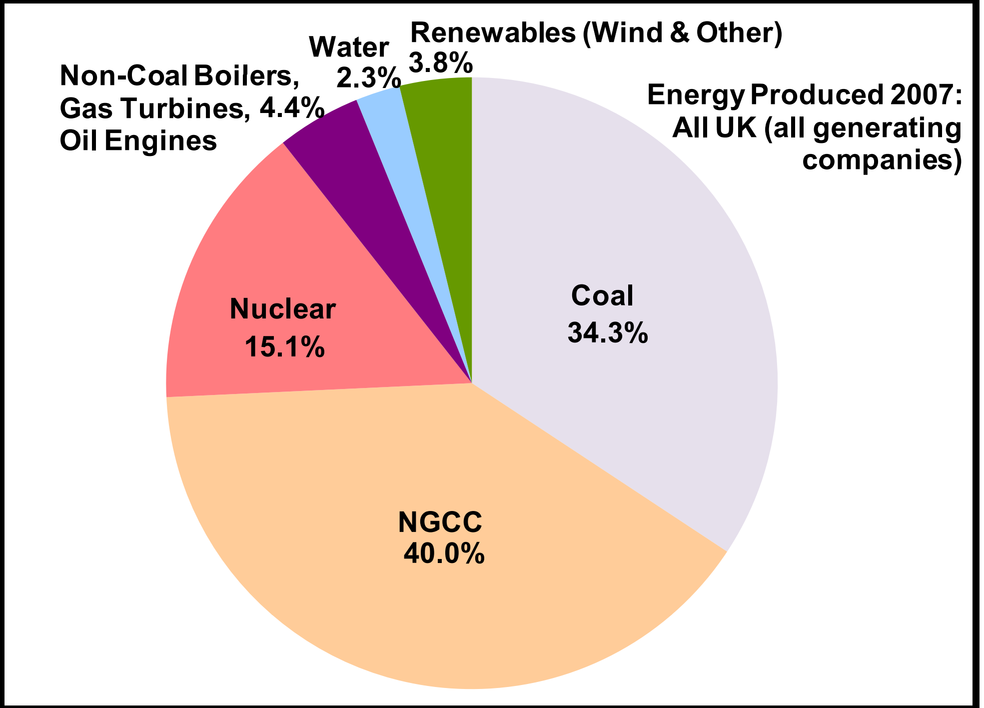
Preliminary Data

The Model is Also Being Used to Compare & Contrast the ERCOT and GB Electric Grids

- **Both "island" electricity systems with competitive wholesale electricity markets**

	ERCOT	All UK
Capacity in 2008 (MW)	72,820	84,880
Demand in 2007 (TWh)	307	373

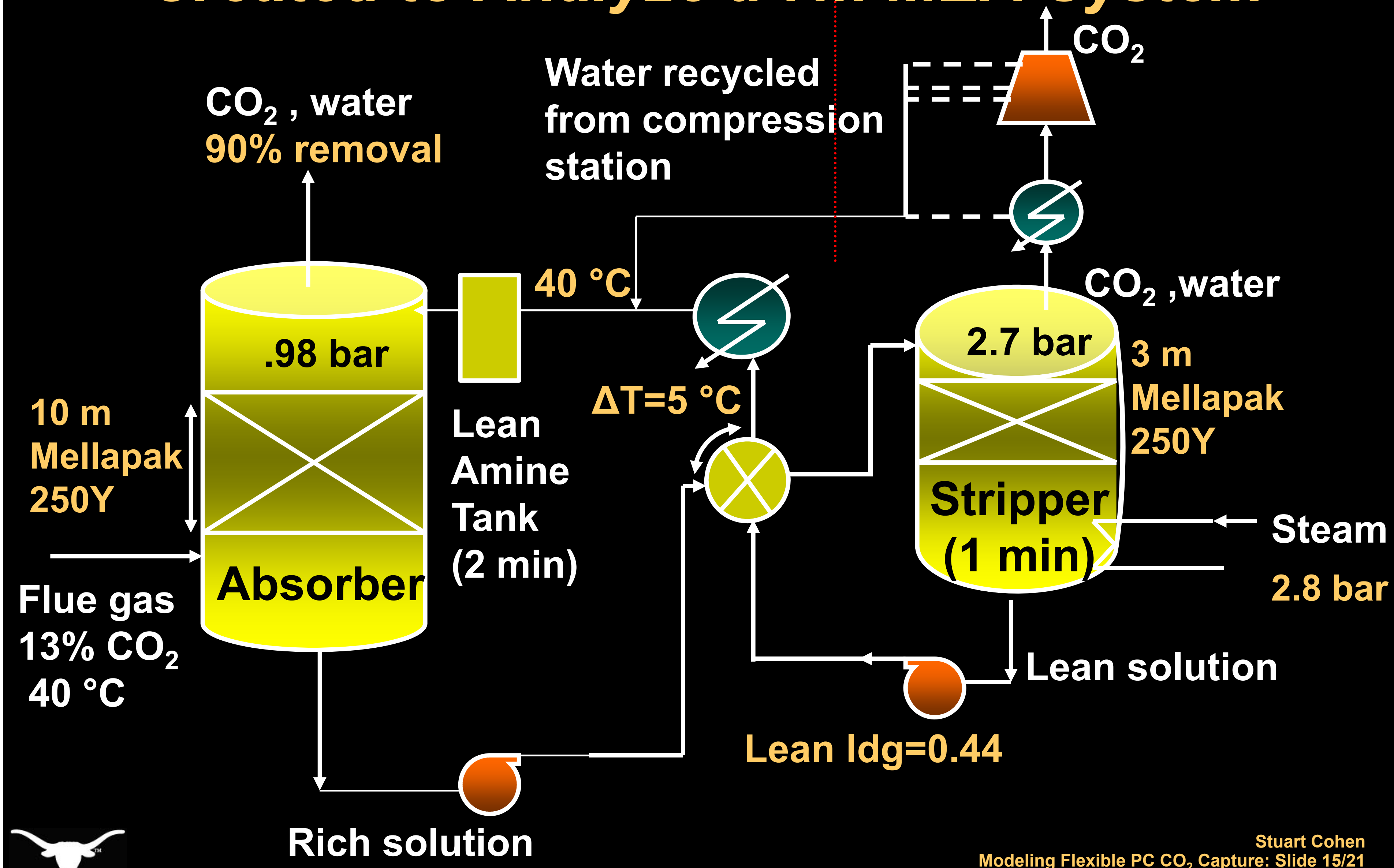




Grid Modeling Conclusions: Flexible CO_2 Capture May Improve Plant Economics

- A model of hourly grid behavior is used to study flexible capture for multi-year time periods and various electric grids
- CO_2 capture has a minor effect on electricity prices relative to fuel and CO_2 prices
- The CO_2 price required for full-load operation is much lower than that required for investment
  - If CO_2 prices remain high after CO_2 capture installation, flexibility does not affect operation in energy markets
  - If fuel and CO_2 prices allow similar operating costs across CO_2 capture operating range, flexibility may improve annual operating profits by $10s-$100s millions
  - Operation of flexible capture is a complex function of fuel and CO_2 prices, operating costs, and the plant fleet
  - Flexibility is a hedge against CO_2 and fuel price volatility
- Regardless of operating economics, NPV is greater for flexible systems when accounting for replacement capacity

A Dynamic Process Model Has Been Created to Analyze a 7m MEA System

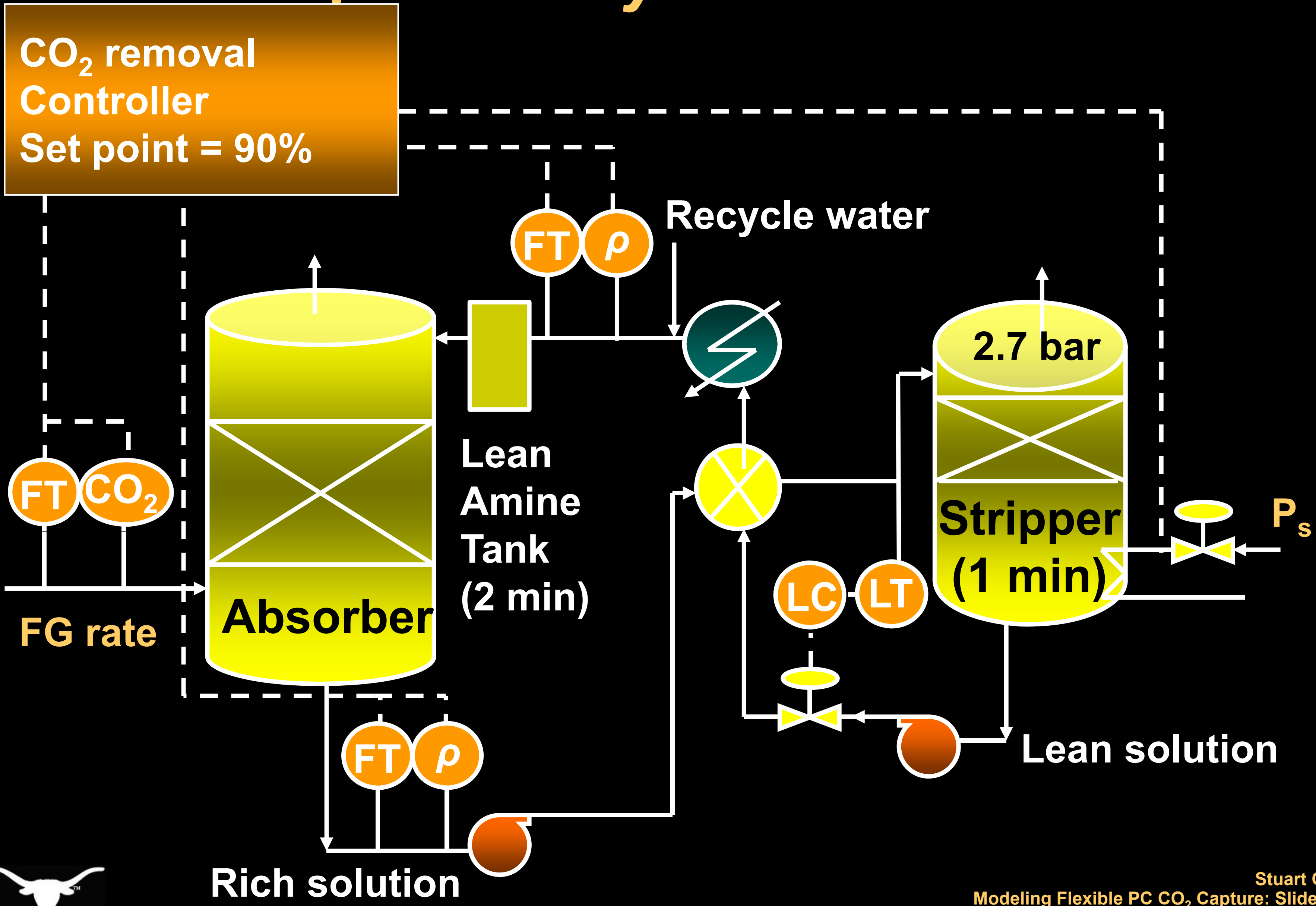


Open-Loop Analysis Shows Effects of ±5 % Step Changes to Steam P and Flue Gas Rate

- **Step changes to each parameter are made separately**
- **New steady state is achieved in under 30 min**
- **Response time governed interactions between column process conditions**
- **Changes disrupt steady state of water balance, but not significantly enough to require real-time control**
- **Liquid level in the stripper sump should be controlled to meet the required min/max**
- **~1% change in reboiler duty with ± 5% step changes**
- **Up to -70% ramp in 30s will converge**

Slide contributed by Sepideh Ziaii, UT Chem. Eng. (sziaii@che.utexas.edu)

Closed Loop CO_2 Removal Control Can Respond to System Disturbances



Slide contributed by Sepideh Ziaii, UT Chem. Eng. (sziaii@che.utexas.edu)

Closed-Loop Control Maintains CO_2 Removal at the Expense of System Response Time and Energy Performance

- The control loops are tuned based on different tuning methods (Ziegler-Nichols, IMC, IAE,ISE,ITAE)
- CO_2 removal controller can track the set point and reject disturbances. Fastest tuning parameters achieve S.S. in ~40 min after ± 5% disturbances
- The system responds slower than open loop system due to tight control on CO_2 removal
- This strategy is not able to maintain optimal energy performance because the lean loading is not controlled at the optimum value

Slide contributed by Sepideh Ziaii, UT Chem. Eng. (sziaii@che.utexas.edu)

Future Work

- Analyze the feasibility and implications of using solar thermal energy for solvent stripping
- Find optimal operation of a flexible system that uses solvent storage to maintain continuous high CO_2 removal
- Model flexible CO_2 capture in ancillary service markets, particularly for complementing intermittent renewable generation

Acknowledgements

- The EPA STAR Fellowship program
- The Luminant Carbon Management Program
- The Industrial Associates Program for CO_2 Capture by Aqueous Absorption
- Dr. Michael E. Webber and Dr. Gary T. Rochelle, and the support and staff of the Cockrell School of Engineering, CIEEP, and the Mechanical and Chemical Engineering Departments
- Sepideh Ziaii of the Rochelle Group (sziaii@che.utexas.edu)
- John Fyffe, Undergraduate Assistant

Questions?

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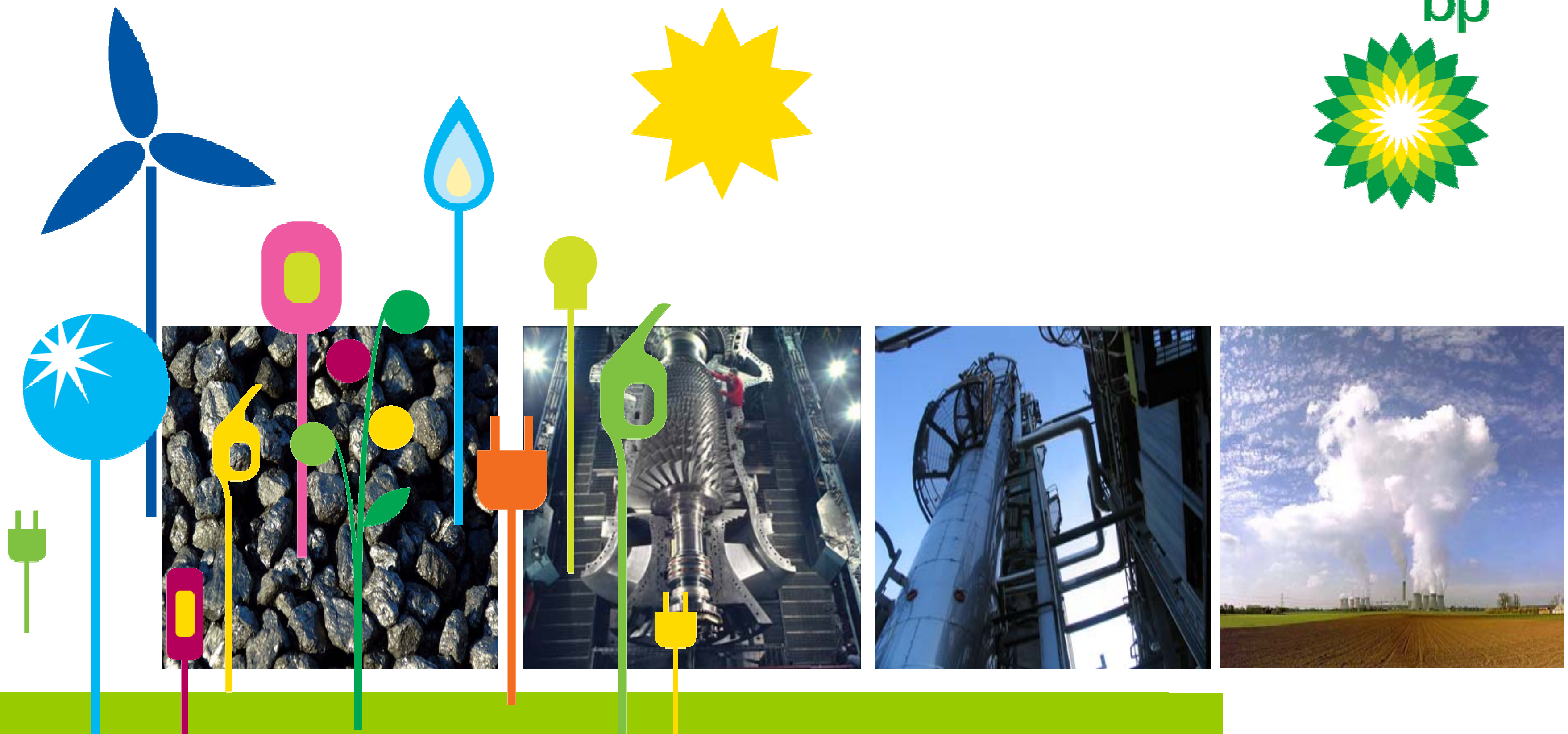

CCS Operating Flexibility Experience from In Salah

Jonathan Forsyth, Technology and Engineering Manager
London, 11 November 2009

alternativenergy

In Salah – Project summary

In Salah Gas
Stockage de CO_2

bp

Successful operations since 2004

The In Salah CO_2 Storage project is the world's largest saline formation storage project, using three state-of-the-art horizontal wells to store 1 mmtpa CO_2 in low permeability carboniferous sandstone, very similar to that commonly found in the UK Southern North Sea. It is located onshore in Algeria, in the southern Saharan desert, 1200 km south of Algiers.

bp
sonatrach
StatoilHydro

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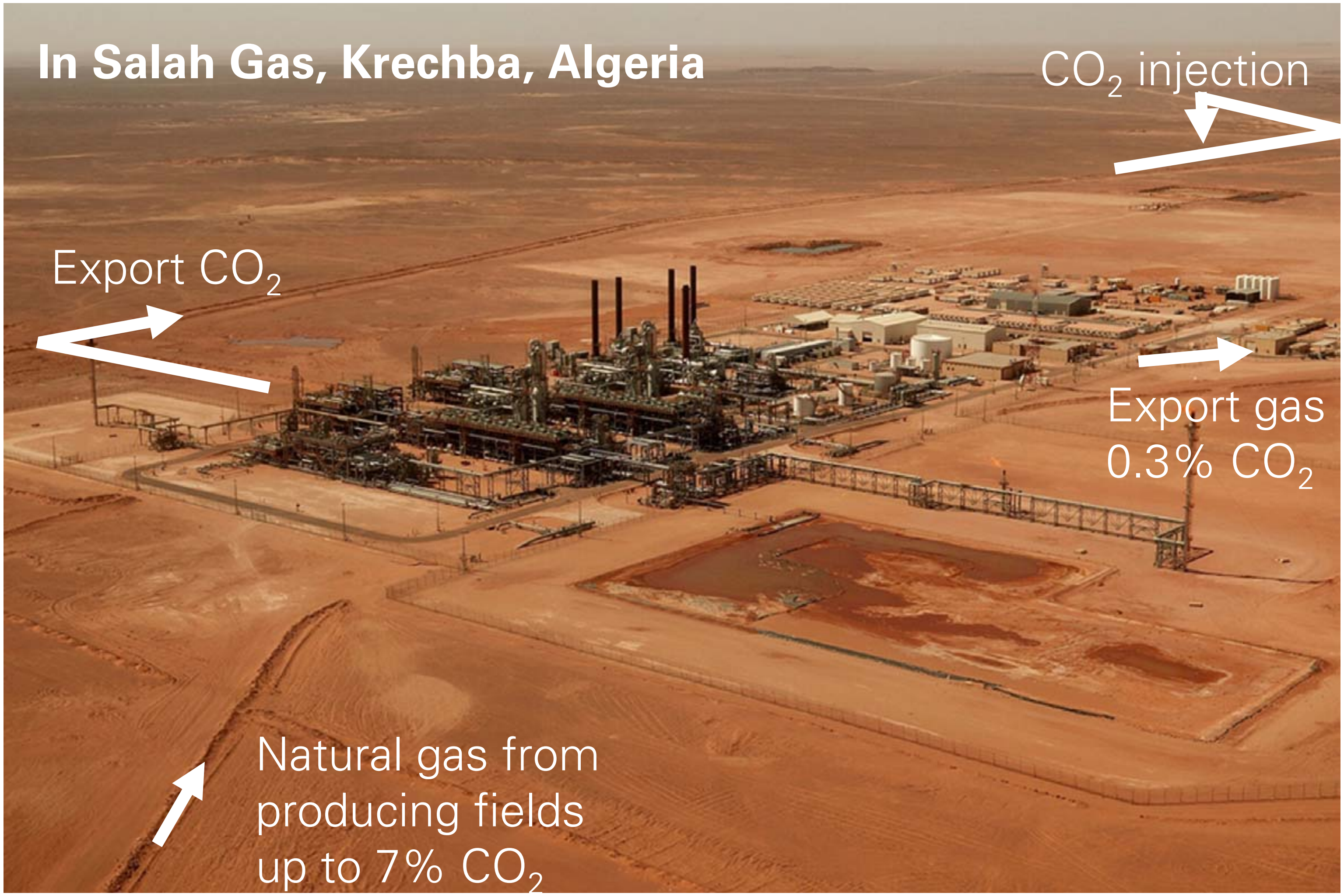
Surface Operations



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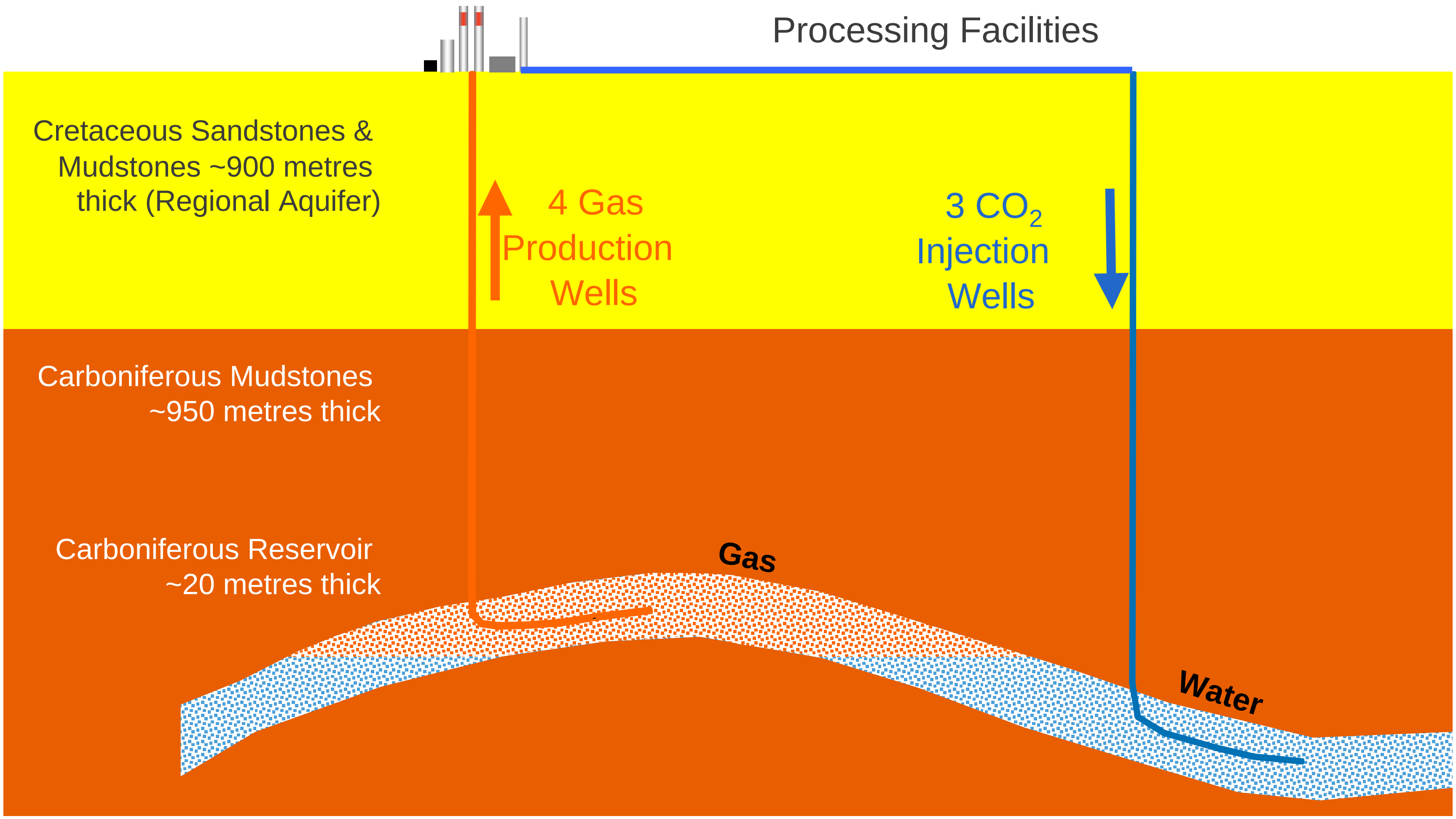
In Salah – CO_2 storage



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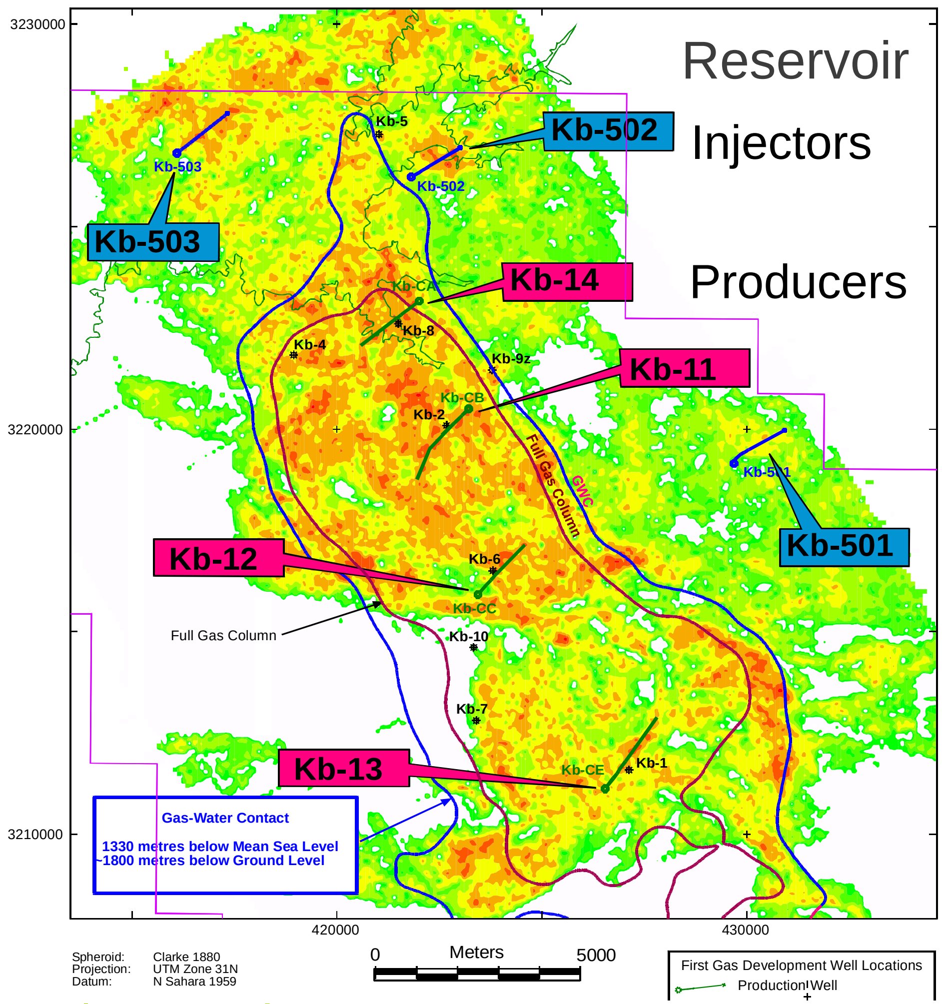
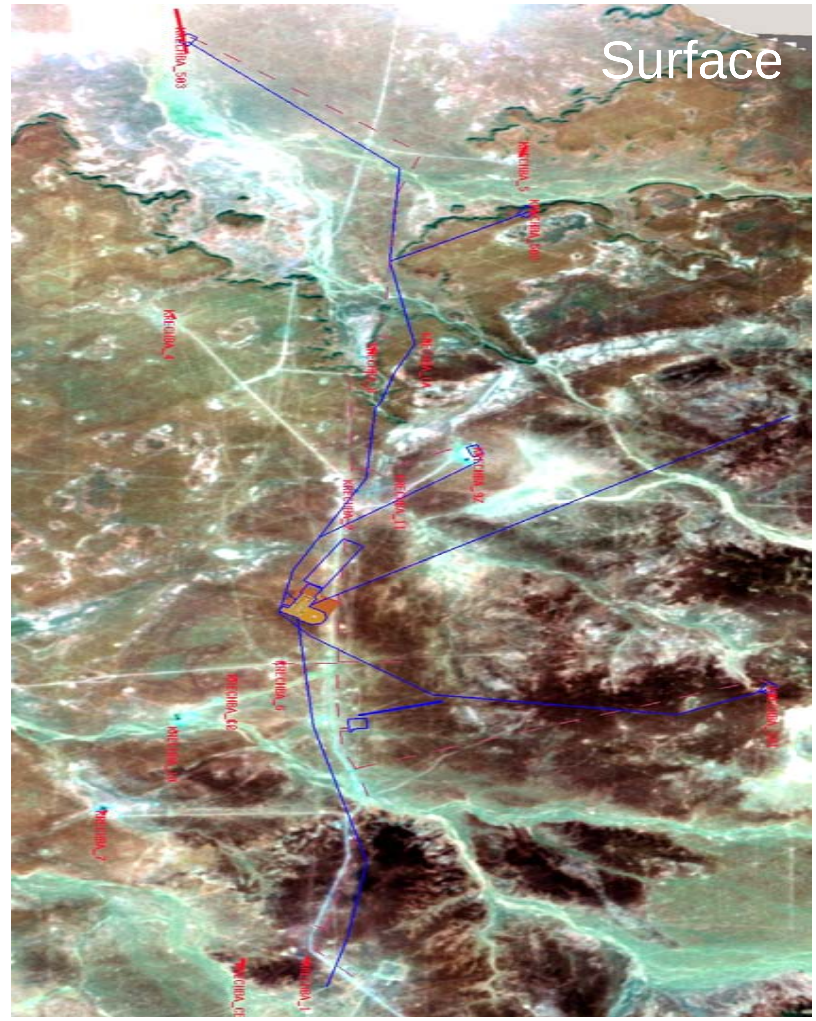
In Salah – CO_2 storage

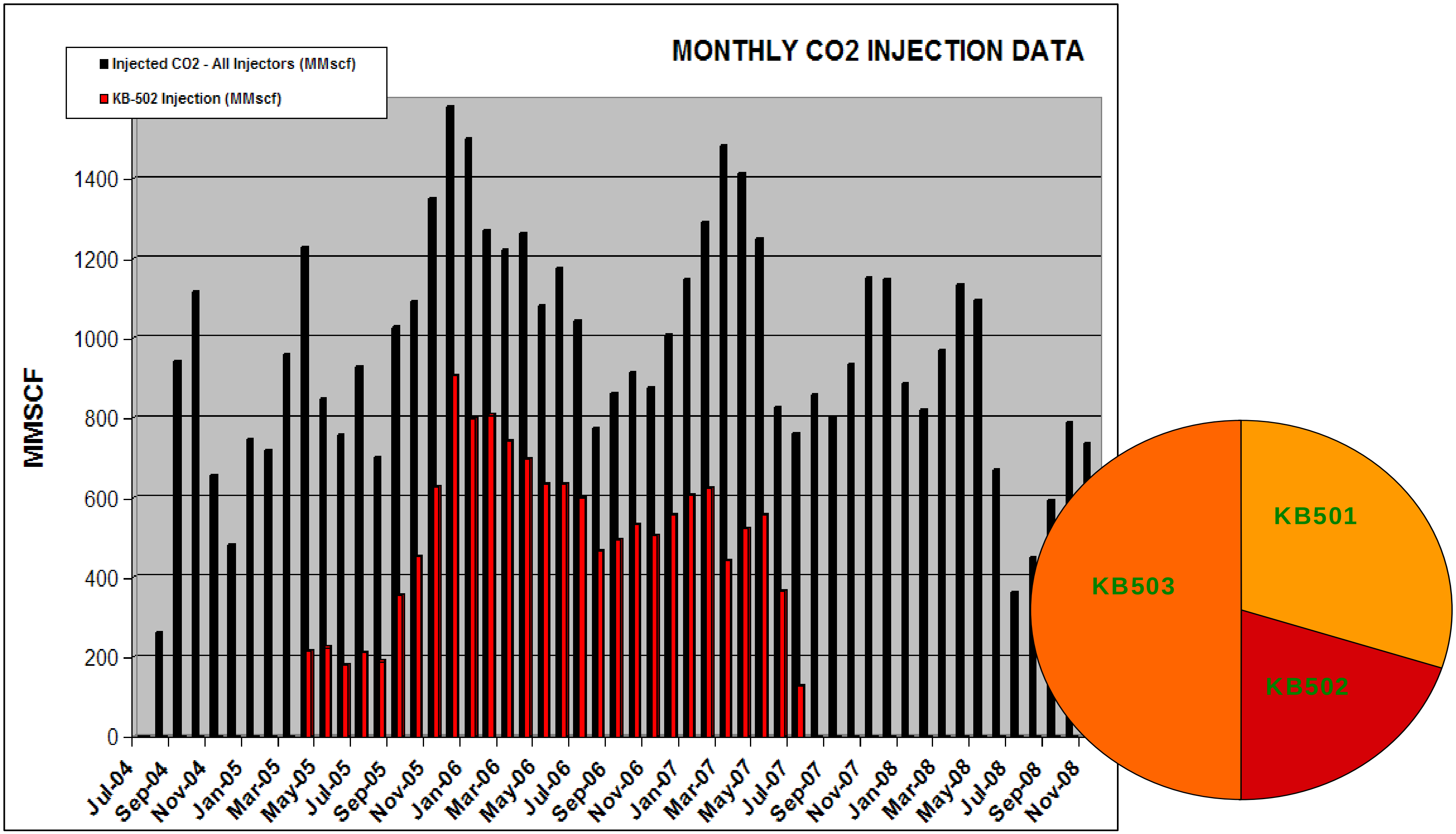
In Salah Gas
Stockage de CO_2

bp





CO_2 injection history



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Overview of CCS plant flexibility modelling

Colin Alie

Workshop on operating flexibility of power plants with CCS
Imperial College London
November 11–12, 2009

Outline

1. Motivation
2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
   - Electricity system modelling and simulation
   - Analysis of results
3. Summary and future work.

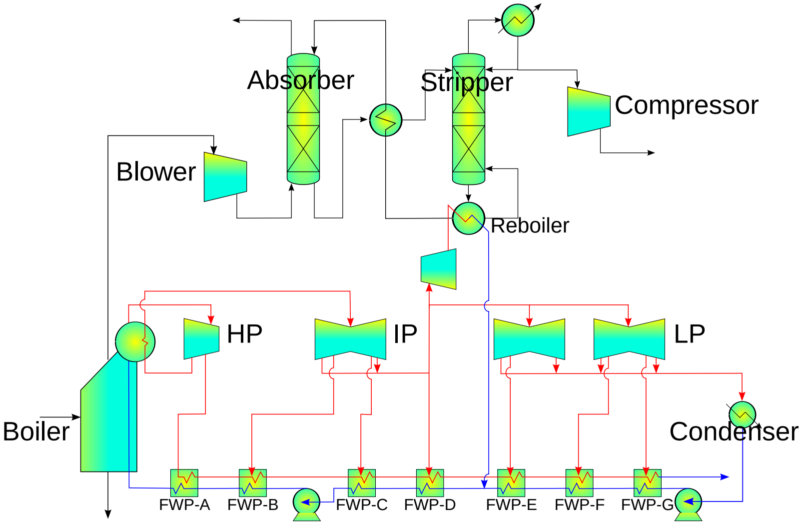
Outline

1. Motivation

2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
   - Electricity system modelling and simulation
   - Analysis of results

3. Summary and future work.

Novel process concept to be evaluated.



Cost of CO_2 avoided oft-used performance metric.

Cost of CO_2 avoided

$$CCA = \frac{(CoE)_{cap} - (CoE)_{ref}}{(CEI)_{ref} - (CEI)_{cap}}$$

where *Cost of Electricity* can be expressed as:

$$CoE = \frac{\left(\begin{array}{c}\text{annualized}\\\text{capital cost}\end{array}\right) + FOM}{\text{annual energy output}} + VOM_e + \left(\begin{array}{c}\text{fuel cost per}\\\text{unit energy}\end{array}\right)$$

- Need a method to predict unit utilization:
  - *annual energy output*
  - *fuel cost per unit energy*
  - CO_2 *emissions intensity*
- Need to assess benefit of operating flexibility

Process modelling + electricity system simulation.

Three-step process:

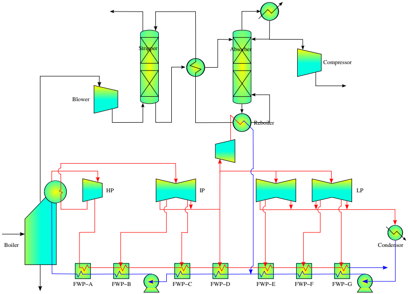
1. Modelling and simulation of generating unit with CCS
2. Simulation of electricity system
3. Analysis of results

Outline

Outline

1. Motivation
2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
   - Electricity system modelling and simulation
   - Analysis of results
3. Summary and future work.

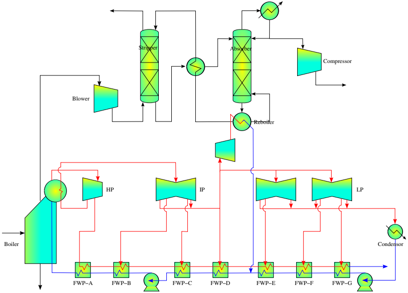
Develop process model of generating unit with CCS.



Example workflow:

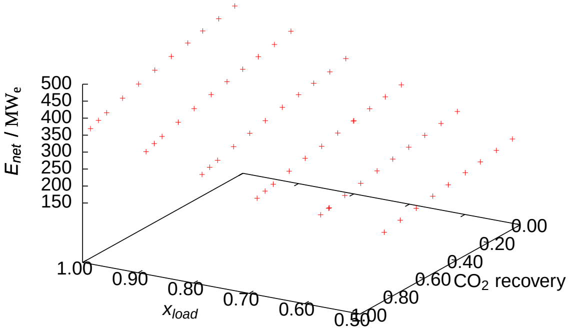
1. develop model of boiler and steam cycle from heat design balance at 50%, 75%, and 100% load
2. design PCC process to recover 85% of CO_2 at nominal load
3. integrate PCC process and generating unit models
4. characterize part-load performance of integrated unit

Objective is to find Pareto frontier of integrated unit.



- interested in the relationship between:
  1. heat input to boiler ($\dot{q}$)
  2. CO_2 recovery (x_{CO_2})
  3. net unit power output (E_{net})
- $E_{net} = f\left(\dot{q}, x_{CO_2}, \ldots\right)$
- only interested in the 'best' performance (*i.e.*, Pareto frontier)
- Find E^*_{net} for feasible combinations of $\dot{q}$ and x_{CO_2}.

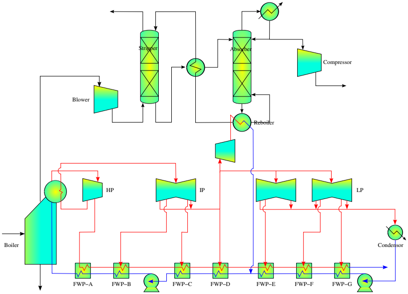
Pareto frontier for generating unit with CCS.



Developed model describing Pareto frontier using linear regression:

$$\dot{q} = f\left(E^*_{net}, x_{CO_2}\right)$$

Summary of data requirements for novel process.

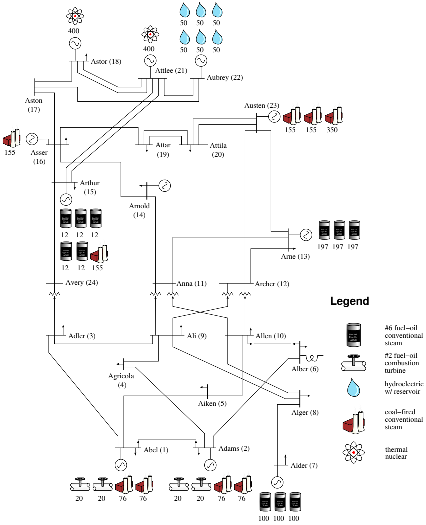


- Key unit parameters:
  - incremental heat rate
  - minimum and maximum power output
  - start-up heat input
  - ramp rates
  - minimum up- and downtimes
  - fuel cost
- Initial assumption is that CO_2 capture process dynamics are fast.

Outline

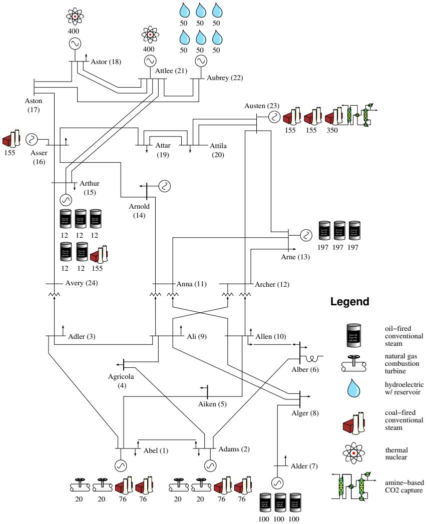
1. Motivation
2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
   - Electricity system modelling and simulation
   - Analysis of results
3. Summary and future work.

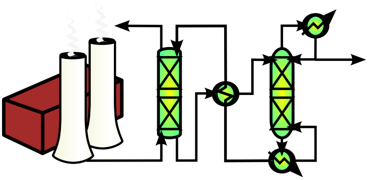
Analysis is electricity system-specific.



- Grigg et al. The IEEE Reliability Test System — 1996, *IEEE Transactions on Power Systems*, 14(3):1010–1021, August 1999.
- Example workflow:
  1. Incorporate novel process into electricity system.
  2. Simulate system operation.
  3. Analyze simulation results.

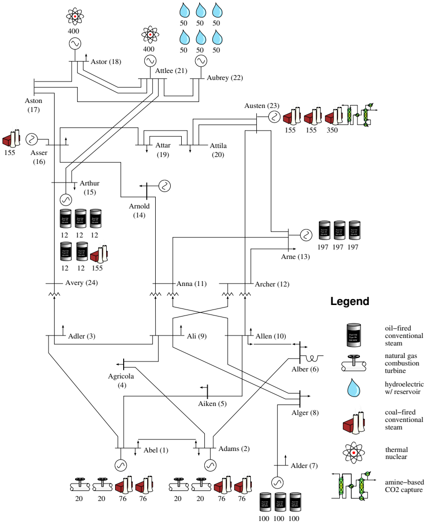
Novel process added to electricity system.

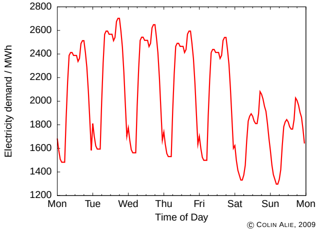




- MEA (monoethanolamine)-based PCC (Post-Combustion Capture) added to 500 MW_e coal-fired unit at Austen
- plant load and CO_2 recovery are flexible

Electricity system operation simulated.





For each time period, select units that will satisfy:

- demand
- reserve requirement
- physical constraints on equipment

such that overall benefit is maximized.

Outline

1. Motivation
2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
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3. Summary and future work.

Cost of CO_2 avoided estimate is easily had.

Cost of CO_2 avoided

$$CCA = \frac{(CoE)_{cap} - (CoE)_{ref}}{(CEI)_{ref} - (CEI)_{cap}}$$

where *Cost of Electricity* can be expressed as:

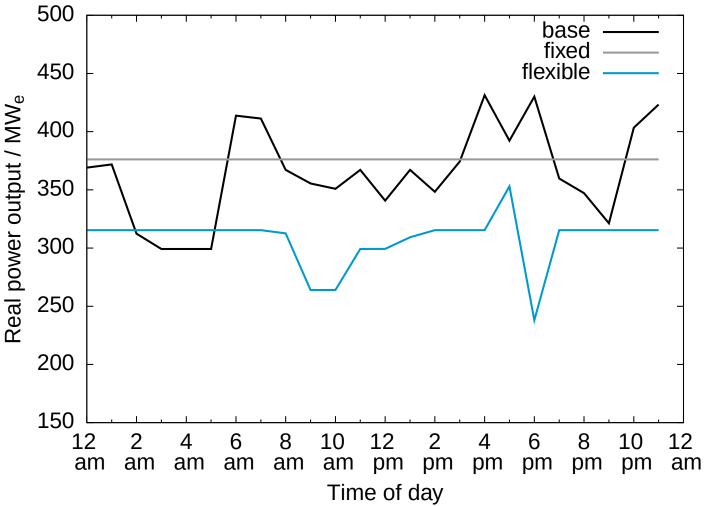
$$CoE = \frac{\left(\begin{array}{c}\text{annualized}\\\text{capital cost}\end{array}\right) + FOM}{\text{annual energy output}} + VOM_e + \left(\begin{array}{c}\text{fuel cost per}\\\text{unit energy}\end{array}\right)$$

Simulation directly provides:

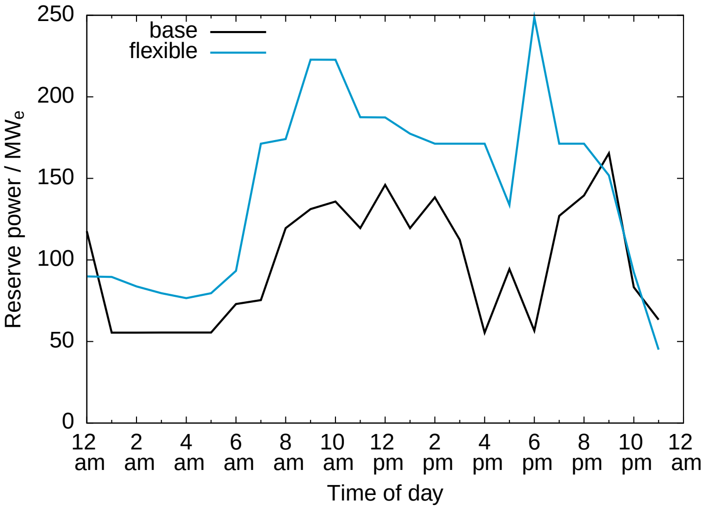
- *Cost of Electricity*
- CO_2 *Emissions Intensity*

so estimate of *Cost of* CO_2 *Avoided* is readily obtained, if desired.

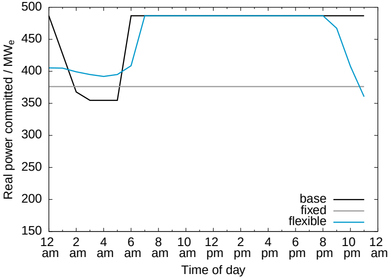
At $40/tonne, flexible case delivers least power.



Flexible case commits more to reserve markets.



Overall utilization similar: base vs flexible.



- Utilization is similar between base case and flexible case.
- However, flexible case has better economics as costs are lower
- Cost of CO_2 avoided wouldn't reflect this

Outline

1. Motivation
2. Assessment of impact of operating flexibility
   - Generating unit modelling and simulation
   - Electricity system modelling and simulation
   - Analysis of results
3. Summary and future work.

Summary and future work

- Able to quantify benefits from operating flexibility.
- Operating flexibility shifted capacity from energy market to reserve markets.
- Assessment of dynamic performance needs to be included!
- Sensitivity analysis.

Acknowledgements

- National Sciences and Engineering Research Council (Canada)
- Eric Croiset, Peter Douglas, Ali Ekamel — University of Waterloo
- Paul Graham — Energy Technology Division, CSIRO

PRECOMBUSTION CAPTURE PLANTS

IGCC WITH CCS, DESIGNS AND EXPERIENCE





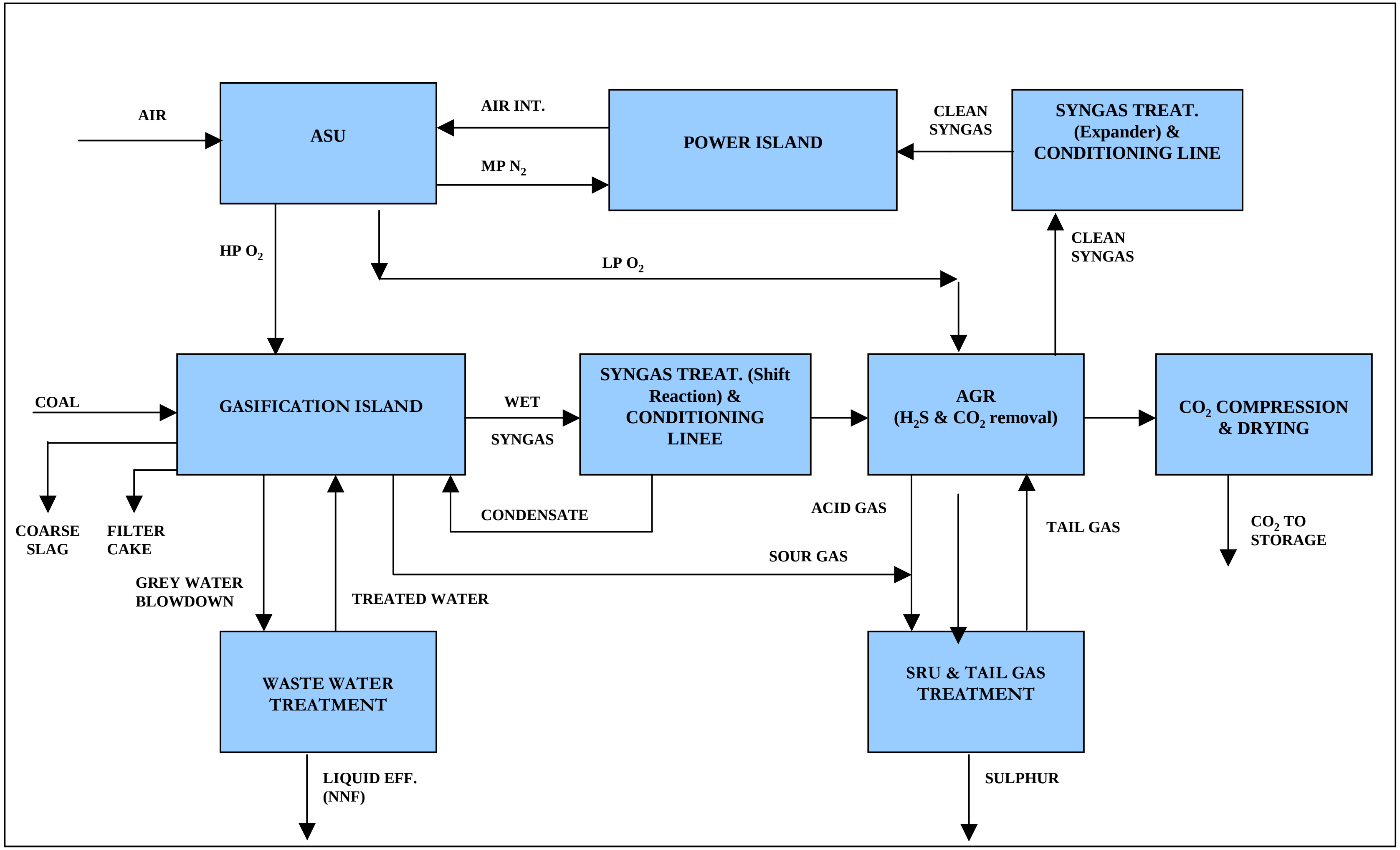

R. Domenichini - Technical Director
Foster Wheeler Italiana - Power Division

Workshop on Operating Flexibility of Power Plants with CCS - London 12th November 2009

A G E N D A

- Configuration of an IGCC plant with CO_2 capture
- Issues related to the plant operation
  - Performance
  - Availability/Reliability
  - Flexibility
  - Electrical Requirements (grid prescriptions)
- How does the design help to meet the operating targets?
- The design tools to be applied in addition to the steady state simulations:
  - RAM (Reliability/Availability/Maintenability Analysis)
  - Dynamic Simulation
  - Electrical Studies
- Some case studies from Foster Wheeler references

Configuration of an IGCC with CO_2 capture



MORE THAN 20 UNITS THAT SHALL OPERATE AS A SINGLE ONE

Issues related to the plant operation

- Performance
- Availability/Reliability → Investment Cost
- Operating flexibility and grid prescriptions

A larger integration improves the plant performance and the investment cost, but can reduce the operating flexibility and the reliability

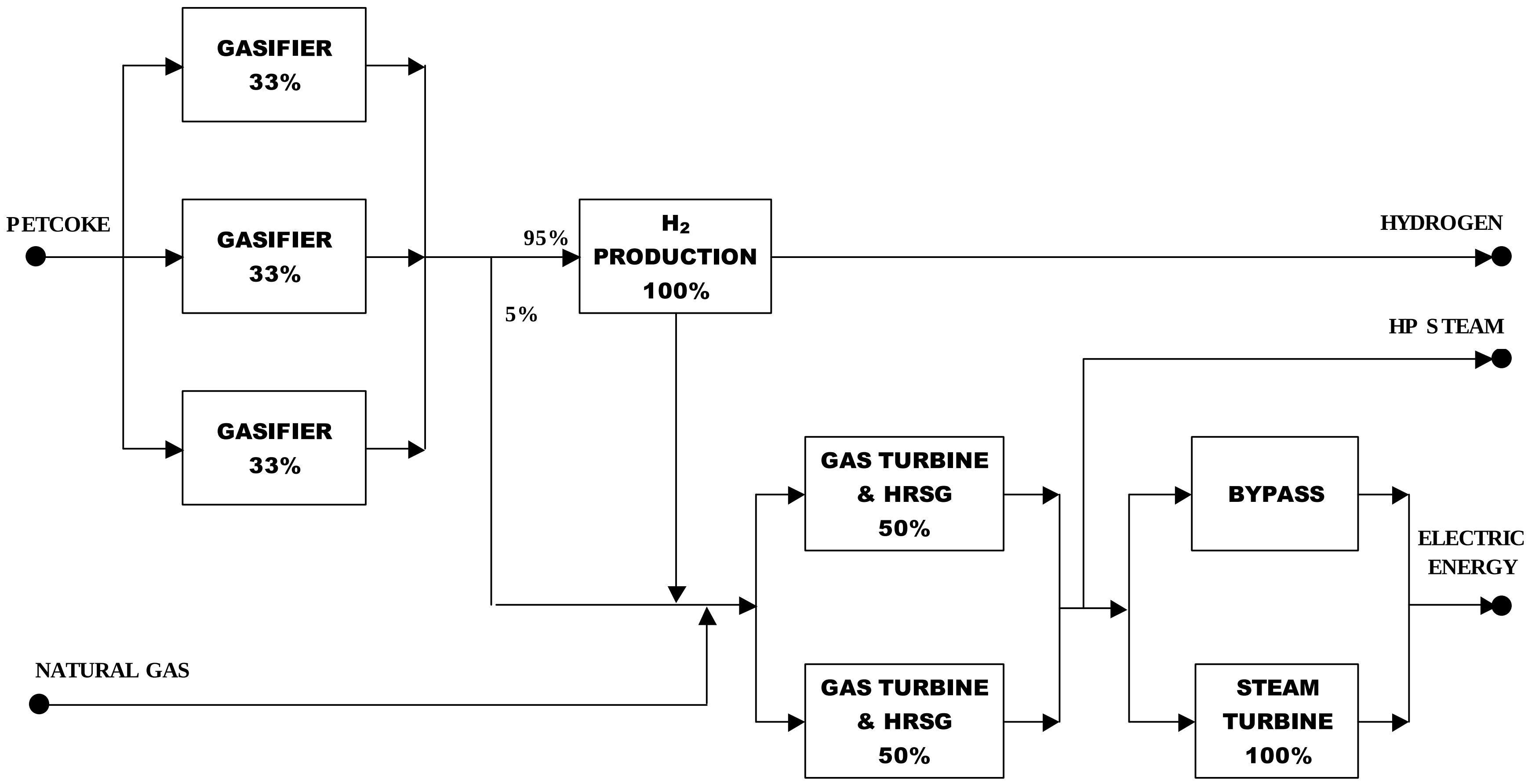
THE DESIGN SHALL FOCUS ON THE RECONCILIATION OF THE ABOVE TARGETS

Design Guidelines

- Adoption of commercially proven technologies & equipment
- Partial Integration only (no full integration) between the gas turbine and the ASU: to be evaluated case by case
- Optimization of heat recovery
- Adoption of sparing and split into two lines just in the critical areas and if justified by the RAM calculations
- Development of a robust control philosophy – suitable control logics to handle all the emergency situations

The Design Tools: RAM Analysis

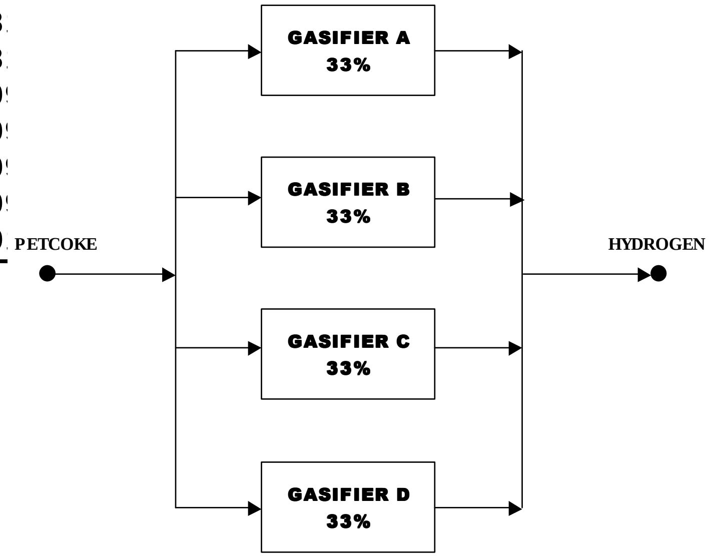
A Case Study: Availability Block Diagram



The Design Tools: RAM Analysis

IGCC availability assessment methodology – states definition

STATE	A Gasifier 1	B Gasifier 2	C Gasifier 3	D Gasifier 4	Capacity	Probability	A Gasifier 1	B Gasifier 2	C Gasifier 3	D Gasifier 4
1	1	1	1	1	100.00%	65.61%	90.00%	90.00%	90.00%	90.00%
2	1	1	1	0	100.00%	7.29%	90.00%	90.00%	90.00%	10.00%
3	1	1	0	1	100.00%	7.29%	90.00%	90.00%	10.00%	90.00%
4	1	0	1	1	100.00%	7.29%	90.00%	10.00%	90.00%	90.00%
5	0	1	1	1	100.00%	7.29%	10.00%	90.00%	90.00%	90.00%
6	1	1	0	0	66.66%	0.81%	90.00%	90.00%	10.00%	10.00%
7	1	0	1	0	66.66%	0.81%	90.00%	10.00%	90.00%	10.00%
8	0	1	1	0	66.66%	0.81%	10.00%	90.00%	90.00%	10.00%
9	0	0	1	1	66.66%	0.81%	10.00%	10.00%	90.00%	90.00%
10	1	0	0	1	66.66%	0.8				
11	0	1	0	1	66.66%	0.8				
12	1	0	0	0	33.33%	0.0				
13	0	1	0	0	33.33%	0.0				
14	0	0	1	0	33.33%	0.0				
15	0	0	0	1	33.33%	0.0				
16	0	0	0	0	0.00%	0.0				



Example: 4 x 33% Gasifiers

The Design Tools: RAM Analysis

IGCC availability assessment methodology – states definition

Example: 4 x 33% Gasifiers

Capacity levels and probabilities

STATE	Probability (Pk) (%)	Duration (hours/year)	Capacity (Ck) (%)
I	94.77%	8301.9	100.00%
II	4.86%	425.7	66.66%
III	0.36%	31.5	33.33%
IV	0.01%	0.9	0.00%
Total	**100.00%**	**8760.0**	-

Equivalent Availability: ratio between actual syngas produced during a year and the syngas which could be produced during the year if operating all time at full capacity

EA = 100% - (100%-66.66%)x4.86% - (100%-33.33%)x0.36% - (100%-0%)x0.01% = **98.10%**

The Design Tools: Dynamic Simulation

The main target of the IGCC dynamic symulation is:

Check of the integration between the gasification section and the combined cycle which shall ensure at any time the balance between the fuel demand and the fuel production

Response time is very quick for the gas turbine, much slower for the process units and the steam cycle

The Design Tools: Dynamic Simulation

Dynamic Model Preparation

- Data gathering: PFDs, H&MBs at different operating conditions, equipment functional and geometrical data, control valves and controllers data, plant operating philosophy and control logics
- Model preparation: Build a dynamic model describing the sections of the plant which are dynamically significant. Generation of a model schematic and definition of modules (from std software library or developed ad hoc) and connections, implementation of control strategy. All the main components (gasifiers, scrubbers, exchangers, drums, absorbers, expander, combustors, gas and steam turbines, HRSGs, etc.) are modeled as a series of resistence and volume modules connected in a thermal/hydraulic network
- Superimpose a H&MB without any disturbance and check that no drift from steady state conditions occurs. The same is made for other operating cases to check the model vs the design and offdesign operating conditions
- Impose a disturbance and predict the consequent transient behaviour of the plant before meeting a new a steady state condition

The Design Tools: Dynamic Simulation

Evaluation of Plant Transients

- Planned events: gasification and combined cycle load variations
- Unplanned events:
  - Trip of one gasifier
  - Trip of two gasifiers
  - Trip of other process key equipment (f.i. saturator, expander)
  - Trip of one gas turbine
  - Load rejection of one gas turbine
  - Trip of one steam turbine
  - Sudden disconnection from the electric grid and island operation
  - Requests from TSO

The System's response in terms of flow, pressure, temperature, power output are observed and discussed

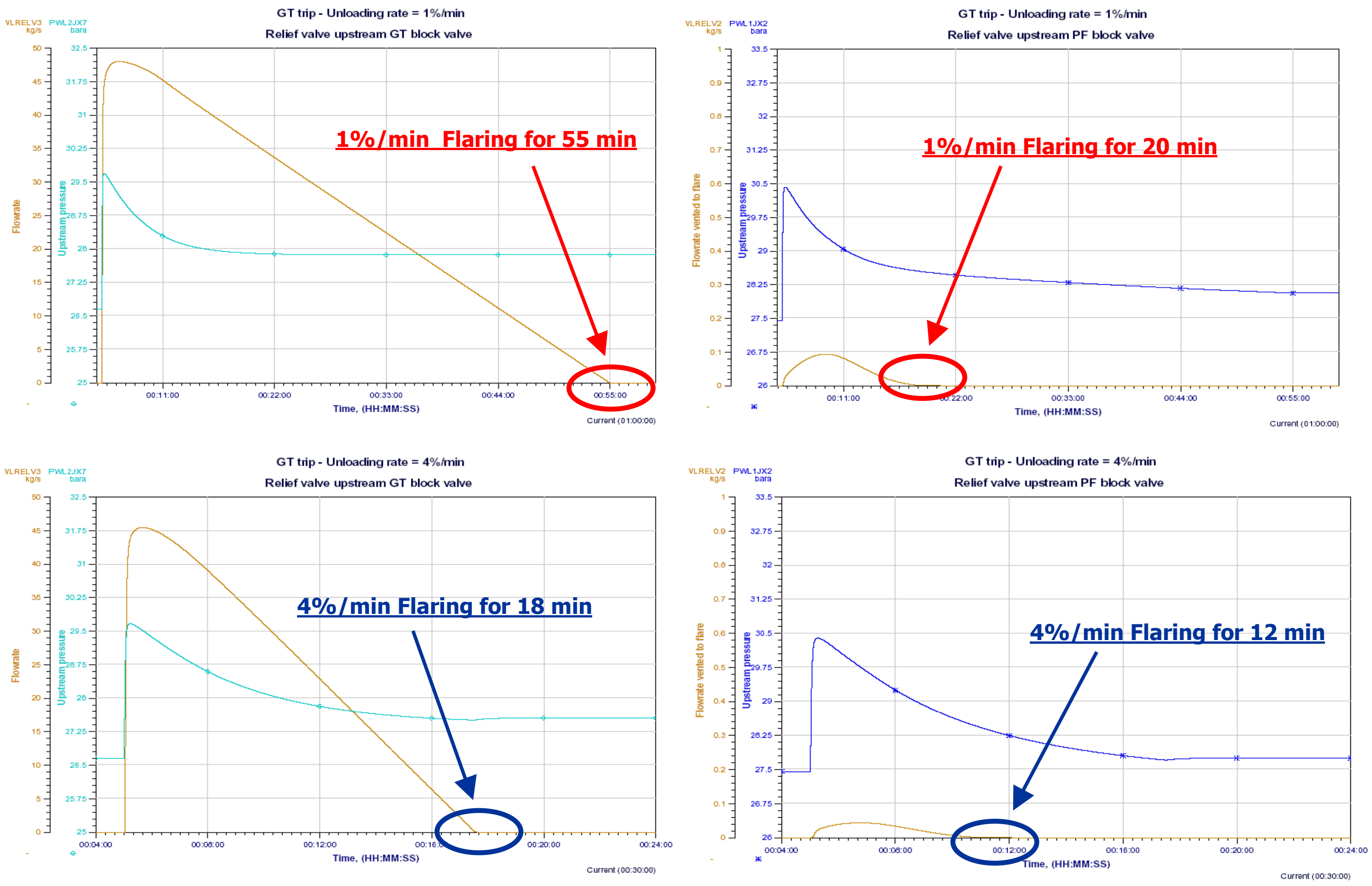
The Design Tools: Dynamic Simulation

The dynamic simulation can be performed at various stages of the project with different level of details, targets and consequent results

Some examples

- Pre-FEED: screening of different alternatives, preliminary definition of the control strategy and operating parameters
- FEED: check of equipment size, definition of control philosophy and preliminary selection of safe operating procedure
- EPC: Final check of equipment size, check of all the control logics, estimate of the controllers parameters for a shorter and less expensive tuning on field
- Plant operation: improvement of the plant operability/reliability

Case Study Pre-FEED - Evaluation of gasifiers unloading ramp after the GT Trip



The Design Tools: Dynamic Simulation and Electrical Studies

FEED Phase: Compliance with the Grid Prescriptions

Even if the intrinsic characteristics of the IGCC technology would require a base load operation, the plan is requested to meet the grid code prescriptions (specific for each Country) which are mainly related to the frequency control

Frequency Control

- **Generated power shall balance absorbed power: no accumulation of electric power is possible**
- **A constant frequency is the result of generated power = absorbed power**
- **Constant frequency= high quality level of electric power**

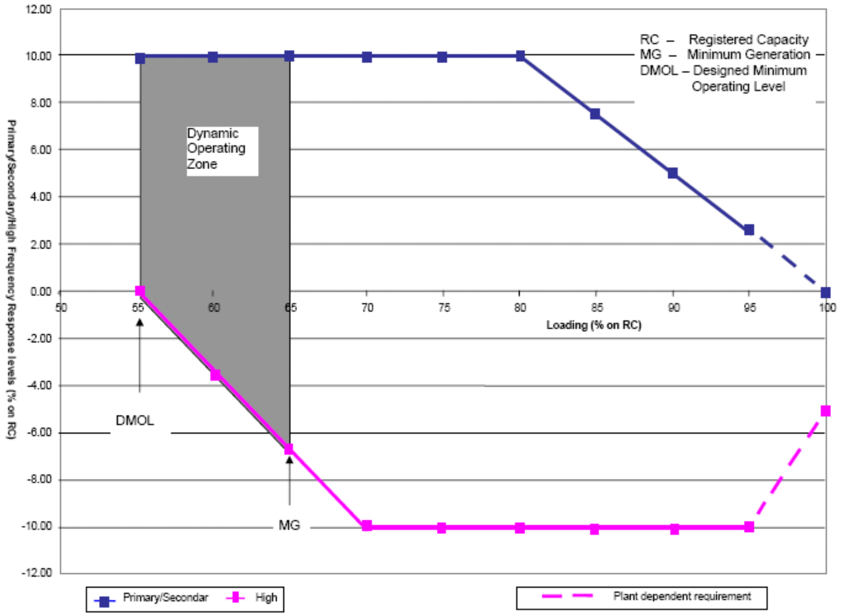
The Design Tools: Dynamic Simulation and Electrical Studies

UK Grid Code - Minimum Frequency Response Requirement Profile

Primary Frequency Control

- allows to continuously balance generated and absorbed power, by automatic modulation of the generated power
- Very short response time required – Action by automatic speed governors of machines

(diagrammatically for a 0.5 Hz change in Frequency)



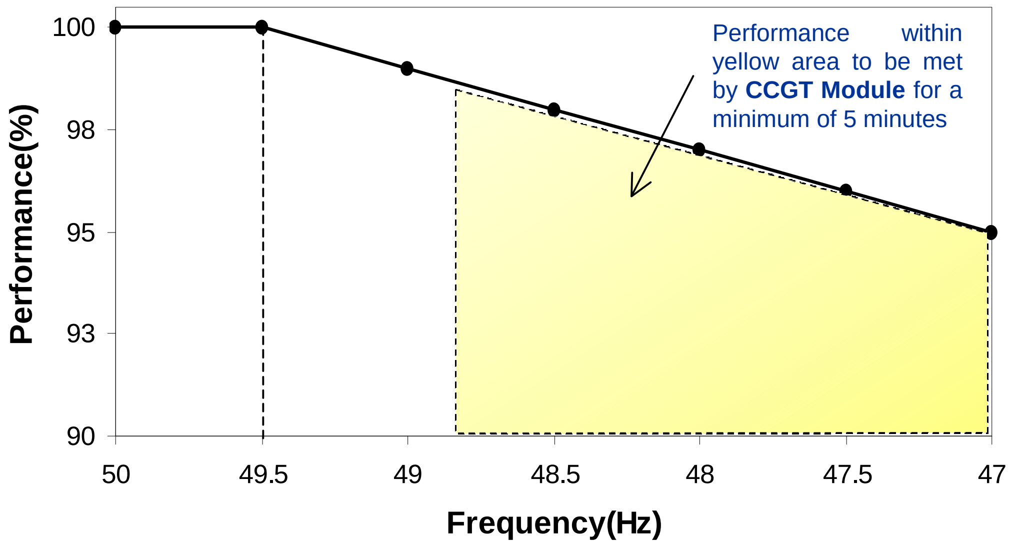
The IGCC plant should be capable to provide Primary Frequency response at least to the solid boundaries shown in the figure (NG cofiring or syngas storage are the only options)

The Design Tools: Dynamic Simulation and Electrical Studies

UK Grid Code – Performance under Frequency Variation

Secondary Frequency Control

- allows to restore the frequency deviation to its nominal value and to restore the power exchanges from interconnected grid to the planned figure
- Response time lower than primary frequency control – Action by modification of power output set-point of the machines via a signal coming from the TSO



Performance(%)= NPO actual/ NPO@50Hz, n.c

NPO= Net Active Power Output

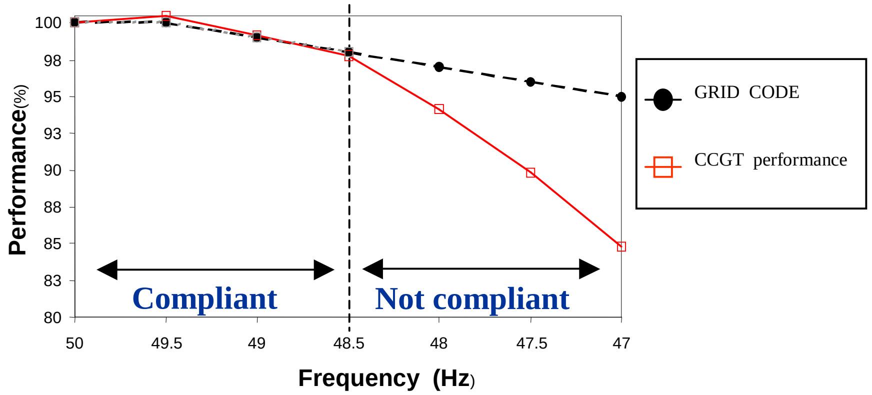
Grid Prescriptions: What to do with an IGCC Plant?

In a plant designed according to the process units approach the response time is stated by the response of the entire chain of syngas production: it is difficult to generate more syngas in a very short time

- **Possible options to be investigated:**
  - **Deviation from mandatory prescriptions (e.g. IGCC operated a base load plant, no contribution or partial contribution to frequency control)**
  - **Storage of syngas (buffer)**
  - **Reduction of Post Firing in HRSG to make available more syngas to GT**
  - **Load shedding on large electric motors on IGCC plant (e.g. CO_2 compressors, etc)**
  - **Action on GT (overfiring, natural gas cofiring, air bleed, etc)**
- **Each options or options combination shall be compared from a technical and investment cost point of view**
- **Impact on gas turbine life cycle and maintenance to be analyzed**

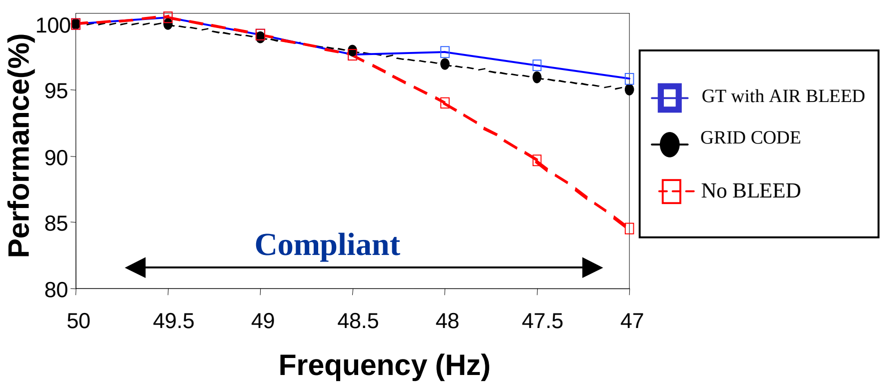
The Design Tools: Electrical Studies

CCGT Frequency Response vs UK Gride Code

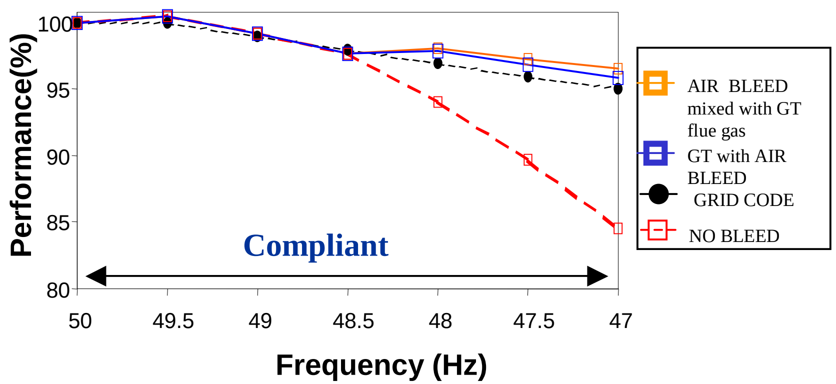


CASE 1: CCGT normal response (GT and ST output decrease)

- Gas turbine has a different behaviour at different ambient temperatures
- Steam Turbine power output changes, depending on GT exhaust energy and PF duty (if any)



CASE 2: With Air Bleed (to vent) on Gas Turbine



CASE 3: With Air Bleed mixed with GT flue gas

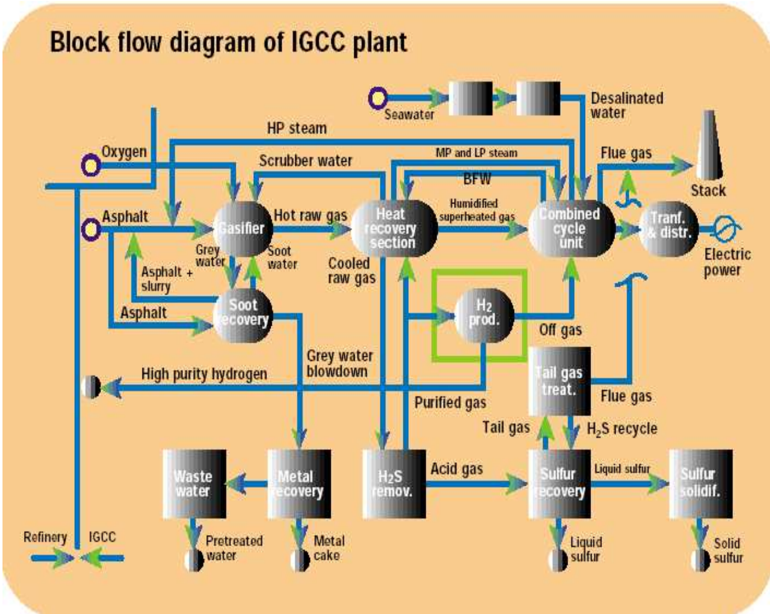
The Design Tools: Dynamic Simulation and Electrical Studies

- Voltage Level Selection and Network Reliability Study
  - optimize IGCC electrical network on the basis of Process Units needs
  - individuate the arrangement capable to minimize IGCC total or partial shutdown at a certain investment cost increase
  - Check the payback time
- Transient Stability Study
  - investigate critical time of generators and larger users (e.g. ASU compressors and CO_2 compressors) during internal or external failure or disturbance, to prevent partial or total IGCC shut-down
  - investigate IGCC behaviour after disconnection from the external grid (island operation)

Case Study: ISAB Energy 550 MWe IGCC (asphalt)

FOSTER WHEELER ITALIANA SCOPE OF WORK

- Feasibility Study
- Optimization Study
- Front End Engineering Design
- EPC (shared with SP)
- Commissioning and Start-up (shared with SP)
- Performance Test Procedure
- Dynamic Simulation Study during EPC (both process and electrical)
- Control System Design and DCS/ESD supply
- Electrical System Design
- Feasibility Study for Retrofit to CO_2 capture



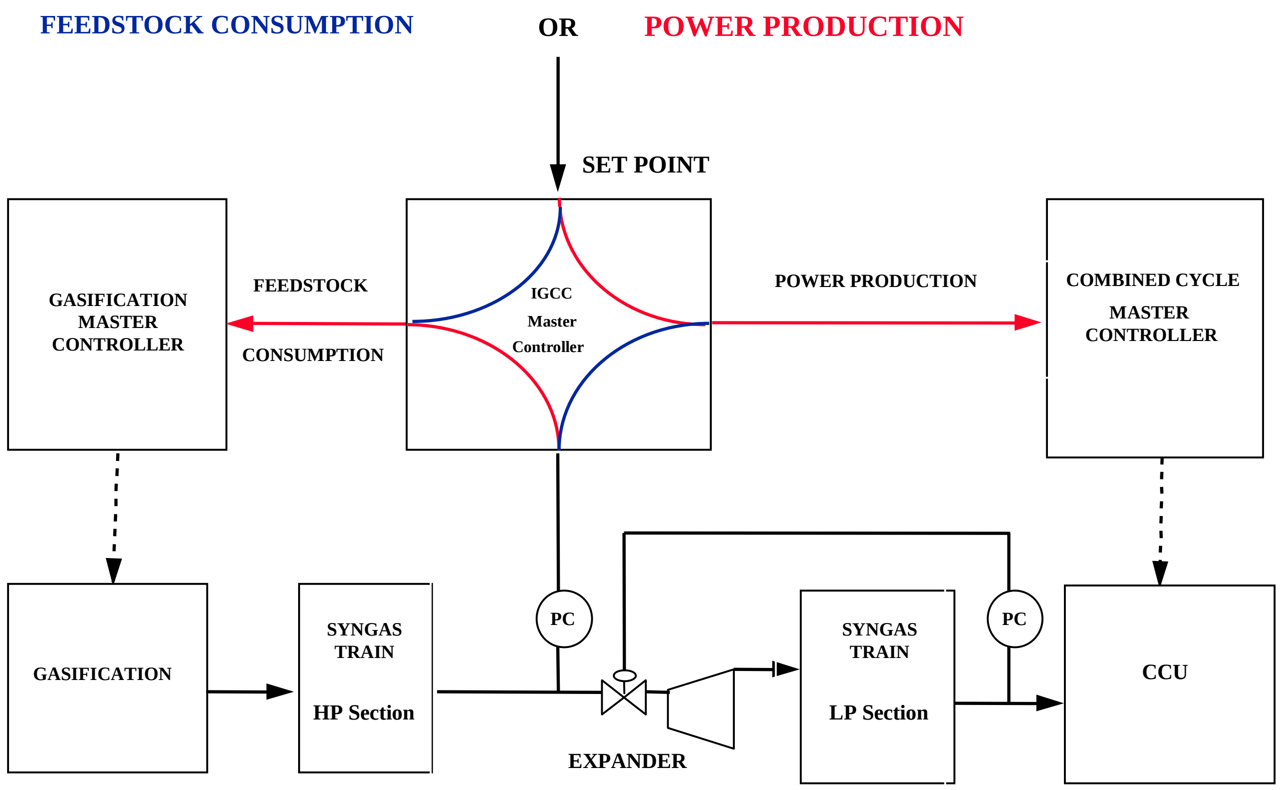
Case Study: ISAB Energy 550 MWe IGCC (asphalt)

Outcomes of the Dynamic Simulation Study

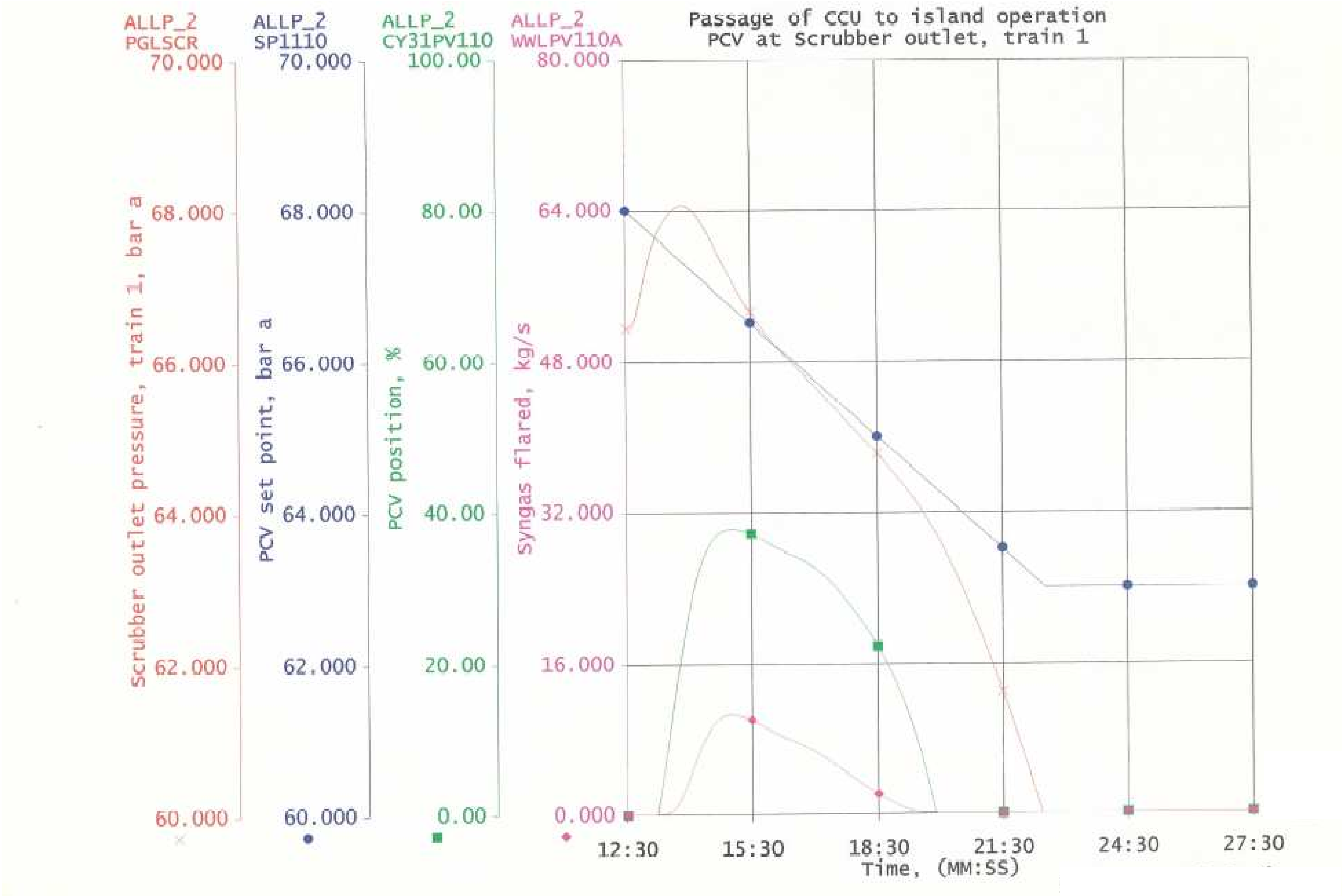
- Equipment Mechanical Design (i.e. geometrical dimensions, design temperature and pressure) and control valves size and characteristics have demonstrated to be adequate
- Control Philosophy: the logics of the Master Controllers (i.e. IGCC Master Controller, CCU Master Controller, Gasification Master Controller) have been validated. Some logics to withstand emergency conditions have been modified
- Controllers parameters defined through the simulations have been successfully implemented during plant commissioning

Case Study: ISAB Energy 550 MWe IGCC (asphalt)

IGCC Normal Operating Control Modes

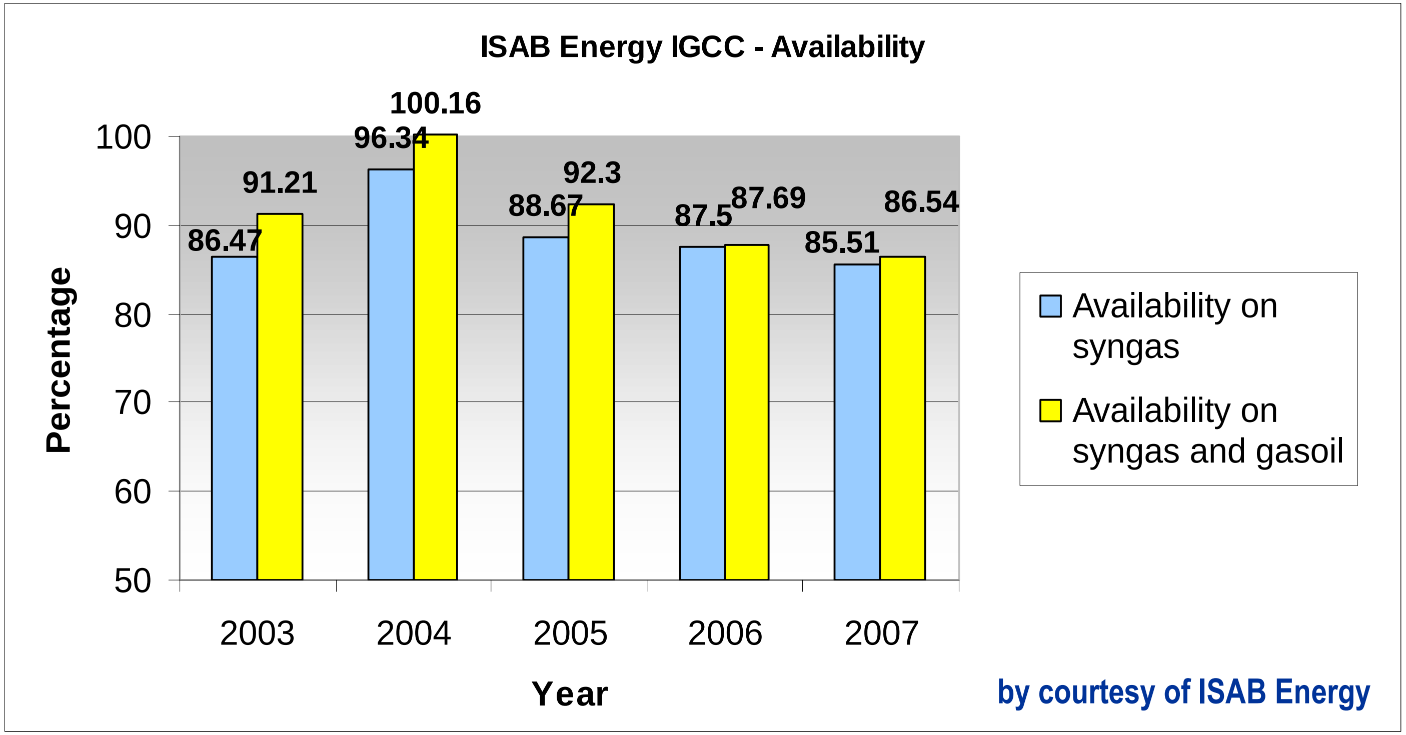


ISAB Energy – Passage of CCU to Island Operation – PCV at scrubber outlet opening



Case Study: ISAB Energy 550 MWe IGCC (asphalt)

Plant Performance and Availability



Excellent Reliability starting from the first operation mainly due to the robust control system

Case Study: ISAB Energy 550 MWe IGCC (asphalt)

Case Study: api energia 285 MW IGCC Project

- Location: adjacent to api Refinery – Falconara (AN)
- 285 MW net power output / feedstock visbroken vacuum residue (60 t/h)
- GE Energy/Texaco gasification quench high pressure with naphtha soot recovery
- Selexol and COS hydrolisis for syngas sweetening
- Combined Cycle with one gas turbine Alstom (ABB) 13E2
- LSTK contract by ABB who was also shareholder
- Entered commercial operation in April 2001

VERY POOR AVAILABILITY DURING FIRST YEARS OF OPERATION

Case Study: api energia 285 MW IGCC Project

FOSTER WHEELER ITALIANA SCOPE OF WORK:

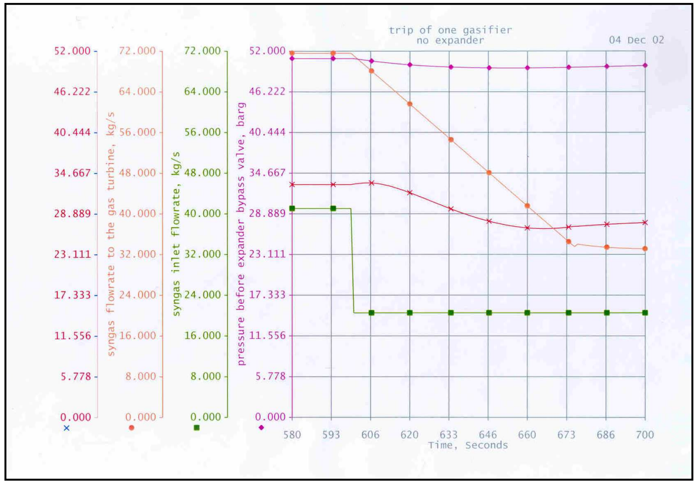
- consultancy services as Owner's Engineer during project execution, start-up and acceptance test;
- SIL evaluation;
- Reliability Improvement Program including Dynamic Simulation;
- Engineering and Construction of Upgrading modifications (Combined Cycle, IGCC Instrumentation and Control System etc);
- Feasibility Study for CO_2 capture
- Frame Agreement for other modifications signed every year

Dynamic Simulation aimed at implementation of an IGCC Master Controller, automatic switchover of the gas turbine from syngas to back-up fuel and start-up of the expander

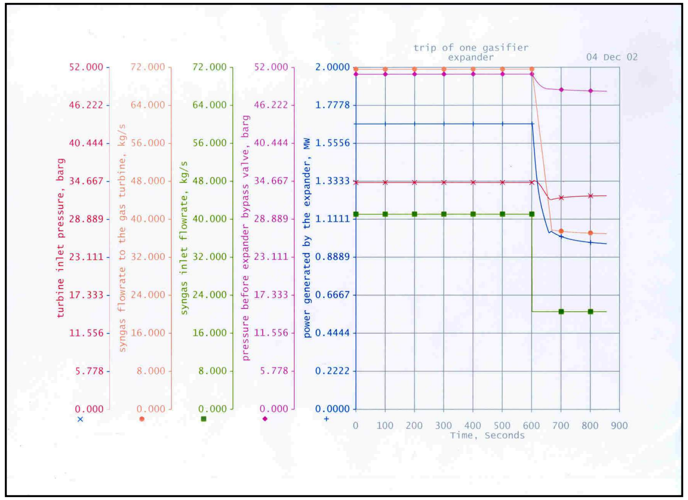
Case Study: api energia 285 MW IGCC Project

GT Automatic Switchover from Syngas to Back-up Fuel (Gasoil)

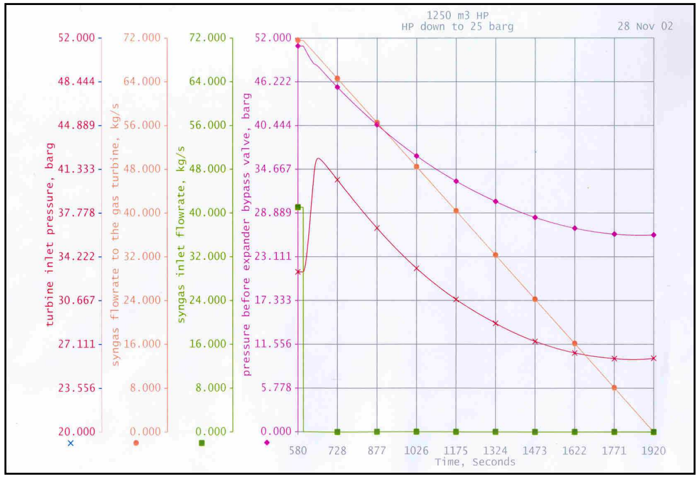
TRIP OF ONE GASIFIER - NO EXPANDER



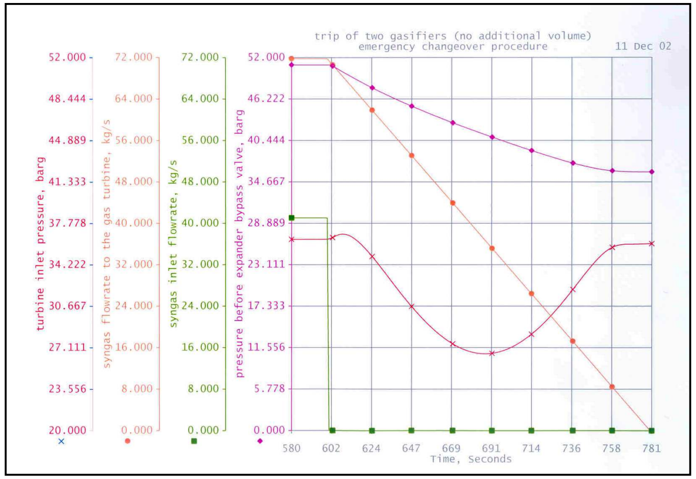
TRIP OF ONE GASIFIER - EXPANDER



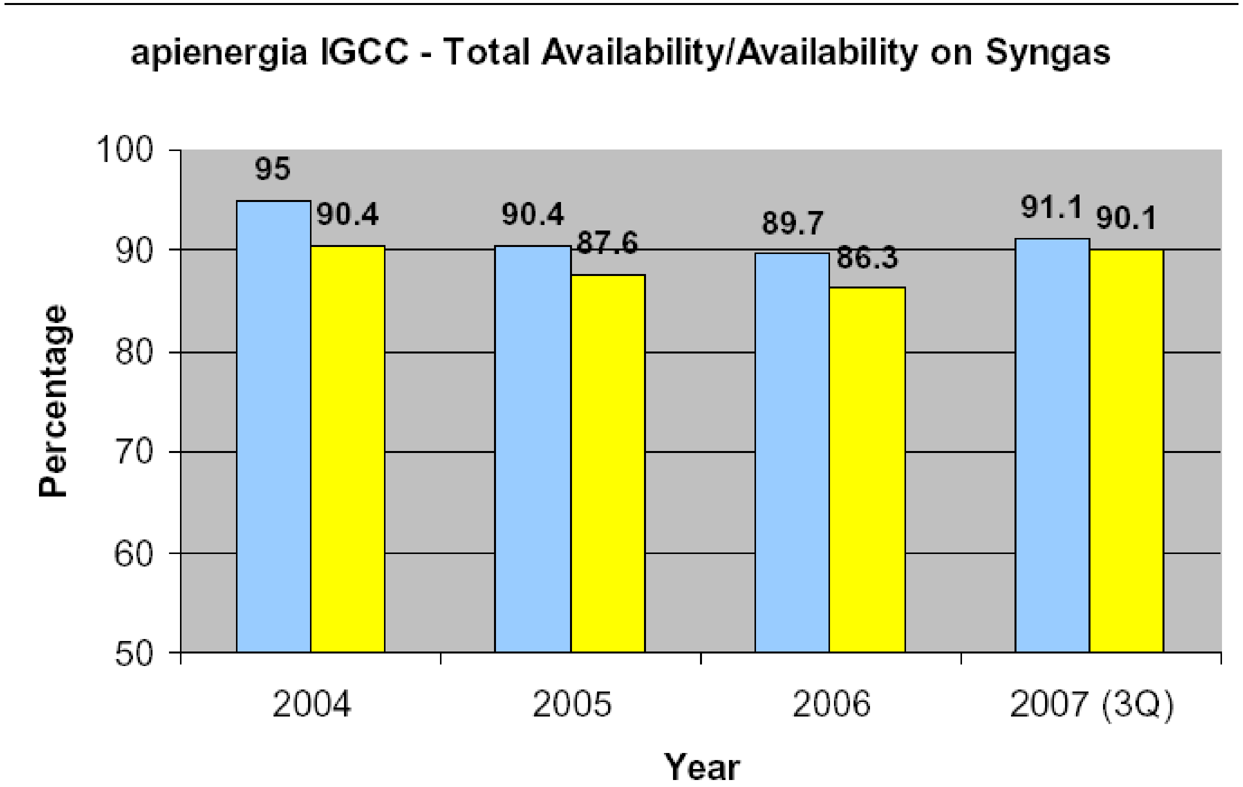
1250 m³ buffer HP – HP DOWN TO 25 BAR G



TRIP OF TWO GASIFIERS (no additional volume) - EMERGENCY CHANGE OVER PROCEDURE



Case Study: api energia 285 MW IGCC Project



Year 2006 availability takes into account 35 days GT major overhaul (every 5 years)

by courtesy of api energia

Case Study: api energia 285 MW IGCC Project

Foster Wheeler Italiana Experience

Other References

- 5 FEED performed on oil and coal IGCC projects
- More than 35 IGCC and Gasification studies since 1988
- International Organization References (5 studies performed for IEA-GHG and 4 studies performed for EPRI)
- CO_2 capture: evaluation of impacts on plant performance and COE (Cost of Electricity)
- Hydrogen Co-production
- Coal to Chemicals/Coal to Liquids Projects
- Coal to Ammonia/Methanol (agreement with Casale)
- Coal to Syngas for iron ore reduction

Foster Wheeler Italiana Experience

EPRI – Assessment of IGCC on Coal for Near-term Deployment

- Feasibility and optimisation study covering the "Engineering and economic assessment of IGCC coal power plants for near term deployment."
- PHASE 1: Technical and economic evaluation of forty IGCC designs, processing different coals (Pittsburgh # 8 and PRB) with five alternative gasification technologies (GE, KBR Southern Energy, Shell, Siemens), without with retrofitted carbon dioxide capture.
- PHASE 2: Technical and economic evaluation of eleven IGCC designs, processing different coals (Pittsburgh # 8 and Eastern Austrialian Bituminous Coal) with five alternative gasification technologies (GE, MHI, Shell, Siemens, Udhe, Prenflo), with and without carbon dioxide capture.
- This work is being performed as part of EPRI's CoalFleet for Tomorrow Programme, a collaboration involving more than 60 power industry companies to encourage the early deployment of advanced coal power generation technology.

THANK YOU

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www.fosterwheeler.it

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Workshop on Operating Flexibility of Power Plants with CCS
Imperial College, London, 11th 12th November 2009

Analysis of flexibility options for electricity generating projects with pre-combustion capture of CO_2

Andy Brown, Engineering Director, Progressive Energy

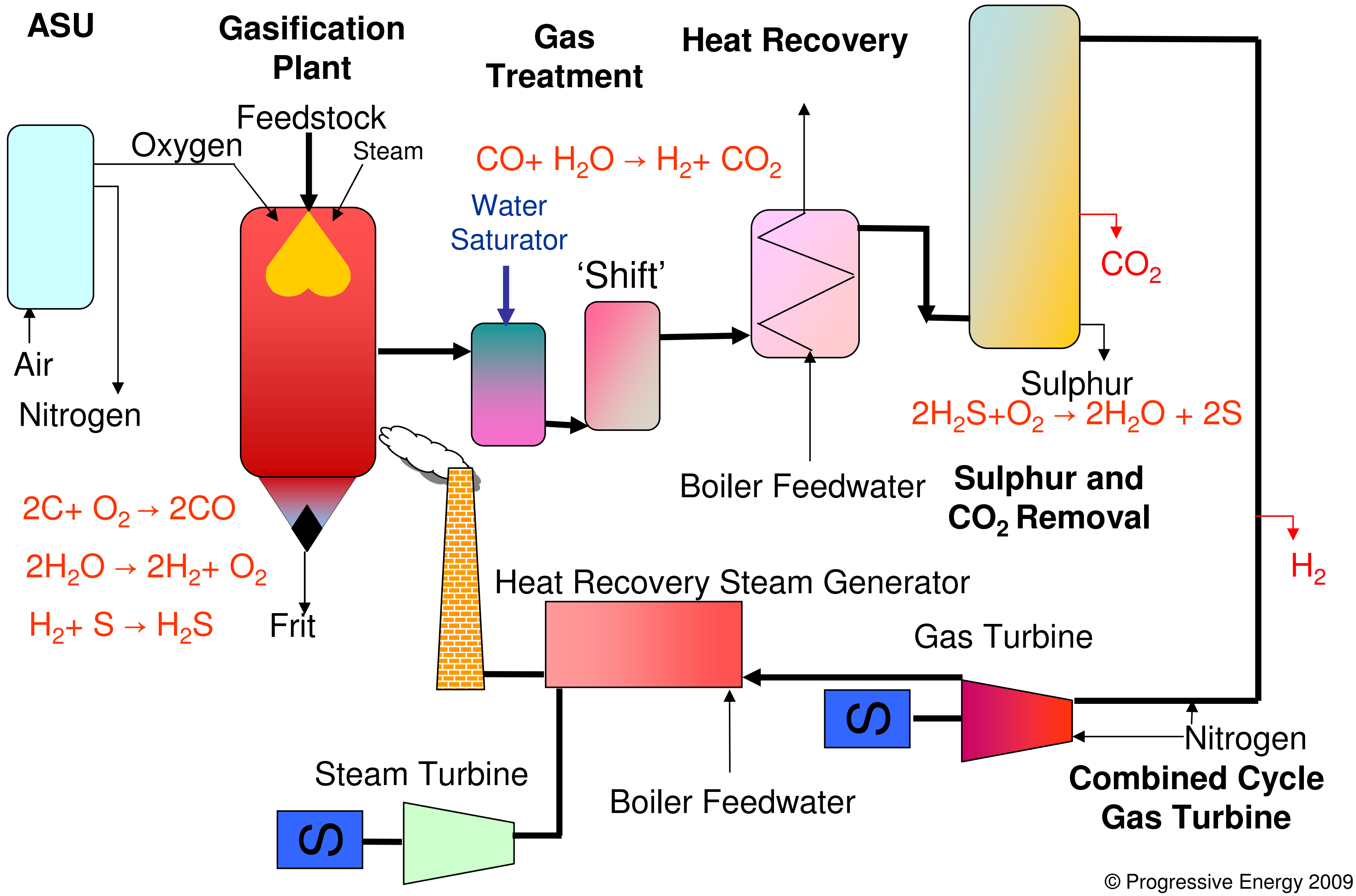
Introduction to Progressive Energy

- An energy project development company, formed in 1998
- Strengths include knowledge of UK energy scene
- Expertise in ‘clean’ fossil technologies, CO_2 capture & storage
- Co-developing an 850MW clean coal power station with pre-combustion CCS at Teesside
- A further gasification project is being developed in the NE
- Waste-to energy (or hydrogen) projects
- Biomass projects
- Involved in the EC ‘Dynamis’ Programme
- Energy consultancy

Pre-combustion CO_2 capture and storage

Pre-combustion capture of CO_2 requires processing the feed supply (coal, petcoke, natural gas) to remove the carbon (usually as CO_2) to leave a gas that is mostly hydrogen, which can be used to produce electricity by combustion (in a combined cycle gas turbine or conventional steam-generating boiler), or in fuel cells. The hydrogen can also be utilised in petrochemical and other processing industries.

Since this workshop is on the operating flexibility of power plants with CCS, the focus of this presentation will be on electricity generation, which implies an understanding of IGCC (Integrated Gasification Combined Cycle).



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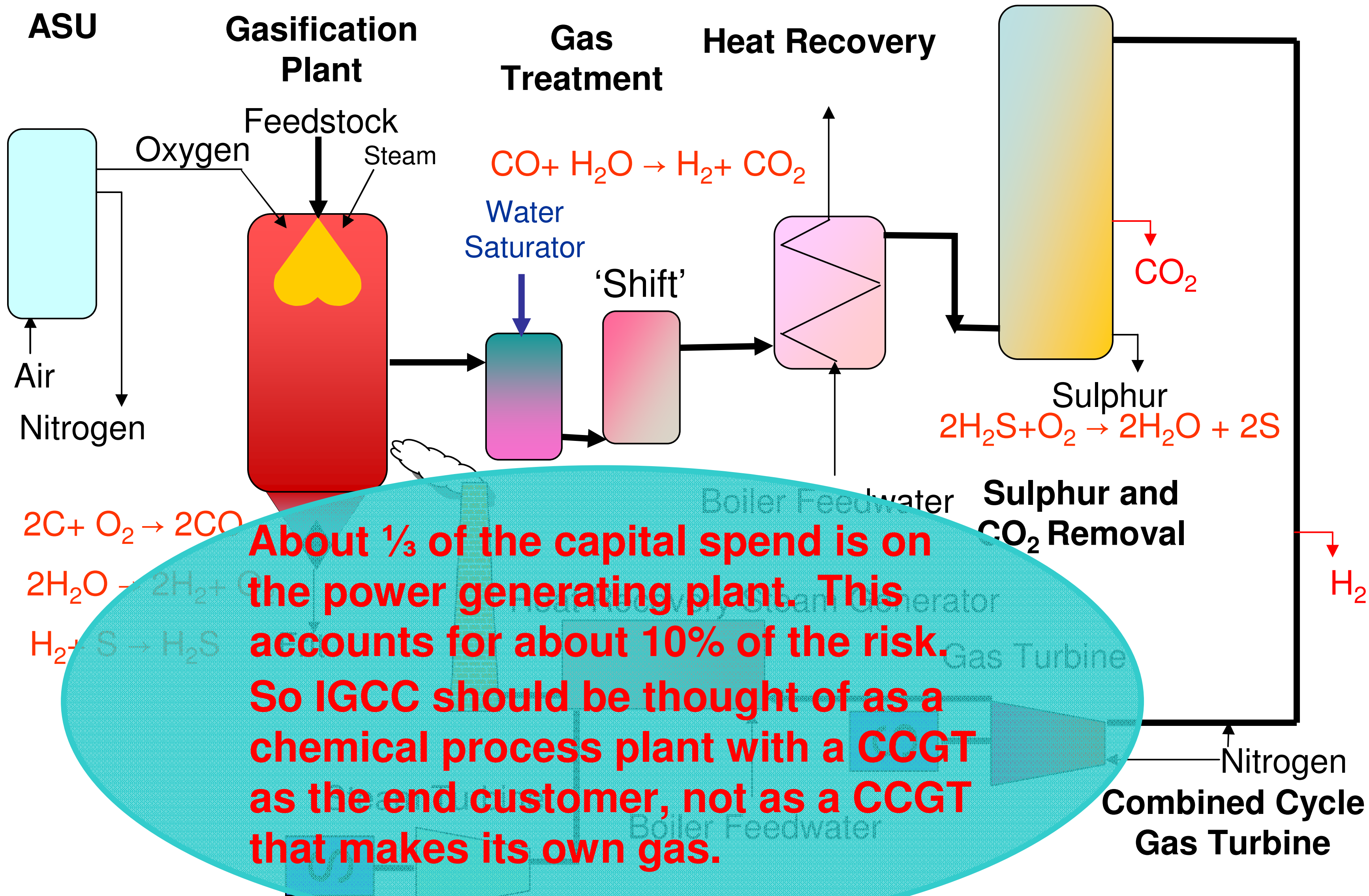

About ⅓ of the capital spend is on the power generating plant. This accounts for about 10% of the risk. So IGCC should be thought of as a chemical process plant with a CCGT as the end customer, not as a CCGT that makes its own gas.

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Pre-combustion CO_2 capture and storage

Requirements for Power Generation

- Variable output to suit hourly grid demand
- Rapid start-up and shut-down, two-shifting
- Ability to accept wide range of fuels based on the lowest cost
- Most equipment is available as an “off-the shelf” design on a turnkey basis
- Frequent operational and other changes to improve efficiency, flexibility or reliability

Requirements for Process Engineering

- Steady-state operation over long periods of time
- Essential shut-downs only, eg for maintenance
- No changes once process conditions are established
- Most plants are ‘bespoke’ designs, optimised around local conditions
- “If it ain’t broke, don’t fix it”

Flexibility in pre-combustion CCS

Progressive Energy has been working with Sintef and E.ON on the EC Dynamis project. Dynamis responded to the EC target of "Preparing for large scale H_2 production from decarbonised fossil fuels including CO_2 geological storage". The main objective has been to prepare the ground for large-scale European facilities producing hydrogen and electricity from fossil fuels with CO_2 capture and geological storage.

An "Additional Project" was accepted to look at some of the more promising possibilities for operating an IGCC with increased flexibility by investigating the technical issues and evaluating the commercial opportunities.

Six flexibility possibilities were considered.

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Flexibility in pre-combustion CCS

The six flexibility possibilities considered were:

1. Load following
2. Diurnal storage
3. ASU interruption
4. AGR/CO_2 turndown
5. Gas substitution
6. Co-production

Flexibility in pre-combustion CCS

1. Technical possibilities

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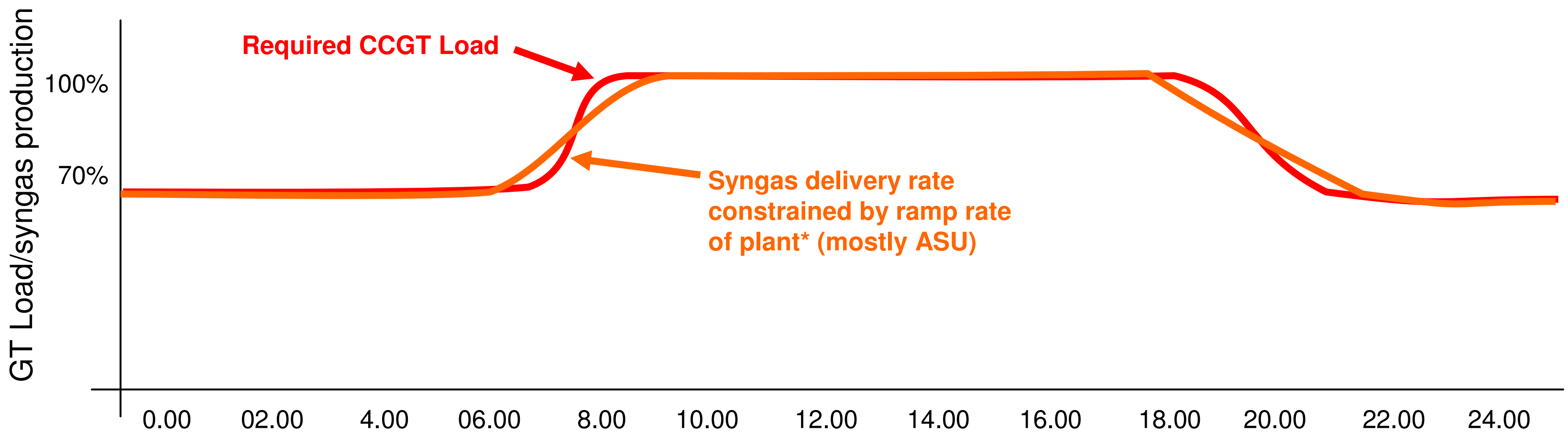
1. Load following

Reducing syngas production overnight (and load on the CCGT) and bringing it up to full load during times of high electricity prices.



- Allows the process plant to operate within stable limits permitting some flexibility from the power production plant
- Reduced use of capital invested
- Plant efficiency drops significantly during overnight periods
- **Can we do better than this?**

* NB. Ramp rates are illustrative only

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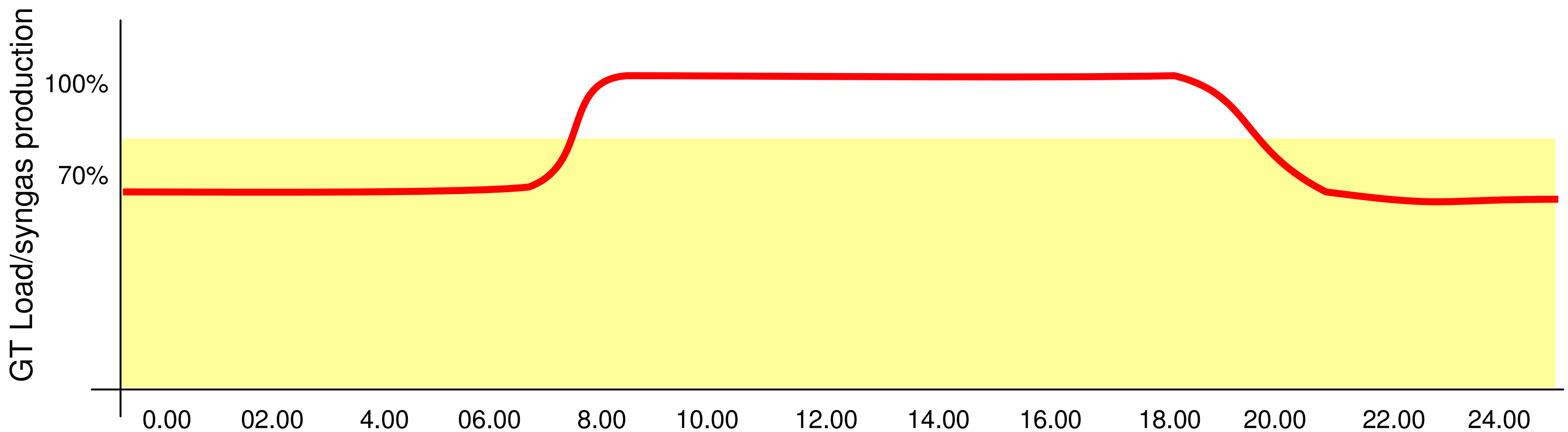
2. Diurnal Storage (1)

Storage of “decarbonised syngas” (eg overnight or at weekends), and subsequent use at times when spot electricity prices are high.



- Allows the process plant to operate “base load”, whilst permitting flexibility from the power production plant
- Possible capex savings, as process plant needs only to be sized for ≈ 80% full load
- Requires significant storage volumes

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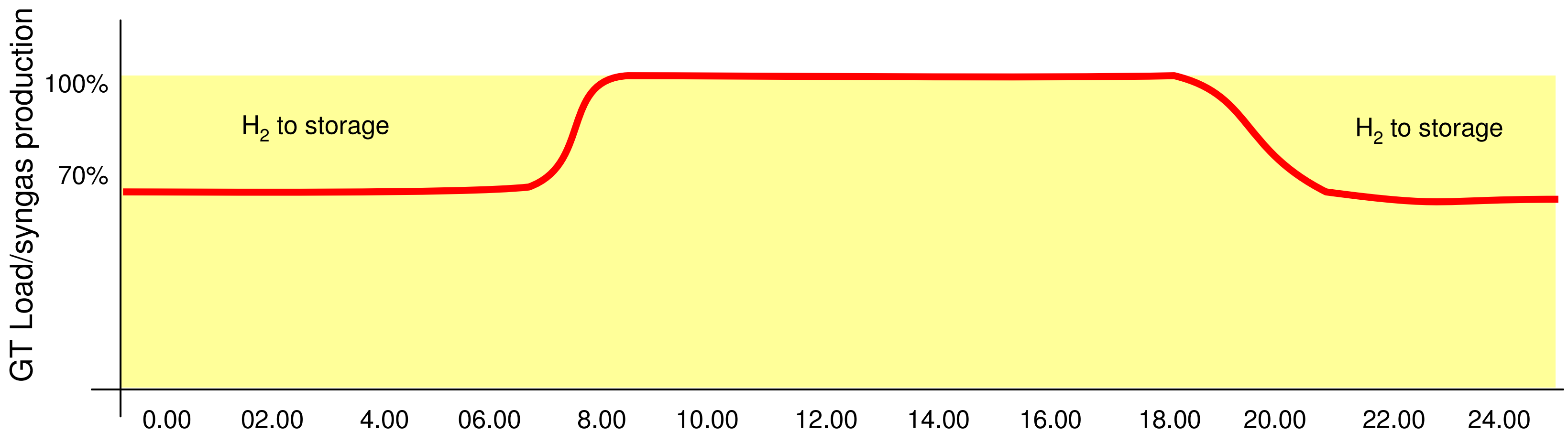
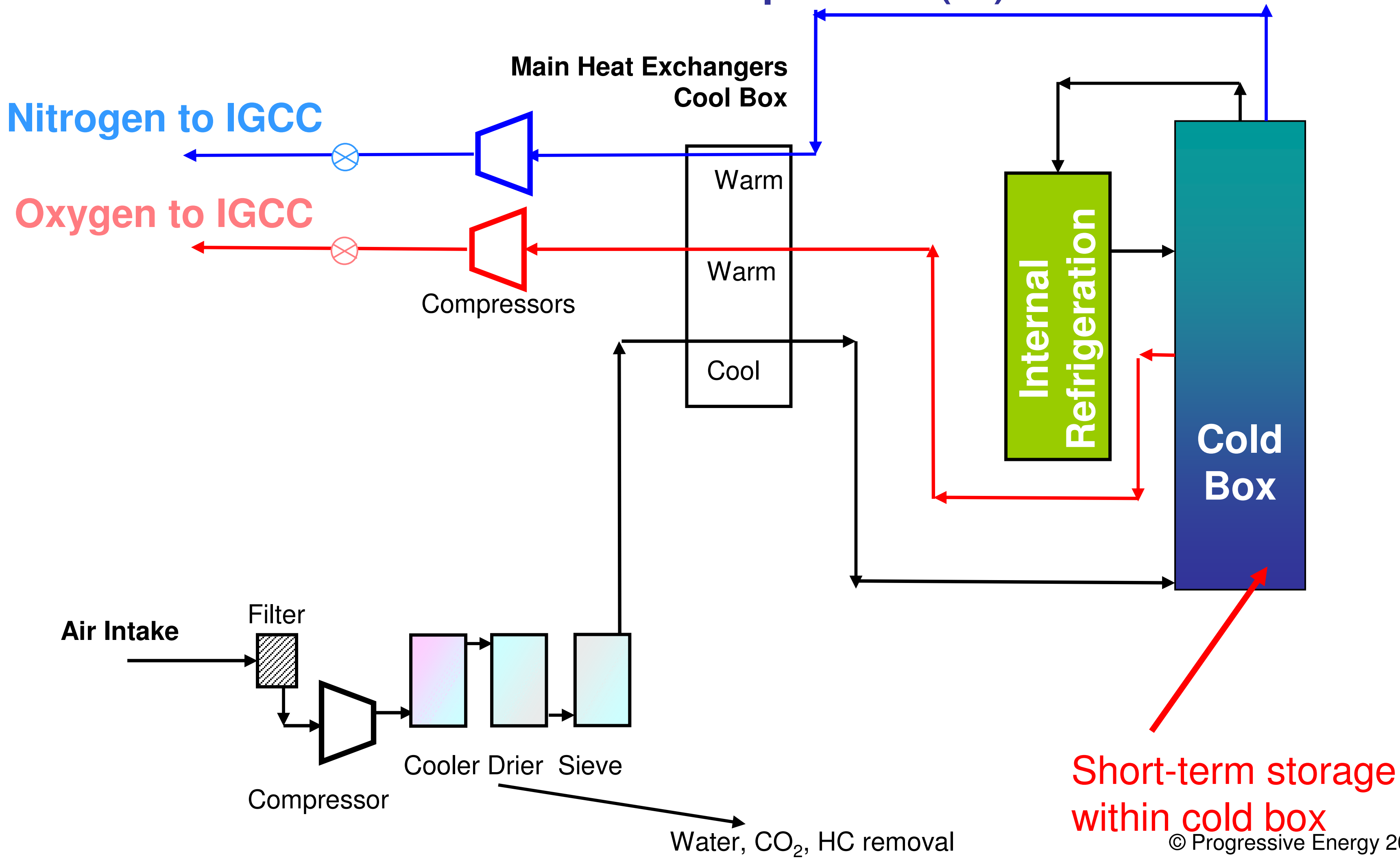
2. Diurnal Storage (2)

Storage of "decarbonised hydrogen gas" (eg overnight or at weekends), and sales to third party.

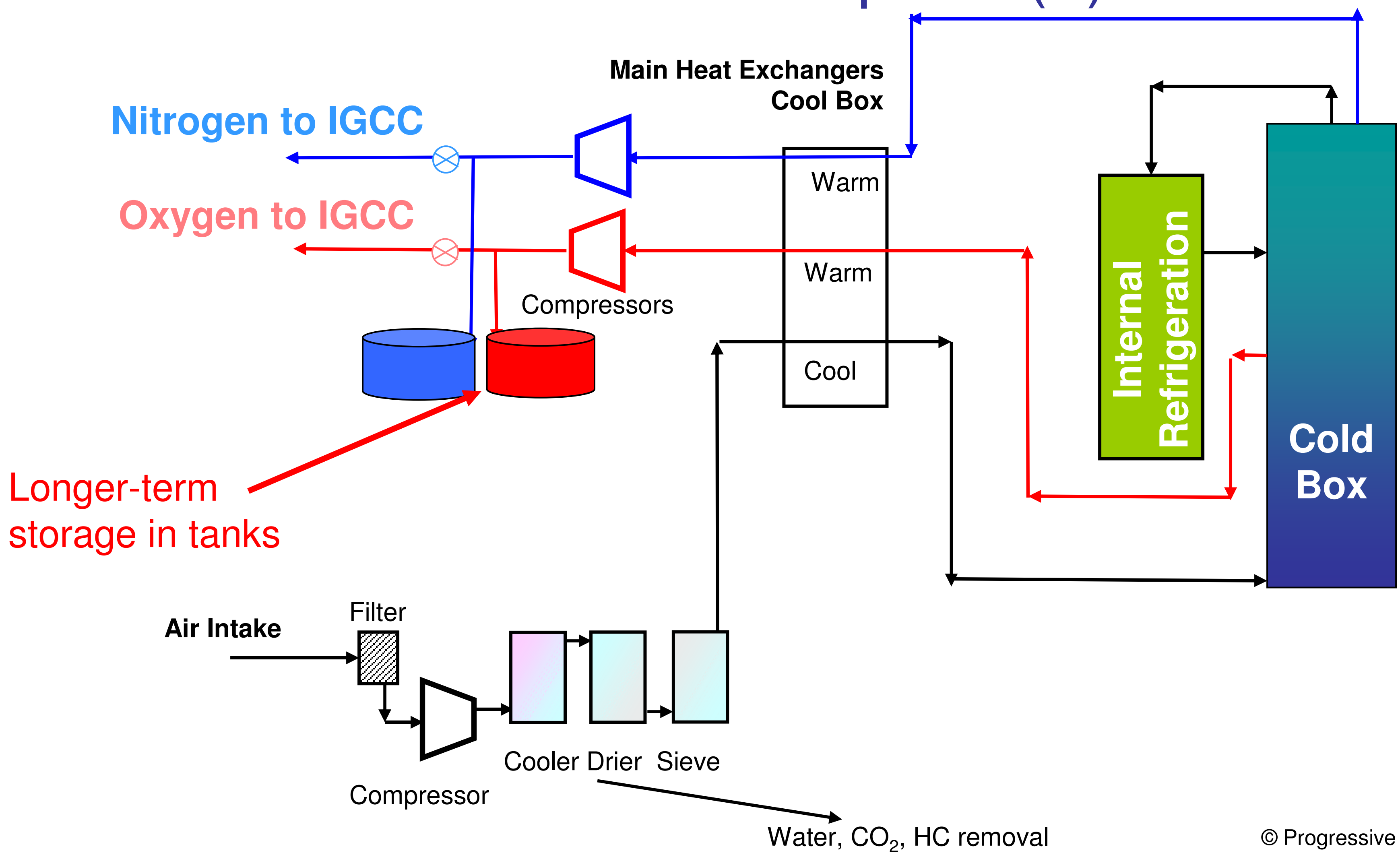


- Allows the process plant to operate "base load", whilst permitting flexibility from the power production plant
- Requires significant storage volumes or introduction into NTS as Hythane®
- Requires PSA to separate out hydrogen from syngas
- Requires a customer for 55 tonnes/day of hydrogen

3. ASU Interruption (1)



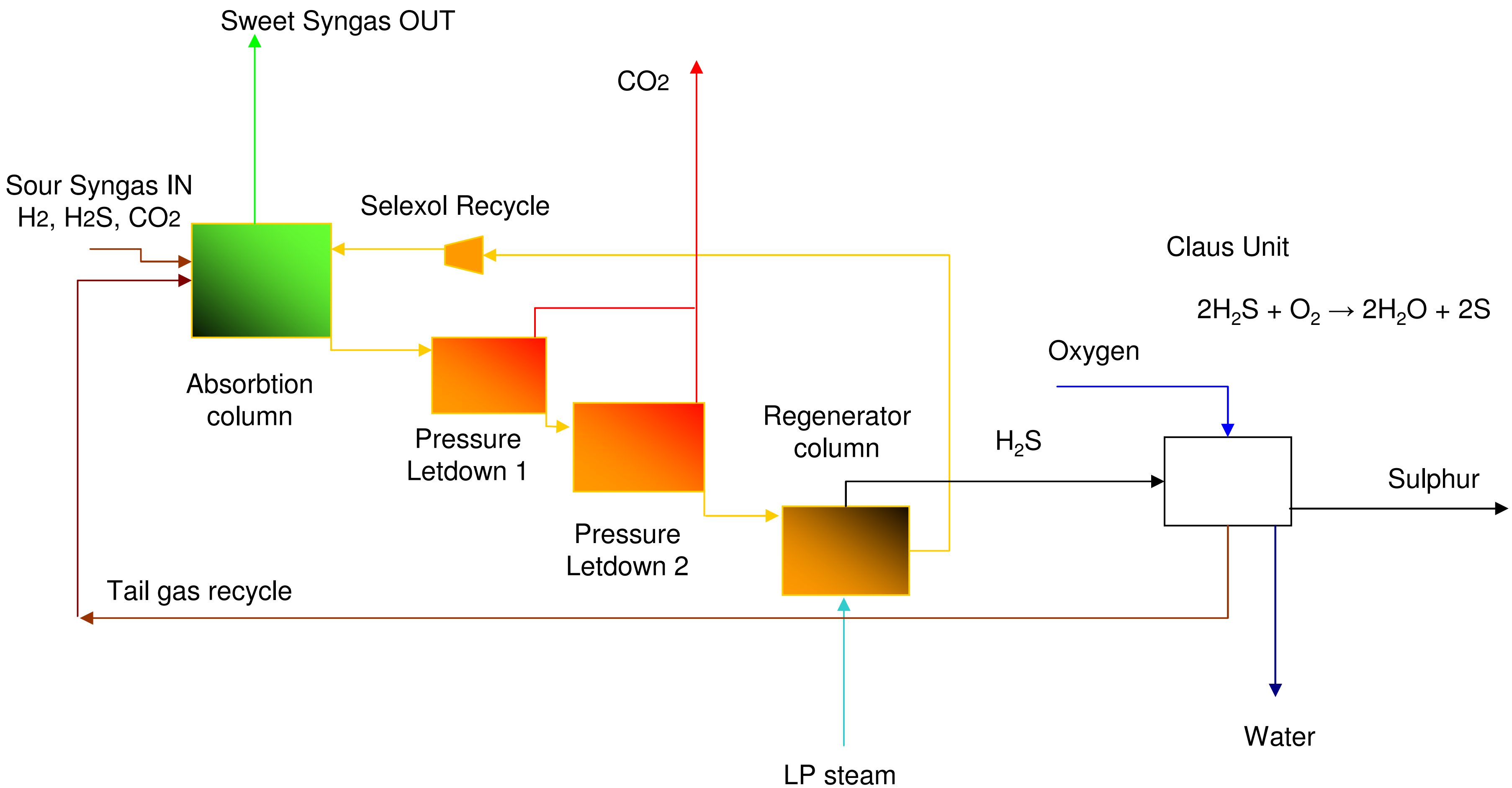
3. ASU Interruption (2)



3. ASU Interruption

- The ASU consumes about 12% of the power, thus tripping it can make this available for export
- The storage tanks could be re-filled overnight by running the ASU at base load and flexing the rest of the plant
- If liquid oxygen or nitrogen is stored in tanks, a gas burner will be needed after about 30 seconds to reheat it to gaseous form.
- Requires significant storage volumes
- Requires capex investment in storage tanks and burners

4. AGR/CO_2 Turndown



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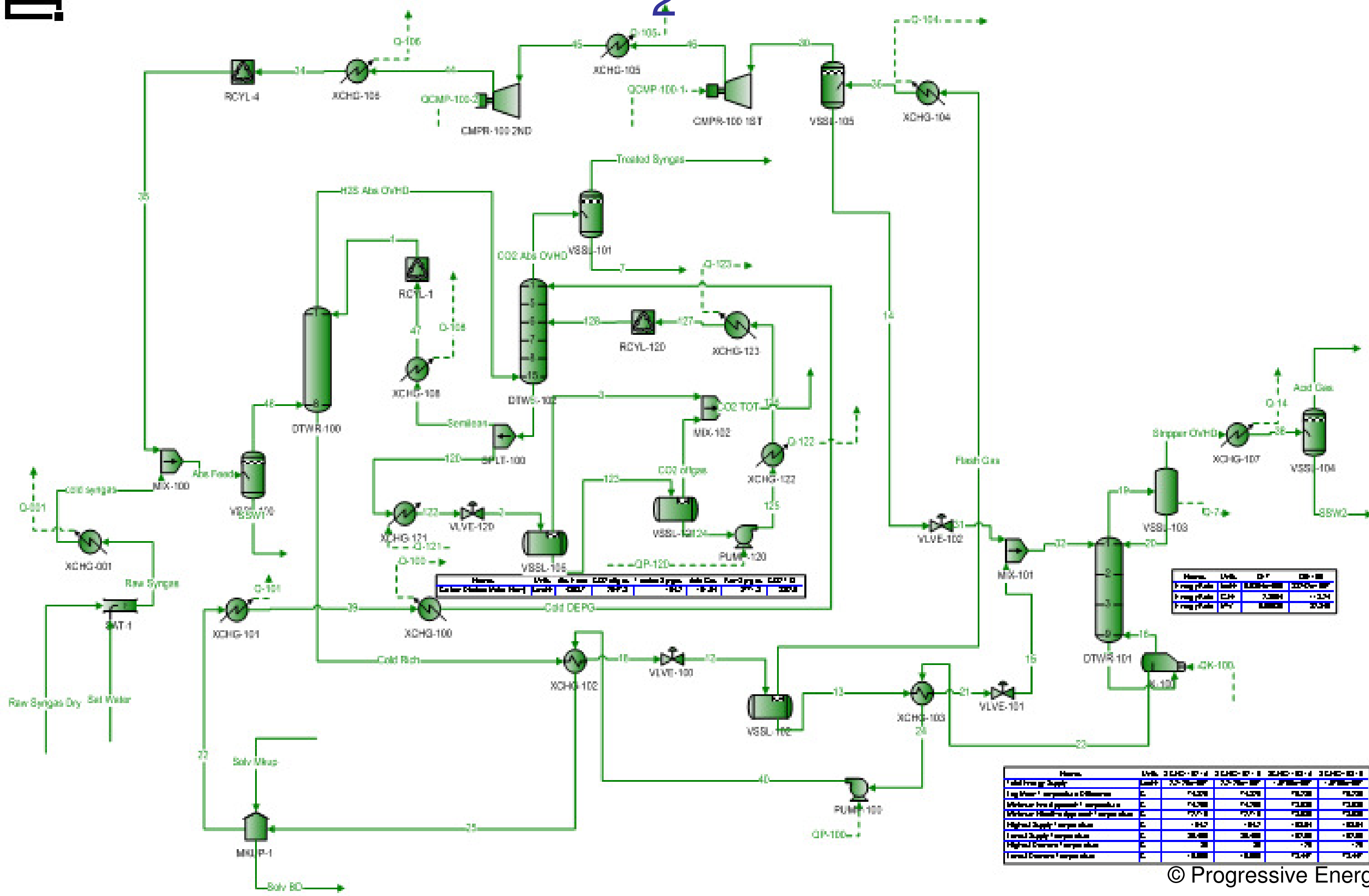
4. AGR/CO_2 Turndown



4. AGR/CO_2 Turndown

Selexol H_2S and CO2 removal plant, Coffeyville, Kansas

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4. AGR/CO_2 Turndown

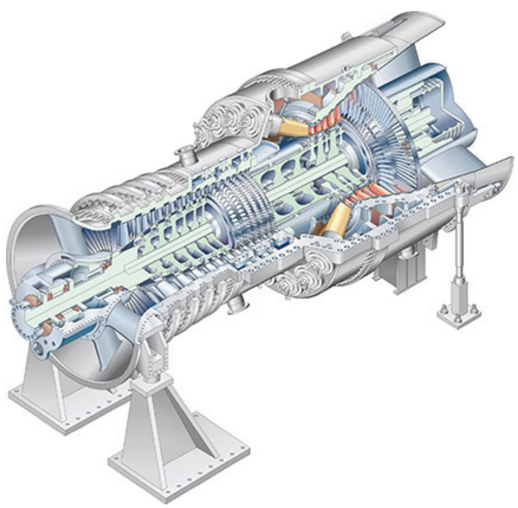
- By not separating out the CO_2 from the syngas, the load on the AGR plant could be reduced.
- The AGR plant could not be shut down completely, as it is needed to remove H_2S from the fuel gas stream
- The CO_2 would be emitted up the CCGT stack (as it would be for a non-CCS IGCC plant)
- Nitrogen diluent would not be required for the gas turbine: tripping the N_2 compressor could release 5% of the CCGT power. The AGR consumes about 3.4% of the CCGT power, and the CO_2 compressor about 4.9% thus not removing the CO_2 can make some of this (about 6.5%) available for export. Total power released about 11.5% of CCGT power.
- The AGR plant will take a while to stabilise. Fuel gas quality will suffer whilst this takes place.
- Emitting the CO_2 will attract financial penalties (€/tonne)
- If the CO_2 is used for EOR applications, there may also be penalties for failure-to supply

5. Gas Substitution

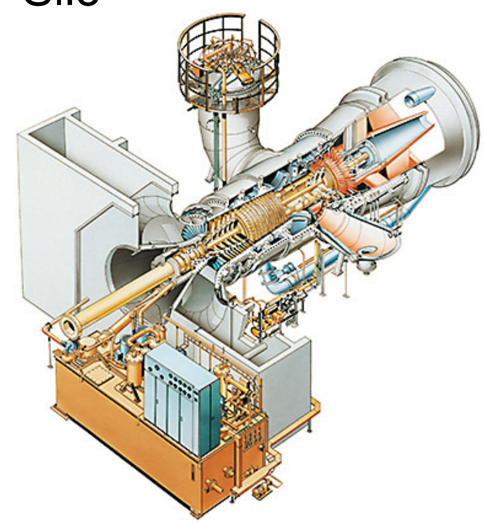
Substituting all of some of the syngas to the gas turbine with natural gas.

There are two types of combustor suitable for burning high hydrogen syngas:

Can-annular



Silo



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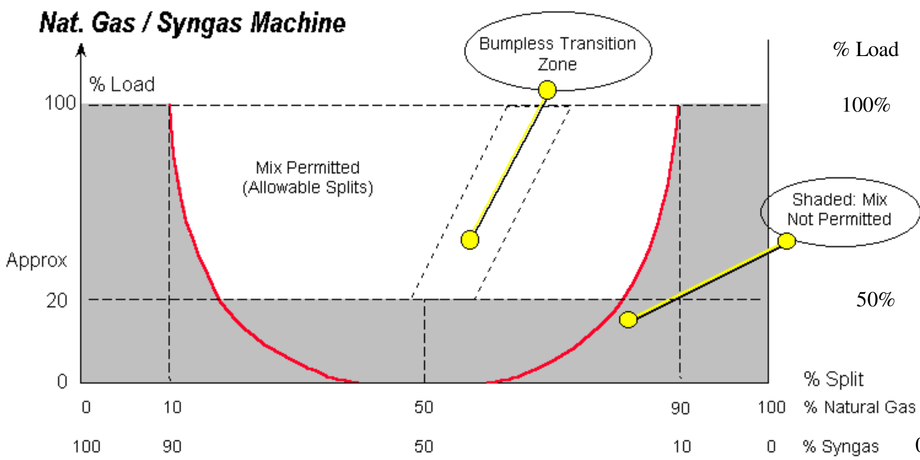
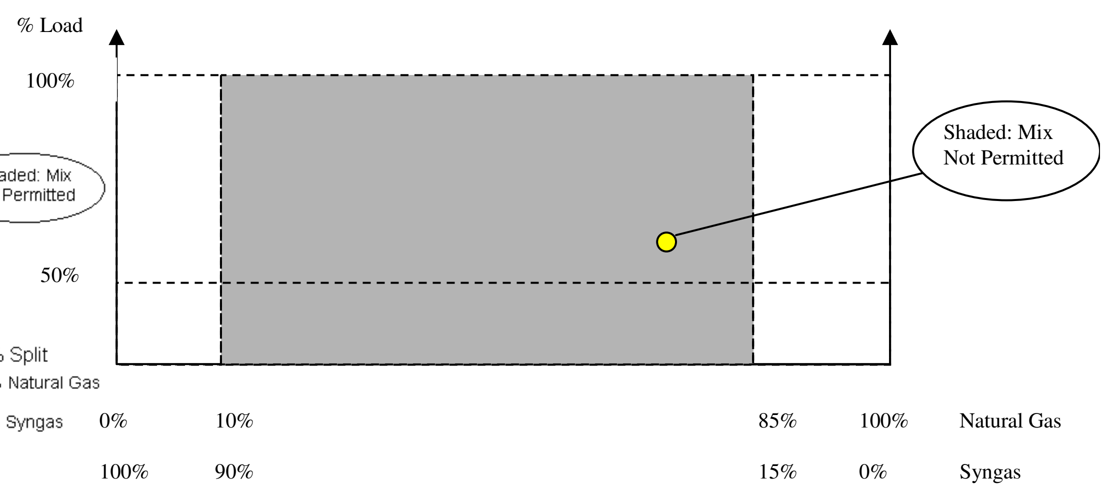
5. Gas Substitution

The two types of combustor have different mixed fuel capabilities:

Can-annular

Silo





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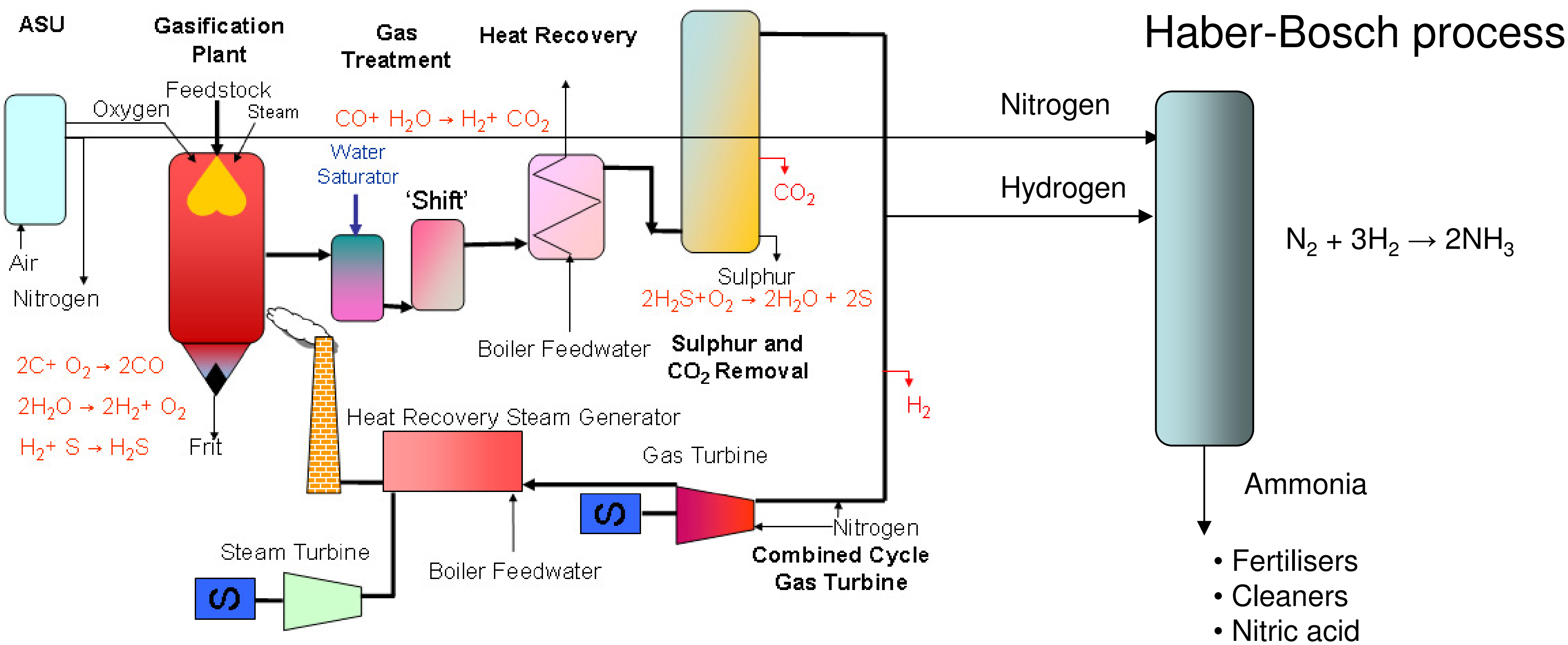
5. Gas Substitution

- Natural gas is necessary to start up the gas turbine, so there will be some compatibility in any case.
- In the event that there were to be a partial plant trip (eg gasifier trip) the energy supply to the gas turbine could be made up by burning natural gas.
- Burning natural gas may require for steam to be injected into the combustor to cool the flame: this robs power from the steam cycle and leads to reduced gas turbine blade life
- The CO_2 from the combustion of natural gas would be emitted up the CCGT stack (as it would be for a non-CCS CCGT plant) attracting financial penalties (€/tonne)
- Syngas is lower in cost than natural gas (p/GJ), so the power price will be higher

6. Additional Products (Polygeneration)

A) Ammonia.



- Fertilisers
- Cleaners
- Nitric acid
- Refrigerants (R717)

6. Additional Products (Polygeneration)

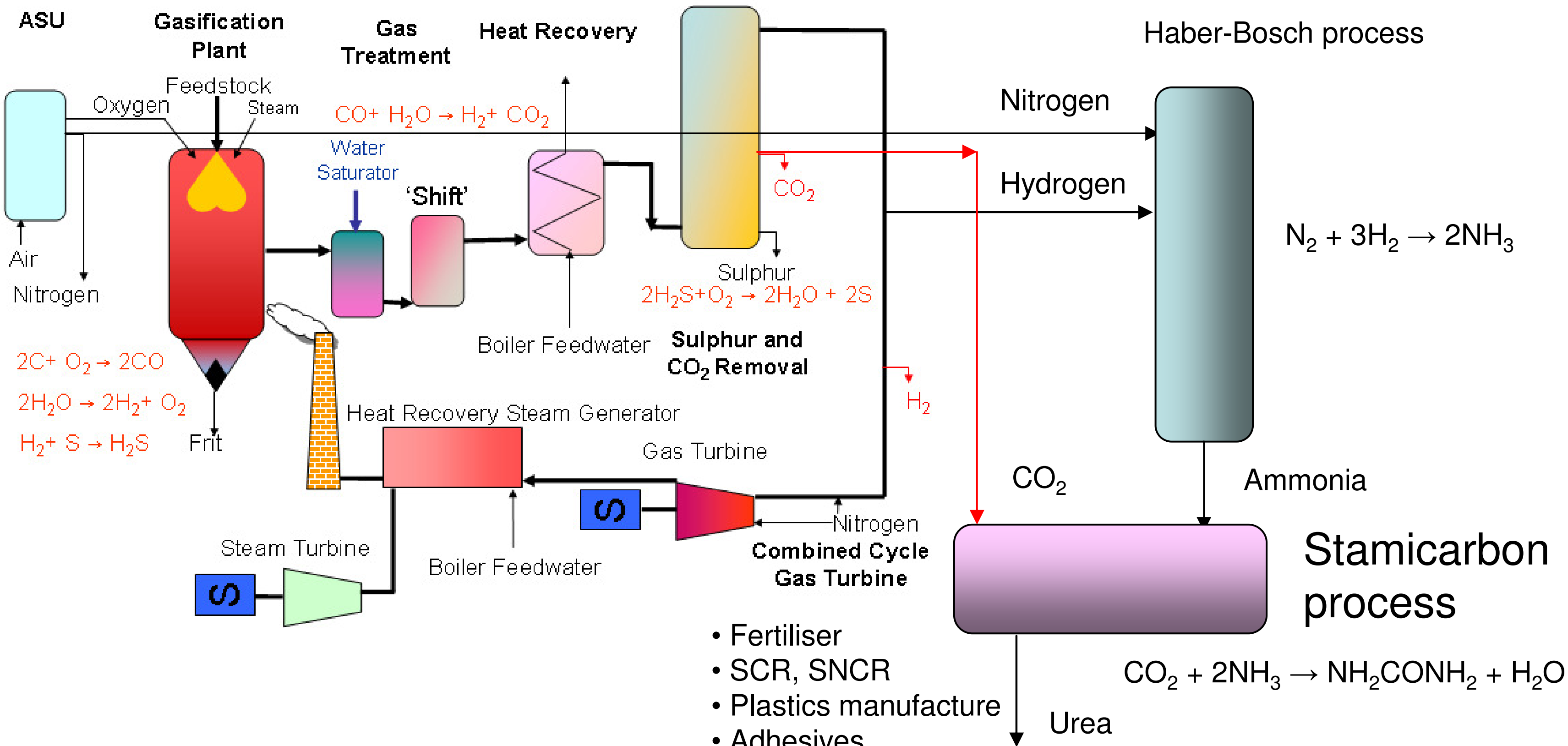
A) Ammonia.

- Worldwide production (2006) is 146.5 million tonnes, so there is a significant demand.
- The Haber Bosch process is a batch operation, so is suitable for “peak lopping”.
- The H-B process takes place at ≈ 150 bar, thus the gases would need additional compression (and/or very high pressure gasification).
- Additional gas purification stages would need to be added to the N2 and H2 streams (eg to wash out trace amounts of H_2S and CO_2) to <5ppm).
- Ammonia storage is needed under pressure (up to 1500 tonnes at ambient temperature, above this at -33˚C)
- The utilisation of the capex for the H-B process is only about 35% of the time
- Market competition is with ammonia plants operating round-the-clock

Progressive energy

6. Additional Products (Polygeneration)

B) Urea.



- Fertiliser
- SCR, SNCR
- Plastics manufacture
- Adhesives
- Explosives

Progressive energy

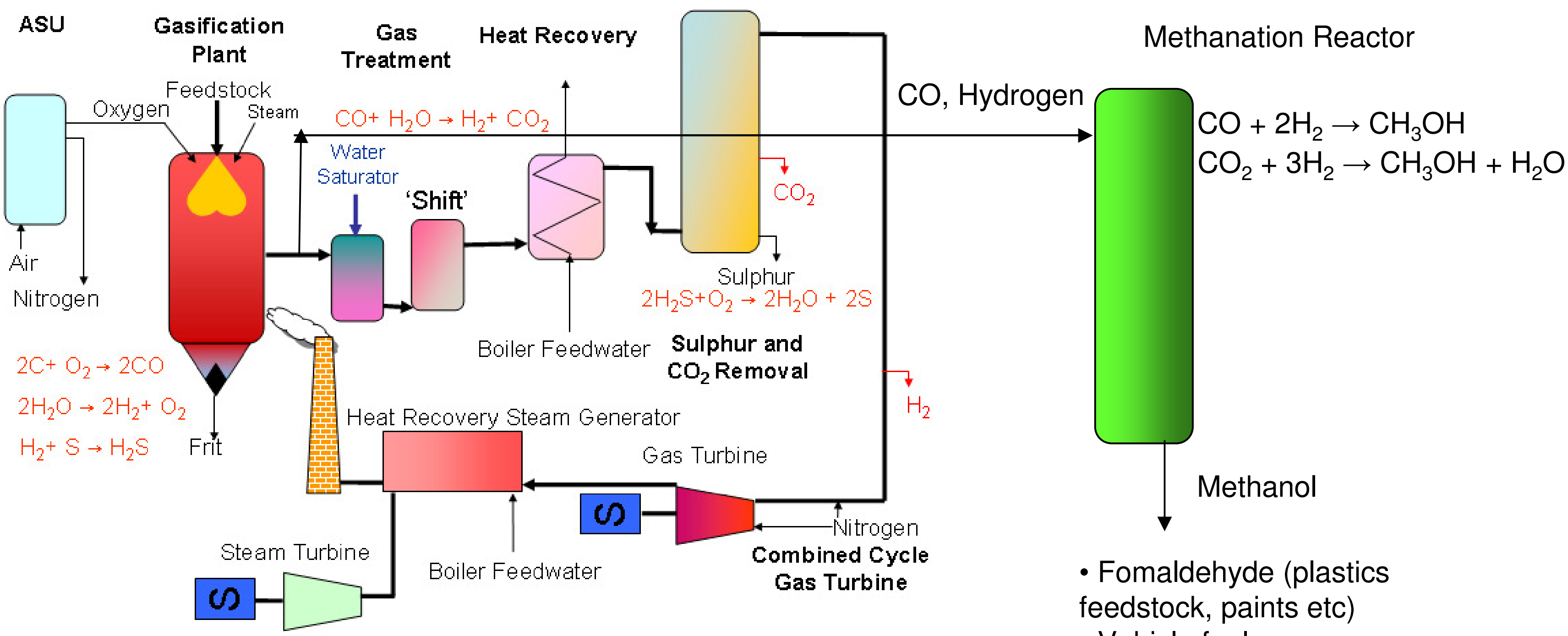
6. Additional Products (Polygeneration)

B) Urea.

• Provides a beneficial use for some of the CO_2 from the plant.
• Potential for beneficial heat integration with the IGCC and H-B plants
• The Stamicarbon process takes place at ≈ 150 bar, thus the CO_2 gas would need additional compression.
• All of the disadvantages from the production of ammonia would apply.
• Significant capital investment in additional process plant would be required
• The utilisation of the capex for the Stamicarbon process is only about 35% of the time
• Market competition is with urea plants operating round-the-clock

6. Additional Products (Polygeneration)

C) Methanol.



- Fomaldehyde (plastics feedstock, paints etc)
- Vehicle fuel
- Methylated Spirit
- Antifreeze
- Fuel cells

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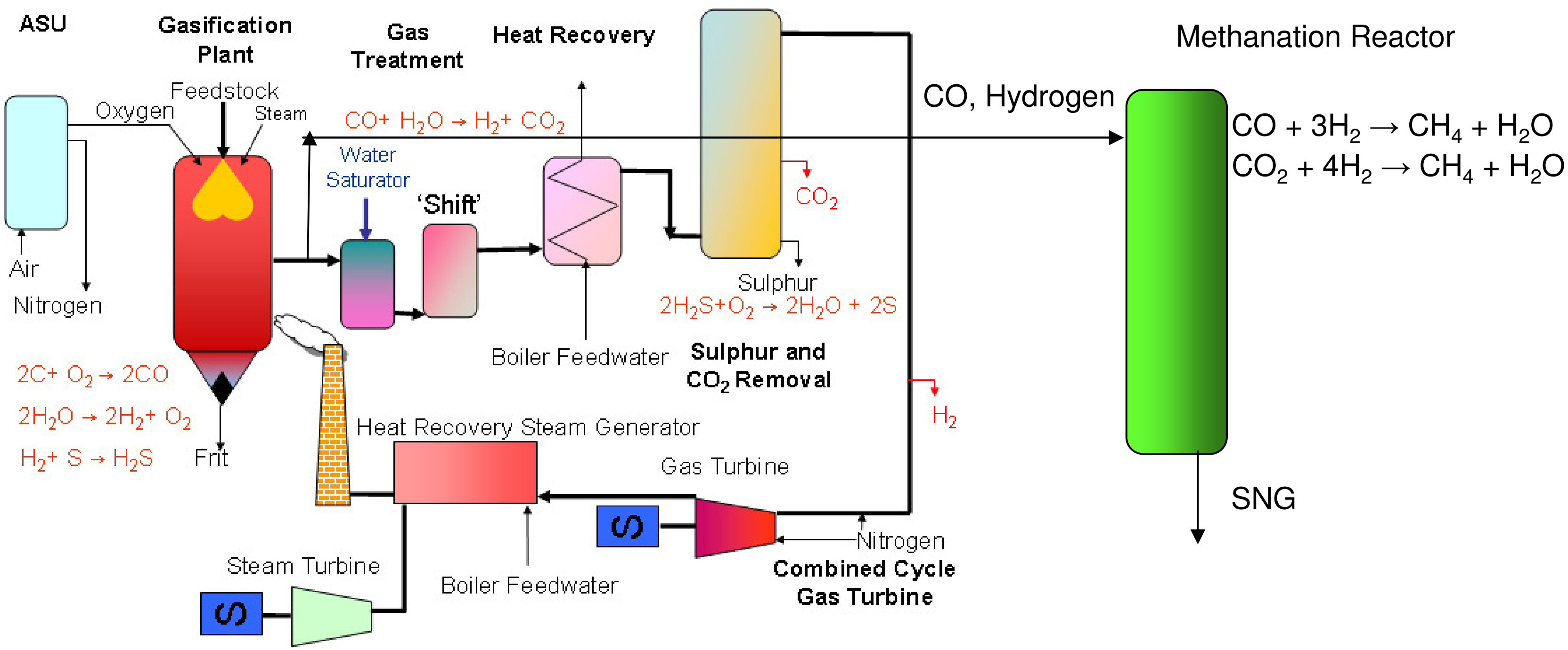
6. Additional Products (Polygeneration)

C) Methanol.

- Utilises carbon from the syngas.
- The methanation process takes place at 50-100 bar for low-efficiency processes, 100-300bar for high efficiency processes, thus the gases would need additional compression (and/or very high pressure gasification).
- The raw syngas will need downstream processing (COS hydrolysis reactor, sulphur removal to ≈ 0.1 ppmv)
- Balance of gases ex-gasifier is not suitable for full conversion 50% max), thus a use for the mix of unused gases needs to be found (if in the gas turbine, combustion issues will arise). Will influence choice of gasifier, making it sub-optimal for power production with CCS.
- Ammonia storage is needed under pressure (up to 1500 tonnes at ambient temperature, above this at -33˚C)
- Significant capital investment in additional process plant would be required
- The utilisation of the capex for the process is only about 35% of the time
- Market competition is with methanol plants operating round-the-clock

6. Additional Products (Polygeneration)

D) Synthetic Natural Gas (SNG)



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6. Additional Products (Polygeneration)

D) Synthetic Natural Gas (SNG)

- Utilises carbon from the syngas.
- The methanation process takes place at 20-25 bar, so no additional syngas compression is needed.
- The raw syngas will need downstream processing (COS hydrolysis reactor, sulphur removal down to ≈0.5ppmv) to be compatible with NTS Standards.
- Balance of gases ex-gasifier is not suitable for full conversion, thus a use for the mix of unused gases needs to be found (if in the gas turbine, combustion issues will arise). Will influence choice of gasifier, making it sub-optimal for power production with CCS.
- A higher oxygen purity than 95% will be needed, so the ASU will need to be of a different design.
- Significant capital investment in additional process plant would be required.
- The utilisation of the capex for the process is only about 35% of the time
- Market competition is with natural gas.

Flexibility in pre-combustion CCS

2. Commercial Issues (1)

Flexing the plant operation

- In all cases some of the IGCC capital investment in under-utilised, and in many instances additional capital (eg PSA for H_2 production, Lox storage with evaporatore) is required
- Emissions of CO_2 can increase, requiring purchase of emissions credits

Polygeneration and hydrogen production

- In all cases for polygeneration, significant capital investment in additional process plant would be required, and the utilisation of the capex for the process is only about 35% of the time.
- In all cases there will be start-up/shut-down energy losses
- In all cases there is market competition with established industries operating continuously.
- There is increased risk associated with operating in multi-markets (eg power/chemicals)

Flexibility in pre-combustion CCS

2. Commercial Issues (2)

Conclusions of Dynamis analysis

- For the price assumptions made (eg coal, power purchase price, natural gas, ammonia, methanol), none of the polygeneration options, gas substitution nor AGR turndown represented attractive commercial propositions.
- ASU interruption and diurnal storage of syngas could be of marginal benefit.
- Given a fertile market for hydrogen, diurnal storage was a possibility worth further investigation.

Other commercial issues

- A different set of conclusions may be drawn for a different set of price assumptions.
- There are project-specific circumstances that may tilt the balance in favour of one or more of the flexibility options (eg. existence of adjacent long-term hydrogen demand).

Flexibility in pre-combustion CCS

Conclusions.

1. There are no technical or engineering reasons why IGCC plants could not provide some degree of operational flexibility.
2. The amount of flexibility possible is likely to be constrained by some items of plant.
3. Options such as diurnal storage may be more attractive where storage facilities are available (eg. salt caverns)
4. The commercial case for enhancing the plant to provide flexibility is less clear: it will depend on specific market conditions at the time.

However, it is possible to provide AFRO, by use of a concept patented by Progressive Energy.

Workshop on Operating Flexibility of Power Plants with CCS

Study of the Process & Operation of Oxyfuel Power Plant

11th- 12th , November, 2009 at Imperial College

Shunichiro Ueno, IHI Corporation

IHI

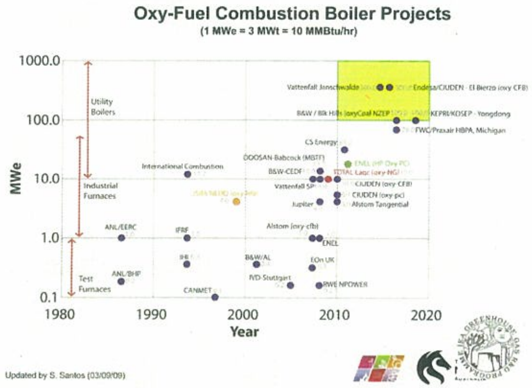
Contents

1. Introduction

Introduction -Position of Oxyfuel power plant-

It is recognized that oxyfuel technology is one of the key technology to capture CO2 from coal fired power plant.

Oxyfuel technology is in the process towards the commercialization. Some of small-scaled (10 – 30MWe) demonstration stage is or will be operated within a few years and there are some of plan of large-scaled demonstration (100 – 300MWe) until 2020.



Introduction
-Position of Oxyfuel power plant-

The followings are presented;

From the results of feasibility study of new-installed power plant
- Oxyfuel process
- Control method and Start-up procedure of future process

From the experience of retrofit design in Callide-A project
- Callide-A Oxyfuel Project
- Issues and action

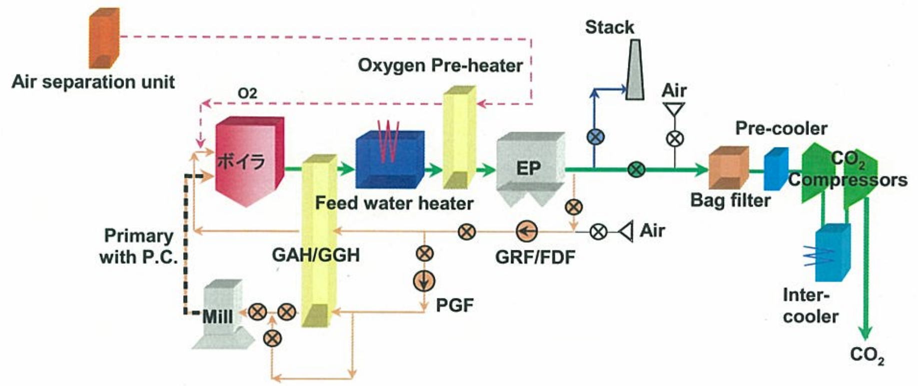
Summary

2. Feasibility study
* Process & features
* Starting-up procedure
* Results of dynamic plant operation
* Main operation issues

Feasibility Study of 1,000MWe class oxyfuel power plant

Boiler unit	1,000MWe output
Fuel	Coal (Blair Athol)
	Light oil for the start up
Air separation unit	Cryogenic air separation
	58-100% range
Flue gas compressors	Axial-type compressors
	20 MPa of outlet
Others	Base load unit
	Min. load 60%L (600 MWe)
	at Oxy-fuel combustion

Oxyfuel process

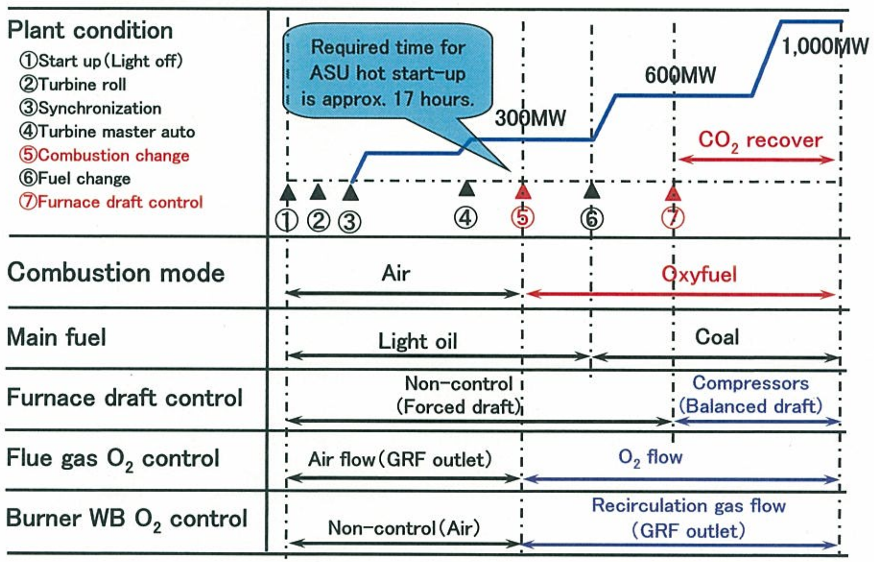


Features

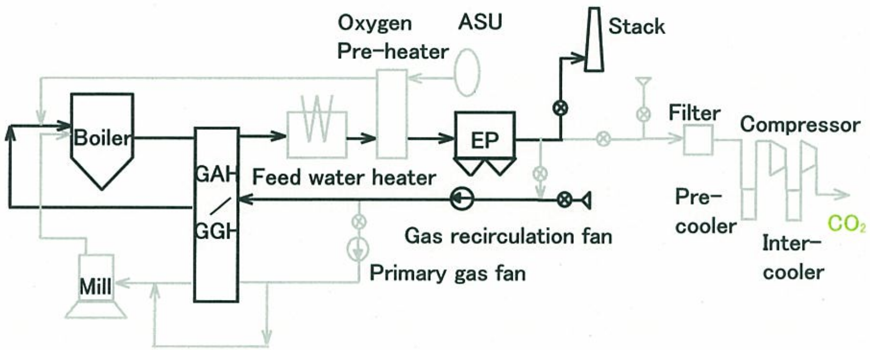
(1) By enriching oxygen concentration to the boiler obtained by reducing the amount of recycled flue gas, it is possible to improve the combustibility leading to a compact boiler furnace.
(2) Furnace pressure is controlled by flue gas compressors to be positive, so as to prevent the air ingress to boiler system. The system does not need ID Fans.
(3) Flue gas is cooled down by boiler feed water. Recycled flue gas is preheated by flue gas through a regenerative heat exchanger before oxygen mixing. Oxygen is preheated by flue gas thorough a non-leak type heat exchanger to avoid oxygen leakage.
(4) It is unnecessary to install the SCR because the amount of NOx emission is small enough. Furthermore, adopting an underground storage of flue gas makes installing FGD unnecessary.
(5) Flexible combustion mode change is ideally achieved at 30%L to 100%L.
(6) Oxyfuel combustion is operated at the range of 60%L and 100%L except for start-up.

Example of starting-up for oxyfuel power plant

Starting up procedure

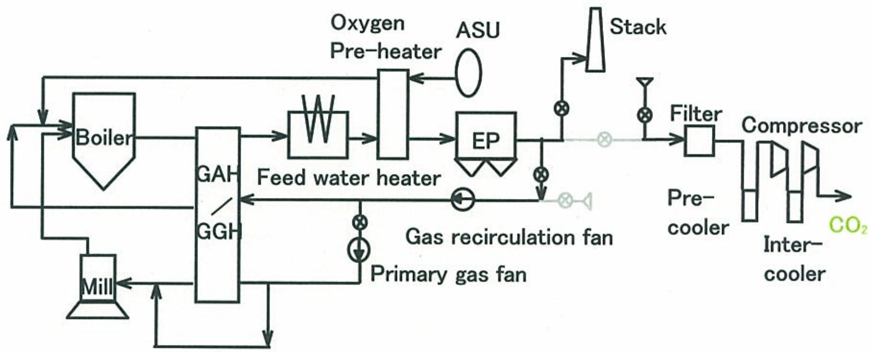


Plant Starting Procedure 1 of 3



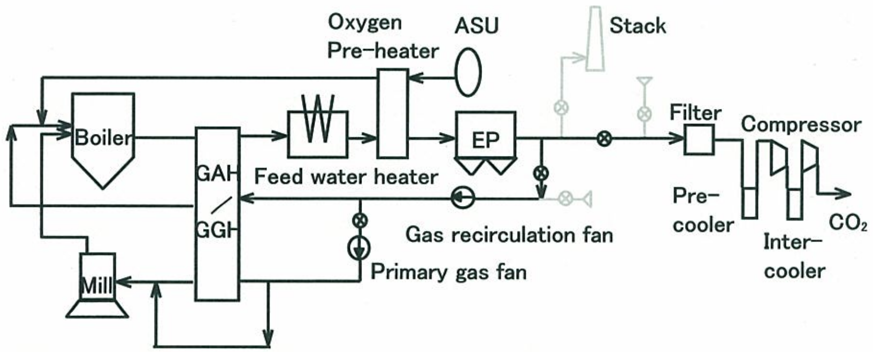
Air combustion until 300MW with Light oil

Plant Starting Procedure 2 of 3



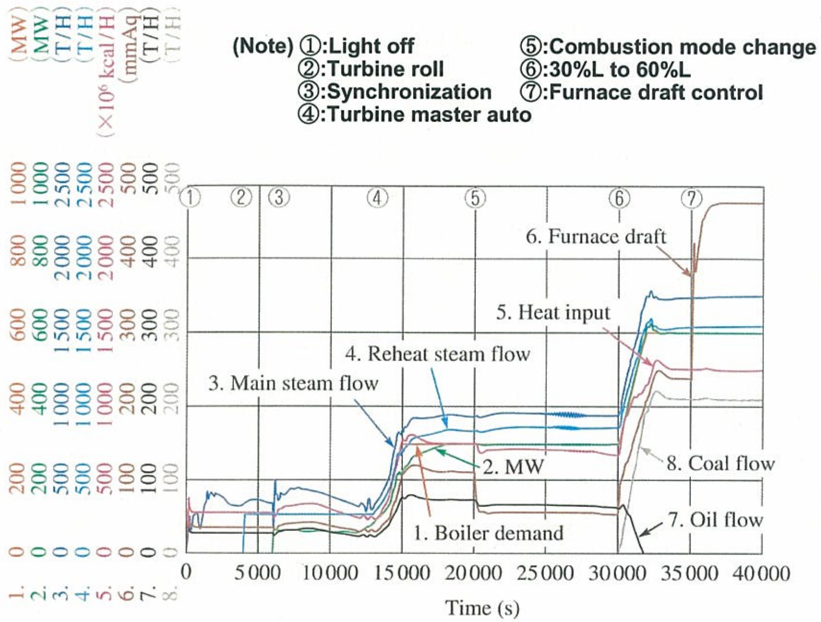
Combustion mode change: Air -> Oxy
Load change: 300MW -> 600MW
Fuel change: Light oil -> Coal
Preparation of CO2 compression unit

Plant Starting Procedure 3 of 3

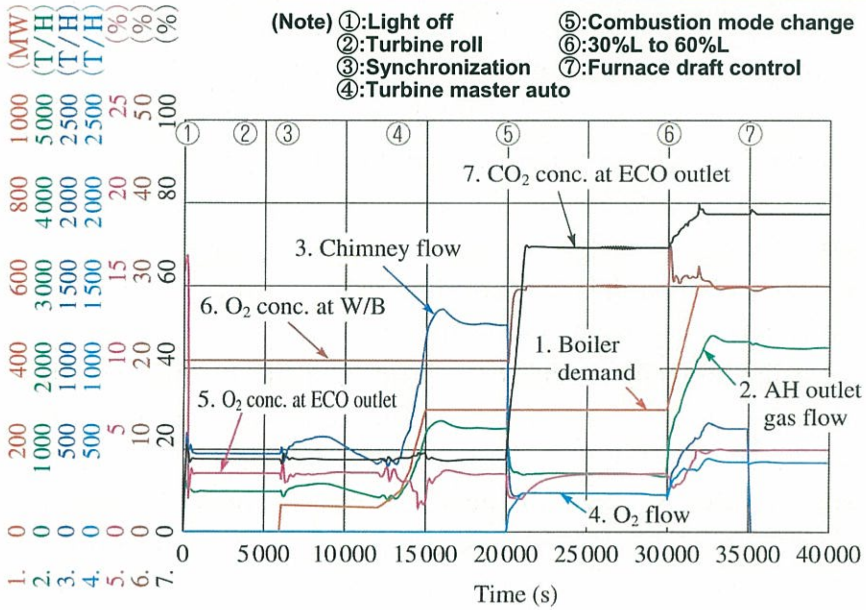


Connection at 600MW : Coal
Furnace draft control start

Result of dynamic plant simulation



Result of dynamic plant simulation



Main operation issues

Operation issues to be achieved during the demonstration stage

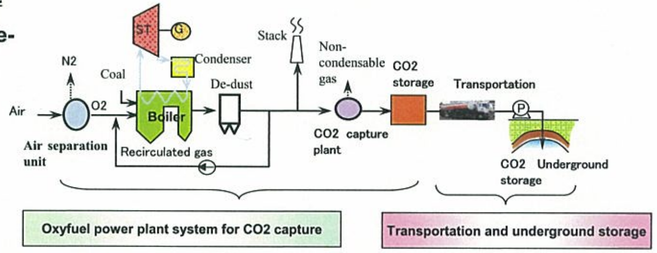
- Stable control regarding the combustion mode change and load change during oxyfuel.
- Furnace pressure control by flue gas compressor to be positive
- Minimum load at oxyfuel
- Mill changing during oxyfuel
- Boiler performance at higher and lower total oxygen concentration to the boiler
- Fully application of CO2 compression unit
- ....

3. Callide Oxyfuel Project

Callide Oxyfuel Project

Callide Oxyfuel Project

Demonstration of Callide-A unit No.4 power plant with CCS using oxyfuel technologies.



Period of time

FY 2008～FY 2016
- ・Retrofit for CO2 capture
- ・Oxyfuel demonstration operation (Up to 4 years operation)
- ・CO2 injection & monitoring

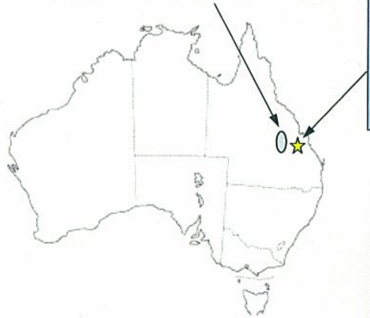
Project partners

Oxyfuel Project Partners: cs energy, xstrata coal, IHI, COAL21 FUND, Schlumberger, J-POWER, MITSUI & CO., LTD., Australian Government, Queensland Government, JCOAL, METI

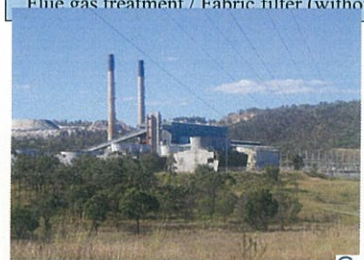
Callide Oxyfuel Project

Callide-A Power Plant

CO2 storage site area



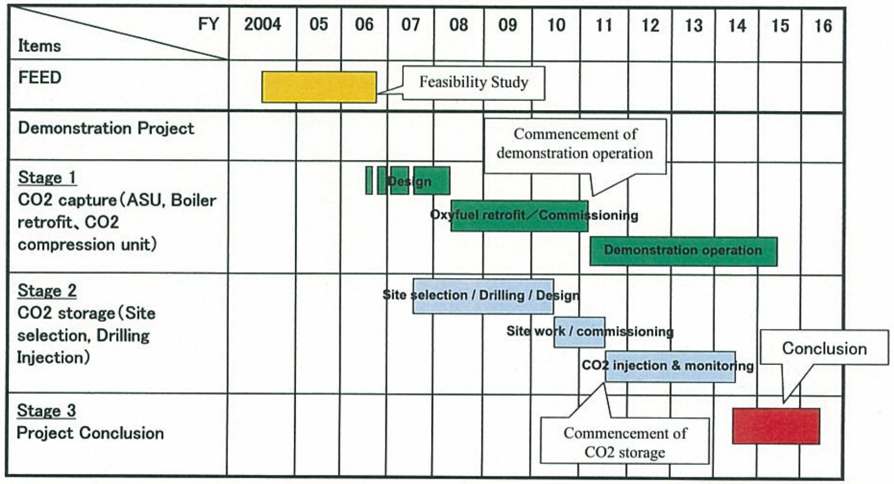
Callide A: 4 x 30 MWe
Evaporation: 123 t/h steam at 4.1 MPa／460°C
Commissioned: 1965 – 69
Refurbished 1997/98
Boiler equipments:
Type / 2-drum type
Burner / 6 burners
Mill / 3 mills
Flue gas treatment / Fabric filter (without DeNOx/DeSOx)



Callide-A Power Plant

Callide Oxyfuel Project

Project schedule



Callide Oxyfuel Project

Features of Callide Oxyfuel Project

(Overall)
* Power Generation with CCS using oxyfuel
* Retrofit to the existing power plant

(Process)
* Process with mill pulverizing
* Multi-mills & multi burners
* Application of 2 types of burners (Original & new)
* Application of feed water heater with flue gas
* Application of moisture remove from primary
* Combination of pre-mixing & partial burner mixing for O2 supply

These will be confirmed during the demonstration operation.

Callide Oxyfuel Project

4. Summary

Summary

(1) In this presentation, the results of feasibility study and dynamic plant simulation are introduced.

(2) There are a number of operation issues that must be solved and clarified for the commercialization, we will obtain much data and knowledge regarding the oxyfuel operation during the demonstration project.

(3) We continue to study towards the success of Callide Oxyfuel Project and next to the commercialization of oxyfuel power plant for CO2 capture step by step.

Thank you for your attention!!

Callide Oxyfuel Project

Oxyfuel Project Partners

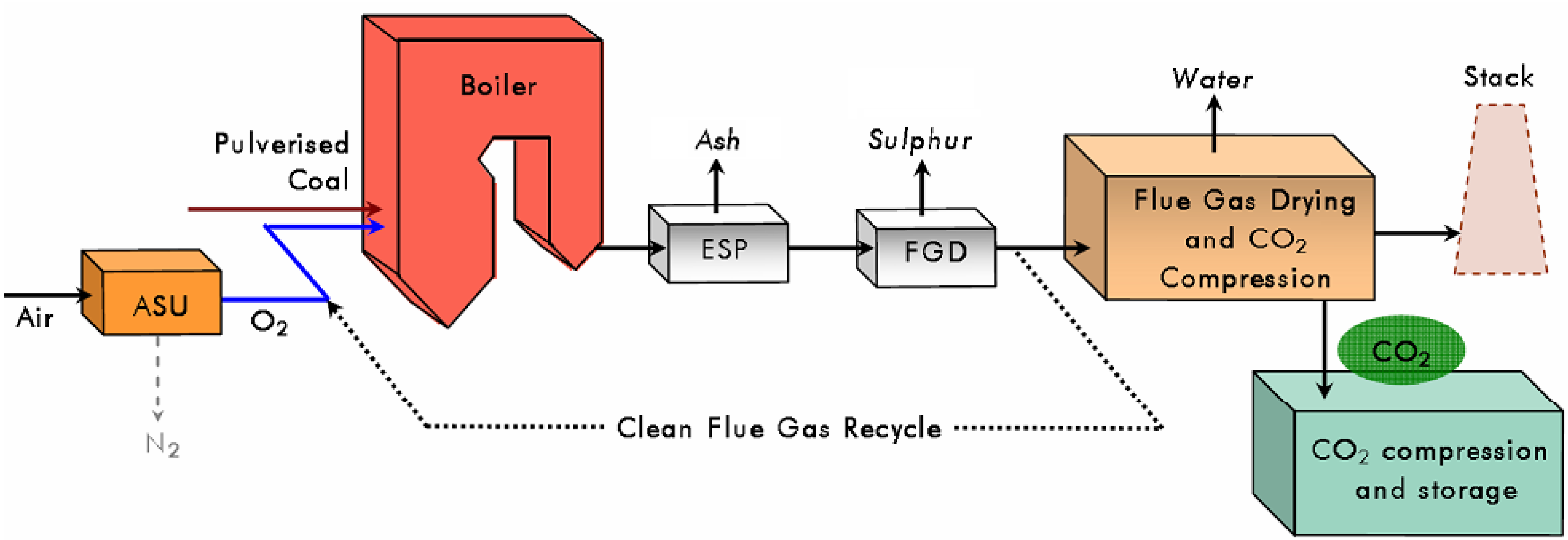
cs energy generations ahead | xstrata coal | IHI | COAL21 FUND | Schlumberger | J-POWER EPDC | MITSUI & CO., LTD. | Australian Government | Queensland Government | JCOAL | METI

Doosan Babcock Energy

Oxyfuel Combustion Technology

Michael Maloney
Workshop on Operating Flexibility of Power Plants with CCS
Imperial College, London
11-12 November 2009

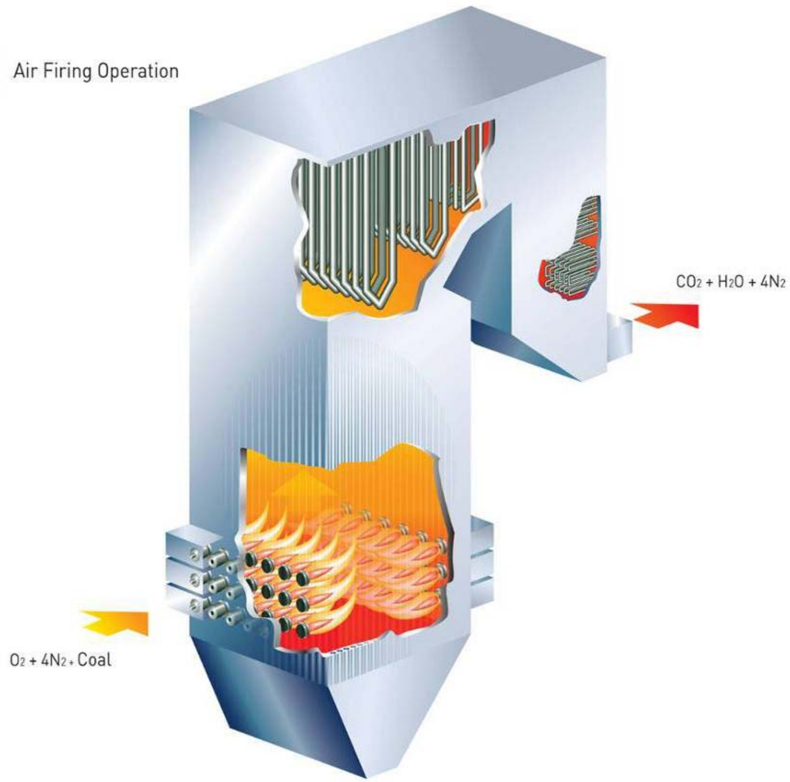
Oxyfuel Technology - Introduction

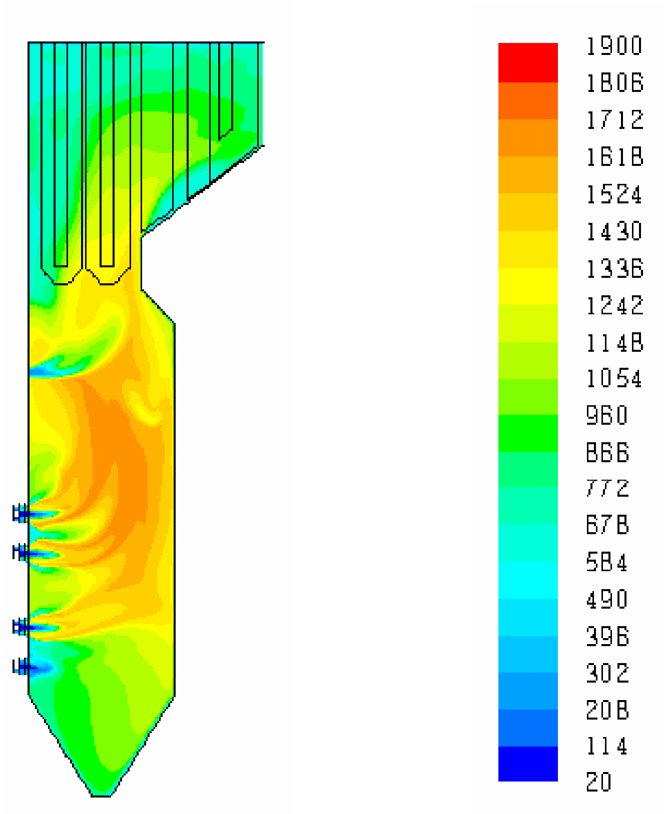


- Air Separation Unit (ASU) to supply nearly pure O_2; N_2 is removed from the process prior to combustion to produce a flue gas that is mostly CO_2 and H_2O
- Fuel burned in O_2/CO_2 atmosphere, Flue Gas Recycle (FGR) mitigates high temperatures from combustion in pure O_2 to maintain combustion and boiler thermal performance
- High CO_2 content allows simple compression cycle for CO_2 purification and capture

Air Firing Technology

Pulverised fuel combustion under air firing operation produces a flue gas CO_2 concentration of typically 15%v/v dry basis.



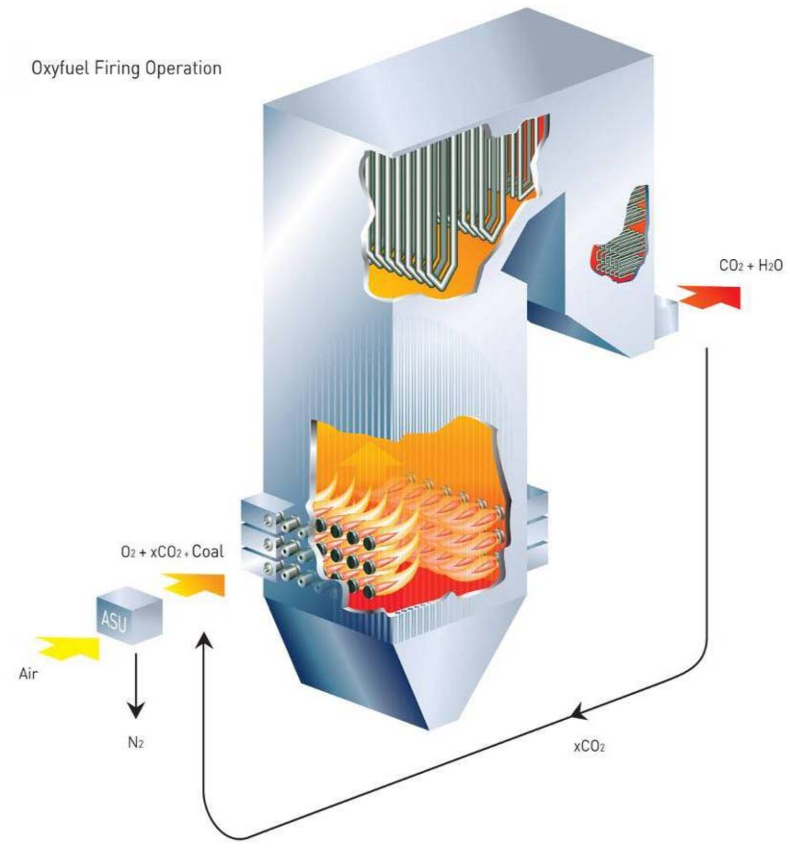


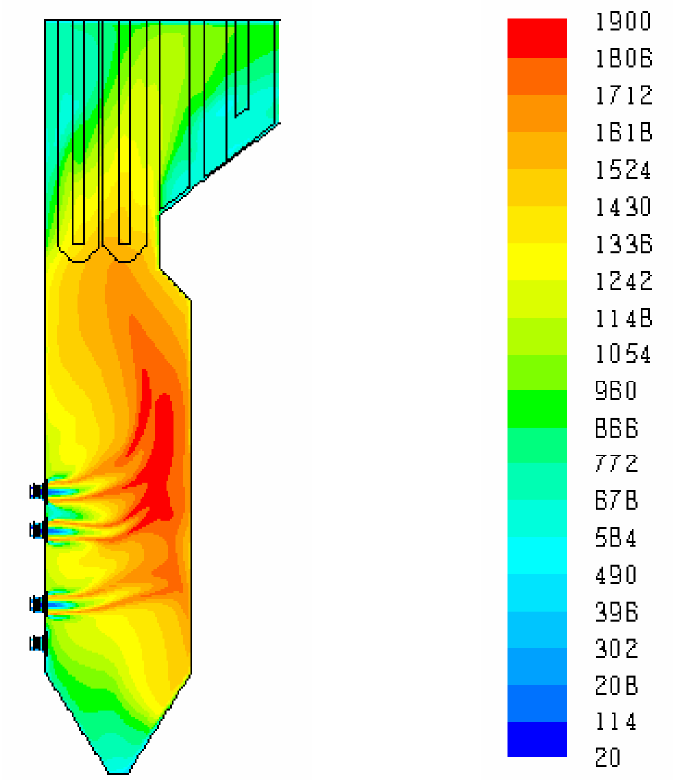
Air Firing Furnace Temperature Profile

DOOSAN Doosan Babcock Energy

Oxyfuel Firing Technology

Pulverised fuel combustion under oxyfuel firing operation produces a flue gas CO_2 concentration of typically >75%v/v dry basis.

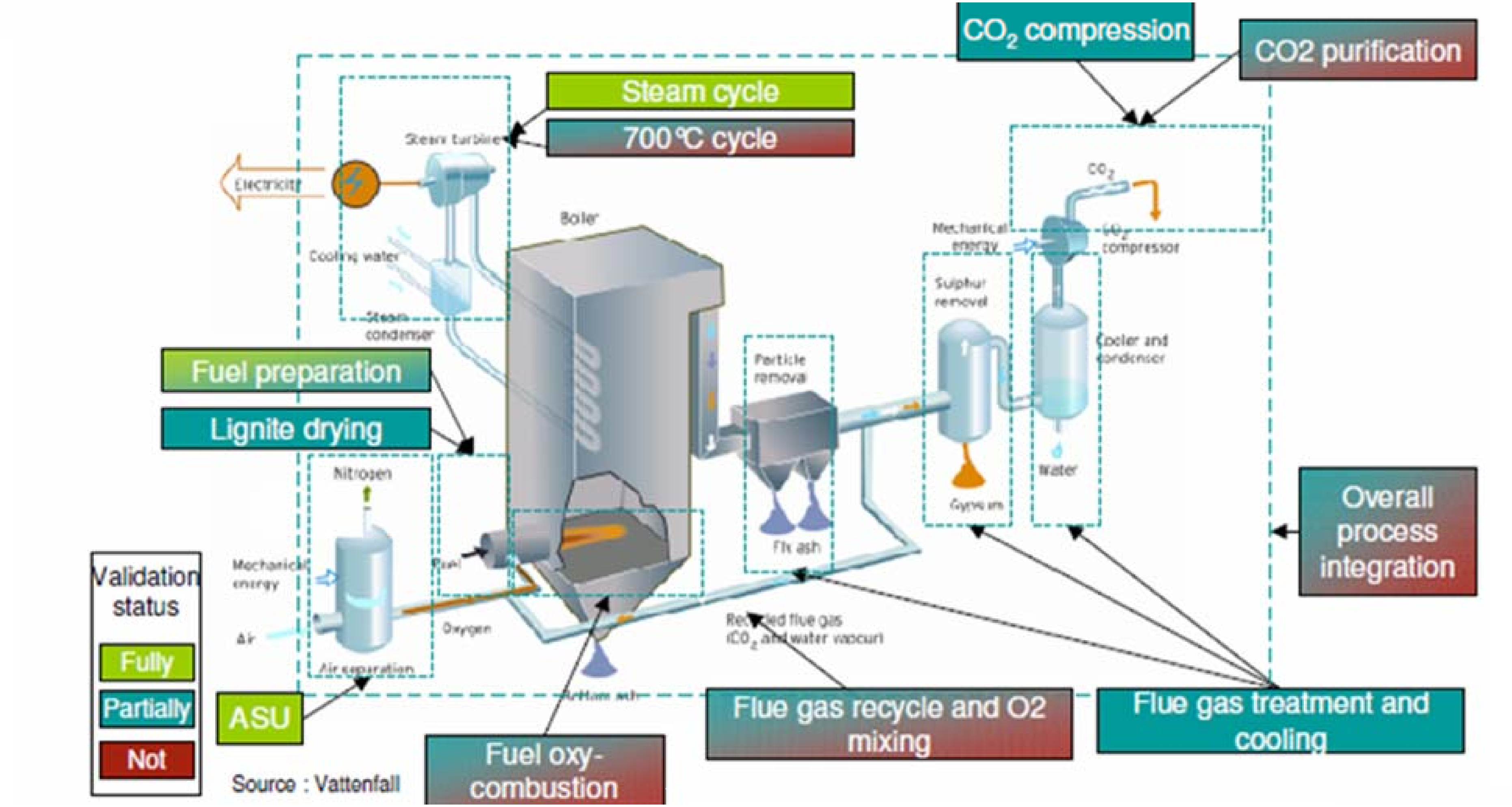




Oxyfuel Firing Furnace Temperature Profile

Doosan Babcock Energy

Oxyfuel Technology – Current Validation Status



Source: ETP ZEP Technology Blocks Nov 2008, reproduced in APGT strategy document, April 2009

Oxyfuel Technology – Air Separation Unit (ASU)

- Cryogenic air separation is a mature technology
  - Available now, but considerable power consumption
  - Drive to reduce specific power consumption from 200 kWh/tonne (current) to ~160 kWh/tonne (by 2012) – in-house R&D by suppliers
- New air separation technologies under development by suppliers – being evaluated in EPRI's "Coal Fleet for Tomorrow" programme

Fully Validated Improved processes being developed

Oxyfuel Technology – Fuel Preparation

- Conventional coal handling / pulverising technology will be used for oxyfuel
  - Engineering issues associated with the use of hot flue gas in place of air
  - Addressed in FEED projects
- Lignite pre-drying
  - Technology is independent of oxyfuel, and will be adopted regardless
  - Moisture content reduced to typically 12% before firing
  - Technology is already in "large" demonstration stage
  - Overall cycle efficiency significantly improved

Fully Validated   Improved processes being developed

Oxyfuel Technology – Steam Cycle

- Oxyfuel can be applied to existing steam cycles, but improved cycles can mitigate the efficiency penalty associated with oxyfuel (and post-combustion) capture
  - Improvements to current steam cycle aim to improve cycle efficiency by increasing temperature and pressure
  - R&D activities are predominantly to develop the boiler and steam turbine materials to allow operation at elevated temperatures and pressures
  - The impact of oxyfuel on corrosion is also under investigation – e.g.
    - TSB OxyCoal-1 Fundamentals & underpinning studies
    - DTI Modelling of fireside corrosion of heat exchangers in advanced energy systems
- The continuing advances in steam cycles will happen, regardless of oxyfuel or post-combustion capture

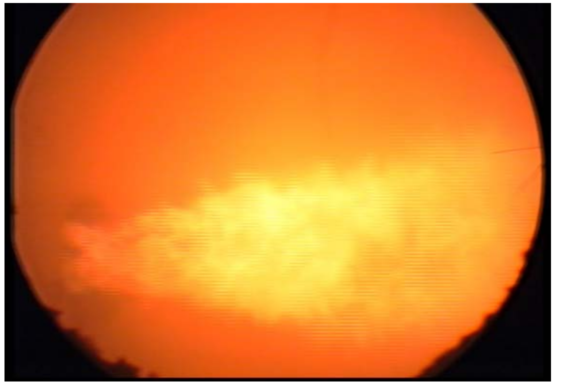
Fully Validated   Improved processes being developed

Doosan Babcock Energy

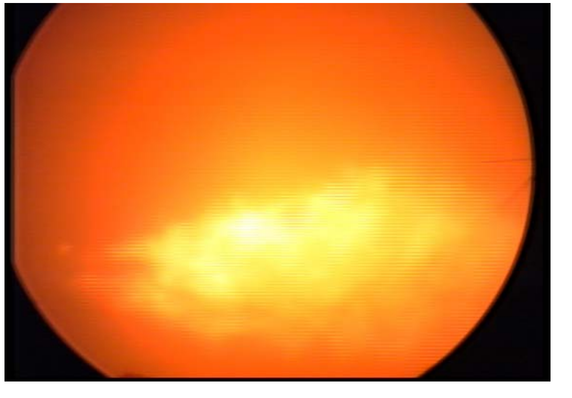
Oxyfuel Technology – Oxyfuel Combustion

- Combustion is at the heart of the power plant
  - If it does not perform to expectation, the impact on the steam cycle can be considerable
- Operating considerations
  - Flame length
  - Flame luminosity
  - Radiant heat transfer in the furnace (combustion / heat transfer interaction)
  - NO_x (does it matter anyway?)
  - SO_2 / SO_3
  - CO
  - Ash properties, slagging, fouling
- Practical experience is required at a realistic scale

Air Firing



Oxyfuel Firing



Oxyfuel Technology – Oxyfuel Combustion

- Considerable laboratory scale experience
  - e.g. in the UK in OxyCoal 1
- Considerable pilot scale experience
  - In the UK at E.ON, RWE, Doosan Babcock (OxyCoal 1, JOULE, etc.)
  - In Europe at IVD, IFRF, Chalmers, etc. (ENCAP, JOULE, OxyMod, etc.)
  - In the rest of the world (e.g. US DoE)
- Large industrial scale experience is becoming available
  - Vattenfall Schwarze Pumpe 30MW_t test facility
  - Doosan Babcock 40MW_t OxyCoal™ Clean Coal Test Facility burner demonstration is in progress (OxyCoal 2)
  - B&W 30MW_t burner test facility is operational (US DoE)
- CFD and Engineering modelling capability is being developed
  - e.g. in Europe in RFCS OxyMod
- Advanced oxyfuel burner development (for utility application)
  - TSB project "Optimised OxyCoal Combustion"

Partially / Not Validated

Oxyfuel Technology – Flue Gas Recycle and O_2 Mixing

- Flue gas recycle is an established means of controlling reheat steam temperature, for gas tempering, and for gas/coal reburn systems in large coal-fired utility boilers
- Mixing of a gas into another (bulk) gas is a common process requirement
- While there is limited experience of flue gas recycle and O_2/flue gas mixing for oxyfuel, there is sufficient expertise to engineer the combustion system, as has been carried out for:
  - Vattenfall Schwarze Pumpe 30MW_t test facility
  - Doosan Babcock 40MW_t OxyCoal™ Clean Coal Test Facility
  - B&W 30MW_t burner test facility
  - Numerous paper studies for full scale plant (e.g. DTI 407, ENCAP, IEA, etc.)

- However a full-scale oxyfuel plant has not been built

Partially / Not Validated

Oxyfuel Technology – Flue Gas Treatment and Cooling

- Considerable air firing experience, but need to apply to oxyfuel
- ESP
  - Laboratory scale work at Korea Institute of Machinery & Materials (KIMM) indicates that dust collection efficiency will be lower in high CO_2 atmospheres
  - ESP performance will be investigated at Vattenfall's Schwarze Pumpe test facility
- FGD
  - Suggestion that high CO_2 content will reduce SO_2 capture
  - Option to use lime (CaO) instead of limestone ($CaCO_3$)
  - Little ongoing R&D, most test facilities with SO_2 capture do not replicate large plant FGD
- SCR
  - Not thought to be necessary for oxyfuel (NO_x captured in CO_2 compression plant)
- Flue Gas Cooler
  - Basic engineering capability exists
  - Little ongoing R&D, test facilities may not be replicating large plant (e.g. rigs tend to use direct spray cooling, whereas indirect cooling may be favoured in large plant for technical, economic, and environmental reasons)

Partially Validated

Sources: KEPRI International Workshop on Oxy-Fuel Combustion 2008
Power Plant Air Pollutant Control Mega-symposium 2008

Oxyfuel Technology – CO_2 Compression

- CO_2 compression technology is required for oxyfuel, pre-combustion, and post-combustion capture technologies
- ASU equipment suppliers and operators already have considerable experience of large scale compression of gases
- There is already experience of CO_2 compression (and pipeline transportation & sequestration)
  - USA – CO_2 captured from the Beulah, Dakota gasification plant is compressed, transported 320km, and injected 1.5km underground in the depleted Weyburn oil/gas fields
  - Europe – the CO2SINK project is compressing and injecting CO_2 into the Ketzin, Germany saline aquifer
  - Australia – CO_2 separated from natural gas is compressed and injected 2.25km underground into the depleted Otway Basin gas field
- CO_2 compression of oxyfuel generated CO_2 is being undertaken at the Vattenfall Schwarze Pumpe test facility
- However there is no demonstration of the compression of CO_2 arising from a full-scale oxyfuel plant

Partially Validated

Oxyfuel Technology – CO_2 Purification

- CO_2 purification undertaken in conjunction with compression
  - Process proven at laboratory and small scale, e.g.
    - Air Products (OxyCoal 1)
    - US DoE Albany Research Centre
  - Process being tested at larger scale by several suppliers

- Capability to design the CO_2 purification process exists
  - Process will continue to be refined

Partially / Not Validated

Sources: GHGT-9 “Purification of Oxy-fuel Derived CO_2”

Oxyfuel Technology – Overall Process Integration

- TheVattenfall Schwarze Pumpe test facility is the first large scale application of oxyfuel that combines the core elements of the ASU, the steam generator, and the CO_2 purification and compression plant
  - The plant is not highly integrated, and it is not optimised for efficiency

- There have been numerous paper studies investigating the options for process integration to maximise cycle efficiency (e.g. DTI 407, ENCAP, IEA, etc.)
  - Impact of integration on operability has not been considered to date (TSB project “Optimisation of Oxyfuel PF Power Plant for Transient Behaviour” starts to address this)
  - The optimisation of the overall process and the optimisation of the individual process operations should complement each other

- Process integration will continue to be refined – but it must not come at the cost of operational flexibility.

Partially / Not Validated

Oxyfuel Technology – Scale-Up and Timescales

Vattenfall Janschwalde 2015 250MWe Lignite

Alstom	Lacq	2009	30MWth	Oil?
Alstom	Schwartze Pumpe	2008	30MWth	Lignite
IHI	Callide	2010	30MWe	
B+ W	B+ W CEDF	2008	30MWth	Coal
Alstom	Alstom CE	2010	15Mwth	Coal
Doosan Babcock	Doosan Babcock	2009	40MWth	Coal

Target is "Commercialised by 2020"

100 - 250 MWe full power plant demonstration by 2012/2014

40 MWt full size OxyCoal burner test at Doosan Babcock 2009

30 MWt full train demonstration at Schwarze Pumpe in operation, 2008

0.5 MW tests at RWE npower 2008/9

1MWt tests at E.ON 2007- 8

160KW tests at Doosan Babcock 1992-4

By the end of 2009 there will have been at least two industrial scale demonstrations of the full process and the Doosan Babcock full size burner demonstration which should give a high level of confidence in going to the next step

Doosan Babcock Energy

Oxyfuel Technology – Coal-Fired Demonstration Projects

Real projects give us the essential experience to commercialise oxyfuel

- It is only by undertaking real plant projects that we learn to make the hard decisions
  - It is too easy to put off decisions in paper studies
  - From Doosan Babcock's perspective, we have gained valuable practical experience during the engineering of our test facility oxyfuel retrofit, construction, commissioning and testing.

- It is only by undertaking real plant projects that we can commercialise the technology
  - No matter how much information and experience we gain from reduced scale facilities, there is always a degree of uncertainty in the performance of the "first-of-kind" full scale plant
  - Until we are fully confident in our design process it is impossible to deliver a plant under truly commercial conditions with performance guarantees

Oxyfuel Technology – R&D Needs

- First and foremost, we need a full-scale demonstration of the oxyfuel process (i.e. >100MW_e) to:

- Demonstrate
  - The operation of the process elements at full-scale
  - The integration of the process elements
  - The operation of the plant, and its ability to respond to grid requirements
  - Selection of optimal materials in oxyfuel service

- Validate
  - The engineering software / design methods, and refine them
  - The performance predictions

- Learn
  - The lessons of real experience, to make the next plant better

Oxyfuel Technology – R&D Needs

Equipment suppliers are capable of engineering a credible oxyfuel power plant today, but further R&D work is required to arrive at better designs and to have greater confidence in the performance

- From the APGTF Cleaner Fossil Power Generation in the 21st Century strategy document
  - Process optimisation, including start-up / shut-down / flexibility
  - Combustion chemistry and kinetics
  - Heat transfer prediction
  - Materials for the oxyfuel environment, corrosion
  - Ash properties – impact of oxyfuel on mineralogy, deposition, ash sales
  - Product gas clean-up
  - Safety
  - ASU – selection, cycle optimisation
  - Novel processes such as gas separation membranes to reduce energy penalty

Concluding Remarks

- Considerable progress has been made in the development of oxyfuel technology
  - The process is technically viable
  - The process is well understood
  - The process has been demonstrated at pilot scale
  - The process is being demonstrated at large scale ($40MW_t$)
  - Most of the individual components are in commercial operation at the required scale
- Oxyfuel combustion is economically competitive with alternative CO_2 capture technologies
- Several utilities are making or planning significant investments in oxyfuel technology
  - Large-scale plant demonstration
- The time is right for the full scale demonstration of oxyfuel
  - Equipment manufacturers are ready to supply the technology

Concluding Remarks

Doosan Babcock is developing the capability to provide competitive oxyfuel firing technology suitable for full plant application post-2010.

- Doosan Babcock has established a dedicated Carbon Capture Business Group to commercialise Carbon Capture technologies.
- We aim to design, supply and construct a $100MW_e$ oxyfuel power plant for a utility client before 2015, and a $1000MW_e$ oxyfuel power plant by 2020.

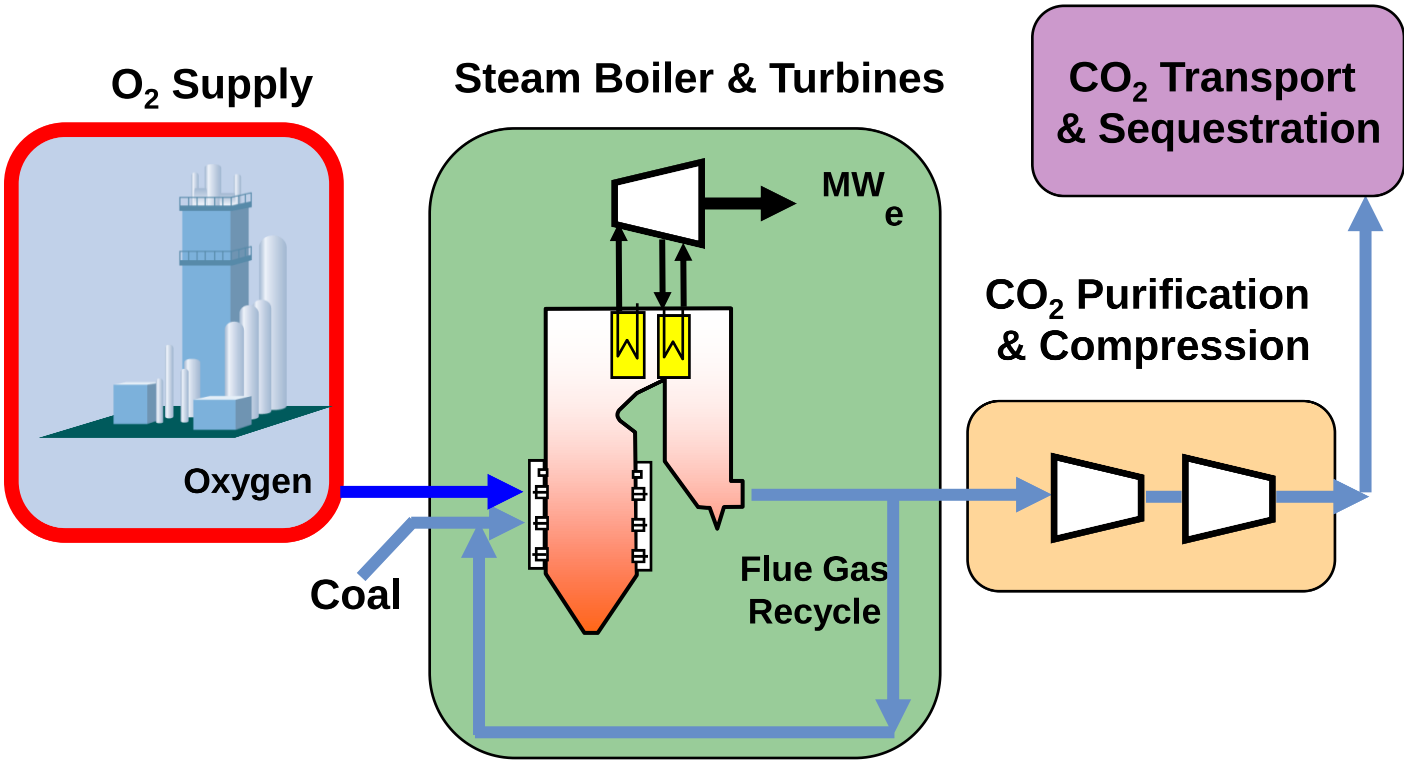
ASU and CO_2 Processing Units for Oxyfuel CO_2 Capture Plants

Vince White
Air Products PLC

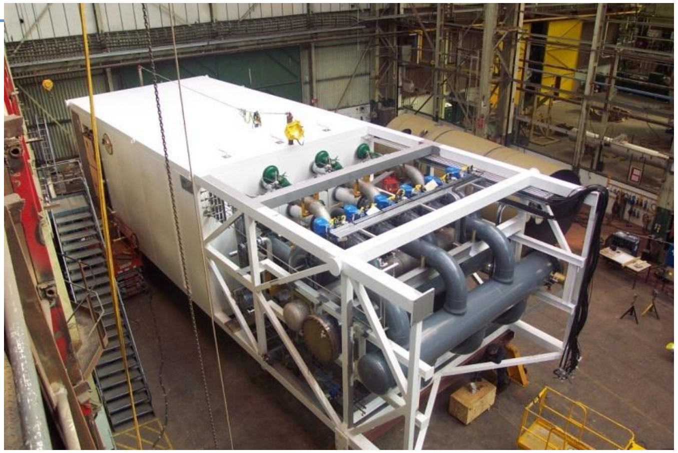
WORKSHOP ON OPERATING FLEXIBILITY OF POWER PLANTS WITH CCS
Imperial College, London, UK
11th – 12th November 2009

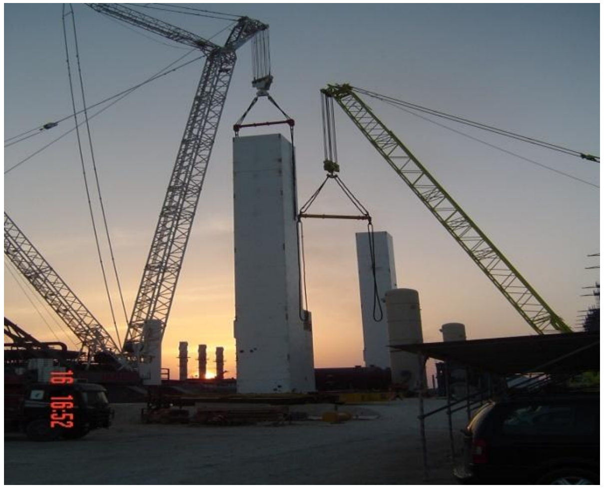
Oxyfuel combustion requires...

- Air Separation Units
- Steam Boiler &Turbine
- CO_2 Purification & Compression
- CO_2 Transport & Sequestration



Large air separation units (ASUs)





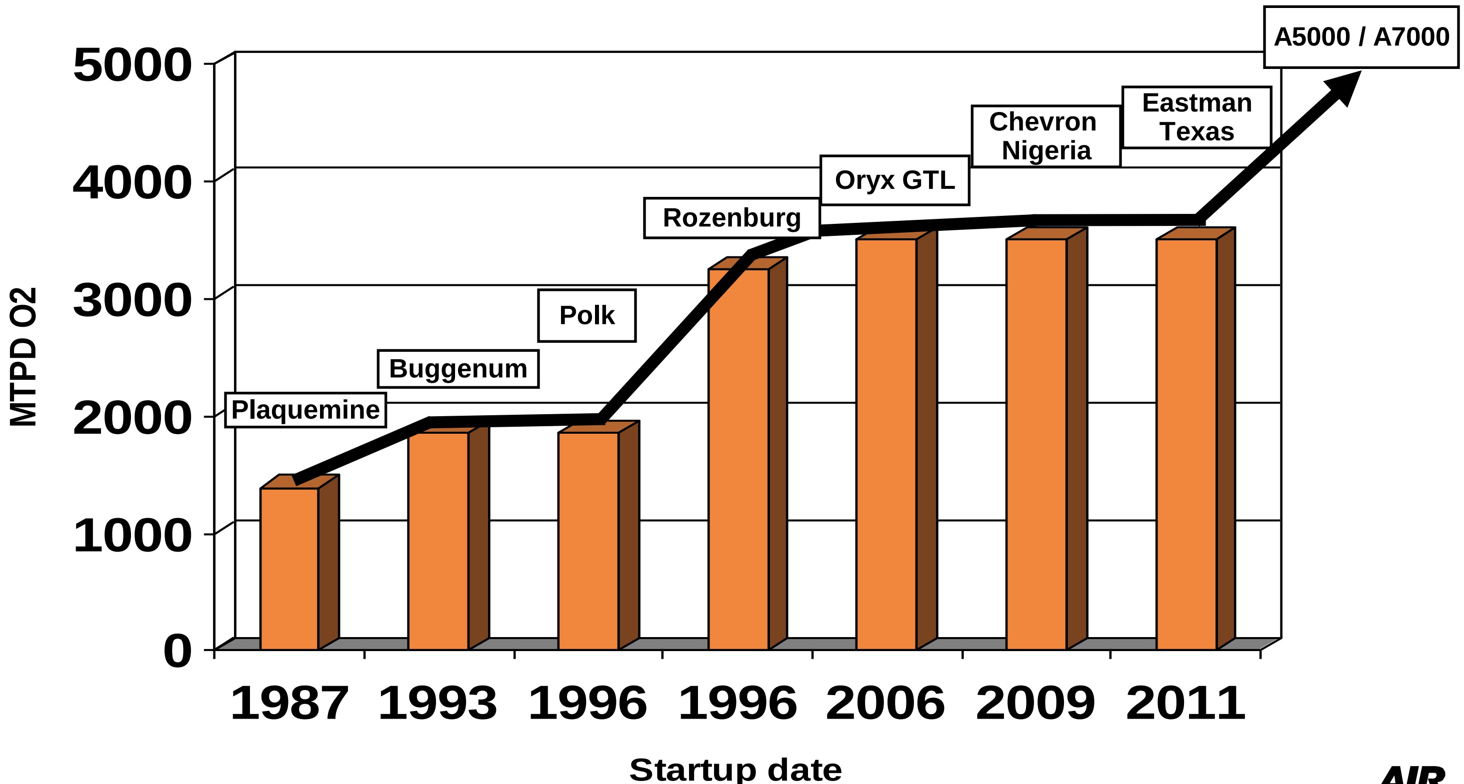
Demonstrated Air Separation Capabilities

- **Technology base**
  - Cryogenic air separation
    - Up to 7,000 t/d
      - plus co-product nitrogen, argon, and other rare gases
    - Nitrogen only configurations
  - Non cryogenic air separation
    - From 2 t/d
    - Adsorption (PSA/VSA)
    - Membrane
- **Experience**
  - Worldwide presence
    - >1,200 air separation units owned or sold
    - >500 units operated and maintained
  - Major pipeline systems include:
    - US Gulf Coast
    - California
    - Rotterdam, Netherlands
    - China
    - Korea
    - South Africa

AIR PRODUCTS

Experience - Large ASU Projects and Train Scale-up

- Market drives ASU scale-up
- Proven 70% scale-up
- Quoting 5,000+ tonne/day today

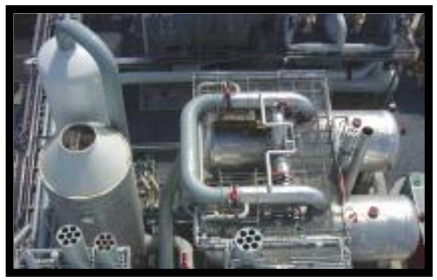


AIR PRODUCTS

Overview Of The Process

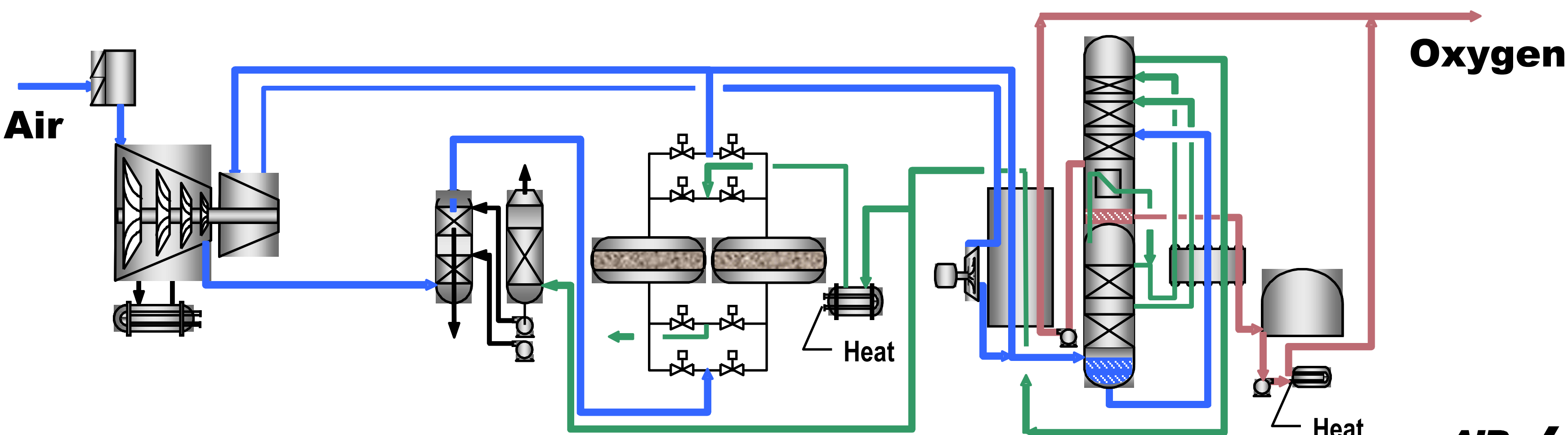
Main and Boost Air Compression

Air Cooling and Pretreatment



Cryogenic Separation

Storage

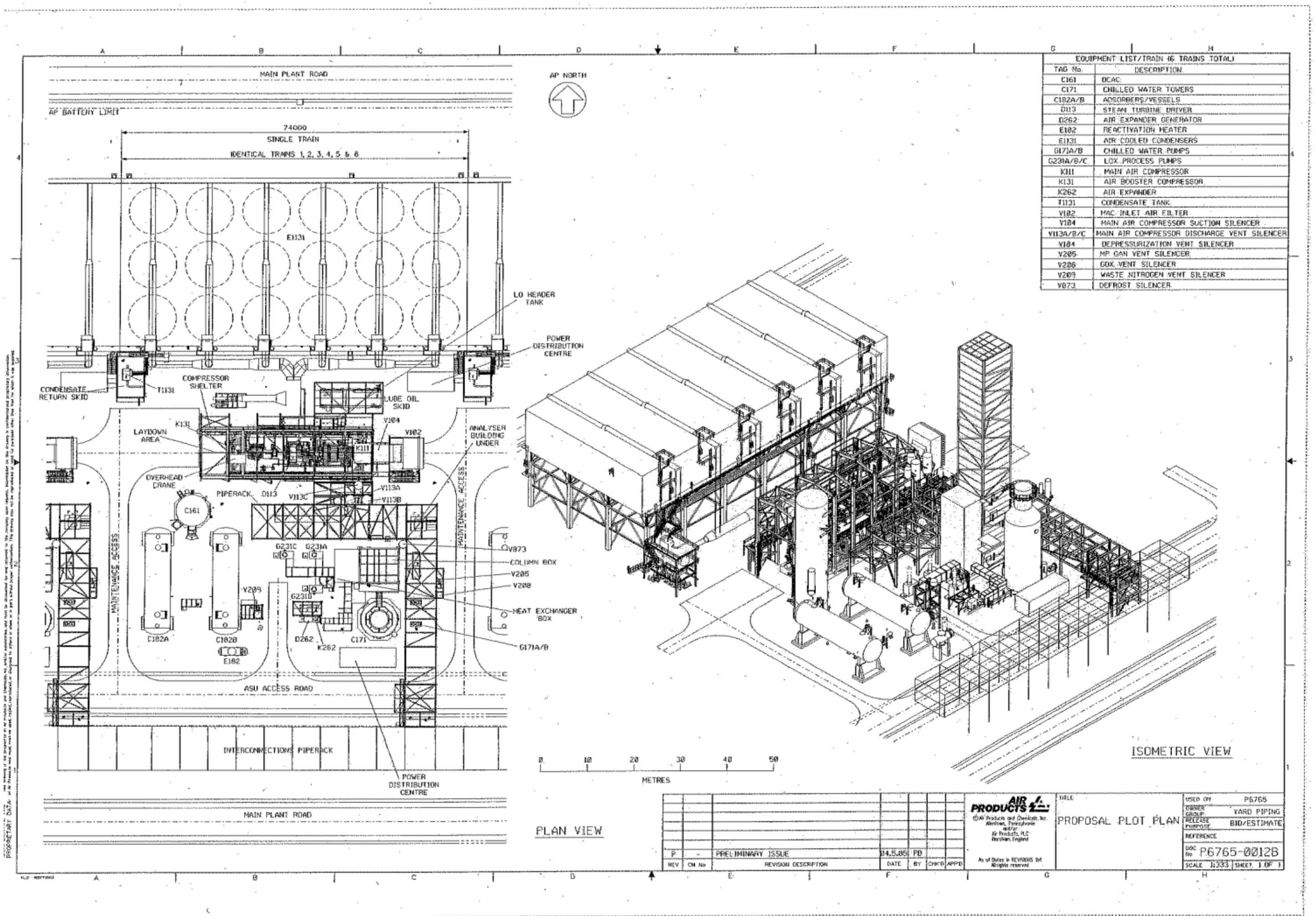


Process Cycle Selection Criteria

- Oxygen demand profile
  - Purity
  - Pressure
  - Demand pattern, quantities, duration, frequency
- Argon co-production required?
- Power evaluation criteria
- Capex sensitivity
- Process integration philosophy
- Utility constraints, e.g. steam availability & quality, water consumption
- Operating constraints, e.g. availability, reliability, time to on stream, ramp rate.

AIR PRODUCTS

A5000 Single Train



AIR PRODUCTS

VLASU Integration challenges to Oxycoal power plants

Design based on customer's specific requirements:

- Parasitic load
  - Power vs. Capital costs
  - Purity requirements
  - Co-products
  - Compression integration
- Manufacturing
  - Transport of ASU(s) to site
  - Reducing construction / erection costs and risks
- Operability
  - Fit with customer's use patterns
    - Turndown / ramping up
  - Advanced control capabilities
- Reliability

Compression: VLASU Design Considerations

- Compression is typically a large component of the cost stack
- We consider power valuation when designing # of trains
  - Multistage or single stage cooling
- Cooling water integration
  - Location of plant
  - Cost of cooling water / Type of systems
- Compression Driver
  - Steam turbines
  - Gas turbines
  - Motor technology / Starting system
- Erection / Packaging strategy
  - Field erect
  - Shop modules (pre-package)
- Cost Impacts
  - Axial vs. In-line cost or integral gear (up to 7000 TPD)
  - Need for soft start as compressor motors increase in size
  - Limited or reverse economies of scale for large vessels, piping and valves
  - Shipping costs or transportation limits

Compression: Design Considerations

Oryx- Qatar – 2x3500 TPD

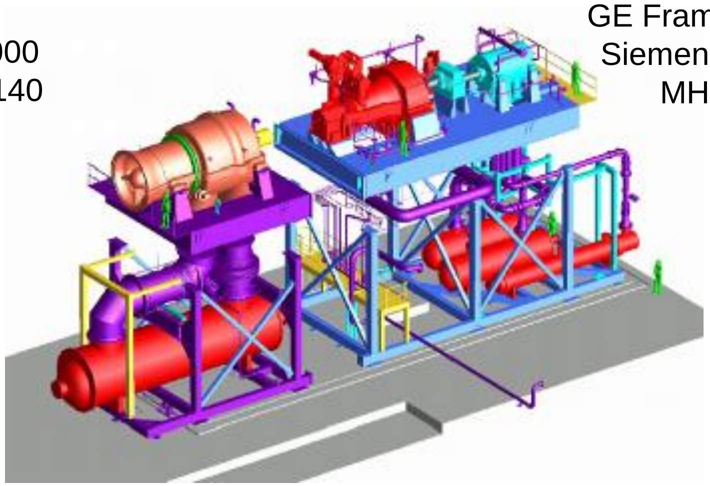
- MAC—Steam Turbine—BAC
- Air Cooled Condenser
- Shop Skids
- String Test

<u>A5000 and A7000 TPD – Single Train Compression</u>

- Axial main air compressor (no GT integration)
- In-line boost air and nitrogen compressors
- Four large suppliers = GE, MHI, Siemens, MAN

<u>A5000:</u>
GE Frame 7
Siemens STC 1000
MAN AR130-AR140
MHI M501D

<u>A7000:</u>
GE Frame 7 - Frame 9
Siemens STC 1300
MHI M501F



A5000 and A7000 TPD – (2x Compression –Multitrain)

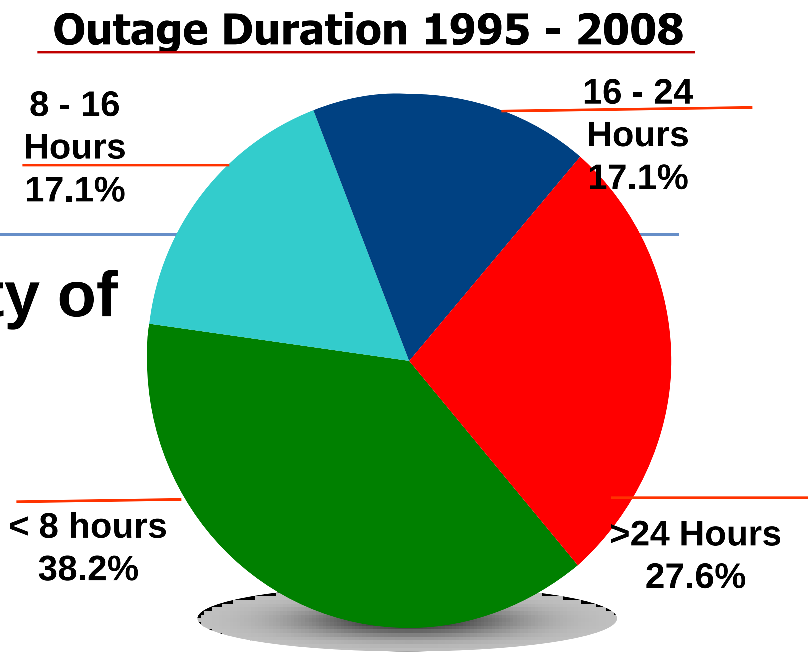
- Integral gear (GT Copco or STC) or In-line air compressors (RIK)

- Integral gear or In-line boost air and nitrogen compressors (if N2 needed))

AIR PRODUCTS

Reliability

- Air Products operates the majority of plants that it designs and builds
- Thousands of man-years of ASU operating experience includes customers that require 100% availability of products
  - Average plant availability is greater than 99%
    - Average duration of plant trip is ~16 hr
    - Spare parts handling strategies in place
    - Maintenance shutdown once/3+ yrs
      - Coincide with normal power plant maintenance
  - Instantaneous back-up systems in place today in safety-sensitive and electronic applications



AIR PRODUCTS

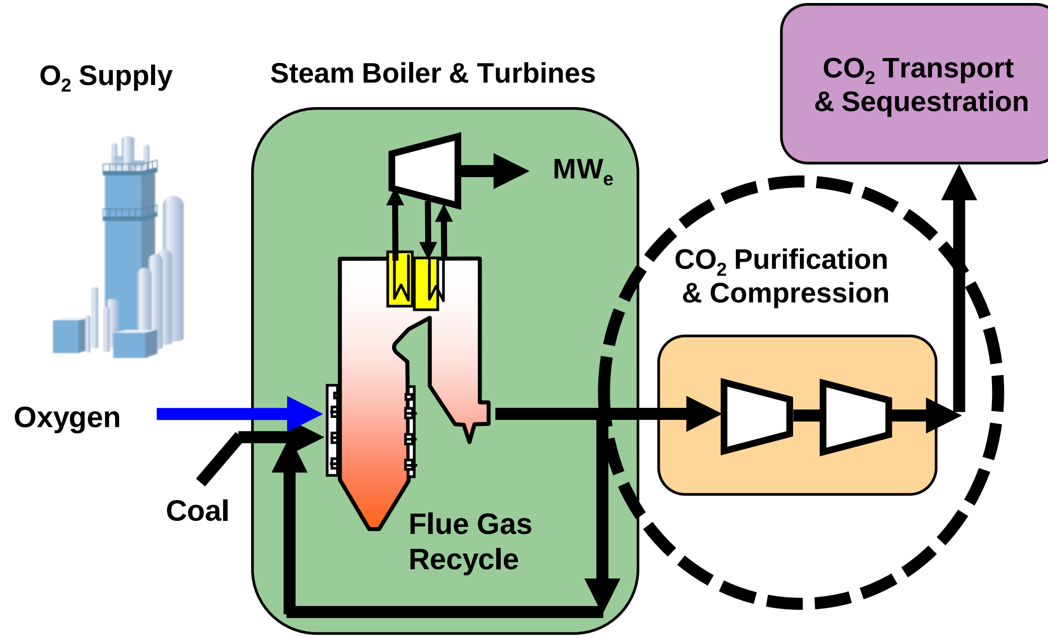
Operability: Plant Ramping, Advanced Controls technology

- **Benefits of Advanced Control capabilities**
  - Lower power consumption
  - Higher product recoveries
  - Faster disturbance response and mitigation
  - Faster response to changing product demands
  - Higher multi-plant efficiency
- **ASU ramping capabilities**
  - 1%/min typical
  - 2%/min achievable with advanced control
  - 3%/min possible when "designed in"
  - Higher rates possible by using liquid oxygen backup

AIR PRODUCTS

Oxyfuel CO_2 Purification

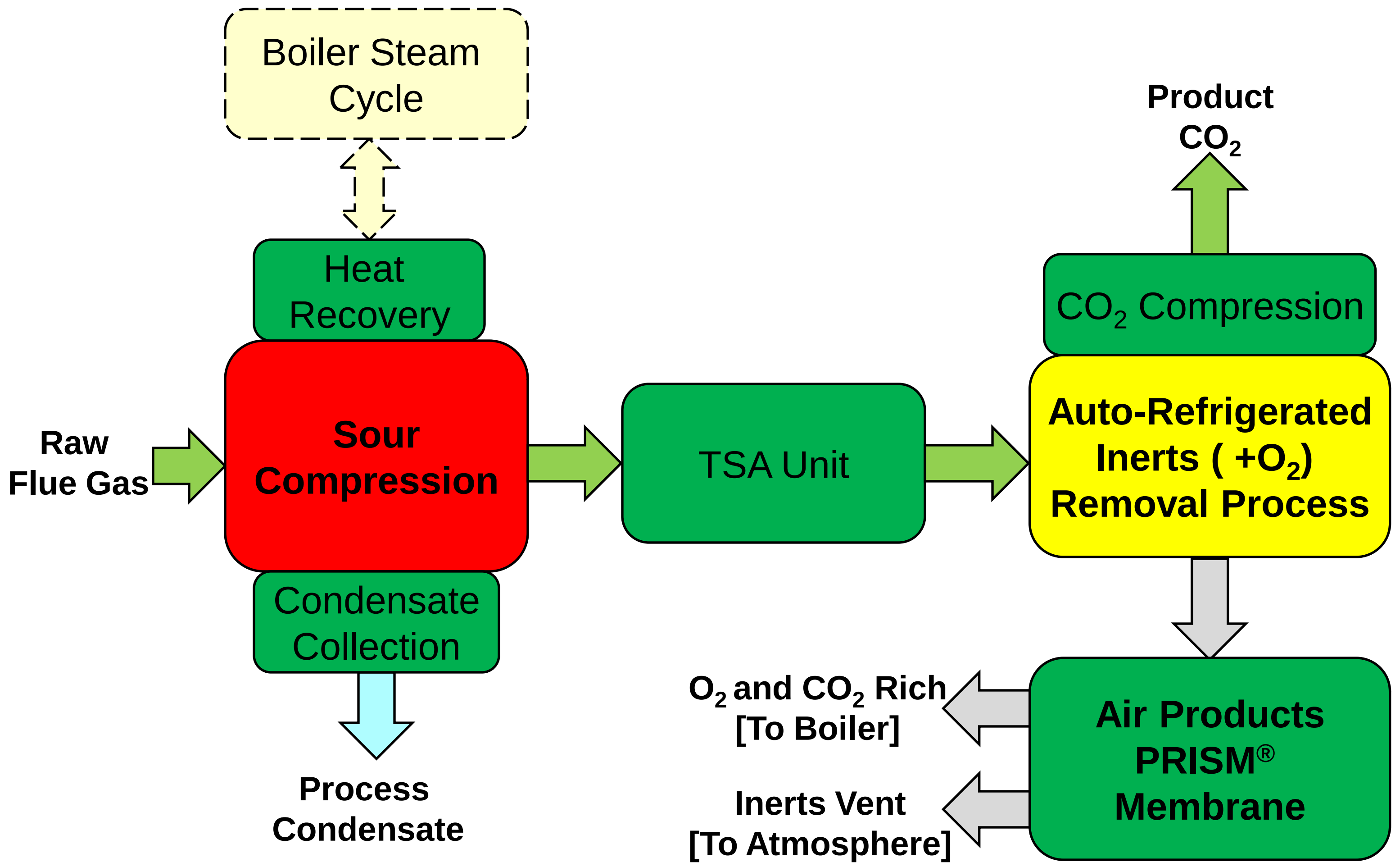
- Oxyfuel combustion of coal produces a flue gas containing:
  - $CO_2 + H_2O$
  - Any inerts from air in leakage or oxygen impurities
  - Oxidation products and impurities from the fuel (SO_x, NO_x, HCl, Hg, etc.)



- Purification requires:
  - Cooling to remove water
  - Compression to 30 bar: integrated SOx/NOx/Hg removal
  - Low Temperature Purification
    - Low purity, bulk inerts removal
    - High purity, Oxygen removal
  - Compression to pipeline pressure

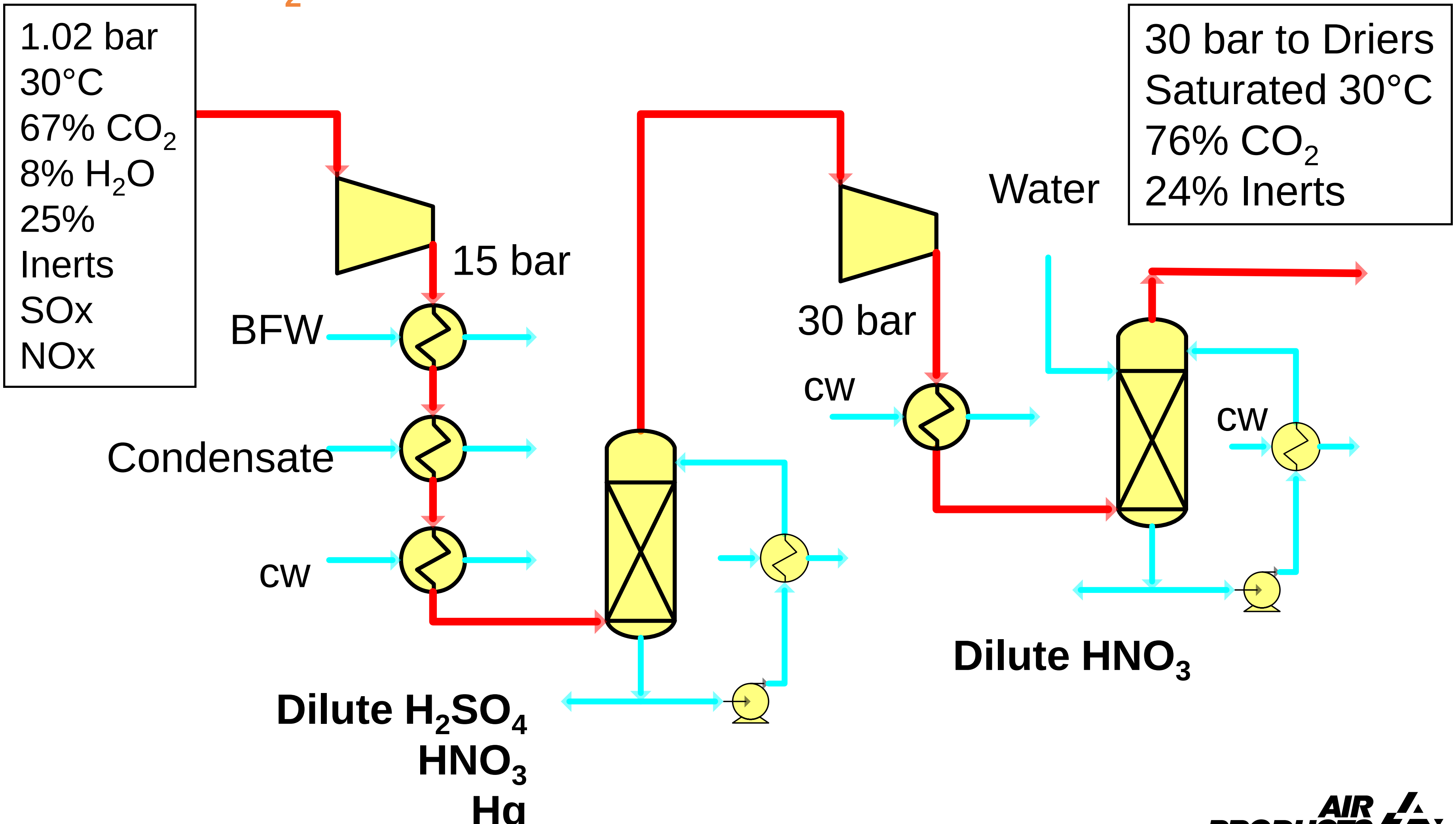
AIR PRODUCTS

Air Products' Oxyfuel CO_2 Capture Technology

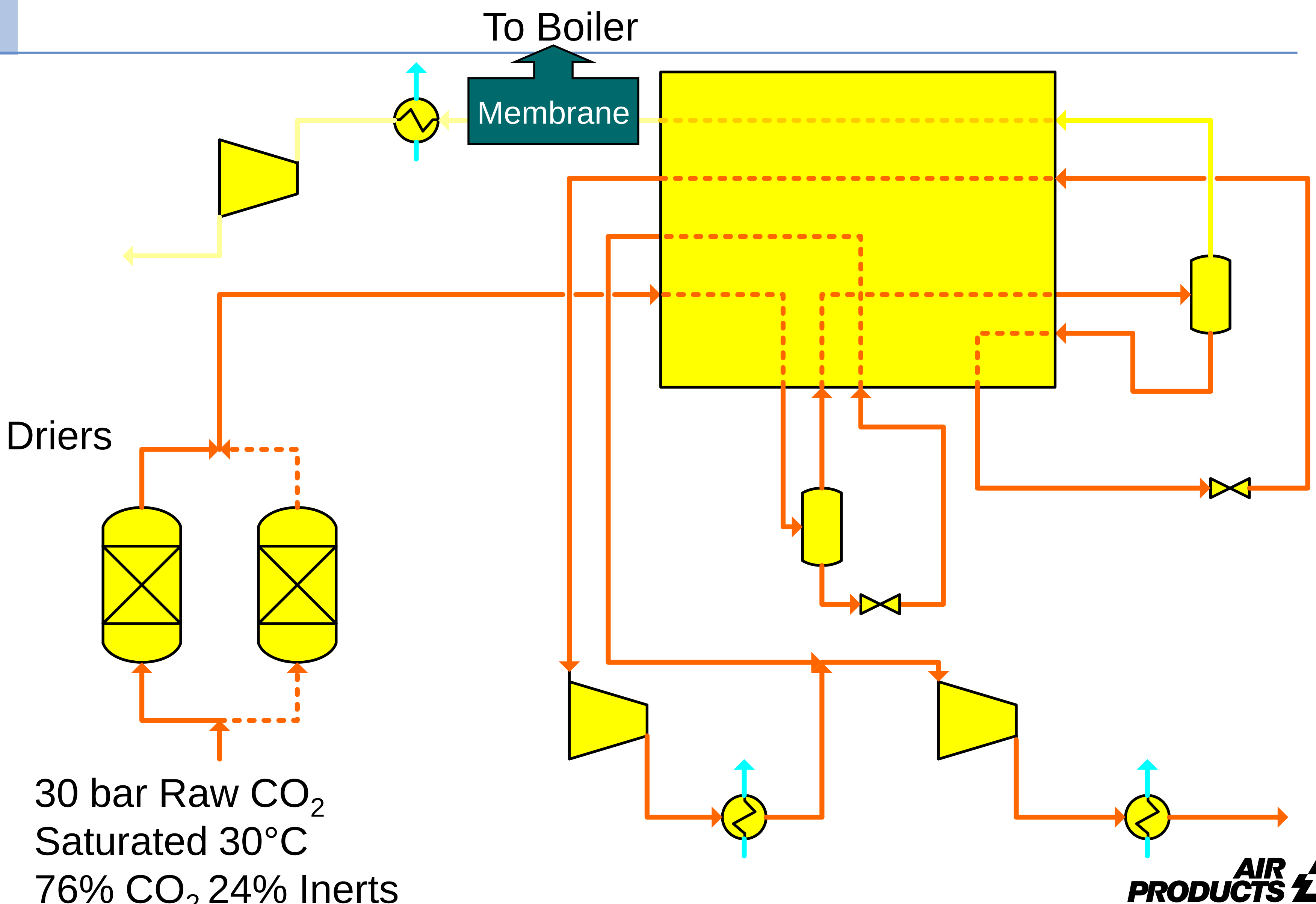


Air Products' CO_2 Compression and Purification System: Removal of SO_2, NOx and Hg

- SO_2 removal: 100% NOx removal: 90-99%



Auto-Refrigerated Partial Condensation with CO_2 and O_2 recovered to the boiler



Air Products' CO_2 Purification and Compression Technology for Oxyfuel

Sour Compression SOx, NOx, Hg Removal	Auto-Refrigerated Inerts Removal Ar, N_2, O_2	Air Products' PRISM® Membrane For enhanced CO_2 + O_2 Recovery

Sour Compression SOx, NOx, Hg Removal

- SO_x/NO_x removed in compression system
  - NO is oxidised to NO_2 which oxidises SO_2 to SO_3
  - The Lead Chamber Process
- FGD and $DeNO_x$ systems
  - Optimisation
  - Elimination
- Low NOx burners are not required for oxyfuel combustion
- Hg will also be removed, reacting with the nitric acid that is formed

Auto-Refrigerated Inerts Removal Ar, N_2, O_2

- Removal minimises compression and transportation costs.
- Optional O_2 removal for EOR-grade CO_2
- CO_2 capture rate of 90% with CO_2 purity >95%
- CO_2 capture rate depends on raw CO_2 purity which depends on air ingress

Air Products' PRISM® Membrane For enhanced CO_2 + O_2 Recovery

- Inerts vent stream is clean, at pressure and rich in CO_2 (~25%) and O_2 (~20%)
- Polymeric membrane unit – selective for CO_2 and O_2 – in vent stream will recycle CO_2 and O_2 rich permeate stream to the boiler.
- CO_2 capture rate increases to >97% and ASU size/power reduced by ~5%

AIR PRODUCTS

Path to from Lab to Demo

Photo courtesy of Imperial College

Cylinder fed bench rig

Photo courtesy of Doosan Babcock

160 kW$_{th}$ oxy-coal rig

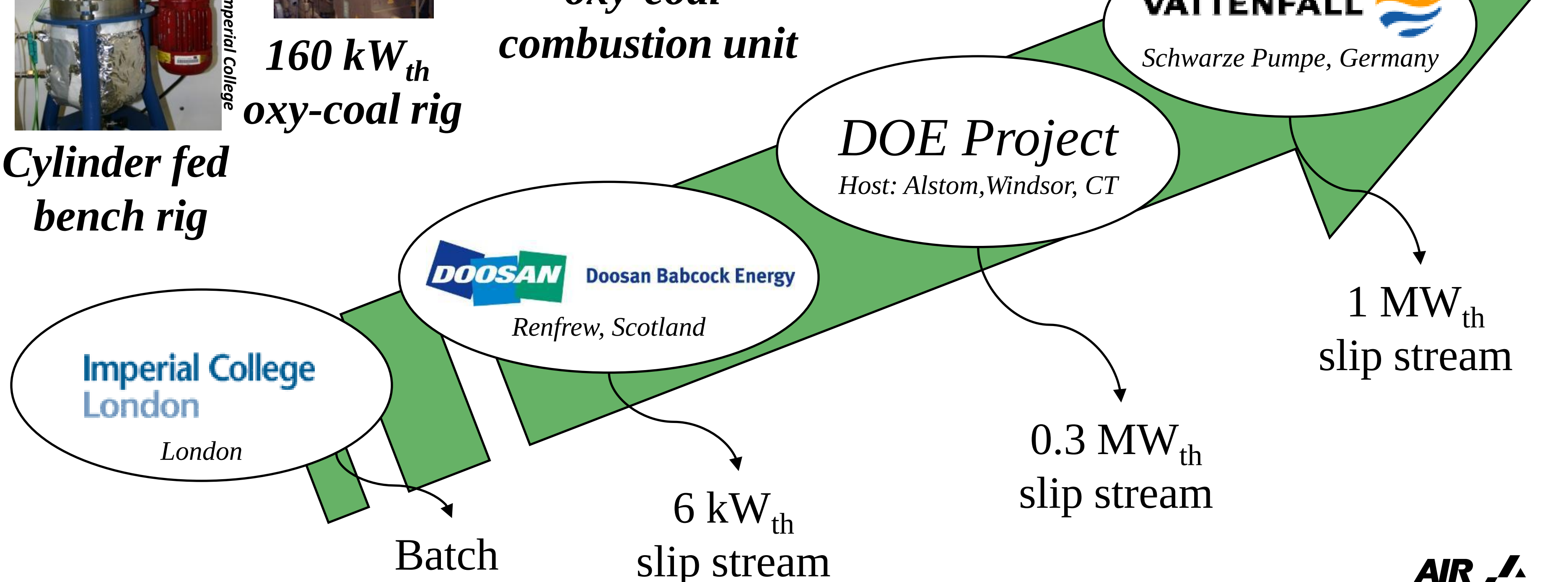
Photo courtesy of Alstom Power

15 MW$_{th}$ oxy-coal combustion unit

Photo courtesy of Vattenfall

30 MW$_{th}$ oxy-coal pilot plant

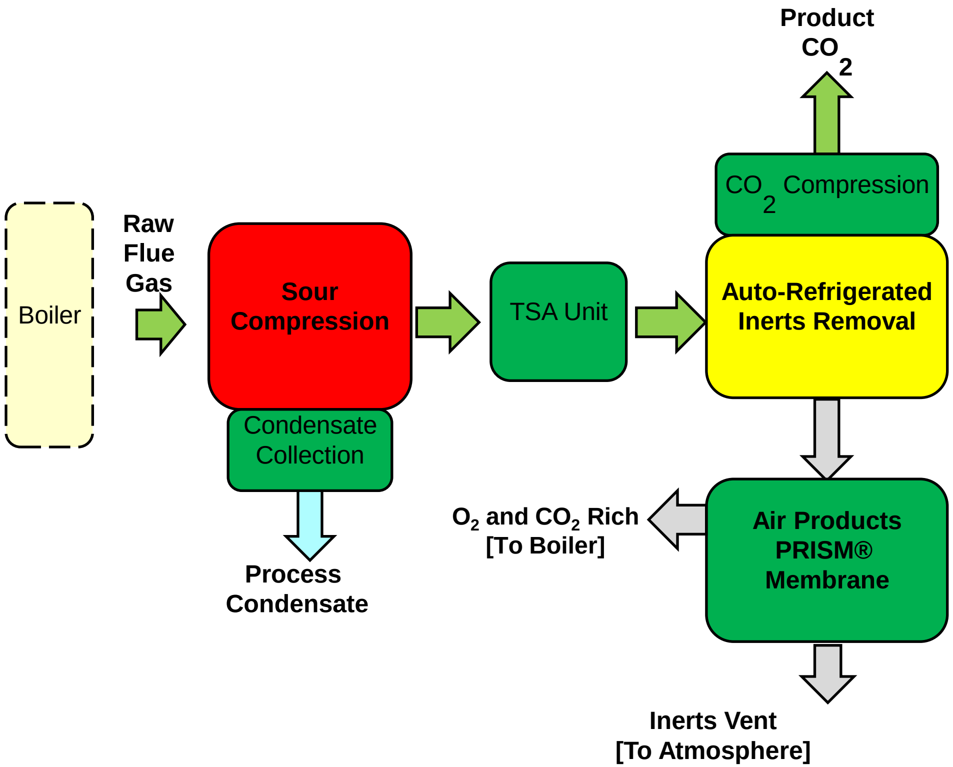
50+MW$_e$ oxy-fuel Demonstration



AIR PRODUCTS

ASU/CPU/Boiler Process Integration: Goals and Methods

- **Reduce cost/improve efficiency without compromising operability**
- **"Easy" integrations**
  - Use of by-product energy (Steam)
  - Combined utility systems (Cooling Water)
  - Air/nitrogen integration with gas turbines
- **"Harder" integrations**
  - Internal streams between process units
  - Start-up requires other units to be in operation



Summary

- There is a major new industry requirement for ASUs from fossil-fuel fired power generation
- ASUs have changed a great deal in the past 15 years
  - New cycles
  - Structured packing for distillation
  - More power efficient
- Single train sizes over 5000 tonne/day
- CO_2 Purification Units (CPU) being developed to purify raw CO_2
- Integration between ASU and CPU

AIR PRODUCTS

It is about more than just O_2...

- Air Products has APPLICATION EXPERIENCE
  - Large oxygen/air separation equipment to all type of applications and industries (Power, Gasification, Metals, Refining / Petrochemicals, etc.)
- Air Products has INTEGRATION EXPERIENCE
  - Air separation plants in all integration modes
    - Oxygen supply control system
      - Load following, start-up shutdown, peak-shaving
    - MAC heat recovery
    - Off-gas oxygen recovery for boiler blended to LASU O_2
    - Standalone, nitrogen integrated, and air/nitrogen integrated (IGCC)
- Air Products has MEGA-TRAIN EXPERIENCE
  - Operating very large single train air separation plants since 1997 in Rozenburg, The Netherlands (3250 t/d); also installed a 2x3500 t/d unit in Qatar
- Air Products demonstrates RELIABILITY
  - First company to supply high-reliability tonnage oxygen for power projects without oxygen backup
- Air Products provides OTHER GAS PRODUCTS
  - Broad industrial gas industry experience creates synergies with H_2, CO, and CO_2 markets

AIR PRODUCTS

Thank you

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Workshop on Operating Flexibility of Power Plants with CCS

Imperial College, London, November 2009

Experience with the CASTOR/CESAR Pilot Plant

Jacob Nygaard Knudsen & Jørgen Nørklit Jensen, DONG Energy Power

Presented by:

Jørgen Nørklit Jensen

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DONG Energy – Business Model

PRODUCTION | OPTIMISATION | SALES AND DISTRIBUTION

NATURAL GAS
OIL
RENEWABLE ENERGY
COAL
BIOMASS

PRIVATE CLIENTS
PUBLIC CLIENTS
BUSINESS CLIENTS
WHOLE-SALE
ENERGY EXCHANGES

Outline of Presentation

- Introduction to post combustion carbon capture (PC CC)
- Introduction to the CASTOR / Esbjerg CO_2 capture pilot plant
- Overview of operation history and outlook
- Interaction of capture plant and power plant
- (Water balance issues & control)
- (CESAR project - Upgrades and process modifications introduced)

Industrial Post Combustion CO_2 Capture Amine Process'

- ABB Lummus / Kerr-McGee: 15 - 20% MEA

  Only technology used on flue gas from coal firing (up to 400 ton CO_2/day)

- DOW MEA / Fluor Econamine FG: 30% MEA

  Large number of plants, up to 330 ton CO_2/day

- Mitsubishi Heavy Industries (MHI): KS-1 solvent

  Large number of plants, up to 450 ton CO_2/day

- Several other vendors of solvents and small scale plants (few tons a day)

A 750 MW_e coal fired power plant will produce > 500 ton CO_2/<u>hour</u>

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Post Combustion CO_2 Capture with Aqueous Amine Solutions

The production of CO_2 by this technology has been applied for decades, however:

- Goal has been commercial production of CO_2, not the reduction of CO_2-emissions
- The consumption of energy has not been important in this commercial production
- Limited experience on CO_2 absorption from flue gasses from coal fired power plants
- The largest plants build are 20 - 40 times smaller than necessary for coal fired power plants

Therefore the erection of the CASTOR pilot plant at the Esbjerg power plant !

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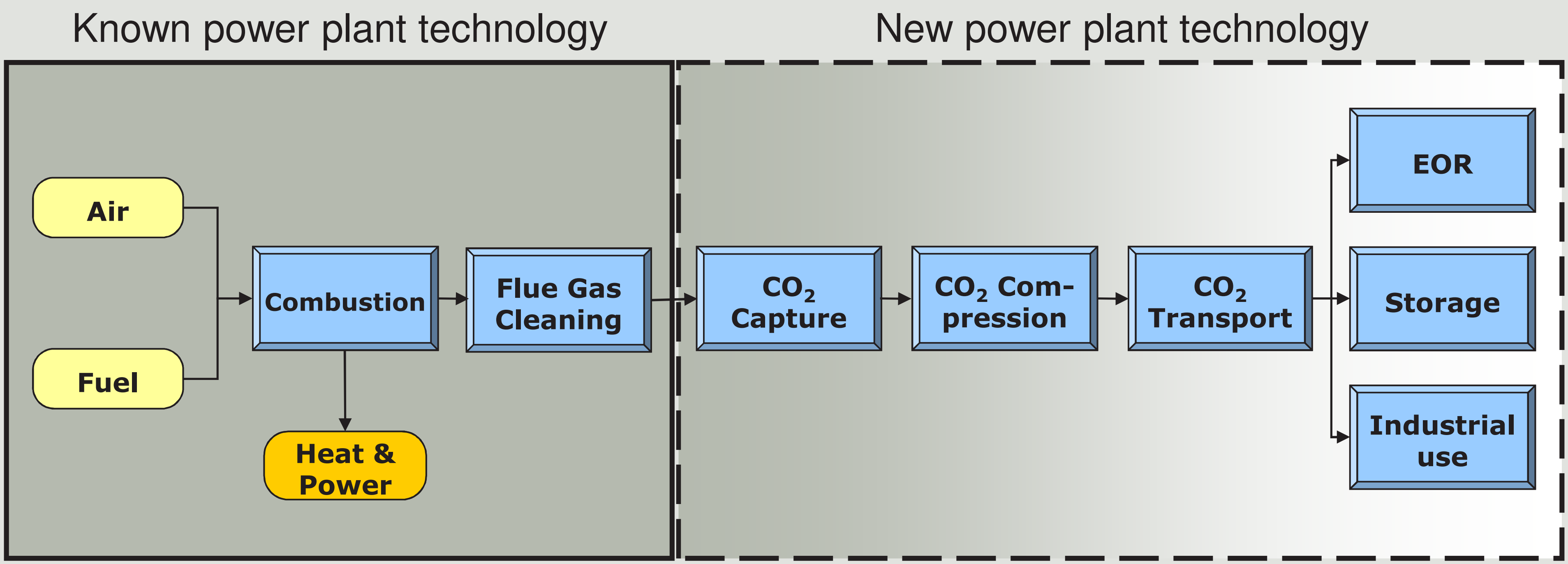
Placing of Post Combustion Carbon Capture Plant



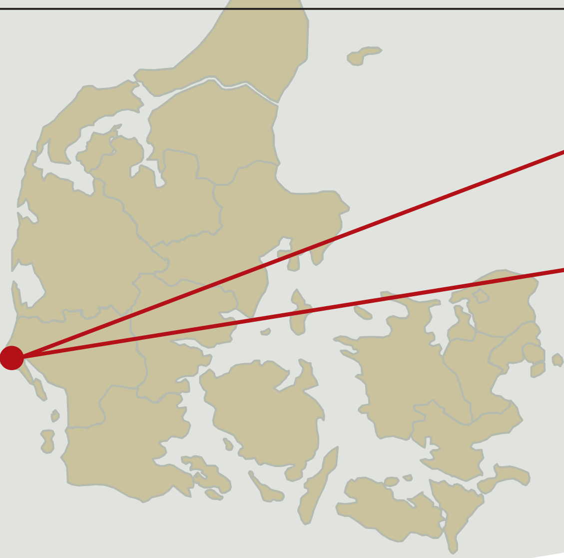
DONG Energy has a unique position because of our 3 business units:

- Power
- Gas Distribution & Storage
- Exploration & Production

Esbjerg Power Station (ESV)

Esbjerg Power Station

- 400 MW_e pulverized bituminous coal
- High dust SCR deNO_x plant
- 3 zones cold-sided ESP
- Wet limestone FGD (saleable gypsum)



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CASTOR Pilot Plant Specifications

- Pilot plant erected and commissioned during 2005
- Design of pilot plant based on a commercial CO_2 production plant (MEA)
- Pilot plant operates on a slip stream taken directly after the wet FGD
- Design flue gas conditions: ~47°C saturated, <10 ppm SO_2, <65 ppm NO_x, <10 mg/Nm^3 dust

Key design parameters

Parameter	*Design value*
Flue gas capacity	5000 Nm^3/h
CO_2 production (at 12% CO_2)	1000 kg/h
Absorption degree	90%
Max solvent flow	40 m^3/h
Max stripper pressure	2 bar$_g$

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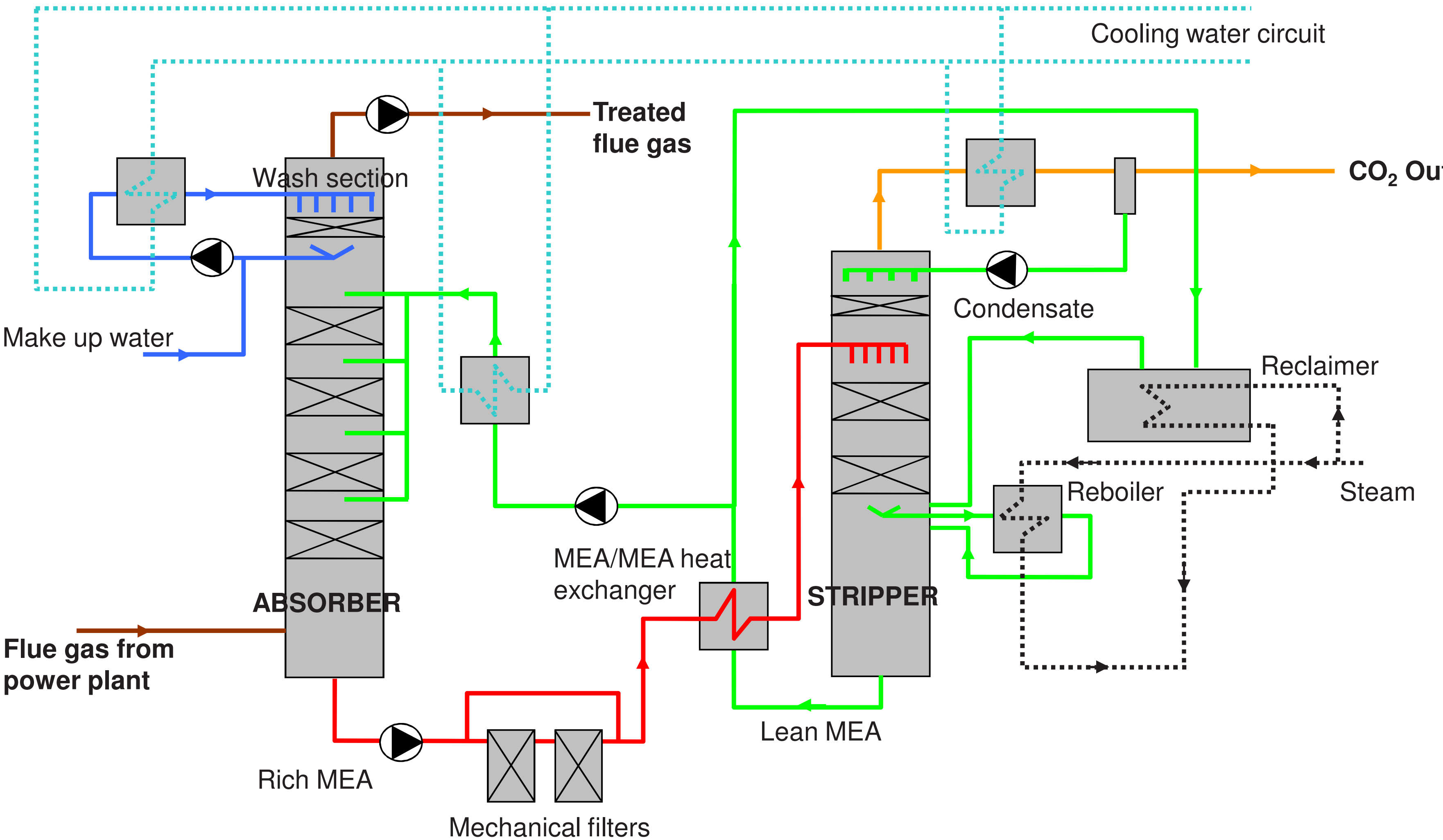
CASTOR Pilot Plant Flow Diagram



Operation History and Outlook at the Esbjerg Pilot Plant

Four test campaigns have been conducted in CASTOR:

- 1000 hours using standard solvent ”30%-wt. MEA” (Jan. – Marts 2006)
- 1000 hours using standard solvent ”30%-wt. MEA” (Dec. 2006 – Feb. 2007)
- 1000 hours using novel solvent ”CASTOR 1” (April – June 2007)
- 1000 hours using novel solvent ”CASTOR 2” (Sep. – Dec. 2007)

During 2008 a series of process upgrades have been installed at the Esbjerg pilot plant as part of the CESAR project.

Test programme in CESAR:

- 2000 hours using standard solvent ”30%-wt. MEA (Mar. – July 2009)
- 2000 hours using novel solvent ”CESAR 1” (fall 2009)
- 2000 hours using novel solvent ”CESAR 2” (spring 2010)

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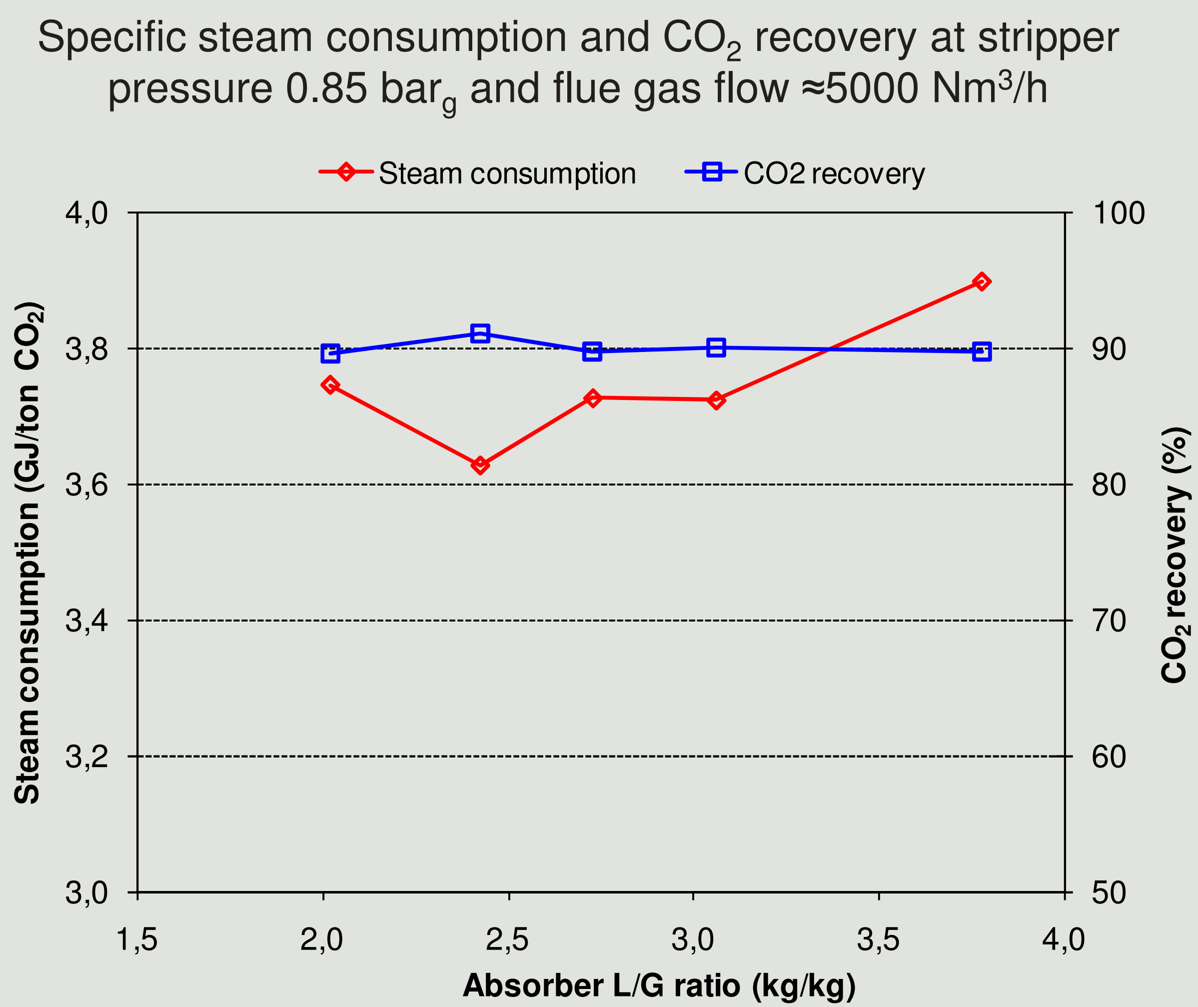
Outline of Test Campaigns

- **Test 1 – Parameter variation**
  a) Optimisation of solvent flow rate (at 90% capture)
  b) Variation of reboiler steam input at optimum solvent flow
  c) Variation of stripper pressure (at 90% capture)

- **Test 2 – 500 hours of continuous operation**
  - Operation at ”optimised” conditions
  - Achieving 90% CO_2 capture (on average)
  - Quantification of solvent consumption and degradation
  - Characterisation of corrosion behaviour

- **Test 3 – Miscellaneous tests**
  - Absorber pressure drop measurements
  - Emission measurements
  - Etc.

MEA Test: Solvent Flow Rate Optimization



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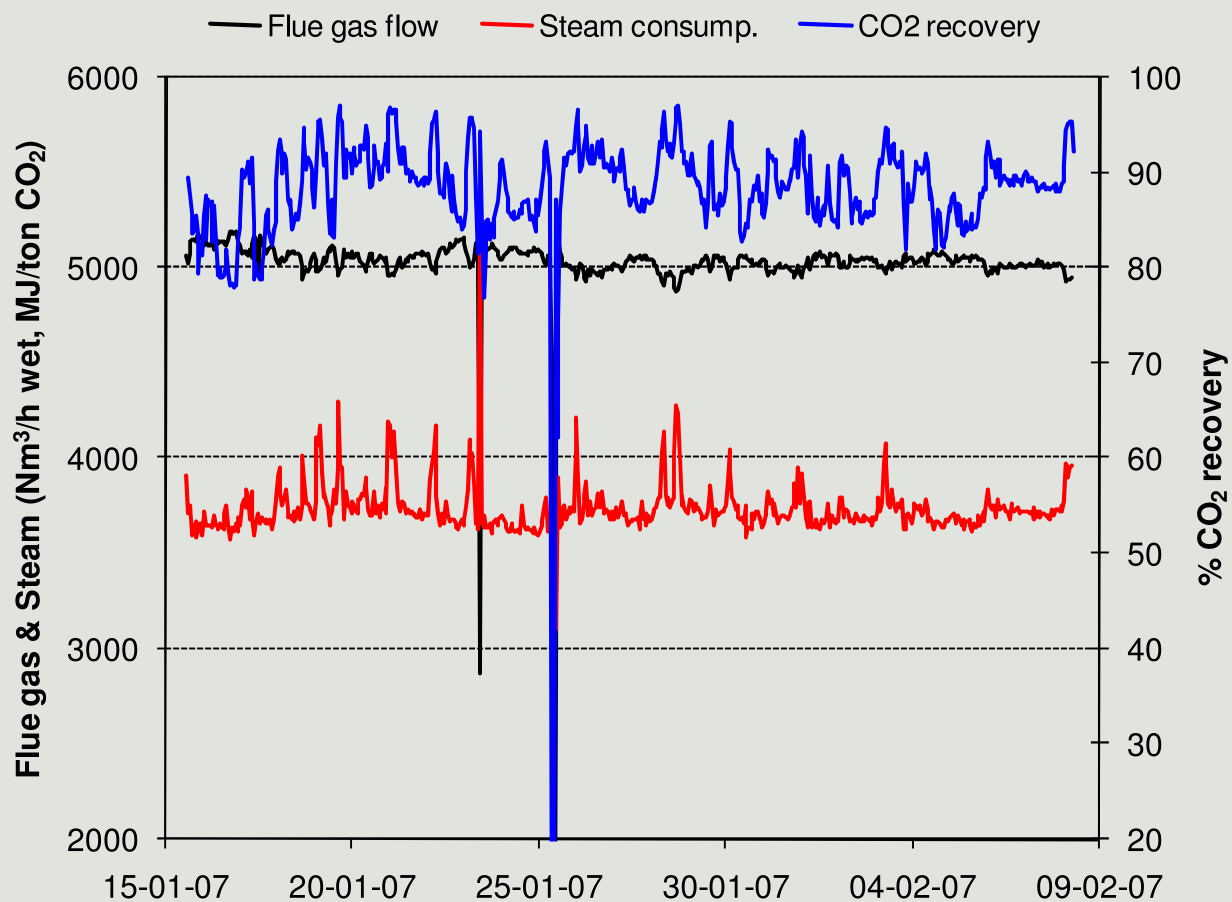
MEA Test: 500 Hours of Continuous Operation



Average steam consumption: ≈3.7 GJ/ton CO_2

Average CO_2 capture: 88 %

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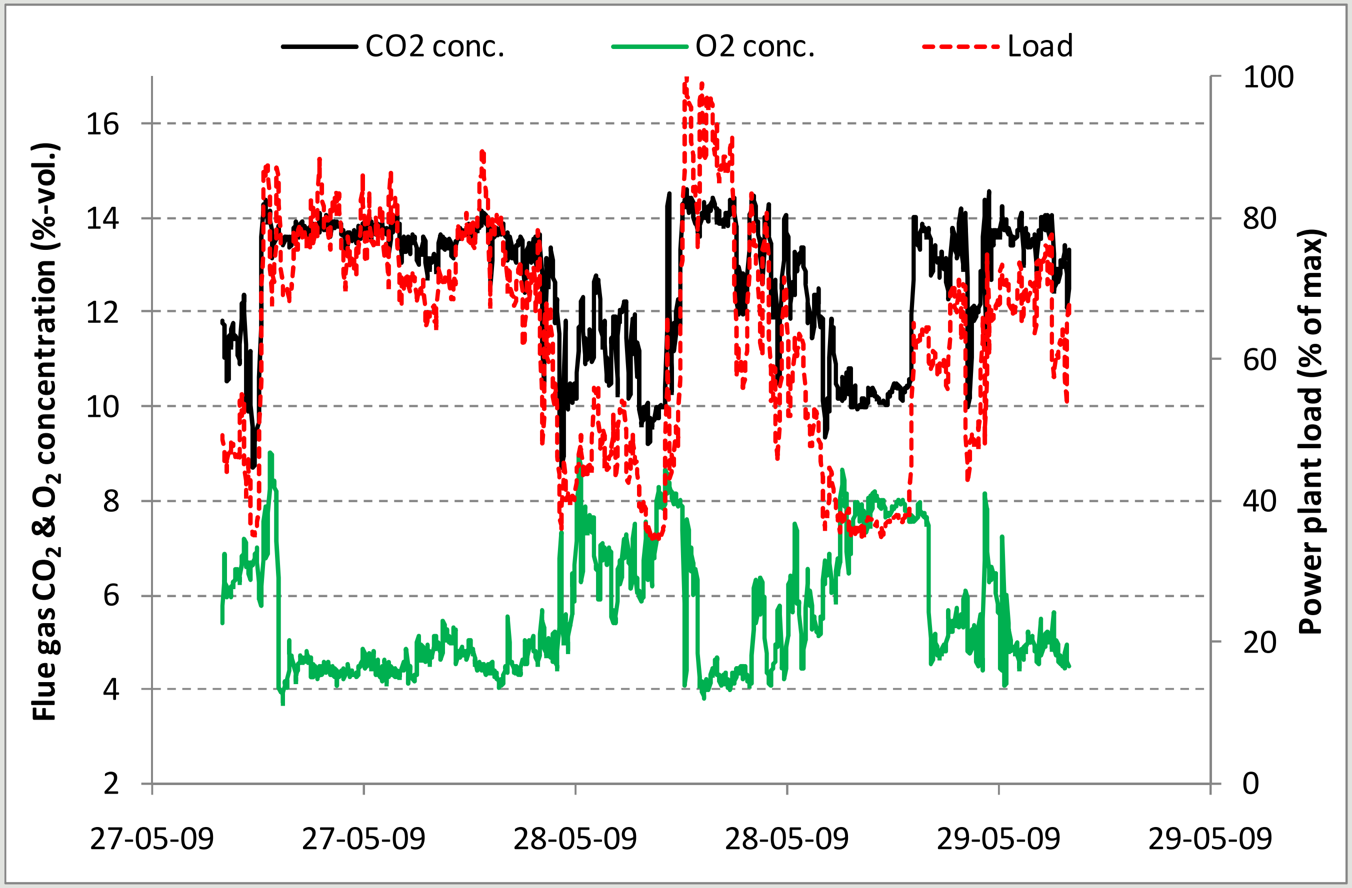
Influence of Power Plant Load on CO_2 Content of Flue Gas



Example: 48-hours load profile at the Esbjerg coal-fired power plant

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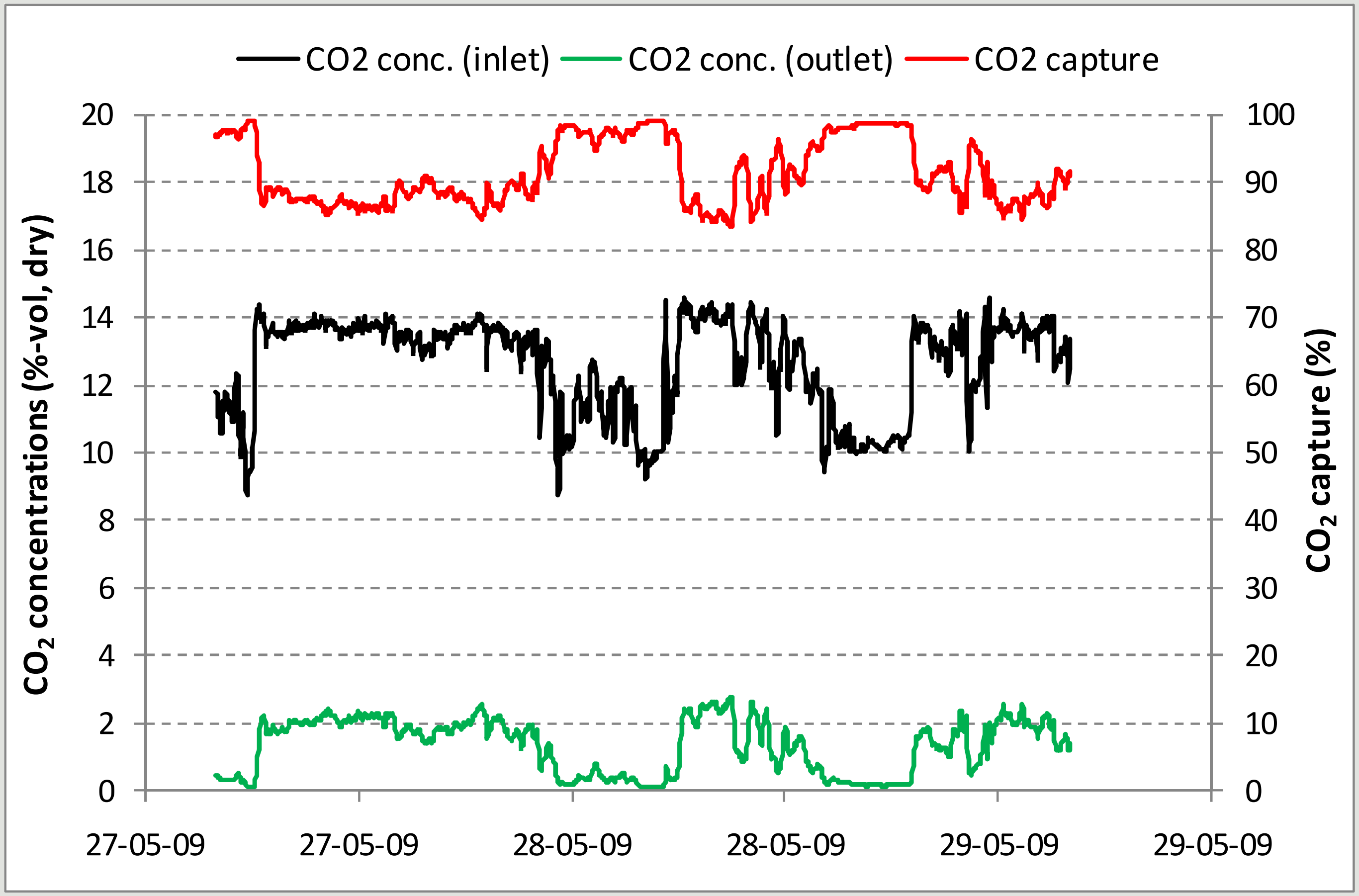
Influence of Power Plant Load on CO_2 Capture Degree



Example: 48-hours operating period with fixed settings at the CO_2 capture plant

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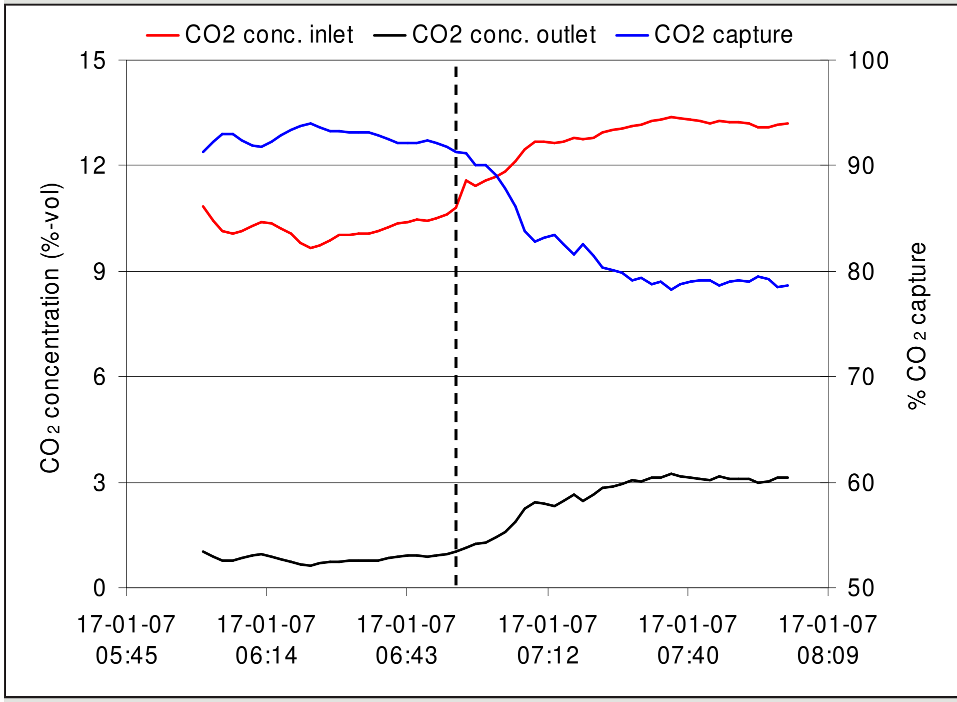
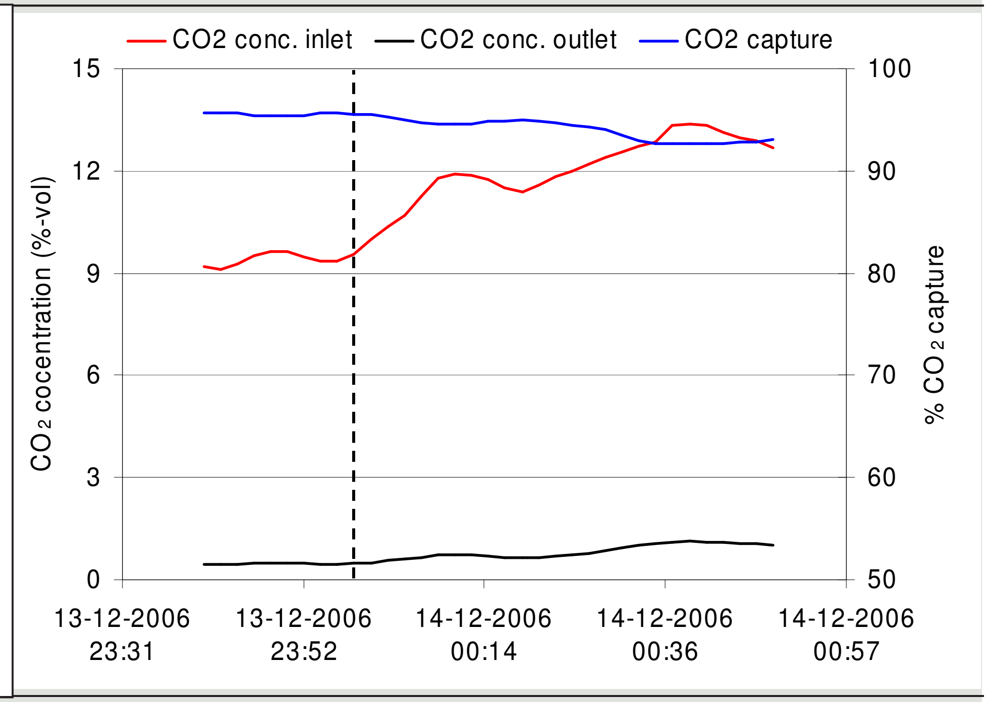
Absorber Response to Step Change in CO_2 Inlet Concentration





”Optimised” conditions

MEA flow: 15.5 m³/h

Solvent flow rate higher than ”optimum”

MEA flow: 19 m³/h

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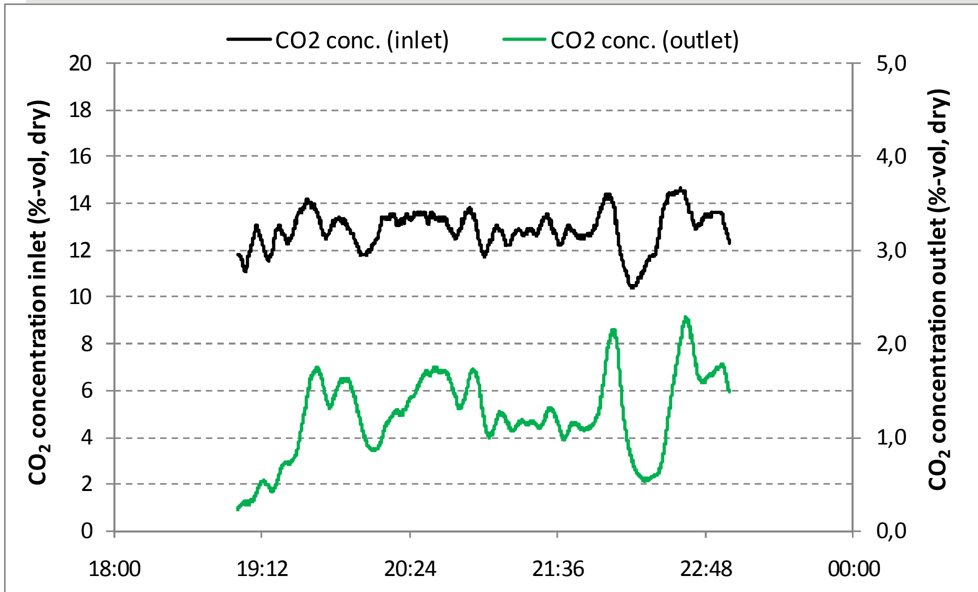
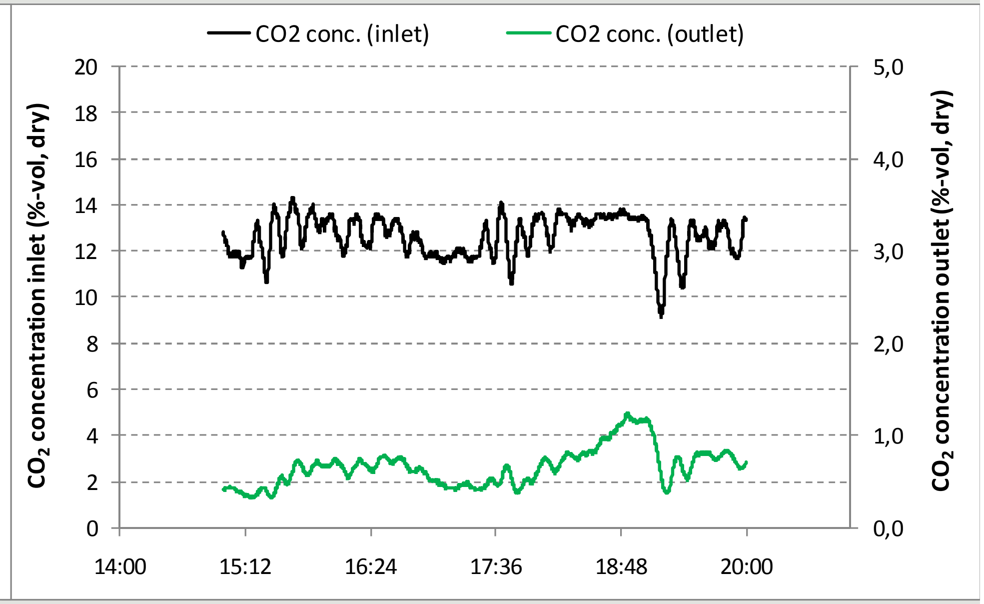
Influence of Absorber Liquid-to-Gas (L/G) Ratio on Absorber Response to Power Plant Load Changes

L/G ≈ 3 kg/kg



L/G ≈ 4 kg/kg



Examples: 4-hours operating period with fixed settings at the CO_2 capture plant

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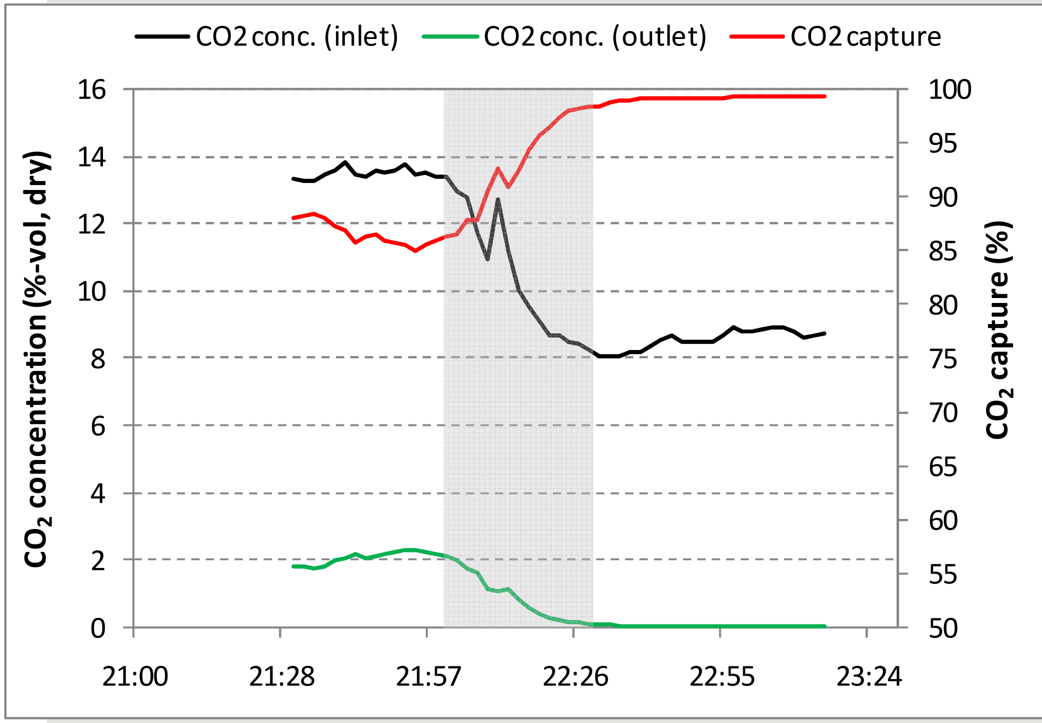
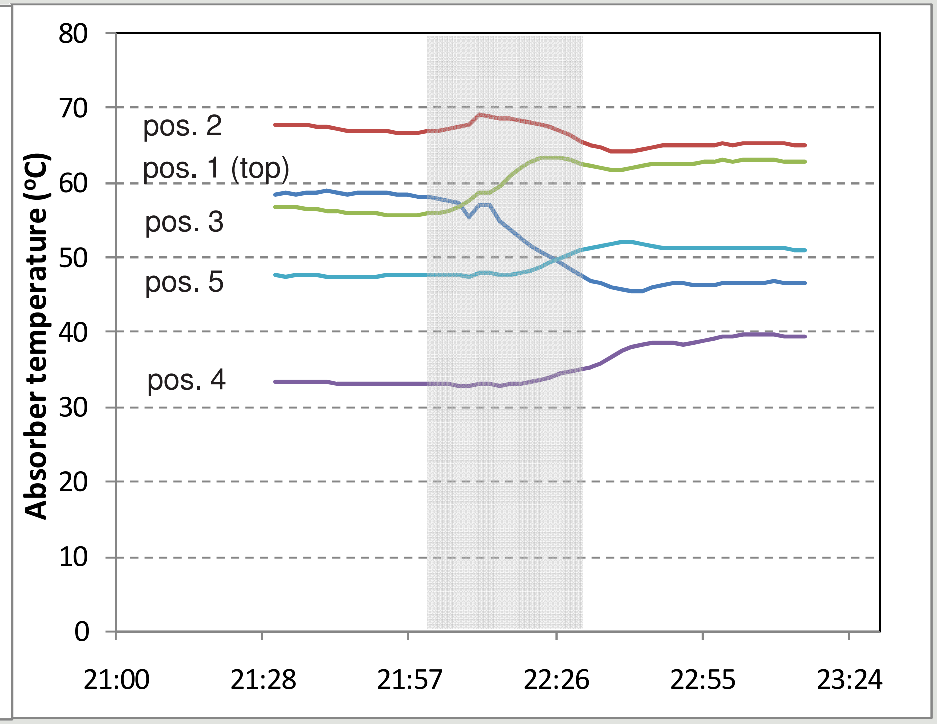
Absorber Response to Step Change in CO_2 Inlet Concentration





Example: CESAR tests with inter-cooling at stage 4

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Conclusion on Operating Flexibility based on CASTOR Pilot Plant

- The CO_2 capture plant will be as flexible as the power plant!
- What about the rest of the down stream equipment?:
  - Compression
    - single stage compressors and no of trains?
    - multistage compressor and no of trains?
    - with or without heat revovery and/or inter-cooling?
  - Transportation
    - pipeline?
    - injection well?
  - Storage / use
    - enhanced oil/gas recovery?
    - depleted oil/gas field?
    - saline aquifer?
    - (Industrial use)?

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Thank you for your attention!

Contact: jornj@dongenergy.dk

The Water Balance Issue

A CO_2 post combustion capture unit is an "open" system concerning water.

A fundamental mass balance apply:

Ingoing water + Make-up water = Outgoing water + Accumulated

- The accumulated term must be zero, if neither dilution nor concentration of the amine solution should take place
- Ingoing: Water content of flue gas entering the plant
- Outgoing: Water content of flue gas, CO_2 product leaving the plant, and drain of condensate
- Make-up: Fresh water supply to wash sections (optional)

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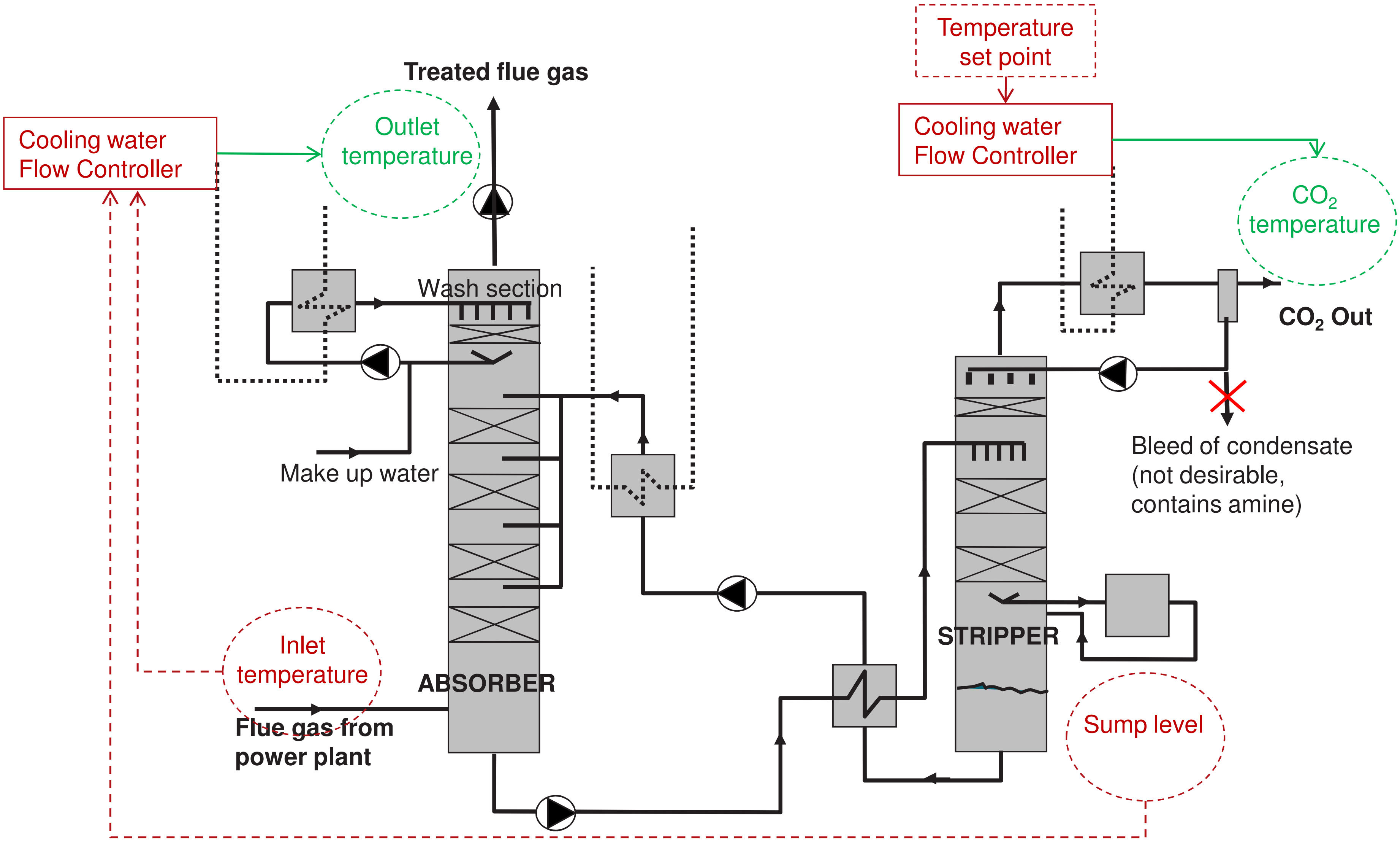
Controlling the Water Balance



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CESAR Project Overview

- The CASTOR project ended in January 2008
- A 3-year follow up EU project "CESAR" was launched 1st of February this year
- 20 partners in the CESAR consortium
- Pilot plant activities in CESAR:
  - Implementation of process improvements at the Esbjerg Pilot Plant
  - 3 × 2000 hours test campaigns (1 benchmark & 2 novel solvents)
  - Focus on minimization of the energy consumption
  - Focus on dynamic behavior
  - Focus on the environmental impact of amine scrubbers

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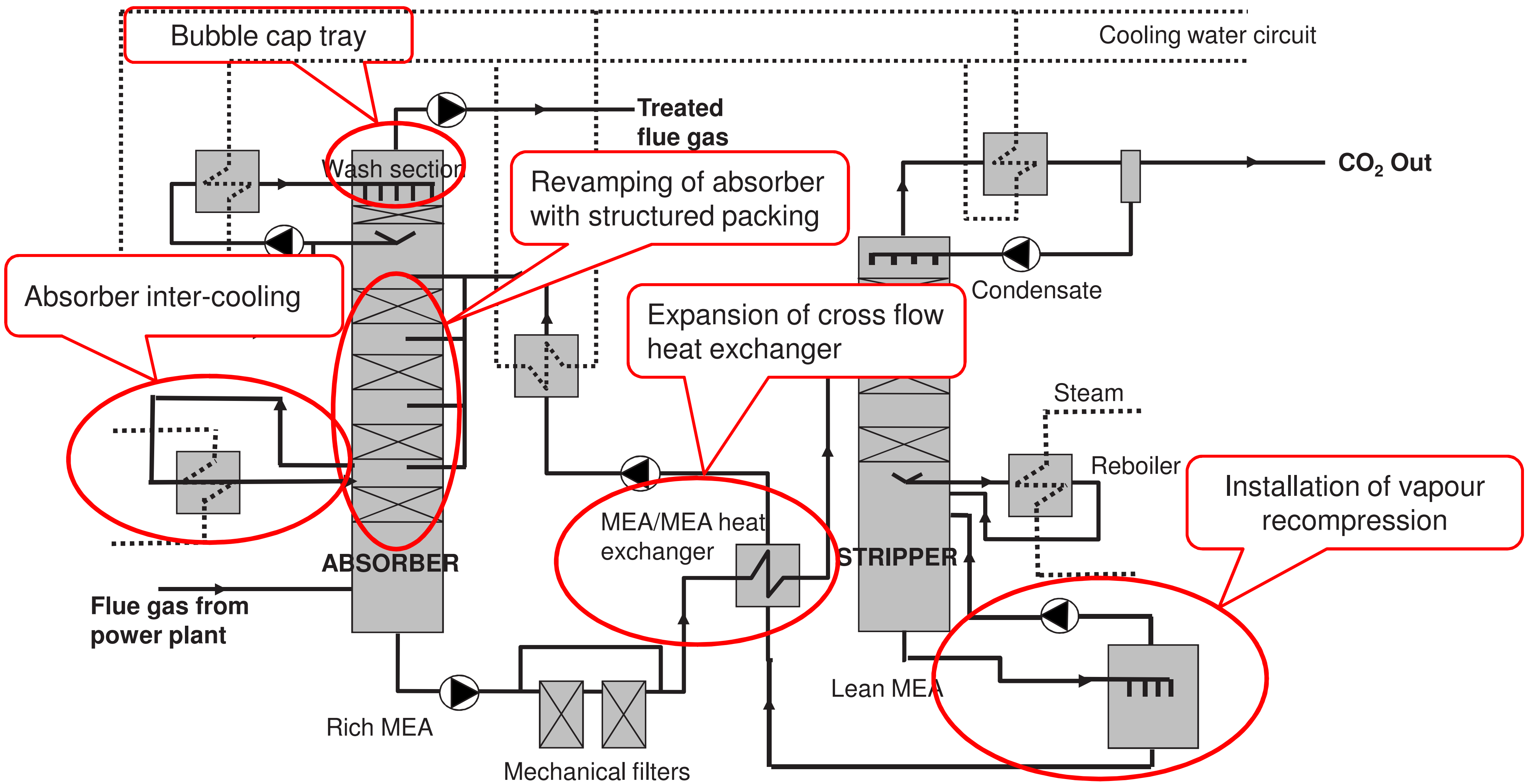
CESAR Pilot Plant Flow Diagram



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CESAR Pilot Plant Modifications: Inter-cooler & Flash

Absorber inter-cooler skid

Flash vessel for vapour recompression

Imperial College London

Workshop on Operating Flexibility of Power Plants with CCS, 11th – 12th November 2009

Steam turbines for operating and future-proof upgrading flexibility

Mathieu Lucquiaud, Hannah Chalmers and Jon Gibbins

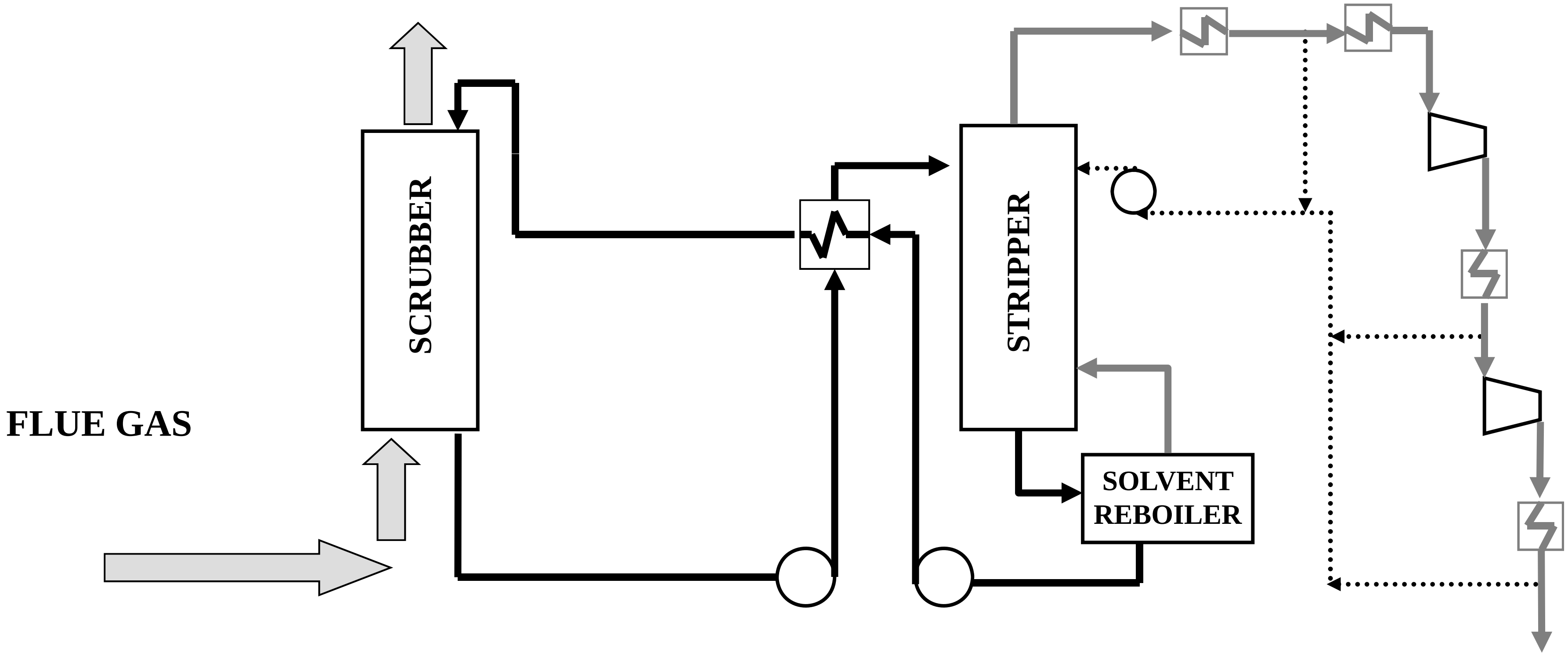
Acknowledgements: DECC, RCUK, IEA GHG

Outline

- Flexible modes of operation
  - Part-load operation
  - Absorber by-pass
  - Solvent storage and delayed regeneration

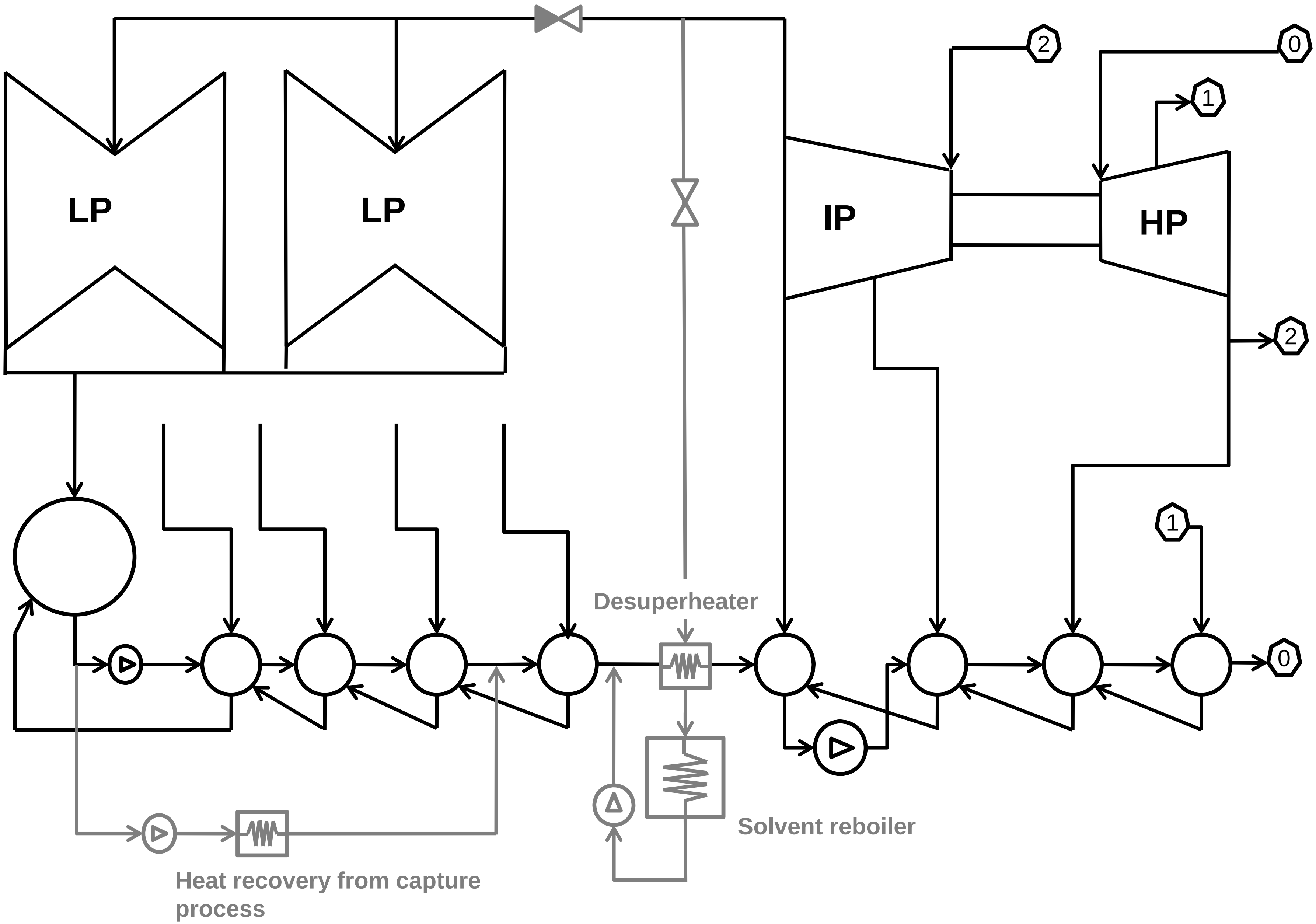
- Future-proof upgrading flexibility
  - Possible solvent improvements
  - Implications for steam cycle design

Part-load operation of capture unit



Change in flue gas flow-rate - Optimal Absorber L/G ratio?
Change in solvent flow-rate - Optimal Stripper L/G ratio?
Temperature of regeneration – Compressor operation
CO_2 output drops - Compressor operation
Temperature pinch in solvent reboiler

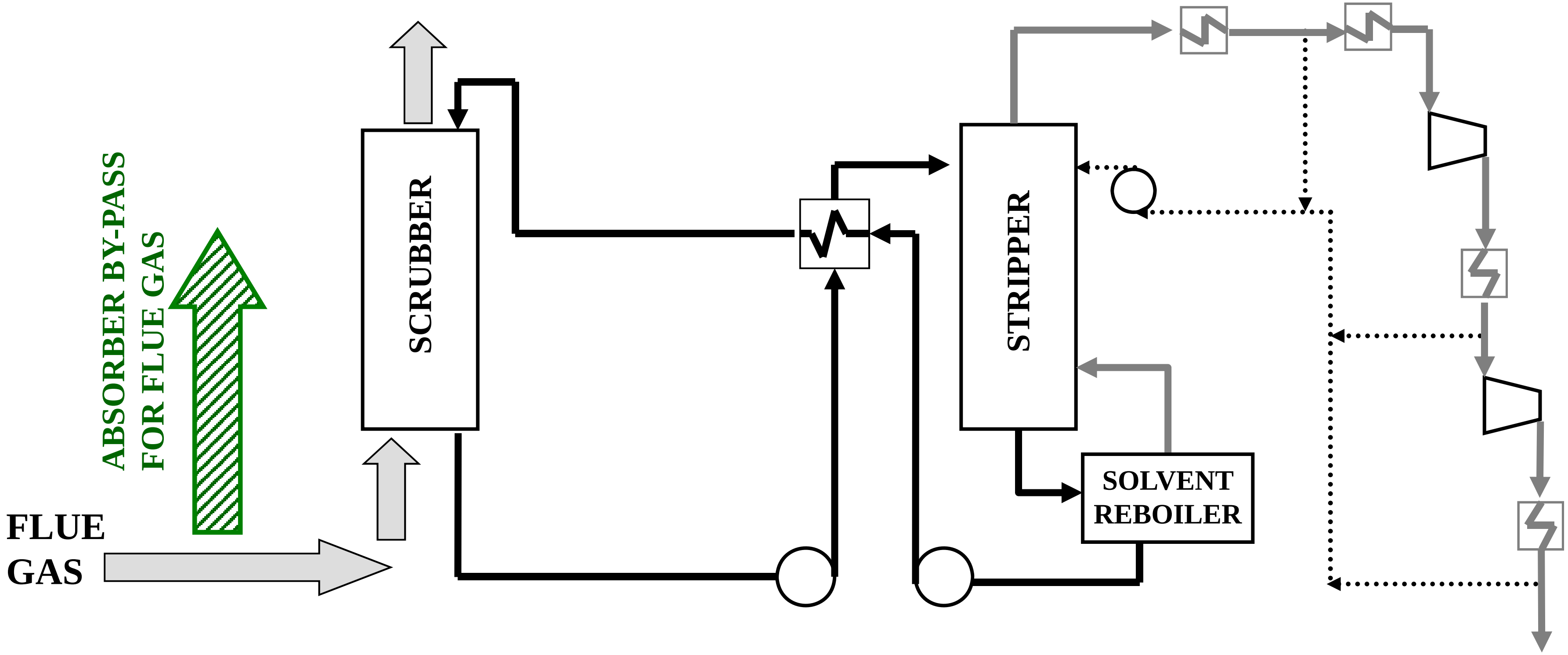
Part-load operation of power cycle



Part-load operation of power cycle

- The temperature pinch in solvent reboiler is reduced. Conduction dominates heat transfer.
- Pressure drop across steam pipe to reboiler reduces with steam flow
- The delivery pressure has to be in line with turbine part-load operation constraints

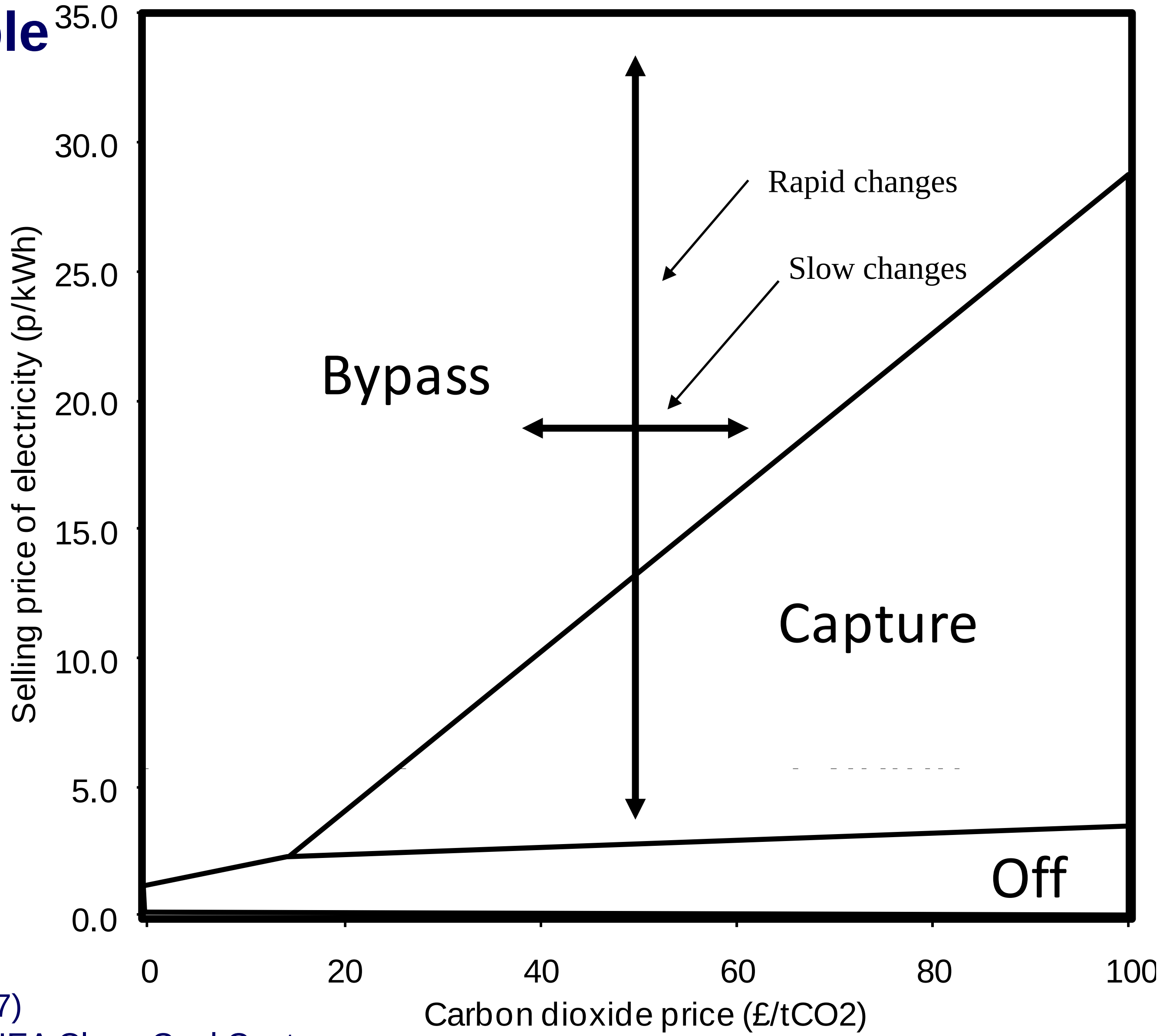
Voluntary by-pass of absorber



Operational Flexibility

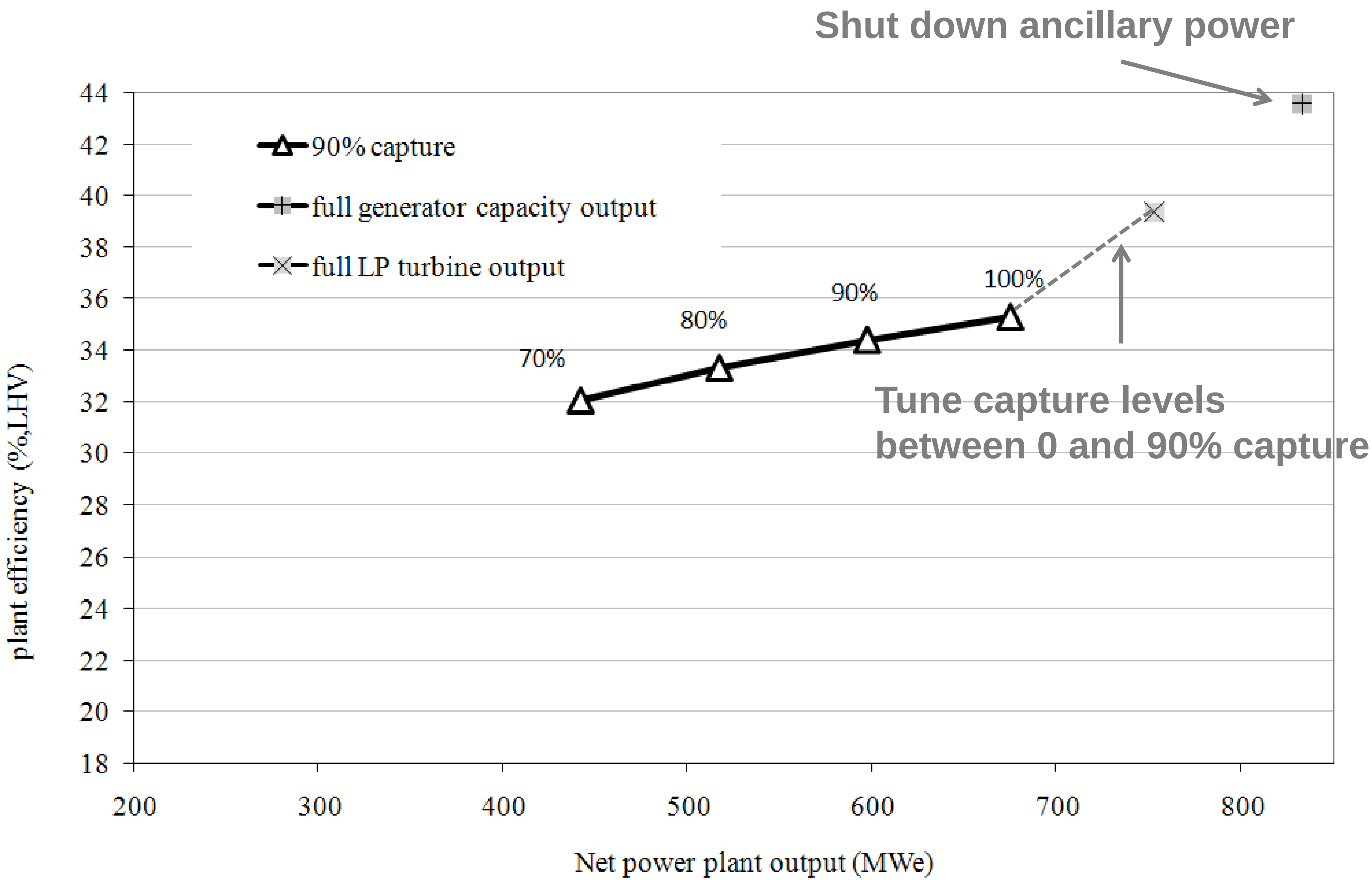
Illustrative example of arbitrage between carbon and electricity prices for full bypass of the CO_2 capture unit

Plant output	750 MW
Coal price	£1.4/GJ
Carbon price	£25/tCO_2
CO_2 transport & storage	£5.5/tCO_2



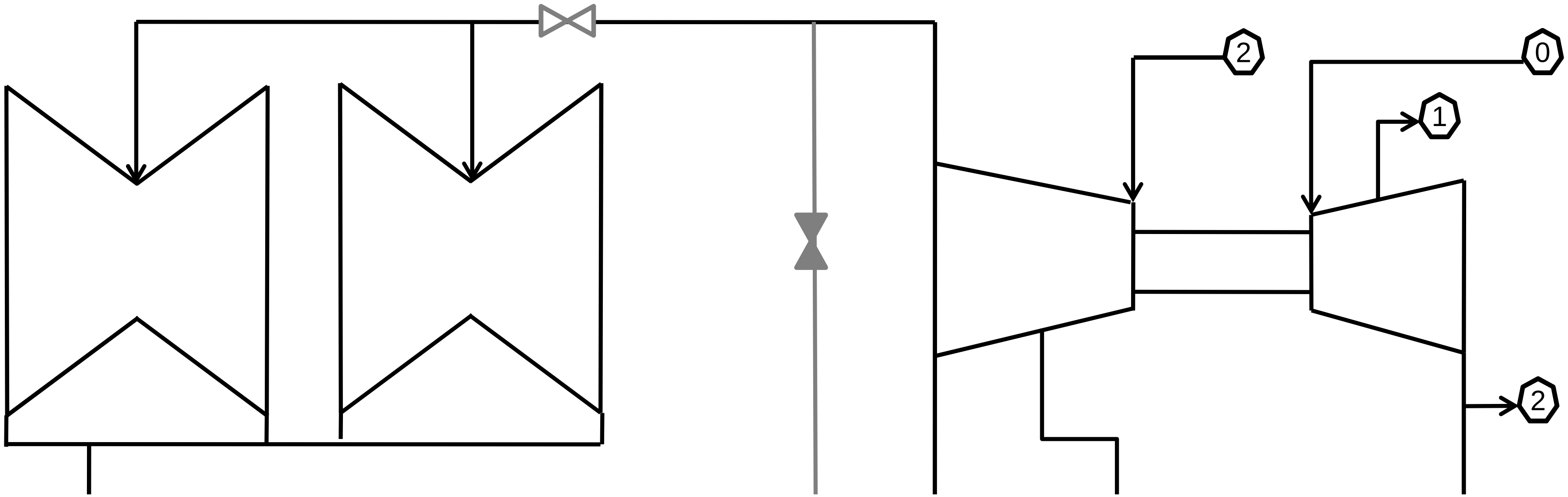
Chalmers H, Gibbins J, Fuel (2007)
Updated in forthcoming report for IEA Clean Coal Centre

Performance at part-load and with absorber voluntary by-pass



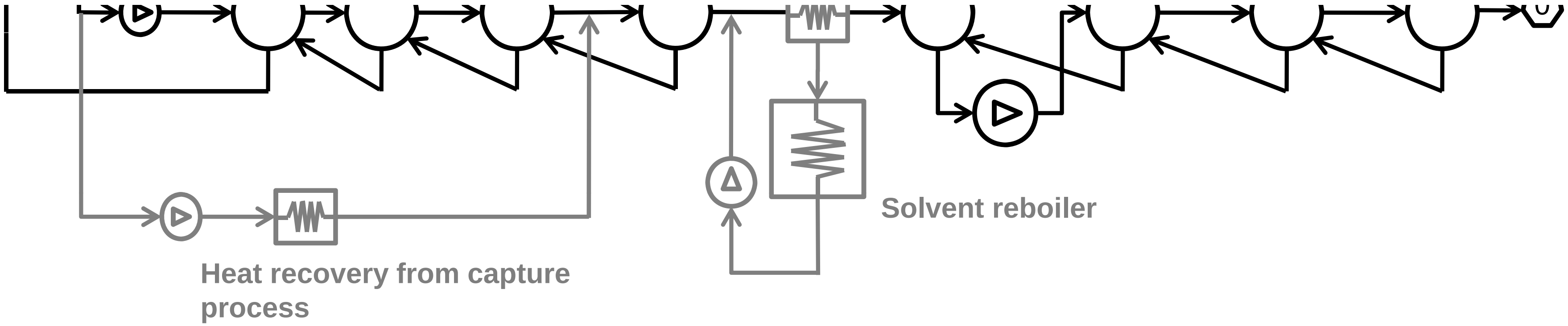
Lucquiaud M, Chalmers H and Gibbins J, Energy Materials 2008 2(3), 177-183

Voluntary absorber by-pass

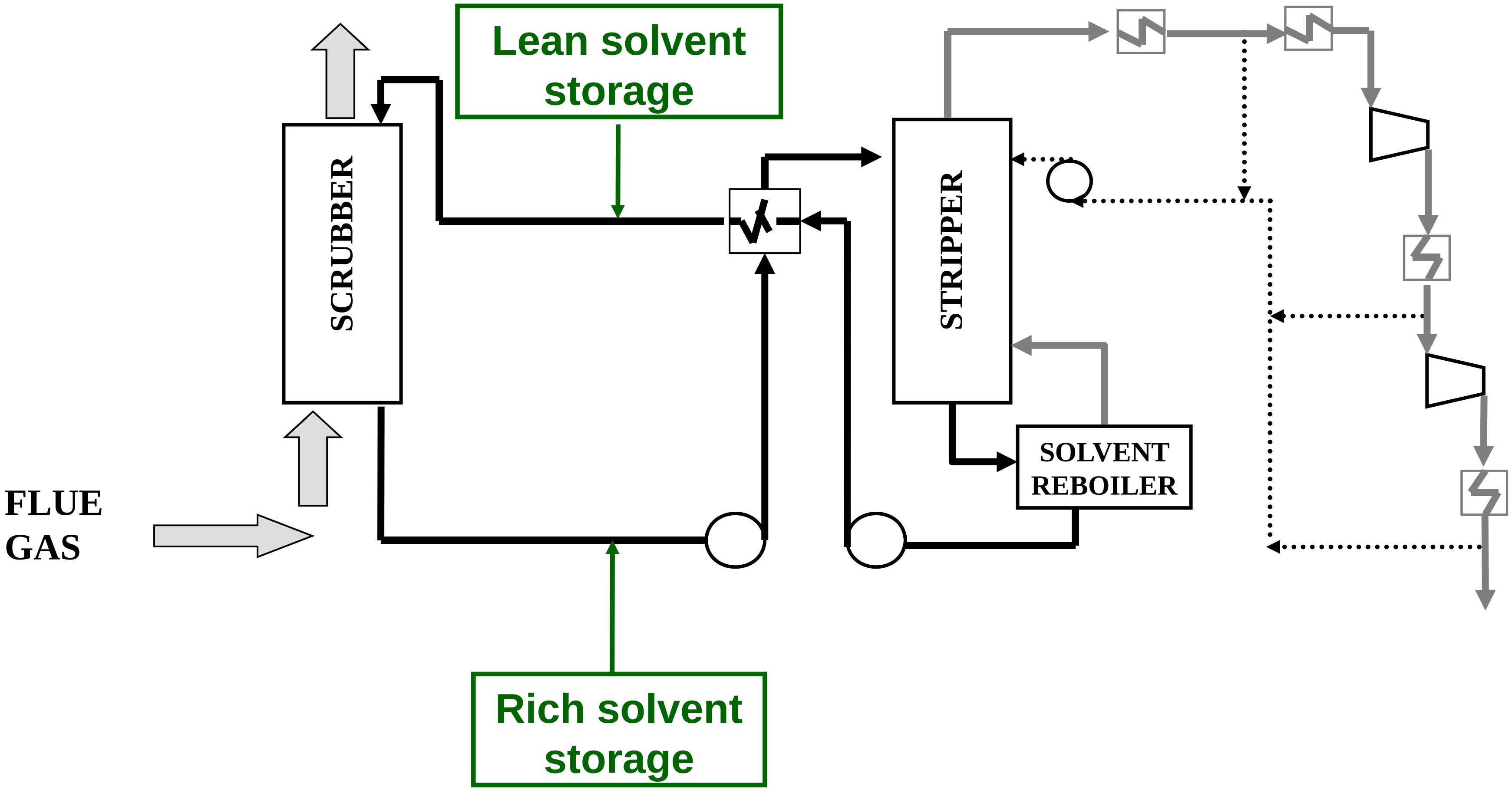


❑**<u>NEW-BUILD UNITS</u>: Oversize generator capacity and low pressure turbines to export additional power available**

❑**<u>RETROFITS:</u> return to initial power output**

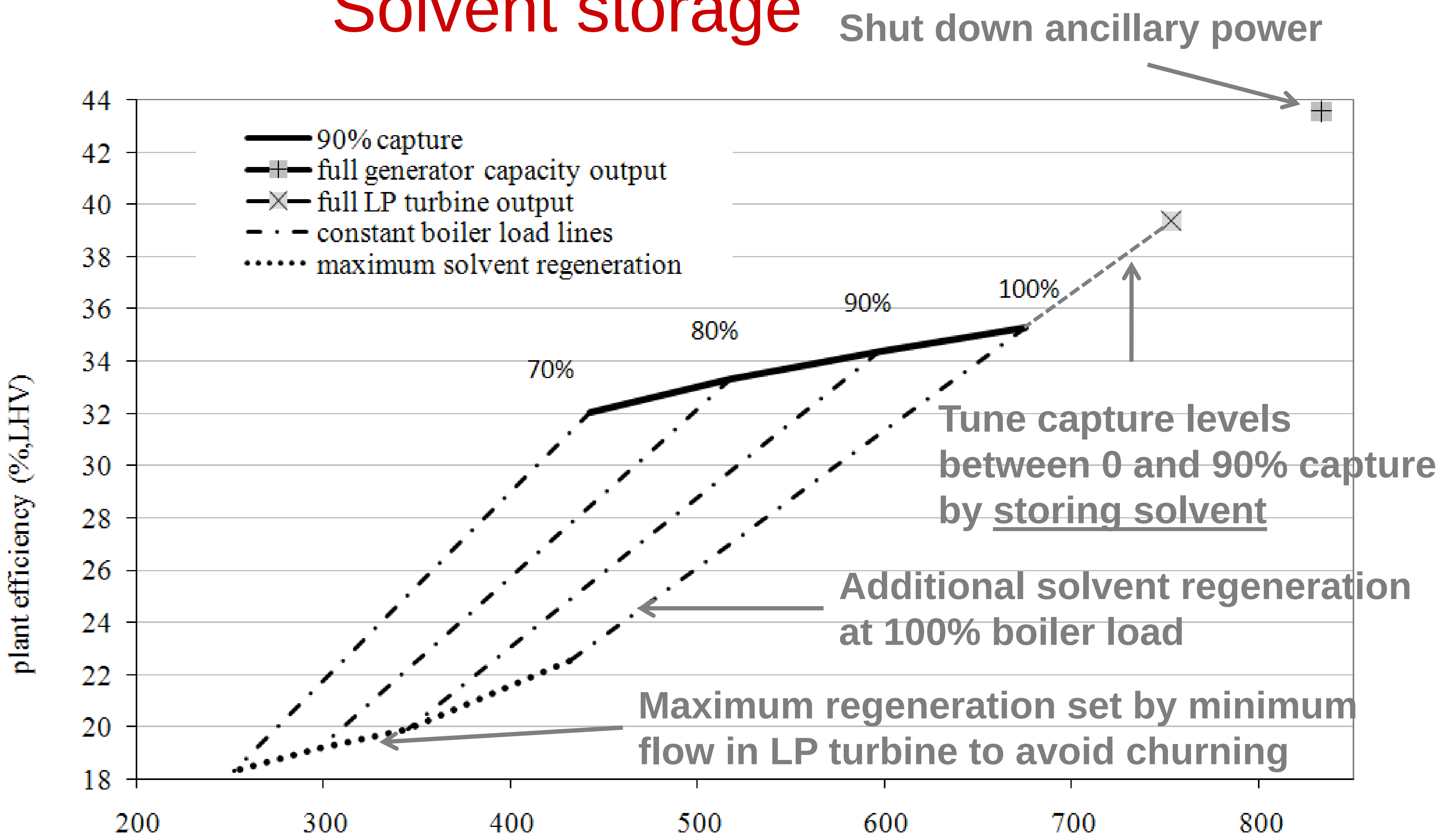


Solvent storage



- Space requirement will depend on number of hours of solvent storage capacity
- Impacts of solvent degradation.
- Implications for environmental permitting

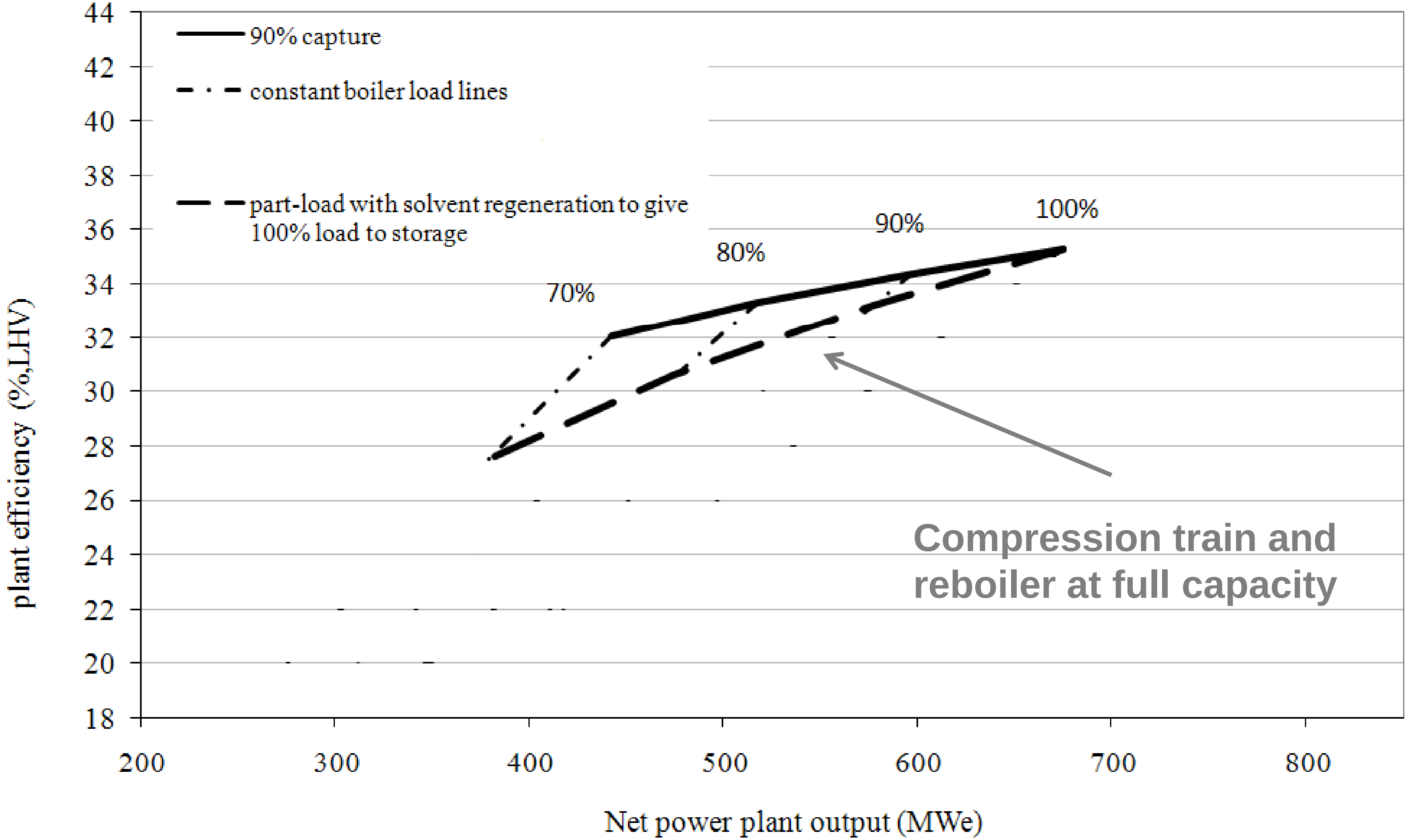
Solvent storage



- **Investment decision: Oversize stripper, reboiler and compression train for additional regeneration?**

Lucquiaud M, Chalmers H and Gibbins J, Potential for flexible operation of pulverised coal power plants with CO_2 capture, Energy Materials 2008 2(3), 177-183

Solvent storage without oversizing regeneration



- ❑Times to regenerate 1hr of solvent:
- ❑At 80% load > 5hrs
- ❑At 70% load 3.5 hrs

- Additional investment costs need to be defined, but baseline will vary
  - Bypass: Extra capacity ‘free’ for some retrofits, but additional for new-build
  - Solvent storage: Solvent inventory and tanks, also additional stripper/reboiler and compressor capacity for ‘aggressive’ options

- Need to consider range of plausible future scenarios for electricity selling price
- Value of ancillary (support) services could also become more important in future networks

Future-proof upgrading flexibility

- Incorporate future improvements in an area of technology change
- Future-proof your asset against 2nd and 3rd generation of CCS plants
- Difficult to predict solvent developments 10-20 years in advance

Future-proof upgrading flexibility

- Possible reasons for a solvent upgrade
  - Reduce fuel costs: More power out of steam cycle and/or lower ancillary power
  - Reduce solvent costs: “cheaper” molecules, reduced inventory, reclaiming, degradation
  - Reduce emission costs: higher capture rate per unit of electricity

Future-proof upgrading flexibility

- With the same pieces of equipment
  - Faster kinetics: reduce the irreversibilities of absorption => lower the energy of regeneration
  - Favourable VLE: lower energy of regeneration and/or higher stripper operating pressure => reduced compression power, increased levels of capture

Future-proof upgrading flexibility

- Faster kinetics => flexibility in the absorber design
- Favourable VLE

  => flexibility in reboiler design

  => flexibility in compressor design

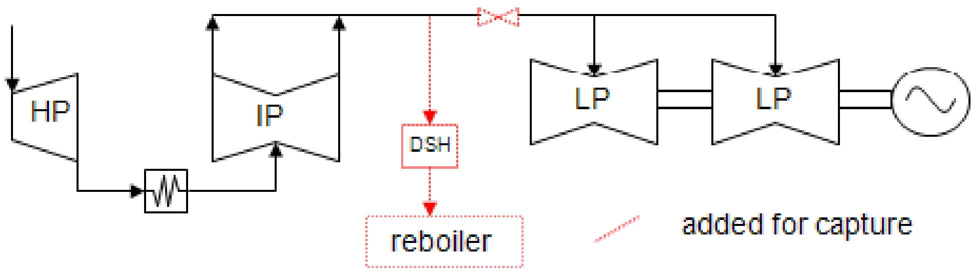
  => flexibility in the steam turbine design to accommodate for changes in

  - Steam extraction flowrate
  - Temperature of regeneration
- What does a future-proof steam turbine design look line?

Capture-ready steam turbine designs and consequences for integration

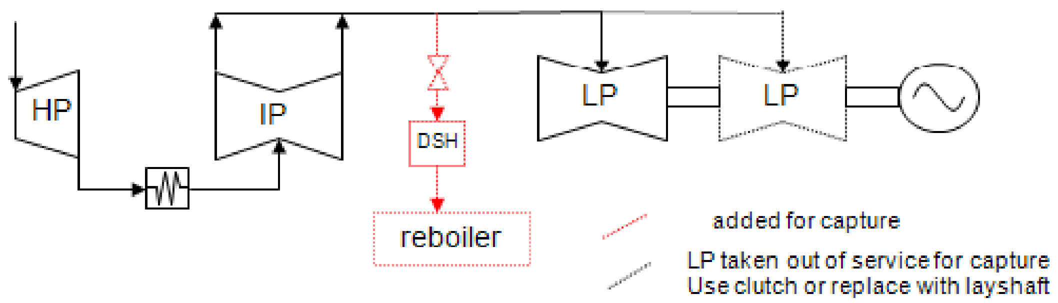
Lucquiaud et al, IEA GHG 2007-4; Proc. IMechE Vol. 223 Part A3: J. Power and Energy, May 2009, p213 & p227

- **Throttled LP turbine**



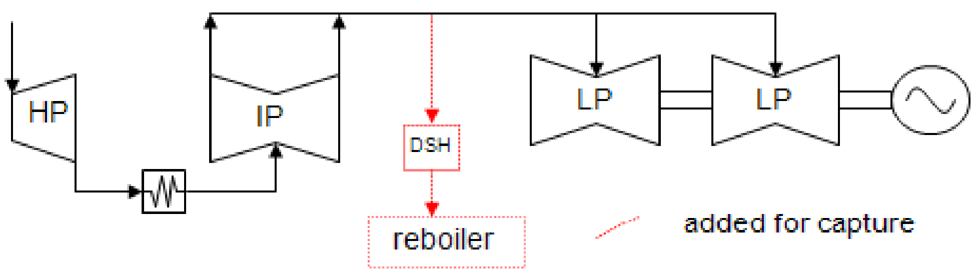
Simplest design, but losses in throttling valve. Initial pressure ~3.6 bar for amine, cannot be varied

- **LP turbine taken out of service**



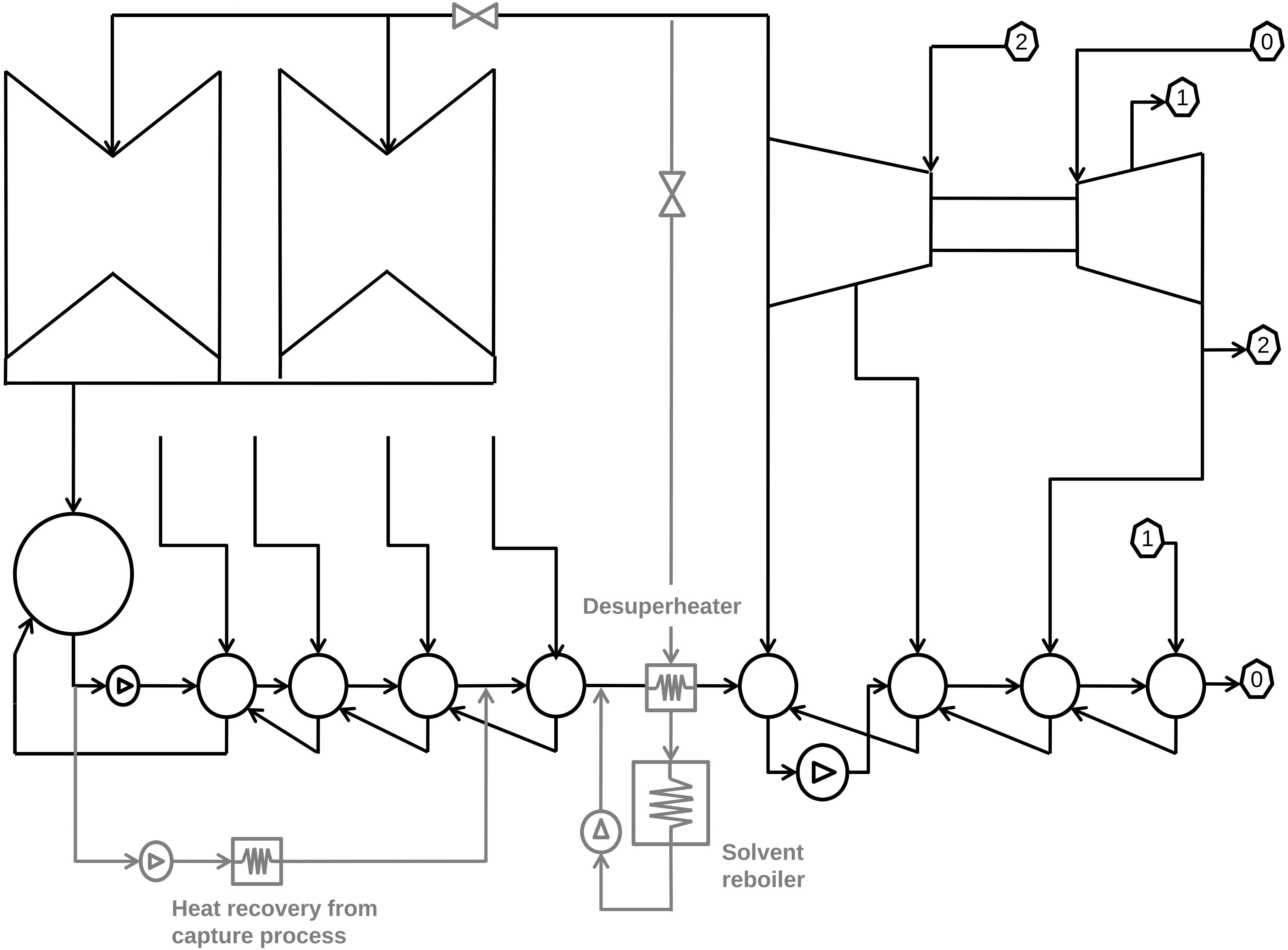
Most efficient design, but cannot vary steam extraction flow. Initial pressure ~3.6 bar for amine, cannot be varied

- **Floating IP/LP crossover pressure**

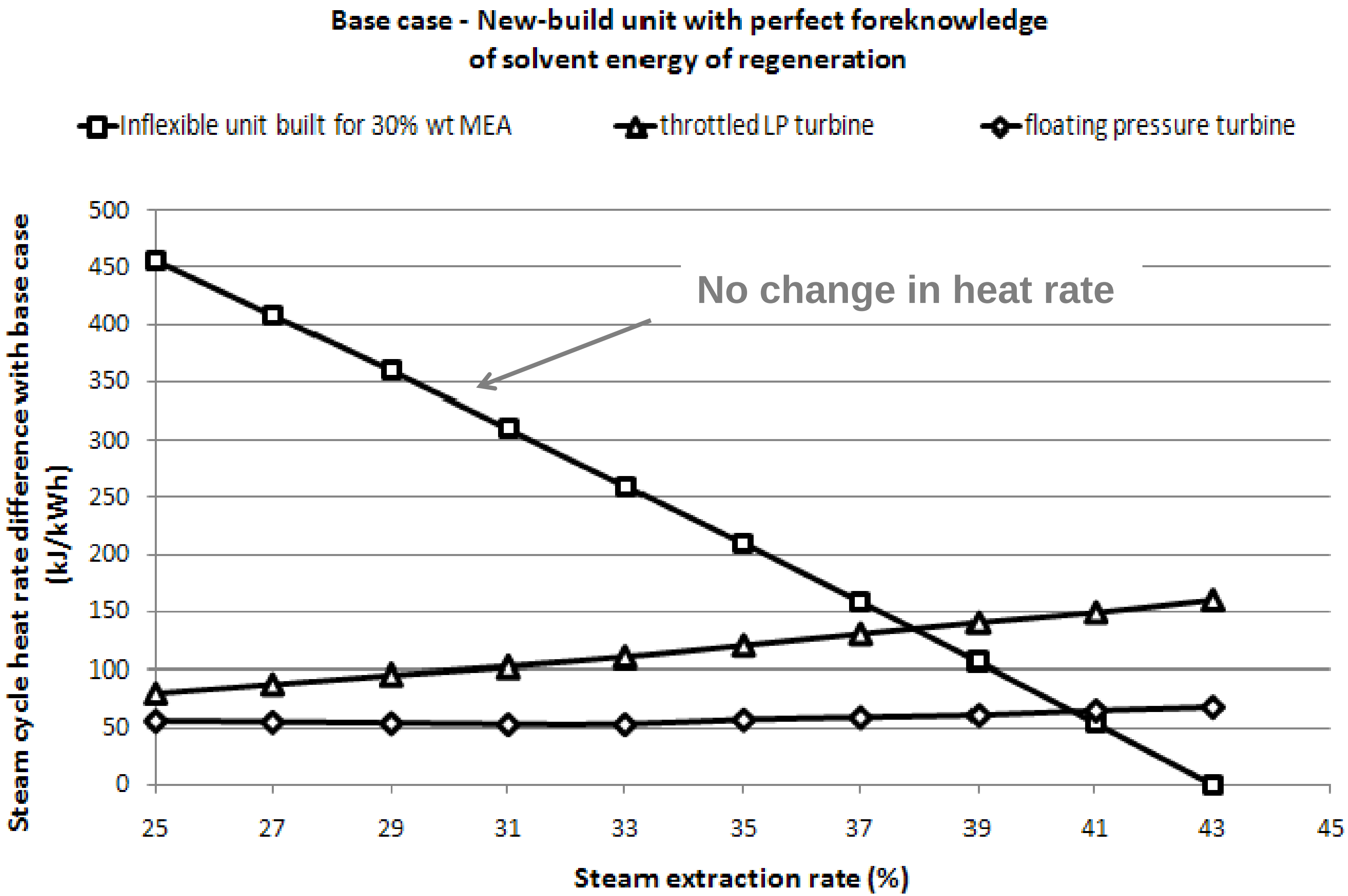


Avoids all throttling losses at design extraction rate. Extraction pressure goes up with reduced flow rate 7 to 3.6 bar possible

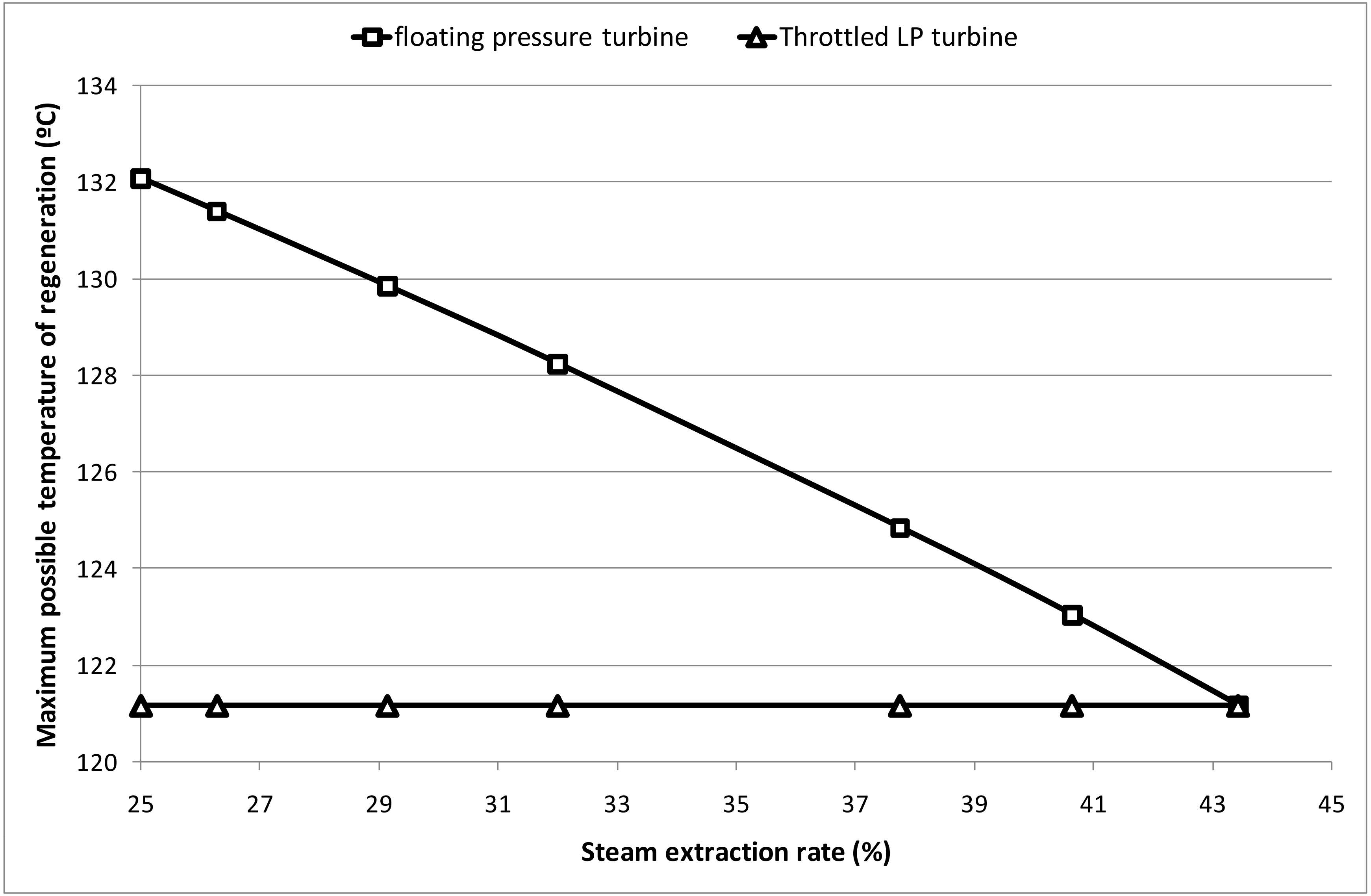
Floating pressure – Valve at LP inlet fully open for base load



Comparison of capture-ready steam turbine options for a range of solvent energy of regeneration – same reboiler temperature



Maximum possible regeneration temperature for solvent with reduced energy of regeneration



Conclusions

- Operating flexibility requires oversizing LP turbine and generator for maximum power output.
- "Aggressive" solvent storage strategy needs oversizing reboiler and compression train.
- For future proof upgrading flexibility steam delivery pressure to solvent reboiler need to be able to change
- Consider floating pressure turbine system for both upgrading and operating flexibility
- Convergence between steam turbine design for capture-ready and new-build units
- Further work needed on compression operation at part-load

Modelling of post combustion capture plant flexibility

Workshop on operating flexibility of power plants with CCS

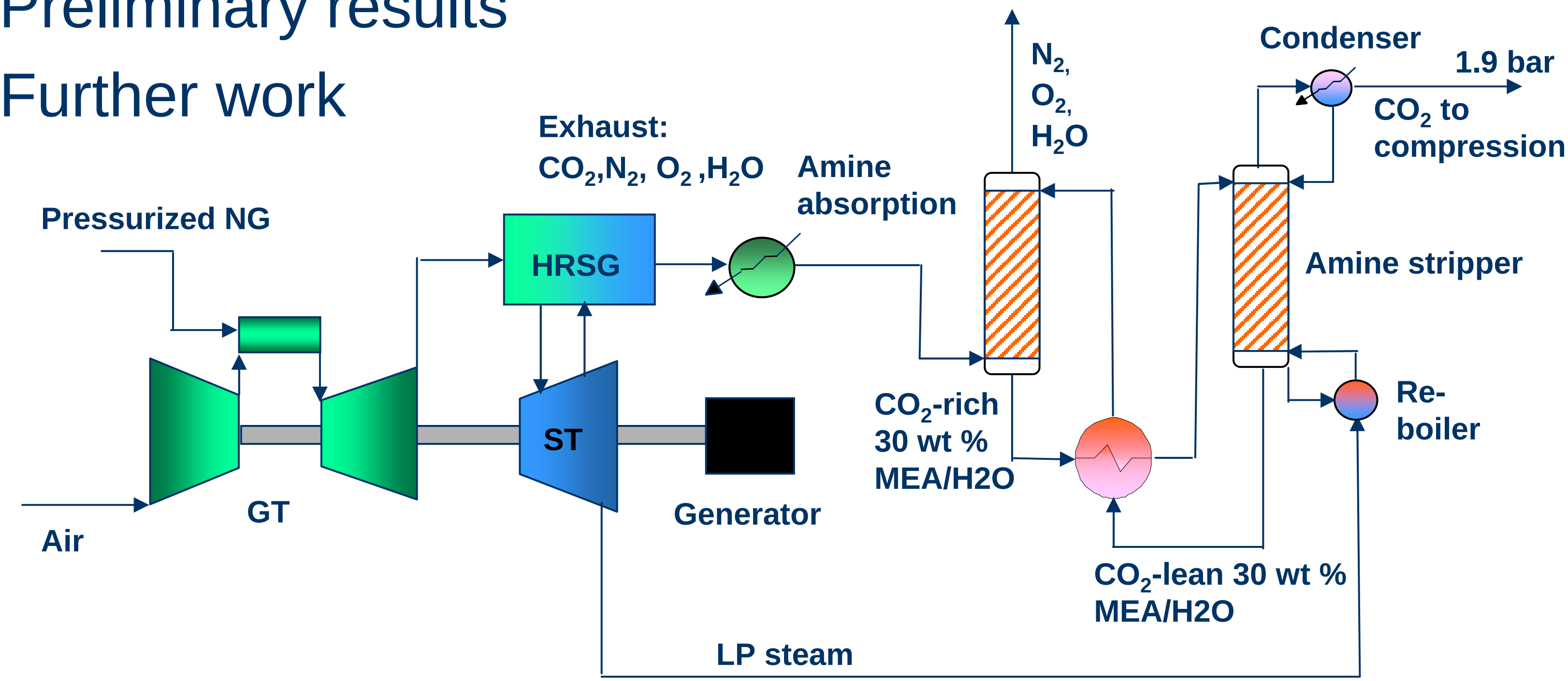
Hanne Kvamsdal

London

November 11-12, 2009

Outline

- Background and motivation
- Dynamic modelling
- Verification/validation
- Preliminary results
- Further work

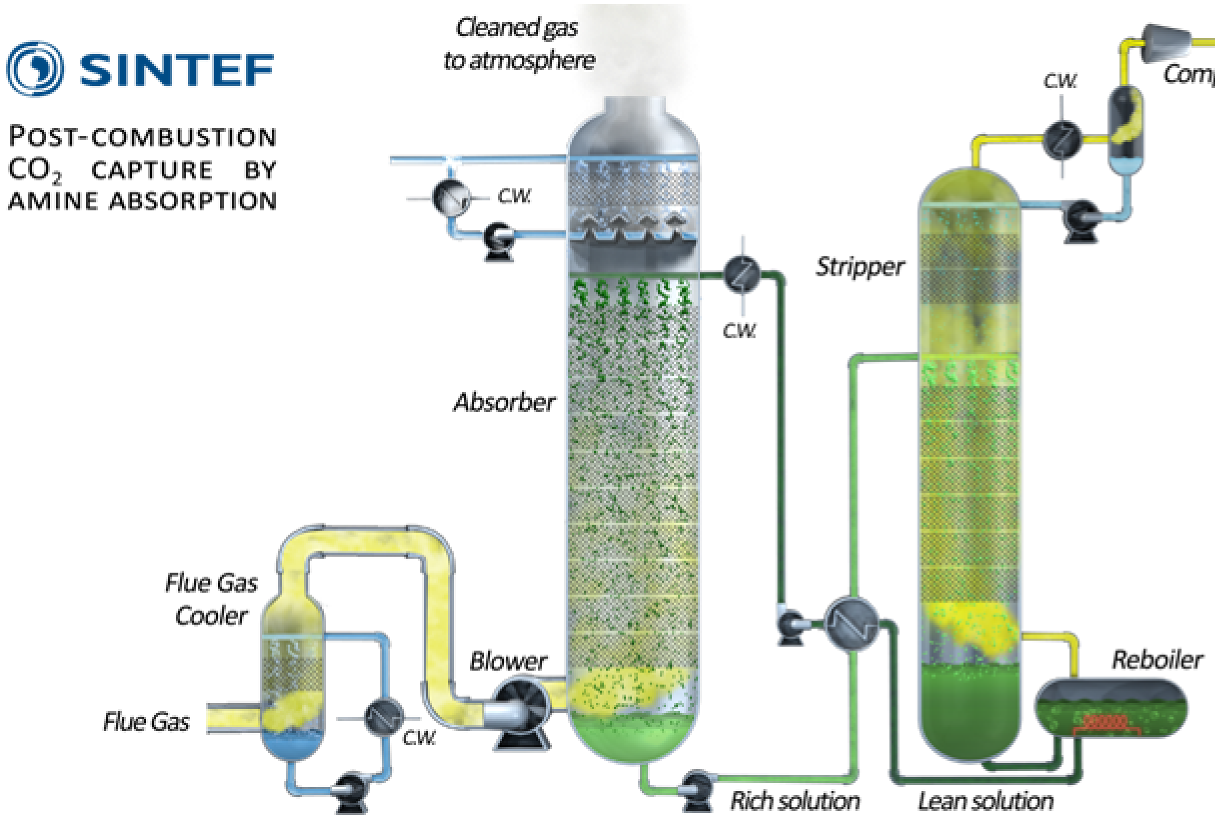


Background and motivation

Dynamic modelling and simulation of CO_2 absorption activities in SINTEF and NTNU

- BIGCO2 – a project started in 2005 as a continuation of a Strategic Institute Project (CO2-SIP) from 2001
  - Dynamic modelling and simulation of CO_2 capture processes from 2001
    - ✓ Fuel cell and membrane-reactor
  - Dynamic modelling and simulation of absorption systems for post-combustion (2005) – co-operation with University of Austin, Texas, group of Gary Rochelle
  - 1 ½ year – to end 2006
    - ✓ Dynamic model of an absorber column in gPROMS
    - ✓ Some initial analyses of start-up and changing load in power-plant
    - ✓ One paper describing temperature profiles in the column and one paper describing the model and the results of the start-up and changing load simulations
  - From January 2009
    - ✓ Revitalise the work from 2005/2006
    - ✓ Includes some master-students
      - – Summer-jobs
      - – Project and master-thesis work
    - ✓ Extra funding (BIGCCS) to include PhD
    - ✓ SINTEF work appr. 1 man-year

Main challenges - steady state



- Heat requirement in reboiler
- Investment cost
- Electricity demand
- Solvent degradation
- Solvent volatility and environmental effects
- Water-balance
- Foaming

Motivation for dynamic modelling and simulations of post-combustion absorption systems (1)

- Absorption systems are regarded as most flexible of all proposed capture processes with respect to operation, but
  - The upstream power plant might operate with a varying load.
    - ✓ The power plant responds very quickly to changes in operating conditions
    - ✓ What about the response in the downstream capture plant?
      - Will non-standard conditions (such as flooding and a higher pressure drop than can be treated by the blower) occur during transient conditions?
        If so, how should the plant be operated in an optimal manner?
      - How will the transient operation affect the water-balance of the system?

Motivation for dynamic modelling and simulations of post-combustion absorption systems (2)

- Absorption systems are regarded as most flexible of all proposed capture processes with respect to operation, but
  - There are no experience with large scale integration with power-plants.
  - The capture plant may reduce the flexibility of the power plant.
    - ✓ Dynamic simulation to identify any operational bottlenecks at transient conditions in the planned integrated plant
  - The absorber/stripper process is complex, optimal design and operation interfere with each other
  - Improvements of the absorption process (e.g. inter-cooling, lean vapour recompression, multi-stage stripping) add complexity
    - ✓ May imply more complex operations
  - In case of bio-fuels and coal-based power plants, the condition of the fuel might vary during operation implying varying flue gas composition

Motivation for dynamic modelling and simulations of post-combustion absorption systems in SINTEF and NTNU

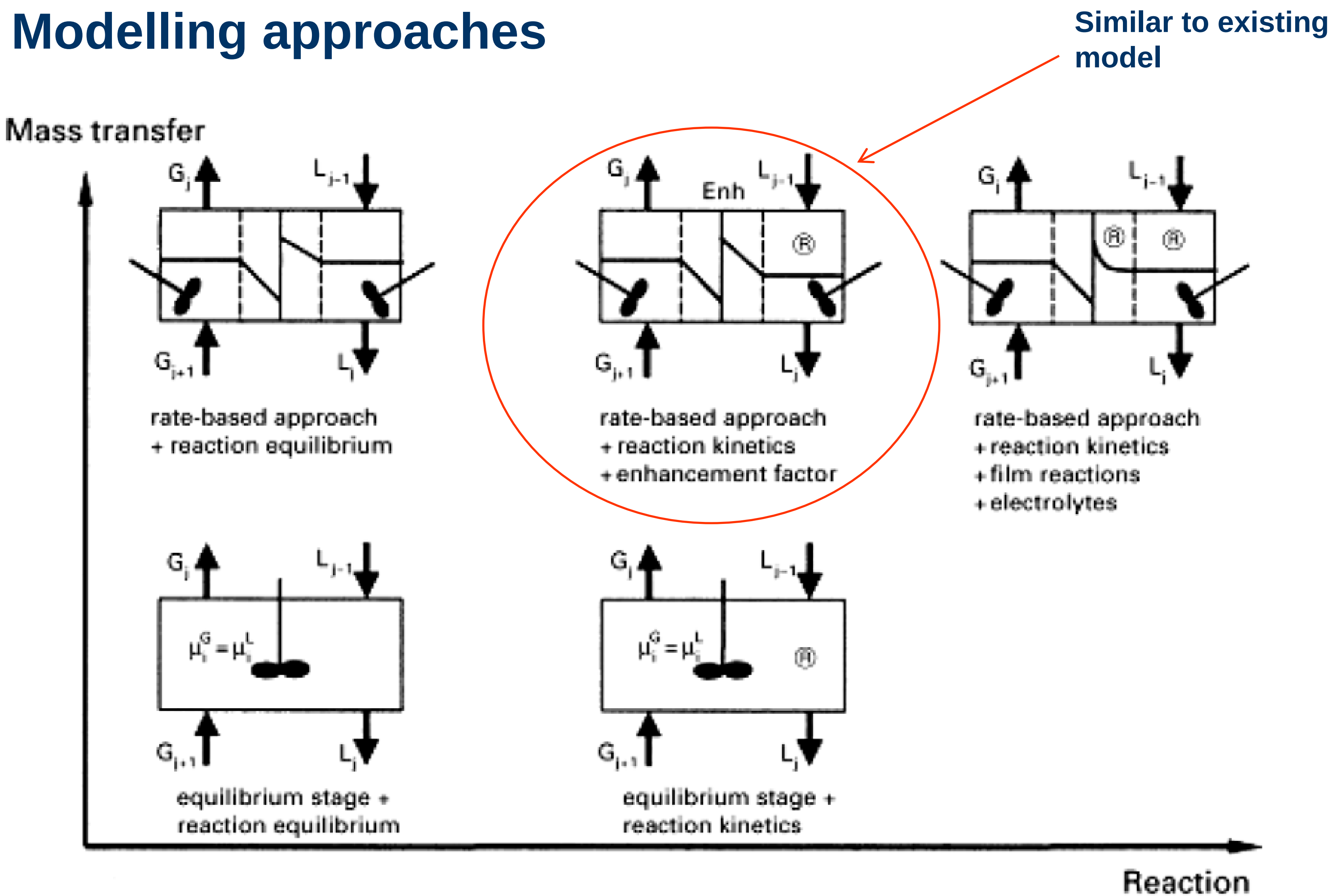
- Main focus development of improved and/or new solvent system and improved processes
- The new solvent systems and processes must perform adequate at transient conditions as well as steady state
  - Simulations (both solvent systems and processes)
  - Test in new pilot plant (is flexible, but not all process configurations can be tested)

Modelling

BIGCO2: Task B: Post Combustion CO_2 Capture
Plans for activity: Process model development and analysis

- Objective (2009-2011):
  - To develop a simplified dynamic model capable of evaluate generic absorption based CO_2 capture processes under transient conditions. Furthermore, it shall be used to develop and assess improved absorption process configuration and it might as well be used to develop a proper control philosophy and system
- Overall plan for 2009
  - The initial work in 2009 will focus on setting up specifications for the model and deciding on the platform. Work will begin on development and implementation of models for different units
    - Started with existing gPROMS model
    - Implementing in Matlab
      - Same framework as in-house steady state tool CO2SIM
      - gPROMS expensive for SINTEF (not NTNU)

Modelling approaches



Source: A. Lawal et al., *Fuel*, in press

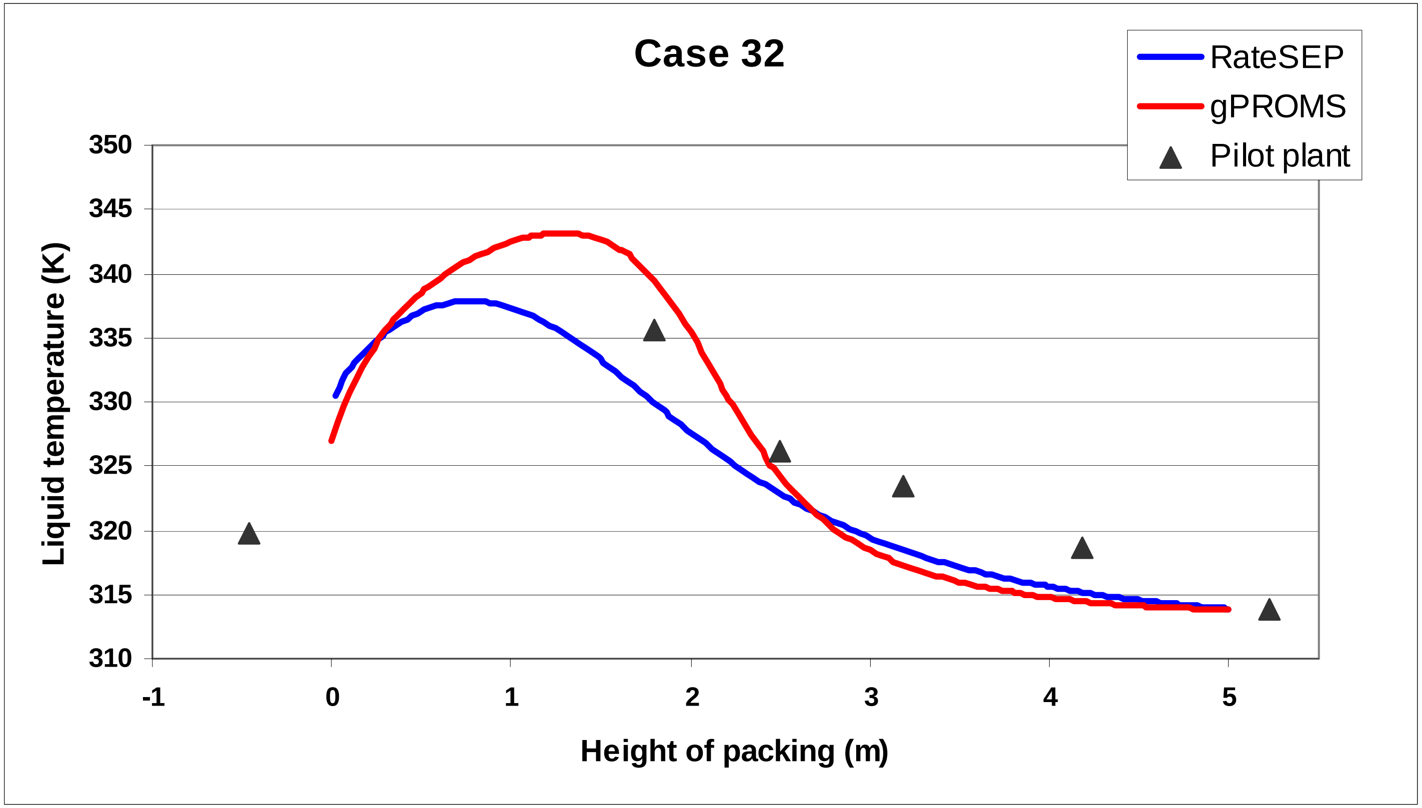
Model assumptions – existing model

- Plug flow regime;
- One-dimensional time-dependent differential mass and energy balances for both gas and liquid phases;
- Linear pressure drop (fixed outlet pressure);
- Ideal gas phase (due to low pressure);
- MEA used as the solvent, meaning that all required thermodynamics are implemented for this specific solvent;
- Rate-based model
- Mass and heat transfer are described by the two-film theory;
- No accumulation in gas and liquid films;
- Liquid film reactions are accounted for as an enhancement factor in the overall mass transfer coefficient;
- Fluxes of CO_2, H_2O and MEA between the two phases are allowed for in both directions;
- Thermal equilibrium is assumed between the liquid and solid phases;
- Water vapor condenses at the wall and at the gas-liquid interface; and
- The packing material specific area is used as the effective contact area between the gas and liquid phases.

Model validation

Steady state

- gPROMS model compared to pilot data at UT
- gPROMS model compared to Aspen Plus, Ratesep model



Steady state – planned model validation

- Matlab model compared to in-house tool CO2SIM
- Matlab model compared to newly updated MEA campaign in lab pilot plant at NTNU-SINTEF as well as new pilot plant in Trondheim

Dynamic model validation - planned

- Possible Cesar Esbjerg plant MEA campaign
- New pilot planned MEA campaign in March/April 2010

Preliminary results

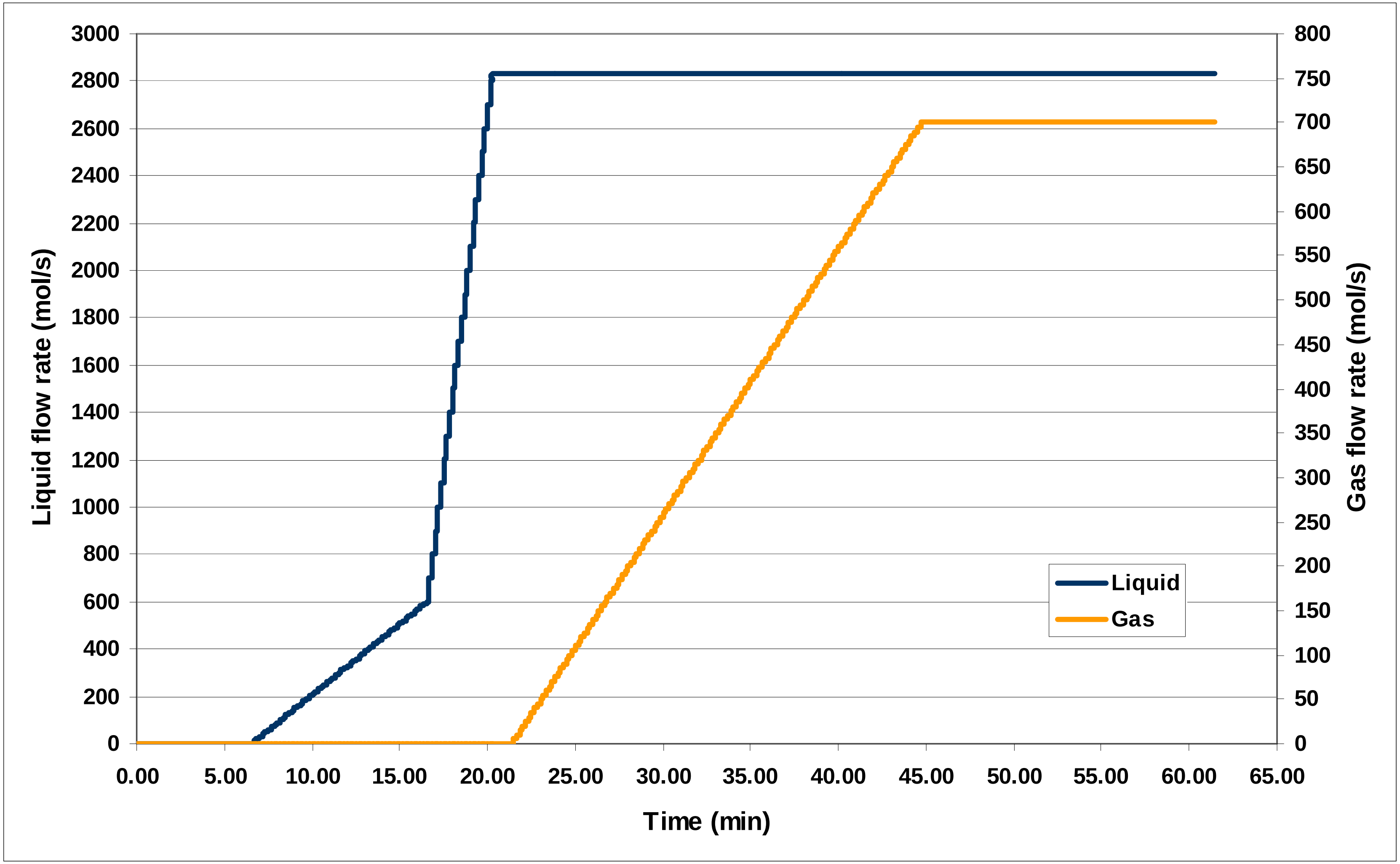
gPROMS model results

- Kvamsdal, H.M. and Rochelle, G.T., (2008), Effects of the Temperature Bulge in CO2 Absorption from Flue Gas by Aqueous Monoethanolamine, *Industrial & Engineering Chemical Research*, vol 47(3), pp. 867-875, (August 2009)
- Kvamsdal, H.M., Jakobsen, J.P., and Hoff, K.A., (2009) Dynamic modeling and simulation of CO2 absorber column for post-combustion CO2 capture, *Chemical Engineering and Processing*, vol 48 (1), pp. 135-144
  - Dynamic simulation
    - ✓ Start-up
    - ✓ Load-reduction

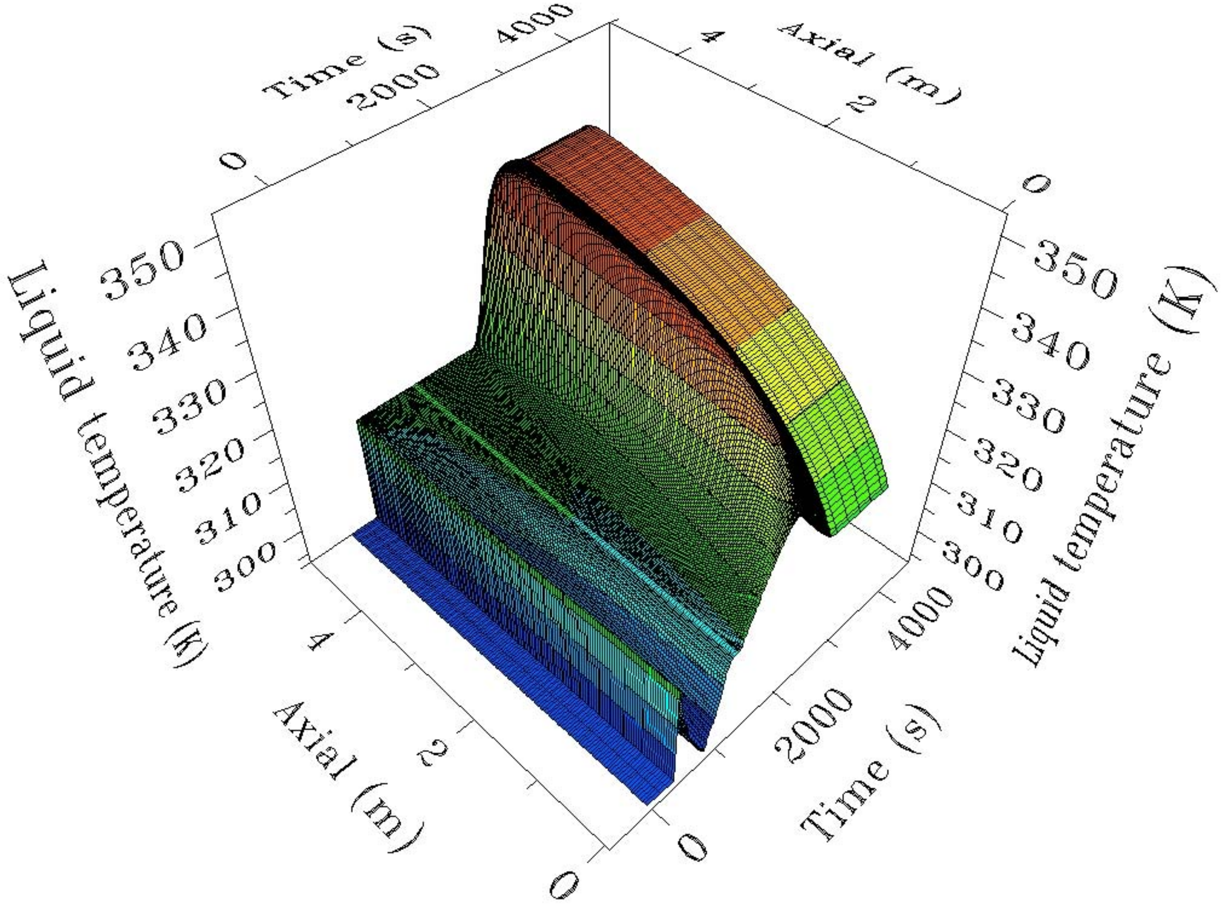
Start-up simulation: Assumptions

- The column at the start of the simulation was filled with air at ambient temperature (293 K);
- The start-up pressure was at atmospheric pressure;
- Heat loss was not accounted for before the liquid was fed into the column;
- In the beginning (before gas was fed to the column) the liquid was fed from a storage tank containing the same amount of CO_2 as under normal operation (same and constant lean loading);
- The liquid feed rate was ramped with an increase of approximately 3.5 moles per second;
- No flue gas was fed to the column before the desired liquid feed rate was approached;
- The flue gas feed rate was ramped with an increase of 0.5 moles per second.

Liquid flow rate and flue gas flow rate during start-up.



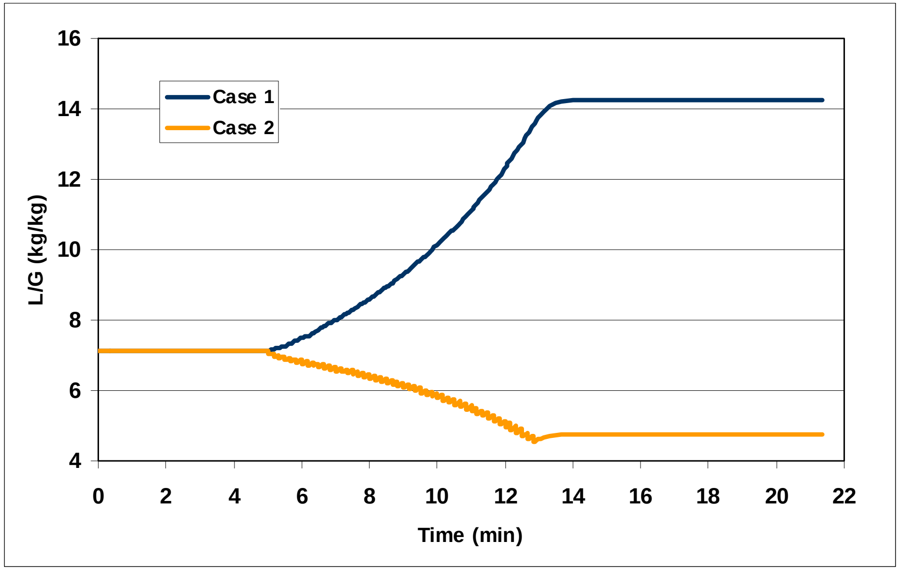
Liquid temperature profiles during start-up



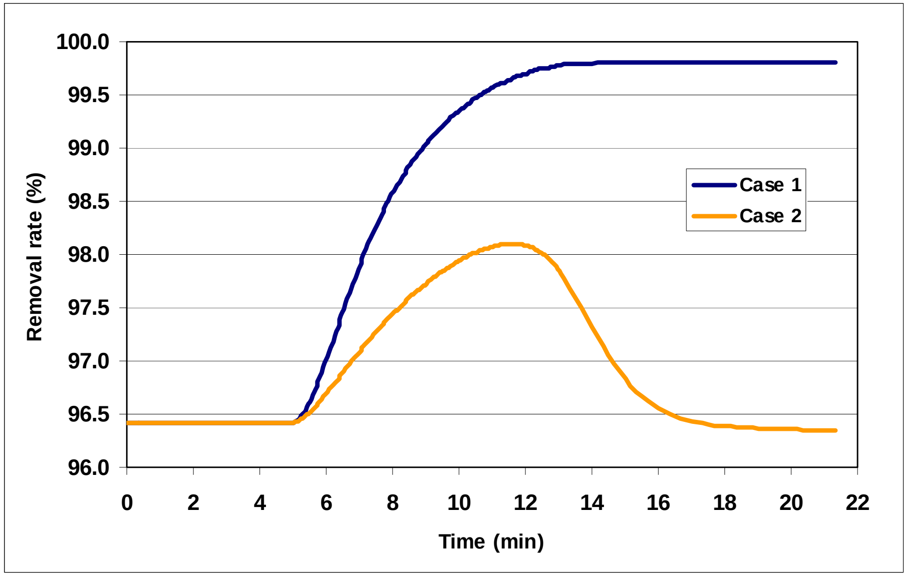
Load-changing simulations - assumptions

- Coal power plant
- Change in load from 100 – 50%
  - Reduce in flue gas flow rate
  - Will affect temperature – but not saturation temperature (constant flue gas composition)
- Included pre-cooler and time delay upstream absorber
- Simulation strategy:
  - 5 minutes at base load conditions
  - Flue gas flow rate to the cooling tower reduced linearly from 300 mol/s to 150 mol/s in 8 minutes
  - 9 minutes simulated to allow the system to stabilize at the new steady-state values
- Two control cases
  1. No reduction in liquid flow
  2. Reduction so that final removal rate same as at 100% load

Change in L/G and capture rate



L/G



Removal rate

Conclusions and further work

Conclusion

- In order to study the effect of transient conditions, the whole capture plant must be modelled
- For integrated processes, other parts should be modelled in the same tool (i.e. the power plant and CO_2 compression), but might require a much simple absorber model
- For plant control and optimisation a much simpler absorber model might be developed

Further work

- Transient validation of absorber model
- Sensitivity analysis of absorber model complexity
- Model development and implementation of other process units in the capture plant
- Validation of capture plant model
- Include other solvent systems in the model
- Connect to CO2SIM (same GUI, but different mode of operation)
- Performance studies as part of development work

Thank you for your attention!

Operability of power plants with CCS

Earlier and ongoing projects at NTNU Department of engineering cybernetics and SINTEF applied cybernetics

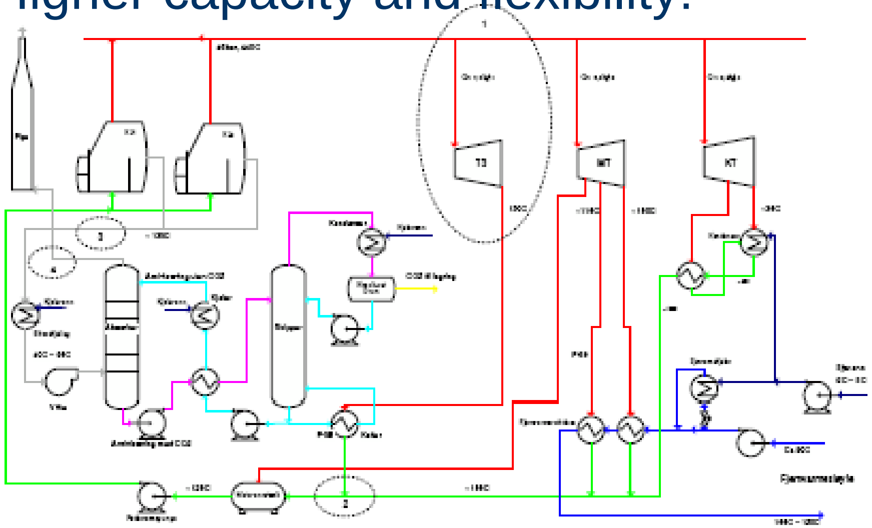
Prof. Bjarne A.Foss, NTNU

Ph.D. student Lei Zhao, NTNU

Finn Are Michelsen, SINTEF ICT

Carbon capture at the coal-fired power plant in Longyearbyen (Svalbard)

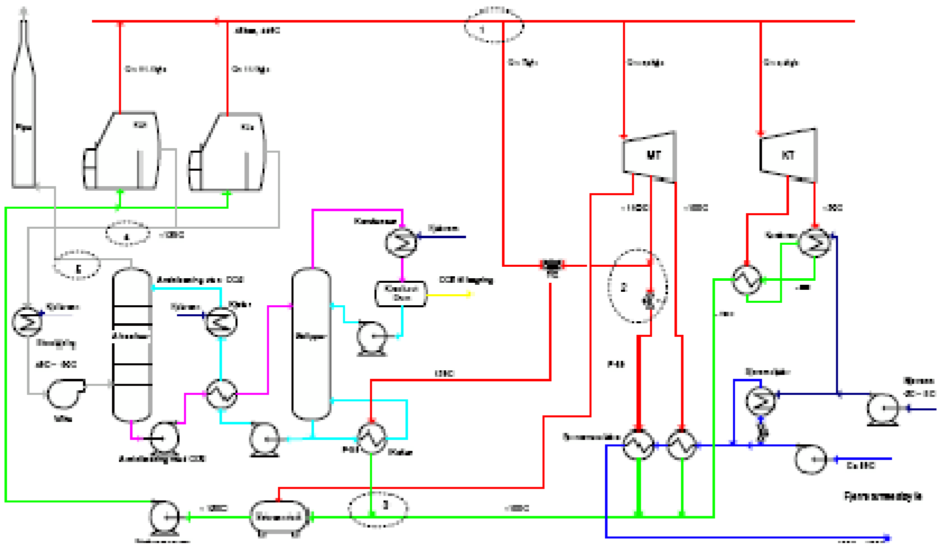
Higher capacity and flexibility:



CO_2 capture 85-95%

Small reduction of efficiency

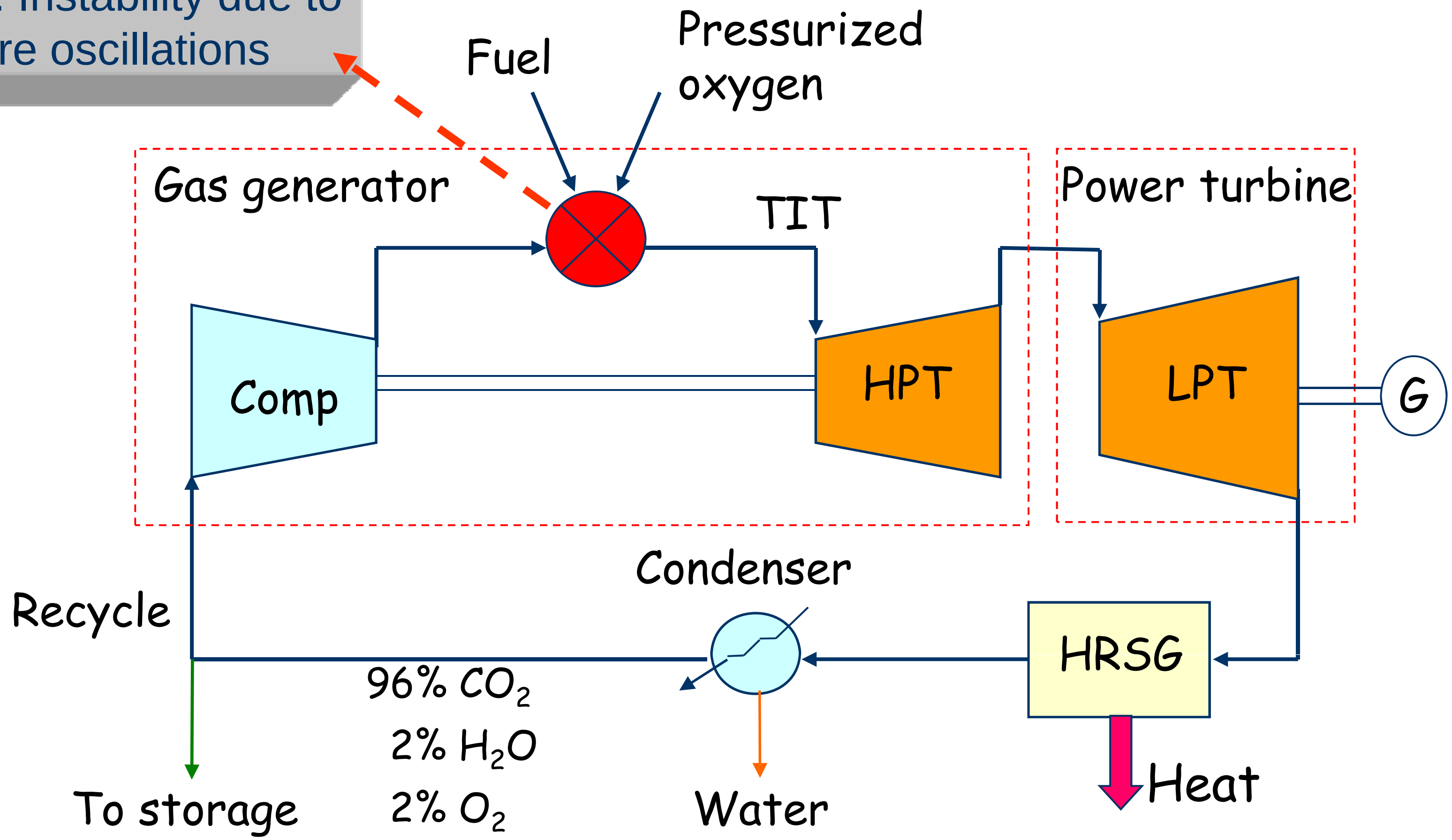
Minimum investment:



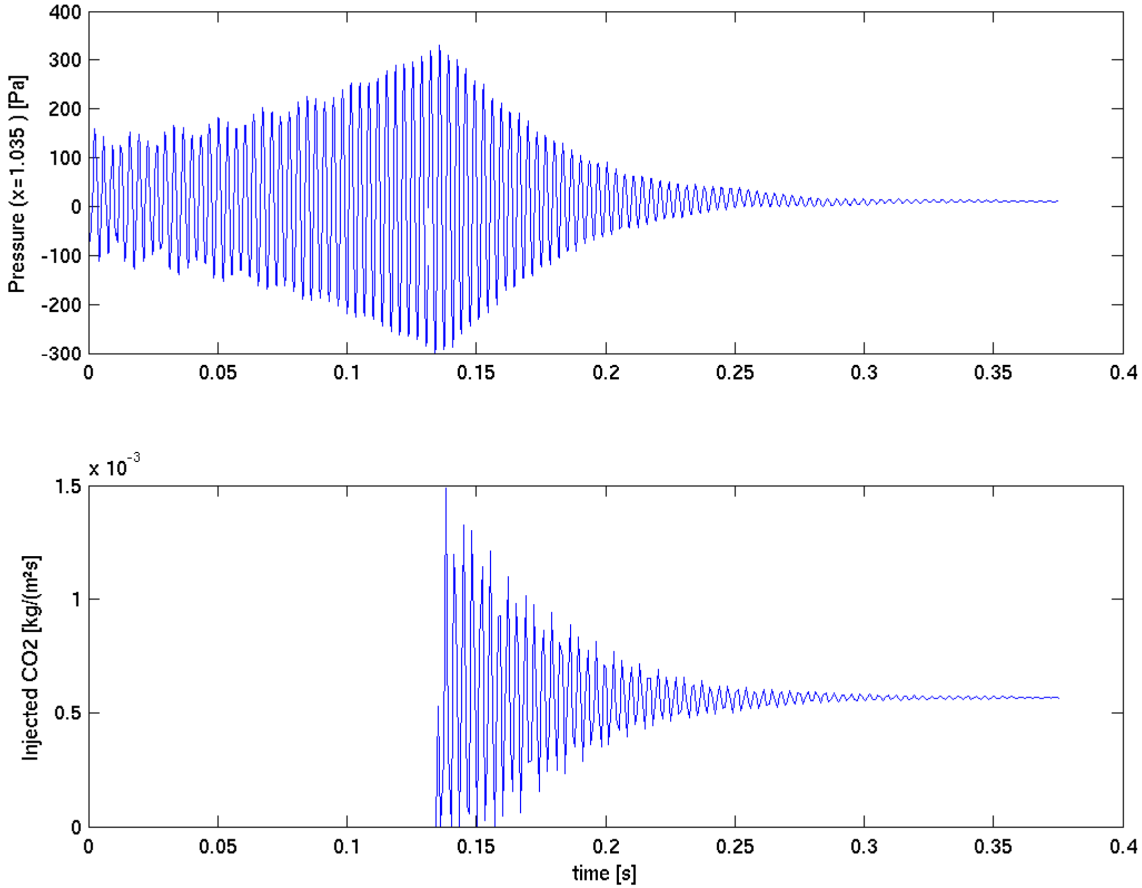
- Master project, Atle Storaker (B.A.Foss)
- Two post-combustion solutions (amine absorption columns) which are integrated with the existing power plant
- Completion July 2008
- In collaboration with professor H. Svendsen, NTNU

Active control of instabilities in oxy-fuel combustion

Challenge: Instability due to HF pressure oscillations

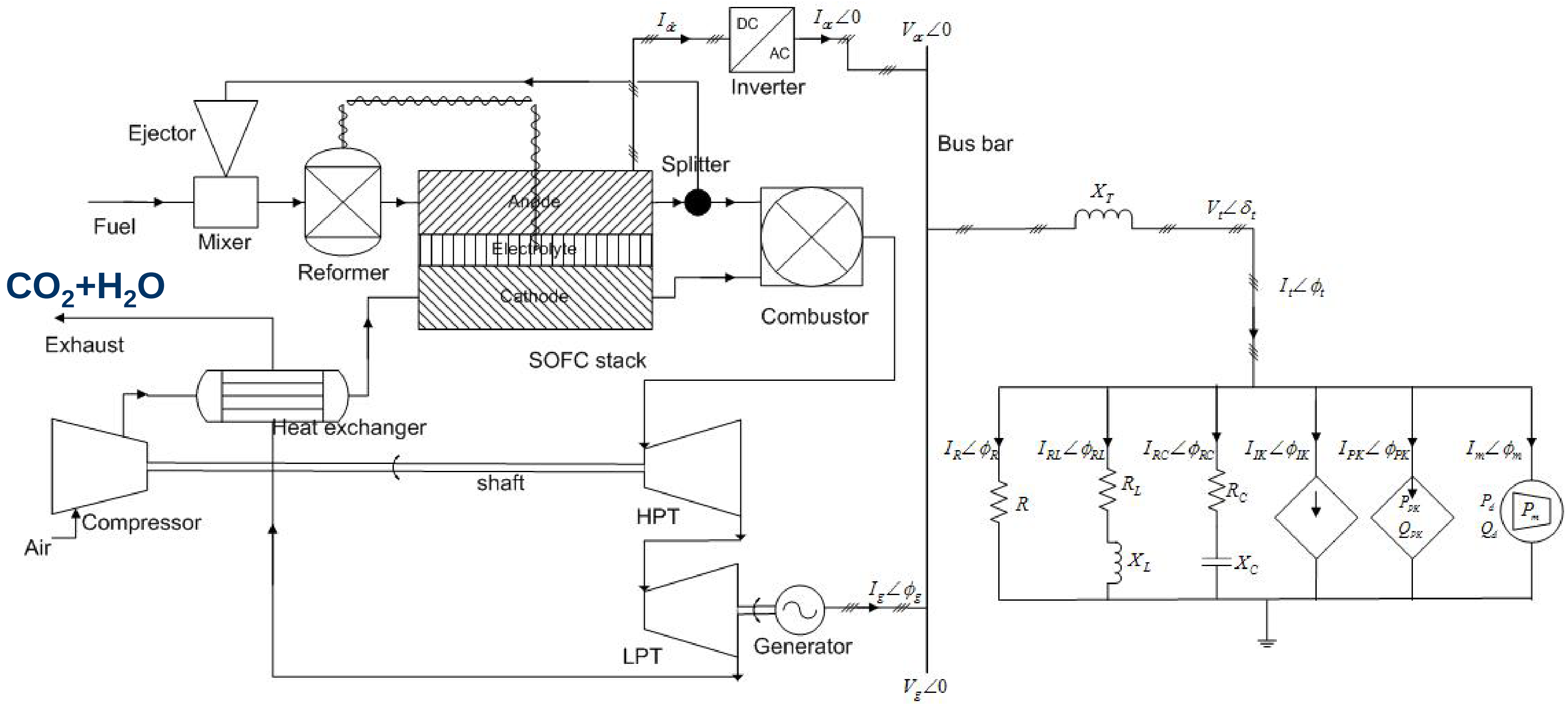


Solution: Injection of CO_2 at the right position in front on the flame



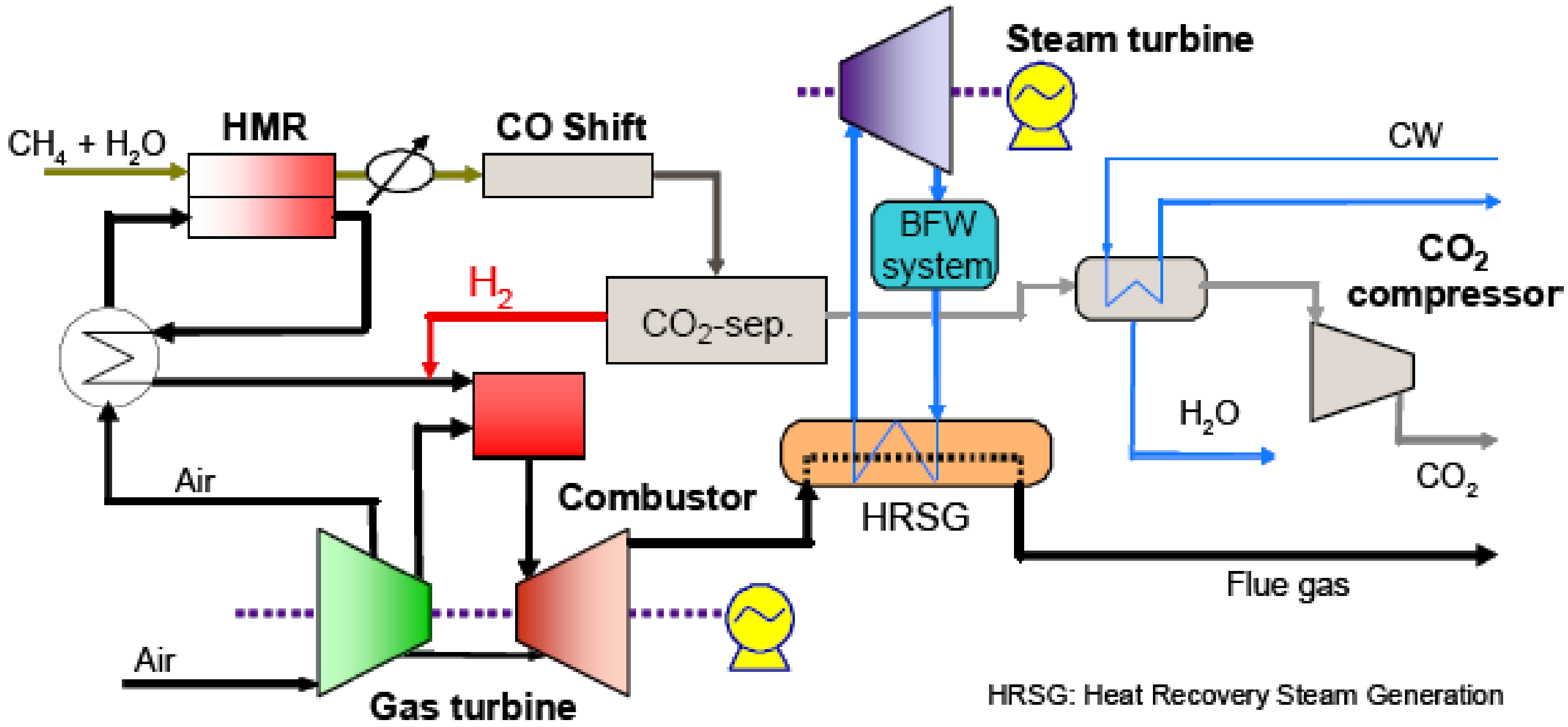
- PhD project, Dagfinn Snarheim (B.A.Foss)
- New low-order dynamic model suitable for control design
- Robust active controller for damping combustions instabilities
- Enabler for active control as a design option for combustion systems
- Completion September 2009
- In collaboration with Dr. Nils E. Haugen, SINTEF and professor Ghoniem, MIT

Control relevant modelling and nonlinear state estimation applied to SOFC-GT systems



- PhD project, Rambabu Kandepu (B.A.Foss)
- New low-order dynamic model suitable for control design
- Control structures for improved transient performance
- New algorithm for online estimation for model-based control
- Completed December 2007
- In collaboration with professor Biao Huang, Univ. of Alberta

Control relevant modelling and control of a HMR reactor system in a pre-combustion carbon capture gas power cycle



- PhD project, Lei Zhao (B.A.Foss)
- New dynamic model suitable for control design
- Control structures for improved transient performance (optimizing operation during startup, shutdown, load changes and disturbances)
- Consideration of CO_2 emission, utility rate of methane, net power output and transition time for load changes etc.
- To be completed in 2011
- In collaboration with professor O. Bolland and H. Svendsen, NTNU and F. A. Michelsen, SINTEF ICT

Common (cybernetic) approach

- Control relevant model
- The impact of process design decisions (sizes, locations,..) on operability, control, process efficiency and carbon capture (and vice versa), e.g.:
  - Active control for stabilization
  - Location of sensors (what to control?) and actuators
  - How easy is the process to control?
- The model for control design can also be used to evaluate more detailed design of process units:
  - Analyse sensitivity from design parameters to controllability
  - Identify critical parameters, e.g. heat exchanger, compressor and turbine sizing.

A systematic procedure for **integrated process and control design** can improve both design and operation. This area should be further explored.