Proceedings from CCS Cost Workshop

22-23 March 2011

CONTENTS

Agenda

DAY 1	22 March
08:30 – 09:00	Registration
09:00 – 09:30	OPENING SESSION
	Welcome: Juho Lipponen, IEA • Purpose and scope of workshop: Christopher Short, Gobal CCS Institute • Introduction of participants (all) • Overview of agenda: John Davison, IEAGHG
09:30 – 11:00	SESSION 1: Audiences and Uses for CCS Cost Estimates
	Keynote: *Howard Herzog, MIT* • Government respondent: Michael Matuszewski, DOE • Industry respondent: Lars Strömberg, Vattenfall • NGO respondent: John Thompson, Clean Air Task Force • Open discussion
11:00 – 11:30	Coffee Break
11:30 – 13:00	SESSION 2: CCS Costing Methods and Measures
	Keynote: *Ed Rubin, Carnegie Mellon University* • Vendor respondent: Jean Francois Leandri, Alstom • Utility respondent: Clas Ekström, Vattenfall • R&D organization respondent: Sina Rezvani, University of Ulster • Open discussion
13:00 – 14:15	Buffet Lunch
14:15 – 15:45	SESSION 3: Status of CO_2 Capture Costs
	Keynote: *Matthias Finkenrath, IEA* • EU respondent: John Chamberlain, gasNatural fenosa • North American respondent: George Booras, EPRI • Asia/Pacific respondent: Li Zheng, Tsinghua University • Open discussion
15:45 – 16:15	Coffee Break
16:15 – 17:45	SESSION 4: Status of CO_2 Transport and Storage Costs
	Keynote for transport: *Per Arne Nilsson, panaware ab* Keynote for geological storage: *John Tombari, Schlumberger* • Transport expert respondent: Alastair Rennie, amec • Storage expert respondent: Wilfred Maas, Shell • Policy analyst respondent: Neil Wildgust, IEAGHG • Open discussion
17:45	DISCUSS PLANS FOR DAY 2
18:00	Adjourn, Day 1
19:00	Reception and Dinner

DAY 2	23 March
09:00 – 12:30	BREAKOUT SESSIONS
	Breakout Session 1a – Capture Costs (Chair: Ed Rubin) *Breakout Session 1b – Capture Costs (Chair: Howard Herzog)* *Breakout Session 2 – Transport Costs (Chair: Per Arne Nilsson)* *Breakout Session 3 – Storage Costs (Chair: John Tombari)* Further discussion of topics presented on Day 1, with focus on identifying: • Major on-going costing efforts • Available costing and analysis tools • Needs for improvements in costing methods, reporting, etc.
10:30 – 11:00	Coffee Break
11:00 – 12:30	BREAKOUT SESSIONS (CONTINUED)
	Discuss need for a CCS costing network • What role would a costing network play? • Who would participate in such a network? • What agenda and structure would be most useful?
12:30 – 14:00	Buffet Lunch
14:00 – 15:15	REPORTS from Breakout Sessions:
	• Capture • Transport • Storage • Open discussion
15:15 – 16:00	GENERAL DISCUSSION
	• Major conclusions/insights from the workshop • Recommendations/plans for follow-up action
16.00	End of Workshop

Participants

Mr. Robert BAILES	Exxon Mobil Corporation
Mr. George BOORAS	Electric Power Research Institute
Mr. Robert BRASINGTON	Massachusetts Institute of Technology
Mr. David BROCKWAY	CSIRO
Ms. Catarina CAVALHEIRO	ENEL Engineering and Innovation
Mr. John CHAMBERLAIN	gasNatural fenosa
Mr. John DAVISON	IEA Greenhouse Gas
Mr. Jean DESROCHES	Schlumberger Carbon Services
Ms. Rosa DOMENICHINI	Foster Wheeler Italiana S.r.l.
Mr. Clas EKSTROM	Vattenfall Research and Development AB
Mr. Nils Henrik ELDRUP	Tel-Tek and Telemark University College
Mr. Richard ESPOSITO	Southern Company
Mr. Matthias FINKENRATH	IEA
Mr. Flavio FRANCO	Power Alstom
Mr. Hans Richard HANSEN	Teekay corporation/Low Carbon Shipping
Mr. Howard HERZOG	MIT Energy Laboratory
Mr. David Richard JONES	BG Group
Mr. Stephen KAUFMAN	Suncor Energy Inc.
Mr. Andreas KOPP	E.ON Gas Storage GmbH
Mr. Jean-François LEANDRI	Alstrom Power
Mr. Juho LIPPONEN	IEA
Mr. Wilfried MAAS	Shell Projects and Technology
Mr. Michael MATUSZEWSKI	US Department of Energy, National Energy Technology Laboratory
Mr. Torgeir MELIEN	Statoil ASA
Mr. Per Arne NILSSON	panaware ab
Mr. Alastair RENNIE	AMEC
Mr. Daniel RENNIE	Global CCS Institute
Mr. Sina REZVANI	Universtity of Ulster
Mr. Richard RHUDY	EPRI
Mr. Ed. RUBIN	Carnegie Mellon University
Mr. Frank SCHWENDIG	RWE Power AG
Mr. Christopher SHORT	Global CCS Institute
Mr. Dale SIMBECK	SFA Pacific, Inc
Mr. Lars STROMBERG	Vattenfall AB
Mr. John THOMPSON	Clean Air Task Force
Mr. John TOMBARI	Schlumberger Carbon Services
Mr. Neil WILDGUST	IEA Greenhouse Gas R&D Programme
Mr. Tsukasa YOSHIMURA	IEA

Introduction

More than 50 studies have been released in the past five years that provide estimates of the costs for operating a carbon capture and storage (CCS) equipped power plant in a variety of regions around the world. There are also many other studies that examine only variants or elements of CCS technologies such as different chemical choices, heat integration issues, retrofits, storage or transport issues or technologies still in the R&D stage.

Some of the variety in cost estimates from these studies reflects the range of technologies selected for capture or particular transport and storage options. However, most of the variance in estimates arises from other factors including differences in methodologies and assumptions for underlying economic parameters. The extent to which the cost and performance parameters are associated with detailed plant designs or whether the study is derived from parameters in previous cost studies also affects estimates. At the same time, some studies do not include all elements for establishing a greenfield CCS power plant whilst others are less than transparent regarding key assumptions.

CCS is one of a number of key low-carbon technologies required to decarbonise energy production this century if the risks of climate change are to be managed effectively. Understanding the current and possible future costs of the technology is important for a number of reasons including amongst others:

- climate and energy policy development;
- raising finance; and
- the allocation of limited R&D budgets.

At the 10th International Conference on Greenhouse Gas Control Technologies in 2010, the need to establish an Expert Group on CCS costs was identified in response to the growing number of reports regarding the costs of CCS. It was agreed that this group should consist of invited members with identified expertise in the various components of the CCS process chain – capture, transport and storage.

An initial Steering Group was formed to organise the first meeting of the group. The inaugural meeting was held on March 22-23 2011, hosted by the International Energy Agency. Steering Group members included representatives from: Carnegie Mellon University (Ed Rubin), Electric Power Research Institute (Richard Rhudy), Global CCS Institute (Christopher Short), International Energy Agency (Matthias Finkenrath), IEA Greenhouse Gas R&D Programme (John Davison), MIT Carbon Sequestration Initiative (Howard Herzog) and Vattenfall (Clas Ekström).

The current understanding of the costs of CCS presented at that meeting and the agreed outcomes for the Group to take forward are included in this document. This work program consists of efforts to improve both the transparency of CCS cost calculations and the broader challenges associated with conveying messages around costs to the broader community.

Figure 1 Attendees at the 1st meeting of the CCS Costs Workshop held at the IEA

Session 1: Audiences and Uses for CCS Estimates

The workshop was used to highlight the wide array of both generators and users of CCS costs estimates and the distinct needs and aims of these two types of entities. These groups include the government, industry, and various other non-governmental organizations (NGOs). The generated CCS cost estimates that are typically used for two broad purposes. The first is for technological assessments in an effort to allocate investment and research and development funding; the second is for policy assessments that are used for regulatory, legislative, or advocacy purposes.

The diverse groups and purposes for CCS cost estimates create a tension between the generators and users of the content. Each distinct audience of the cost estimates is evaluating the information from different perspectives and from different agendas, while the generator of the content is also trying to fill a knowledge gap for a particular purpose. This makes the ideal goal of using a common language and message difficult to achieve. If a common framework, methodology, and terminology is established, then the differences can be elaborated in a clear manner.

Within different CCS cost studies there is uncertainty, variability, and bias that is often not presented or explicitly stated with the publication of the estimates. This makes comparison across different studies both within the same type of technology and across other low carbon technologies difficult. The uncertainty of the costs of CCS technologies is never explicitly stated with the results. Variability across regions, even within specific country boundaries, and different time frames make direct comparisons difficult. Bias is often perceived with costs estimates as the generators of the content have a vested stake in the deployment of such technologies. For example, in comparisons of low carbon technologies, bias can be introduced because analysts may believe there is bias, whether perceived or real, in the cost data of competing technologies. The goal is to achieve consistency across all of these considerations for costs estimates.

Some of the other variables that were highlighted during the workshop included:

- There is a perceived high variability in the content contained within the generated cost estimates for the investors and the utilities when compared to those supplied to the regulators and public. Explaining the context of these numbers will help to reduce the uncertainty of the public.
- The difference between top-down and bottom-up estimates differs greatly. The top-down estimates often incorporate estimates from different sources. This presents a problem for the consistency of these types of generated numbers.
- There is high variability in the cost estimates given the location, coal type (coal is often perceived as a uniform substance), labour productivity, construction schedules, and currency denominations.
- Organizations often role out different CCS cost estimates without explaining the reason for change or the context of the numbers. This also adds to the uncertainty of the public in the legitimacy and accuracy of these estimates.
- China likely offers opportunity for cheaper costs for the deployment of CCS. hese projects could be used as feedback for other worldwide costs and encourage development of West-China partnerships for CCS.
- General studies are not the same, nor intended to be the same as specific studies. The variability of assumptions, such as the role of first-of-a-kind projects to reduce risk and Nth-of-a-kind projects to reduce costs, are often not articulated in the context of the study. This relation of costs to technological readiness needs to be clearly stated.

The idea of establishing a commonality between the assumptions and the way the assumptions are presented within the context of the CCS costs estimates was clearly stated as a goal of the attendees of the workshop. While one often focuses on the specific audience of a particular study, one has to be cognizant of the larger audience that will use these numbers presented. Assumptions and the uncertainty associated with those assumptions should be clearly stated when publishing these numbers to make the numbers understandable to the wider audience.

Session 2: Methods and Measures for CCS Costs

This session included presentations that demonstrated the different methods used for CCS cost estimates and the typical reporting measures used. The methods that derive the estimates vary in time, cost, and detail. They can range from simply asking an expert for an estimate to commissioning a detailed front-end engineering and design (FEED) study. Even though these studies differ greatly in the amount of resources used to arrive at a cost number, they are often reported with the same level of confidence and with no explanation of the uncertainty or variability of the estimates. Organizations have also developed their own methodology to develop these estimates that often result in significant difference that are independent of the methodology of other organizations. This leads to high variability in the assumptions used and the estimates reported.

There are many factors that affect the outcome of CCS cost estimates. Some of these factors are the type of capture technology, difference in various process design parameters, the boundary conditions of the estimates, and the time frame of the estimates. These different factors often take on different assumptions between studies, but ultimately are used to produce similar measures. These similar measures are often, but not limited to, CO_2 avoided cost, CO_2 captured cost, added cost of electricity, capital cost, and dispatch (variable) cost.

Due to these similar metrics with variable assumptions, reported numbers often differ across studies. These assumptions can often lead to uncertainty, variability, and bias within the costs estimates. By understanding these concepts and the variability of assumptions, a framework can be established and similar methodologies can be used to communicate CCS costs consistently and transparently.

Some of the other variables that were highlighted during the workshop included:

- Measures, such as CO_2 avoided costs, are based on a reference plant. The results are highly sensitive to the reference plant that is used. Consistency of this reference plant is often complicated as the electricity sector is undergoing a transition, such as more natural gas combined cycle plants being built, or in cases where no reference plant may exist (i.e. IGCC without CCS).
- There are many different ways to report what may seem to be a singular measure, such as the cost of electricity (COE). A first year COE, and year by year COE, or a levelized COE demonstrate how many different parameters and the ultimate measures used can influence the different ways of reporting the cost of CCS.
- The context of system wide costs and singular plant costs are an important factor when presenting CCS estimates. The variable costs will often demonstrate the option value of the technology within a system, while capital costs or levelized cost of electricity is meant for comparison of single plant options.
- Terms such as owner's costs encompass no consistent set of categories but are often reported as being the same concept across different studies.
- Key parameters of interest should be highlighted and presented in the context of the report. This will enable the audience to capture the magnitude of the affects of these parameters on the overall numbers.

The true costs of a CCS plant are yet unknown as there has been no commercial scale plant built. This demonstrates the need for CCS cost estimates to have a consistent methodology and measures of reporting across organizations so that the data is understandable to the audiences. The gaps in methodology must be identified so that this common framework may be established. When there are justified deviations from this common methodology, a credible storyline should be established with assumptions clearly stated. The message from this session and the previous session are consistent in the call for commonality in generation of CCS cost estimates so they may be used in a consistent manner. This will ultimately lead to a reduction in the uncertainty, variability, and bias of CCS costs estimates.

Session 3: Status of CO_2 Capture Costs

The session opened with the results from a comparative study undertaken by the IEA, published in March 2011, evaluating cost and performance trends of CO_2 capture. This was based on extensive analysis of data from major engineering studies published between 2006 and 2010. This working paper concluded that the absolute costs have been found to vary significantly, whereas the relative increase in costs compared to reference plant have been found to be largely stable. While this was a conclusion that appeared to be supported by the other presentations, there was also an extensive discussion on the use of reference plant data itself – including the need for the consistent and transparent use of the assumptions and variables.

A number of the presentations during the workshop considered the published cost estimate data, and in investigating the causes of some of the core reasons for the large variations in absolute cost estimates (and the variance of estimates against real cost), a number of causes were identified. It was suggested that the variation seen was primarily due to a number of key variables and assumptions used when calculating costs – many of which were not clearly articulated. The discussions following the presentations also stressed the lack of transparency and clarity in the publicly available cost estimates. While calling for complete openness when considering such data, the participants of the workshop also highlighted the need for a harmonisation of costing methodologies, terminologies and underlying assumptions.

An interesting comparison was also made between a public cost estimate and the real costs experienced by an IGCC plant. A wide variance was shown, with cost of $4.660/kw comparing to the study's expected $2.600/kw. It was found that again assumptions differed – including fuel type (in this case the grade of coal), engineering costs, interest during construction, owner's costs, etc. – as did the cost components. In particular site costs were not included. This again stressed the need for a consistent use of categories, and assumed parameter values.

Some of the discussed key causes of variance in capture cost estimates (in terms of variables and assumptions) included:

- Design & Technology

Fuel type, fuel quality, plant design, plant efficiency, new vs. retrofit projects, site conditions, CO_2 quality, capture rates and efficiencies, compression requirements, capture penalties, labour costs, merit order of the plant, boundary of 'capture', plant operating flexibility, boundary and scope.

Retrofitting cost estimates may be problematic for a number of reasons, including the scope of such projects (i.e. whether a new boiler is required etc.), and the used assumptions may also vary depending on what is considered as part of the costs.

- Financing

Investment costs, fuel price, reference year, plant life, use of cost curves, operational regime, merit order and operational hours, other M&O assumptions, site costs, interest, discount rates, overnight costs, currency and date.

- Location

China was found to have about half of some costs reported in OECD countries, but there have been few broader studies of costs in China or other non-OECD countries.

- Politics

That if CCS was mandated there would not be such a 'padding' of the figures in order to mitigate against uncertain climate policies. Equally retro-fits costs are going to be different for regions where it is obligatory for new plant to be CCS Ready.

- Metadata

It was also noted that it was particularly important to be transparent over the assumptions and cost used – as most of them will change over time. Therefore, metadata (or more specifically metacontent) should be consistently and transparently used – such as the reference year for costs.

- Transport and storage

While not addressed during the capture session, the capture cost estimates also assume that there are adequate and available transport and (possibly multiple) storage solutions. If there are not then the costs will vary substantially.

- Timing

Having controlled for all power station cost variances there was still evidence of cost differences of 30% which was attributed to contracting and market price volatility.

Building on the above issues that were identified, it was expressed by some of the attendees of the workshop that there was a need for a ‘universal’ list of items that should be included in a cost model – while it was also acknowledged that some of the above parameters had a larger influence on the variation seen between models than others (location, fuel cost, overnight cost and discount rates in particular).

Given the large number of cost elements identified that could result in substantive variations in cost estimates for public use, it was primarily felt that there was a need for public cost estimates to have complete transparency regarding the data and assumptions used, preferably in a consistent way. Ultimately, it was felt that the variations seen in public CCS capture costs could be minimised if there was a consistent use of metrics, terminology, and cost elements.

Session 4a: Status of CO_2 Transport Costs

The presentations given during the session concluded that while there were a variety of methods for assessing transportation costs, including bottom up and top down, the costs were largely known and understood. While there can be a high degree of difference between costs, these were based on a high level of cost component certainty – and are largely dependent on source location, transport type, onshore verses off shore pipeline, distribution, and storage sites. It was suggested that within Europe the transport costs for the complete CCS chain were around 7 – 12 per cent of capture costs. Nevertheless, some key items were raised in regards to the assumptions used when creating CCS cost estimates for CO_2 transport – that should be considered and made transparent when used for public consumption.

The optimal costs for pipelines were based on sufficiently sized networks with shared access. Simple single source to single store systems may be relevant for quoting CCS costs for a single integrated CCS system, but were proportionally much more expensive. In particular it was pointed out that there was no second chance for a pipeline network, and that with significant upfront investment an undersized pipeline route could not easily have its capacity increased. Simple point to point CO_2 pipeline costs may therefore not be realistic.

Economies of scale hold particularly true for transport. Many of the 'CO_2 transport costs' that are quoted within public CCS cost estimates are based on optimised network infrastructure – but which may not be relevant to higher project specific CCS costs estimate. Such optimised cost estimates will be based on large-scale networks with low amortised capital costs, and may become regulated monopolies. As such, project costs may only see the tariffs associated with CO_2 transport rather than direct or amortised costs.

Networks with multiple sources and multiple sinks provide the highest level of risk mitigation and most optimal cost per tonne of CO_2. These costs are therefore very sensitive to the assumptions used regarding the availability of CO_2 from multiple sources and the availability of storage sites. Questions (and therefore assumptions) regarding the merit order of the CCS capture plant, and the volumes of CO_2 available by time were therefore raised.

Timing and volume ramp up issues (and assumptions) are other issues regarding pipeline transport costs, as with a large scale network the cost per tonne of CO_2 will be significantly higher in the first year of operation (around 45 euros) than in the 10th year (around 5 euros) due to the ramp up in CO_2 availability associated with the Network of generators.

It was stressed that shipping represented an alternative option for CO_2 transportation over certain distances, which could also de-risk early projects. While there was less of a discussion regarding the issues and assumptions used for calculating shipping costs, assumptions and variables included: the need for liquefaction (assumed to be around 5 euros t/CO_2), distances, capital investment in the ships themselves, and temporary storage when necessary.

For both pipelines and shipping, battery limits were again addressed as an assumption. If transport costs are going to be considered completely separately from 'capture' then consistent pressure, compression and other process assumptions need to be made which would differ from reality.

Session 4b: Status of CO_2 Storage Costs

The CO_2 storage workshop again revealed a high level of variance in the estimation of CO_2 storage costs. Some numbers included a range of 1 to 20 euros per ton.

The primary causes of this large variance was due to the different type of storage site considered, the size of storage site, number of storage sites (per 'project'), uncertainty and variability of geophysical characterization of certain types of site, and large regional variances. It was stressed that any cost estimate must clearly articulate the assumptions used regarding these primary parameters.

In particular it was pointed out that the cheapest forms of storage were also the rarest. Costs will vary greatly depending on whether long term storage sites are chosen for a 'CCS cost estimate', with far higher costs associated with them and which may be part of a network of sites– or whether a single cheap storage site is used (for a limited time).

Some of the other variables that were highlighted during the workshop included:

- The question of exploration costs and site failures, in relation to 'CCS costs', was highlighted during the workshop. Should a significant amount of effort be made in investigating failed sites, then the costs associated with that work should be reflected in the 'cost' of a successful storage site. The number of investigations and their costs (or not) is another set of assumptions that needs to be made and illustrated in any cost estimation.
- The method of cost calculation tended to be project-based, though it was highlighted that the cost also varied due to the risk appetite of the operator (as if there is a low risk-appetite extensive pre-final investment decision work is undertaken, increasing the overall cost of successful sites).
- Liability will take very different forms and levels, depending on the regulations and CO_2 costs per region. Property and ownership costs will also vary significantly.
- As noted in the transport section, individual project 'CCS' costs should consider the tariffs that may be associated with CO_2 storage – given that this may also be a regulated monopoly. Such tariffs would also include the issues of ownership and liability.
- Like the CO_2 transport costs, assumptions for the cost of storage are also made about the availability of CO_2 from capture plant(s) and the ramp up in availability.
- Other assumptions need to be made regarding CO_2 storage, including project financing issues such as the time and cost of permitting, and whether certain costs should be treated as operational or capital expenditure (and when).

Therefore, although component costs may be known with some degree of accuracy – the regional differences and the assumptions made will have a huge impact on the resulting 'cost' of CO_2 storage. This again supports the call for there to be a unified and transparent set of assumptions that are used when relating CCS costs.

Breakout Session 1A: CO_2 Capture Costs

Session Chair: Ed Rubin; Rapporteur: Chris Short

On the 2nd day of the workshop, participants split into smaller breakout sessions in order to further discuss topics presented on Day 1 and identify needs for follow-up activities and potentially a CCS costing network.

Breakout Session 1a focused on costs for CO_2 Capture. As CCS is considered a moving target as elements of the technology are in development, the breakout group raised a number of concerns relating to existing cost studies including:

- That underlying elements in the cost accounts can vary widely
- That transparency is lacking in many models
- That the purpose of the model needs to be understood:
    - Is it concerning current costs?
    - Is it concerning future costs?
    - Is it a cost minimization approach by design?
    - Is it a best performance design?
- In what context is 'cost' used – market price? Negotiated price?
- That CCS is a moving target as elements of the technology are in development

With regard to improving the approach, questions raised including:

- Can we design a standard model (that is standard performance parameters) against which to identify the range of subsequent cost estimates?
- Is there a desire to establish a Costing Network where different models can discuss the range of costs?
- Could such a group do a better job of cost aggregation regarding:
    - transparency; and
    - standards.
- How could the group contribute to improving the information conveyed to policy makers?
- How can modelers better incorporate the variability into large scale policy models?
- Is there a desire/need for a public model(s)?

Overall, it was the group felt a costing network would be useful particularly if it could assist in developing an appropriate approach and guidelines. Areas for improvement included sensitivity analysis, and how to incorporate uncertainty for unknown technologies (eg membranes) vs established technologies (such as amines). Issues around consistent nomenclature, as well as what is and isn't included in studies.

The group put forward the recommendation that a Costs Network is desirable with the aim of improving consistency and transparency in methodology. This was further defined as:

- Achieving consistency by:
    - Identifying a consistent and complete set of cost elements:
        - nomenclature and definitions;
        - aggregated and disaggregated; and
        - incorporating refinements in T&S costings into an integrated CCS cost analysis.

- Improving transparency
    - Establish standards around what is reported in studies, for example;
        - years, and rebasing approach (cost indexes, actualisation); and
        - real/nominal (constant, current).

The agenda proposed for the Costs Network included:

- develop costing guidelines;
- develop common/public modeling tools;
    - What public tools currently exit? how to improve them?
    - What new tools need to be develop?
    - Scope to identified: cost, performance?
- Characterising variability and uncertainty:
    - especially for developing processes (pre-commercial technologies); and
    - incorporating variability/uncertainty into broader policy/climate/energy models.
- Stakeholder communication challenges need to be considered.

Breakout Session 1B: CO_2 Capture Costs

Session Chair: Howard Herzog; Rapporteur: Matthias Finkenrath

Breakout Session 1b focused on costs for CO_2 Capture. The breakout group discussed several areas related to CO_2 capture cost estimation that could be of interest for future work:

- Work towards developing a common terminology and framework for cost estimates, at least for aggregated cost figures, using consistent boundary conditions
- Develop a recommended methodology and improve understanding on specific issues, e.g. how to best escalate costs of previous studies.
- Improve the understanding of regional differences in cost estimates in terms of cost structures across globe; gather additional cost data also for emerging countries.
- From a site- and project-specific perspective, improve the understanding of the breakdown of cost estimates and specific uncertainties (including e.g. cost of permitting).
- Improve communication of cost estimates and their characteristics to policy makers, considering differences between costs for CO_2 capture in the near- and long-term, and between regions.

In addition benefits of establishing a CCS cost network were discussed. It was concluded that a network between CCS cost experts would be useful for information exchange. Ideas for related activities included addressing the lack of common terminologies and methodologies, improve general understanding of costs and work towards best practices or guidelines, as outlined above. A network could help to collect and organise relevant studies and information, and to communicate the current status of CCS costs more clearly. Future activities could include identifying gaps in knowledge, peer review cost evaluations and relate costs to technological development status and challenges.

A broad range of potential members was identified in the context of a CCS costs network, such as the power, oil and gas industry, equipment manufacturers, academia, NGOs, engineering companies, governments and other energy-intensive industries. Membership could be based on application process during which interested parties would need to describe what they could bring to the table as input to the network. Institutions such as the IEAGHG Implementing Agreement or Global CCS Institute were suggested to manage the network, guided by a steering committee and supported by working groups on specific subjects.

Appendix A

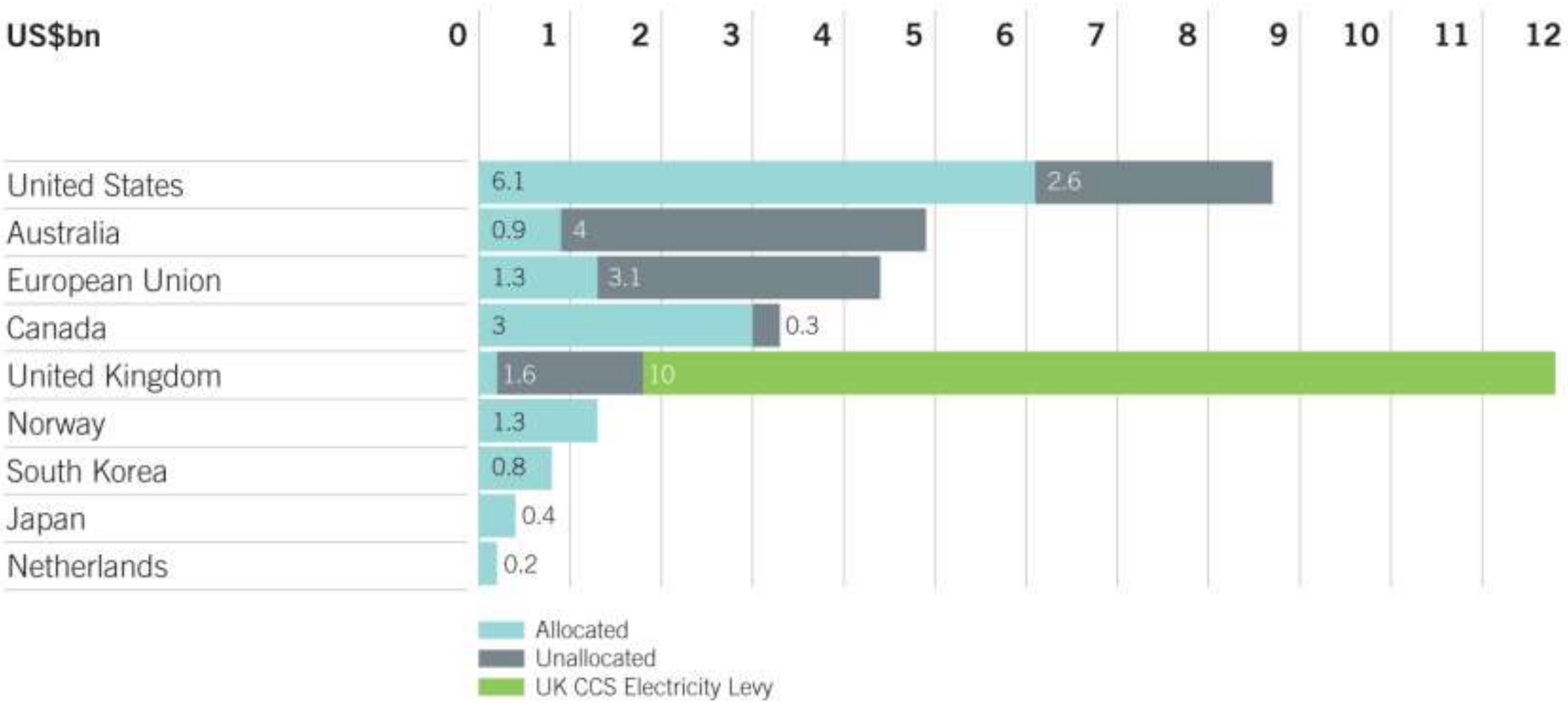
The following presentations from the workshop feature in the order they were presented.

Costs – what are they needed for?

Christopher Short

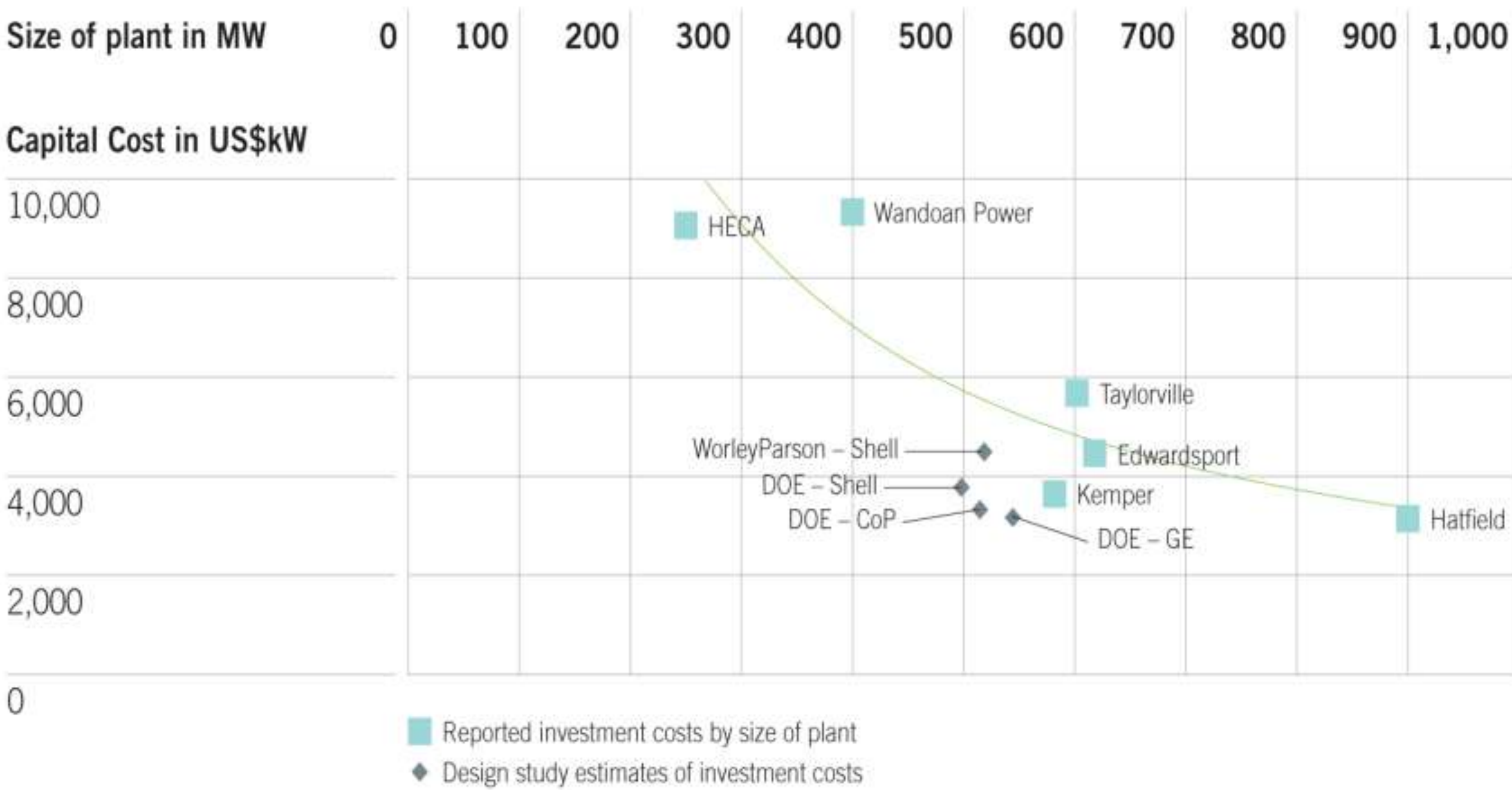
CCS Costs Workshop

Public funding commitments to CCS by country

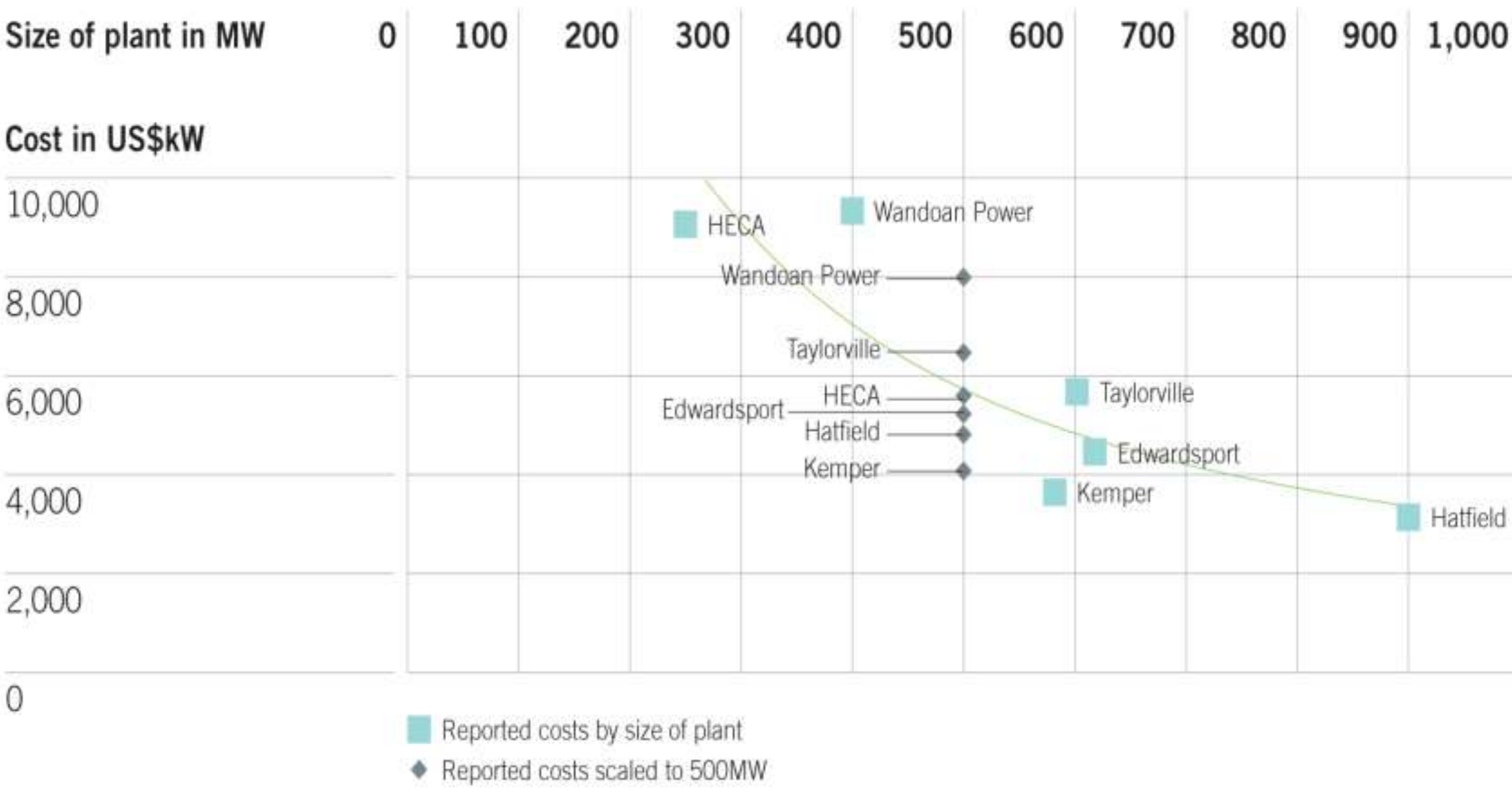


[10] The United Kingdom CCS Electricity Levy's value used in this figure and subsequent quantitative analysis is GBP6.3 billion (US$10bn), which is the midpoint of the estimated range of GBP5.6 billion (US$8.8bn) to GBP7.1 billion (US$11.2bn).

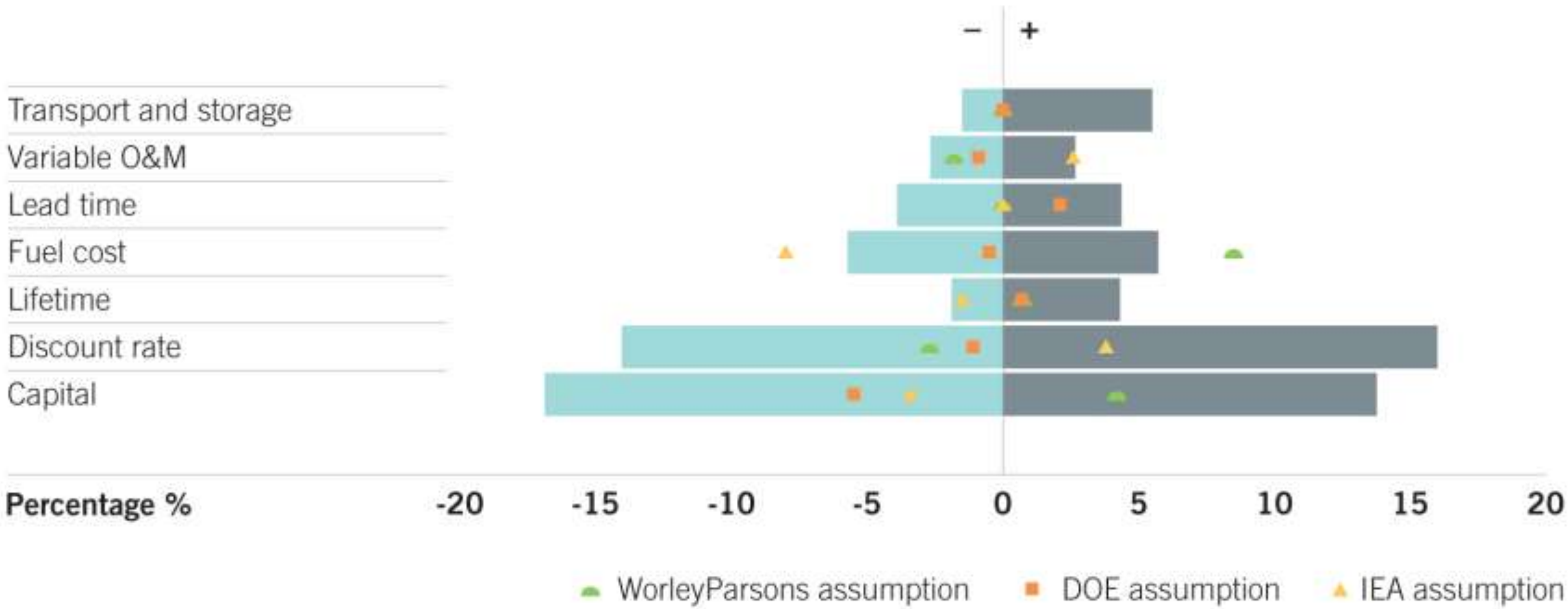
Design studies vs real projects



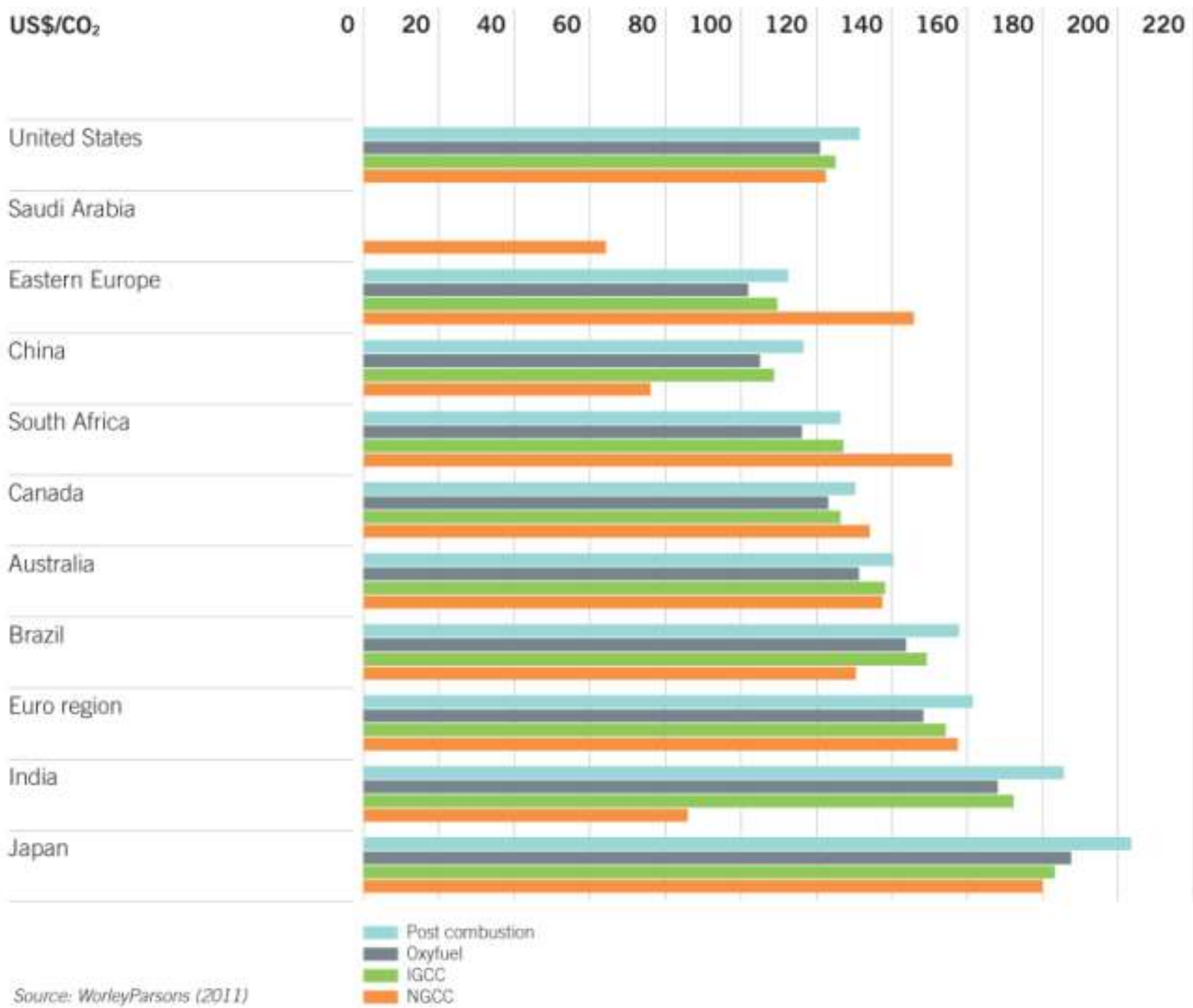
Contrasting emerging project costs



Contrasting assumptions

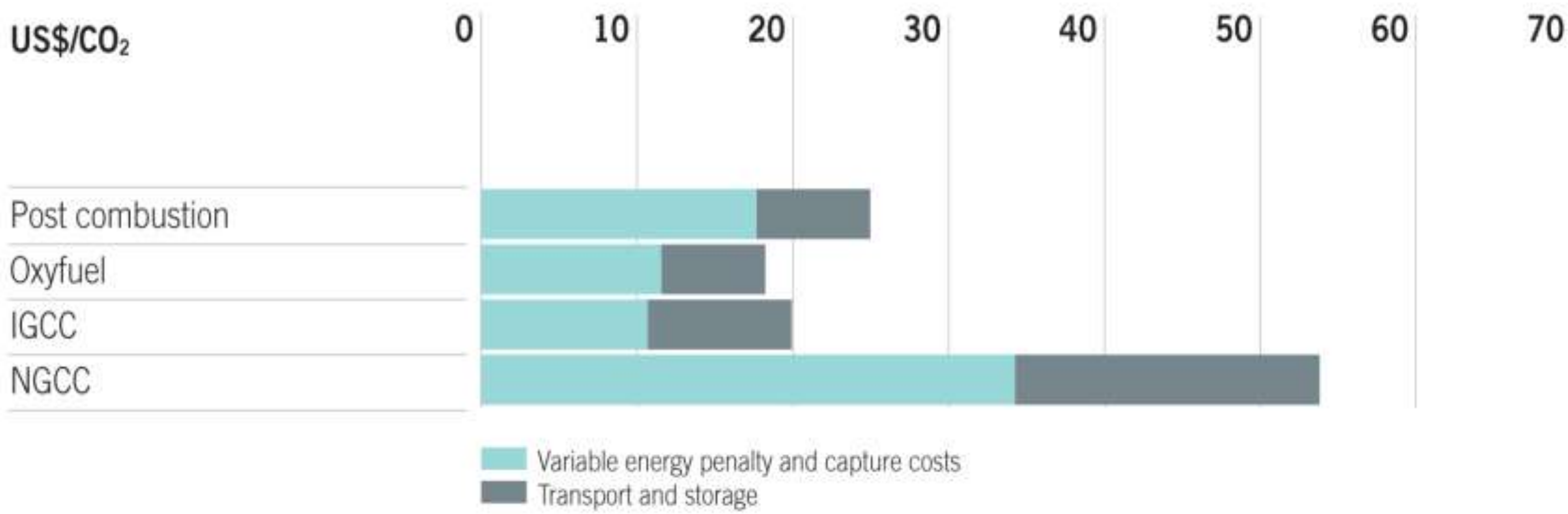


Costs by location

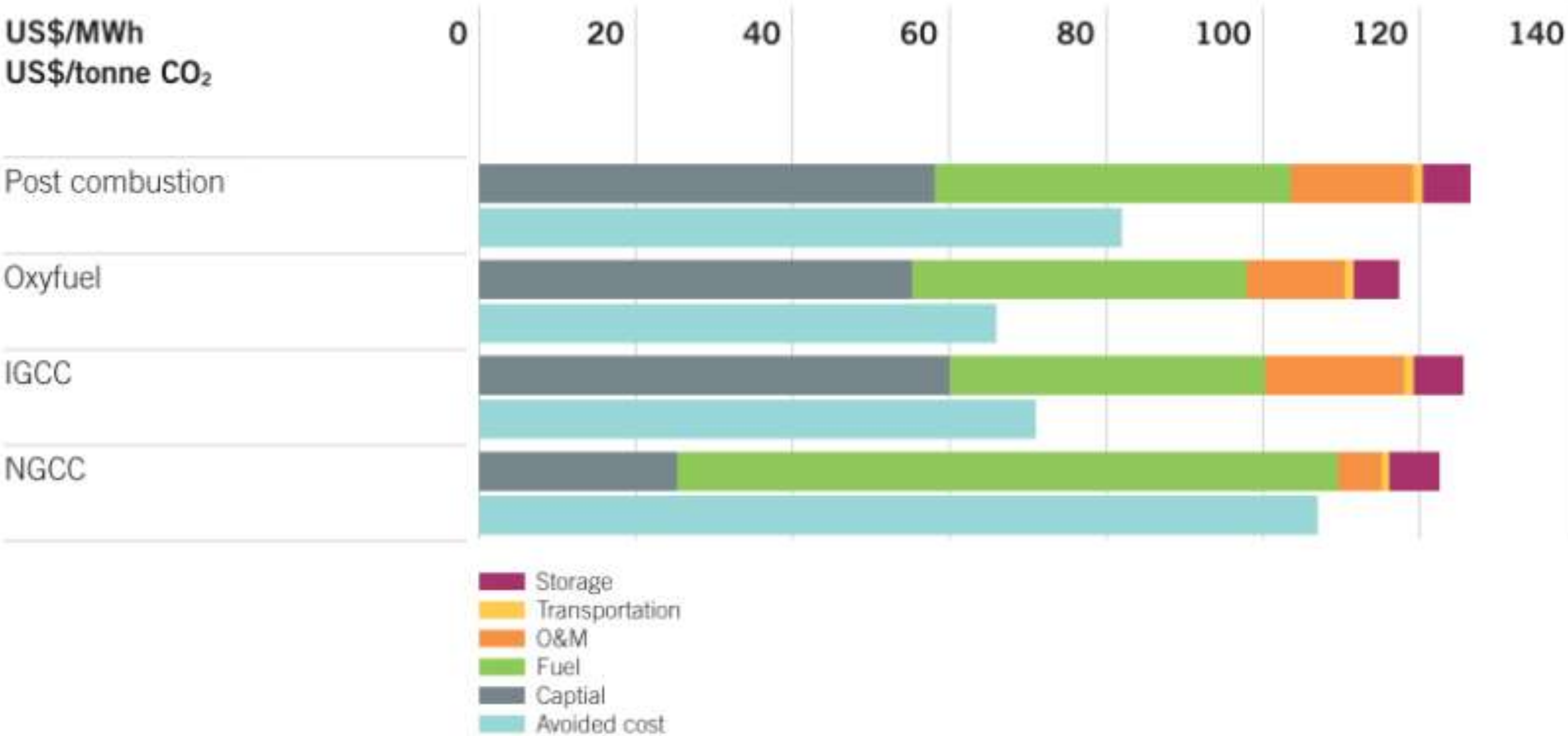


Source: WorleyParsons (2011)

Variable costs & offset markets



Levelised and avoided costs



[1] The reference facility for calculated avoided costs is the lowest cost option for the same fuel source in the absence of CCS technologies. This is a supercritical coal pulverised coal plant, and NGCC plant without CCS for coal and gas technologies respectively.

[2] 2010 dollars.

Source: WorleyParsons (2011)

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Overview of the Agenda

John Davison
IEA Greenhouse Gas R&D Programme

Workshop on CCS Costs
IEA, Paris, March 22nd-23rd 2011

Day 1 - Plenary

- Audiences and uses for CCS cost estimates
  - 9:30-11.00
  - Keynote: Howard Herzog
  - Respondents: Michael Matuszewski, Lars Stromberg, John Thompson
  - Open discussion
- CCS costing methods and measures
  - 11:30-13:00
  - Keynote: Ed Rubin
  - Respondents: Jean François Leandri, Clas Ekström, Sina Rezvani
  - Open discussion

Day 1 - Plenary

- Status of CO_2 capture costs
  - 14:15-15:45
  - Keynote: Matthias Finkenrath
  - Respondents: John Chamberlain, George Booras, Li Zheng
  - Open discussion
- Status CO_2 transport and storage costs
  - 16:15-17:45
  - Keynotes: Per Arne Nilsson (transport)
John Tombari (storage)
  - Respondents: Alastair Rennie, Wilfred Mass, Neil Wildgust
  - Open discussion

Day 2 – Breakout Sessions

- Breakout sessions (9:00 – 12:30)
  - Capture costs (2 groups)
  - Transport costs
  - Storage costs
- Further discussion of topics presented on day 1
  - Major on-going costing efforts
  - Available costing and analysis tools
  - Needs for improvement in cost methods, reporting etc
- Discuss need for a CCS costing network
  - What role would a costing network play?
  - Who would participate in such a network?
  - What agenda and structure would be most useful?

Day 2 - Plenary

- Report from breakout sessions (14:00 – 15:15)
  - Reports from capture, transport and storage groups
  - Open discussion
- General discussion (15:15 – 16:00)
  - Conclusions / insights
  - Recommendations / plans for follow-up action
- Adjourn (16:00)

Workshop Report

- Content
  - Agenda
  - Attendees list
  - Group photo
  - PowerPoint presentations
  - Summary of discussions
- Unrestricted distribution
  - Except for any slides identified as confidential by the presenters

Audiences and Uses for CCS Cost Estimates

CCS Cost Workshop

Howard Herzog

MIT

March 22, 2011

Who is the Audience for CCS Cost Estimates?

- Many people use cost estimates in many ways
- Many = more than you realize

Users (and Generators)

Government

- Policymakers
- Analysts
- Regulators
- R&D Agencies

Industry

- Operators
- Vendors
- A&E Firms
- Venture Cap
- Tech Developer
- R&D Orgs

NGOs

- Environmental
- Media
- Academia
- Foundations

Simplified View for the Use of CCS Cost Estimates

Cost Estimates

CCS (and others)

Technology Assessments

R&D Priorities

Capital Investments

Marketing

Policy Assessments

Legislation

Regulation

Advocacy

Usage Example, E-mail, March 4, 2011
Audience: Government/Analyst
Use: R&D Priorities, Legislation

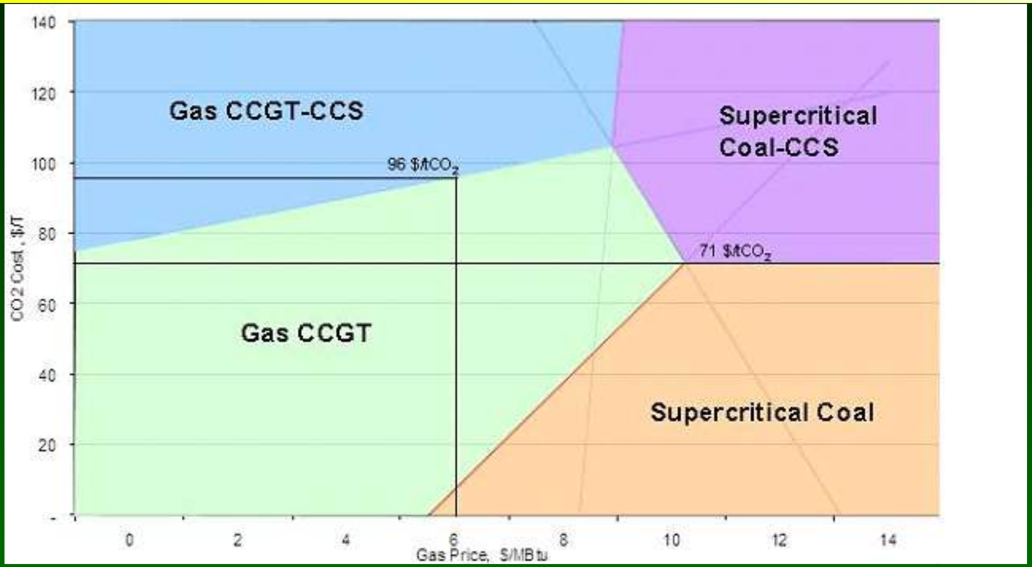
I work at the Congressional Budget Office, where I am currently writing a report on carbon capture and storage.

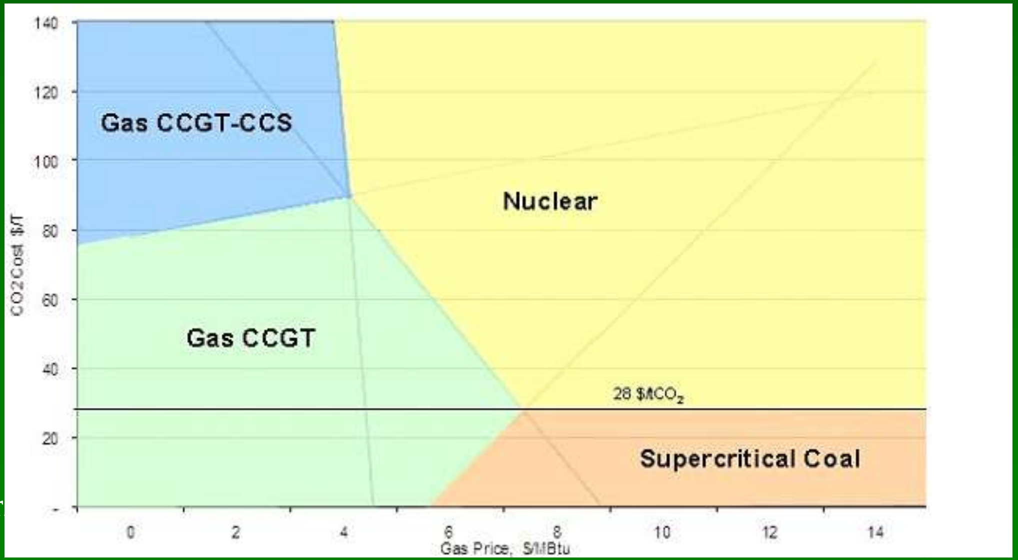
I was wondering if I could ask you about the estimation of IGCC capital costs. The EIA for example published estimates last November that the overnight capital costs for a 600 MW IGCC plant were $3565/kW. The overnight capital costs for a 650 MW advanced PC were $3167/kW. Similarly EIA puts a value of the technological optimism for IGCC at the same level as that for scrubbed coal, despite the fact that there are hundreds of scrubbed coal plants and a handful of IGCC plants.

What are such numbers based on? (It isn't only them. All sorts of models present this type of relatively small cost differential.)

I just find it hard to believe that a novel technology like IGCC, which is struggling with massive cost overruns everywhere it is being actually built, is only 12% expensive than a mature technology such as PC. What am I missing?

Usage Example, Paper, November, 2010
Audience: Industry/Operator
Use: R&D Priorities





From Khesghi *et al*, SPE 139716-PP, 2010

Howard Her

Usage Example, Press Release, October 27, 2010
Audience: Industry/Technology Developer
Use: Marketing

- Nexant Confirms MaGIC™ Technology's Potential to Fight Climate Change
  - In its report entitled "Due Diligence on Wormser Energy Solutions MaGIC™ Technology for Retrofitting of Existing Power Plants to Reduce CO2 Emissions," Nexant estimated the 20-year levelized cost of electricity (LCOE) when upgrading an existing coal plant to provide additional capacity as well as carbon capture, to be as follows. The LCOE with a conventional Selexol scrubber will be 6.99 cents per kWh and 6.53 cents per kWh when using WES' ACL system. These compare with 6.33 cents/kWh for a super critical pulverized coal plant (SCPC) without carbon capture and 6.84 cents/kWh for natural gas combined cycle plant (NGCC) also without carbon capture.

Bottom-up Cost Estimates

- Limited number of public comprehensive, independent engineering studies
- Quite a few "derivative" studies

Bottom-up Cost Estimate
IPCC Special Report on CCS

CCS system components	Cost range
Capture from a coal- or gas-fired power plant	15-75 US$/t$CO_2$ net captured
Capture from hydrogen and ammonia production or gas processing	5-55 US$/t$CO_2$ net captured
Capture from other industrial sources	25-115 US$/t$CO_2$ net captured
Transportation	1-8 US$/t$CO_2$ transported
Geological storage[a]	0.5-8 US$/t$CO_2$ net injected
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected
Ocean storage	5-30 US$/t$CO_2$ net injected
Mineral carbonation	50-100 US$/t$CO_2$ net mineralized

[a] Over the long term, there may be additional costs for remediation and liabilities.

Bottom-up Cost Estimate
MIT Coal Study

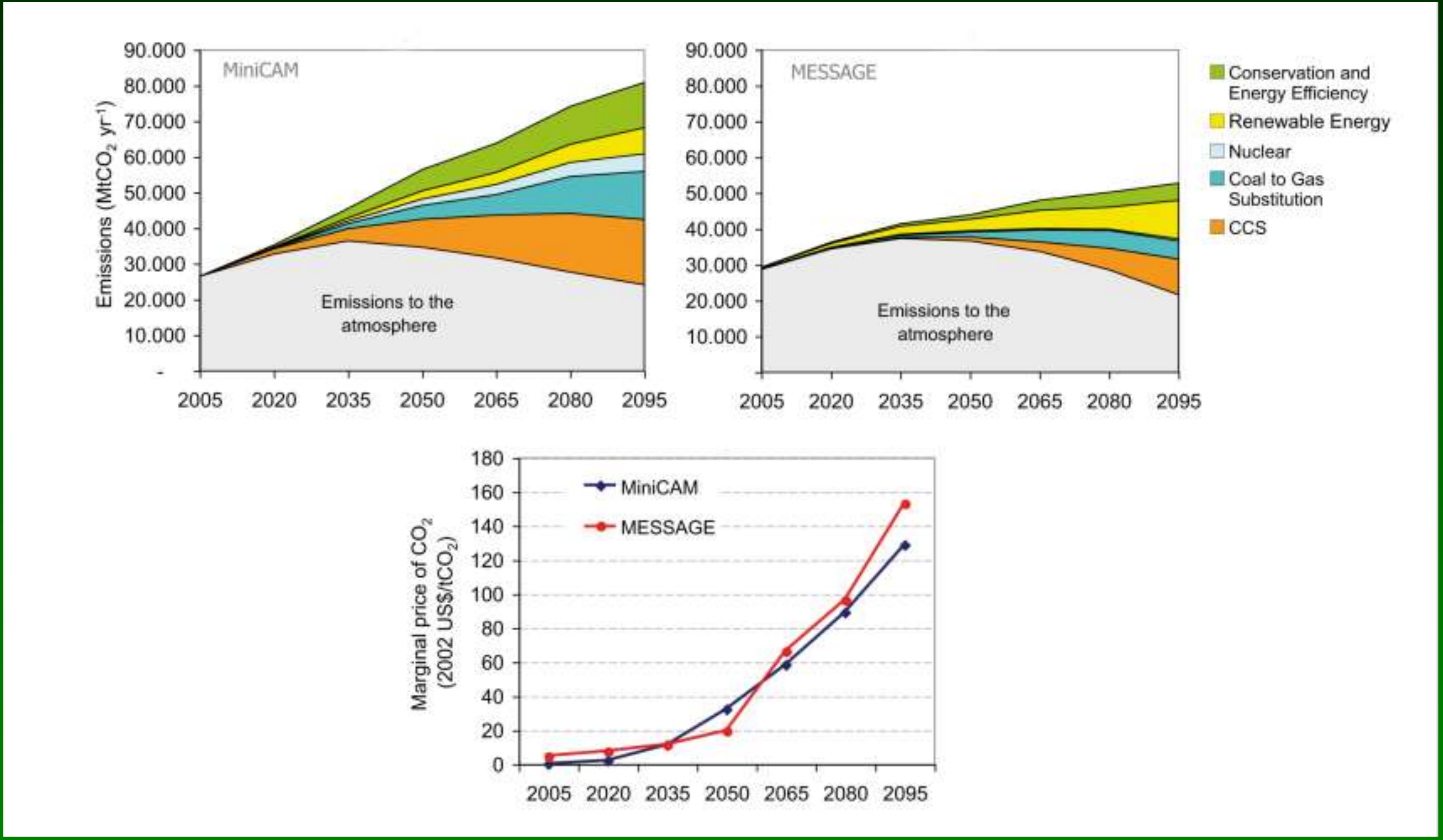
Table 3.5 Representative Performance and Economics for Oxy-Fuel Pulverized Coal and IGCC Power Generation Technologies, Compared with Supercritical Pulverized Coal

	SUPERCRITICAL PC		SC PC-OXY	IGCC	
	W/O CAPTURE	W/ CAPTURE	W/CAPTURE	W/O CAPTUREQ	W/CAPTURE
PERFORMANCE					
Heat rate (1), Btu/kW_e-h	8,868	11,652	11,157	8,891	10,942
Generating efficiency (HHV)	38.5%	29.3%	30.6%	38.4%	31.2%
Coal feed, kg/h	184,894	242,950	232,628	185,376	28,155
CO_2 emitted, kg/h	414,903	54,518	52,202	415,983	51,198
CO_2 captured at 90%, kg/h (2)	0	490,662	469,817	0	460,782
CO_2 emitted, g/kW_e-h (2)	830	109	104	832	102
COSTS					
Total Plant Cost (3), \$/kW_e	1,330	2,140	1,900	1,430	1,890
Inv. Charge, ¢/kW_e-h @ 15.1% (4)	2.70	4.34	3.85	2.90	3.83
Fuel, ¢/kW_e-h @ \$1.50/MMBtu	1.33	1.75	1.67	1.33	1.64
O&M, ¢/kW_e-h	0.75	1.60	1.45	0.90	1.05
COE, ¢/kW_e-h	**4.78**	**7.69**	**6.98**	**5.13**	**6.52**
Cost of CO_2 avoided vs. same technology w/o capture (5), \$/tonne		**40.4**	**30.3**		**19.3**
Cost of CO_2 avoided vs. supercritical technology w/o capture (5), \$/tonne		**40.4**	**30.3**		**24.0**

Top-down Cost Estimates

- Bottom-up estimates embedded
- Usually need to "translate" estimates from bottom-up studies
- Multiple technologies – each technology may be from different sources – no guarantee they are on consistent basis

Top-Down Cost Estimate
IPCC Special Report on CCS



CCS in a Mitigation Portfolio

- Many users of CCS costs are also interested in costs of other CO_2 mitigation technologies
- An important use of CCS costs are to compare them to the cost of other CO_2 mitigation technologies

Example of an Energy Policy

- In September 2010 the German government announced the following new aggressive energy targets:
  - Renewable electricity - 35% by 2020 and 80% by 2050
  - Renewable energy - 18% by 2020, 30% by 2030, and 60% by 2050
  - Energy efficiency - Cutting the national electrical consumption 50% below 2008 levels by 2050
- At GHGT-10, in his keynote talk Anders Levermann of the Potsdam Institute for Climate Impact Research said if CCS isn't ready by 2030, it will be too late

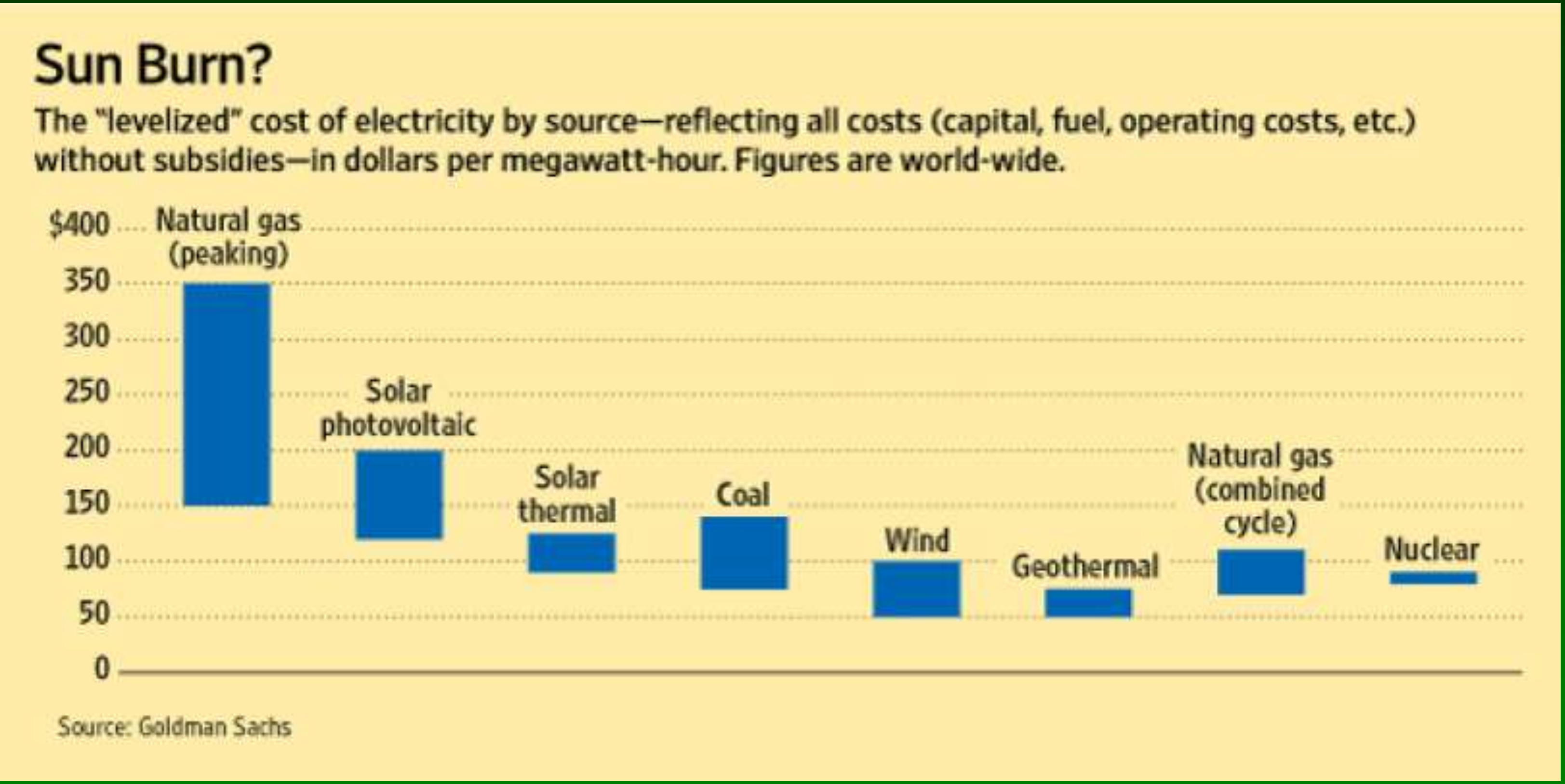
DOE's EIA

2009 Levelized Cost of New Generating Technologies

Plant Type	Total Levelized Cost ($/(MWH))
Conventional Coal	$95
Advanced Coal	$103
Advanced Coal with CCS	$123
Natural Gas-Fired	
Conventional Combined Cycle	$84
Advanced Combined Cycle	$80
Advanced CC with CCS	$116
Advanced Nuclear	$110
Wind	$142
Wind – Offshore	$230
Solar PV	$396
Solar Thermal	$264
Biomass	$107
Hydro	$115

The Wall Street Journal

September 13, 2010, page R4



Paul L. Joskow , Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies, September 2010

MIT CEEPR WP-2010-013

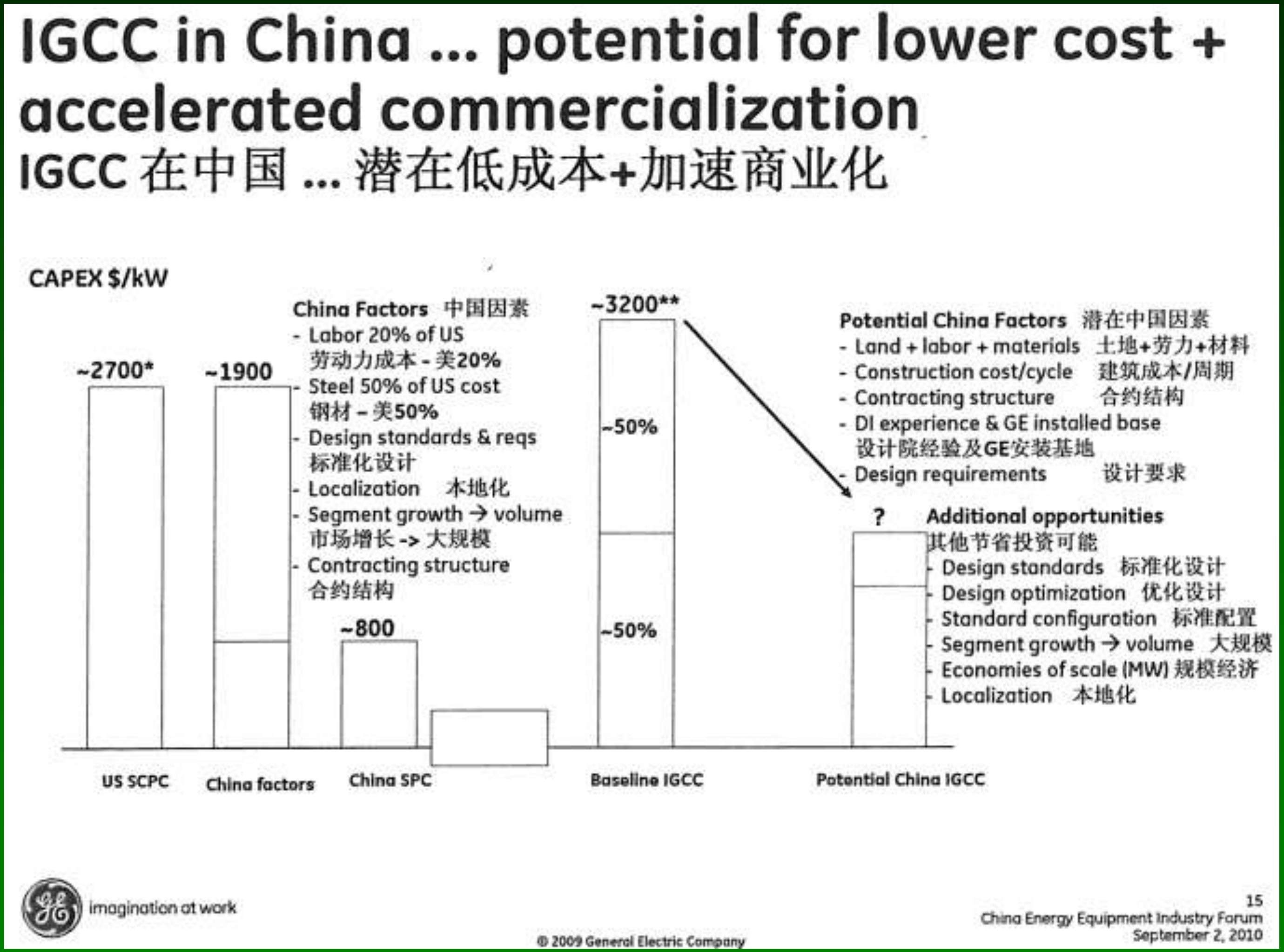
- While levelized cost calculations may be a simple way accurately to compare different dispatchable base load generating technologies with different capital and operating cost attributes, it is not a useful way to compare generating technologies with very different production profiles and associated differences in the market value of the electricity they produce.
- Levelized cost comparisons overvalue intermittent generating technologies compared to dispatchable base load generating technologies.
- Using traditional levelized cost calculations to compare dispatchable and intermittent generating technologies is a meaningless exercise and can lead to inaccurate valuations of alternative generating technologies.

http://web.mit.edu/ceepr/www/publications/workingpapers/2010-013.pdf

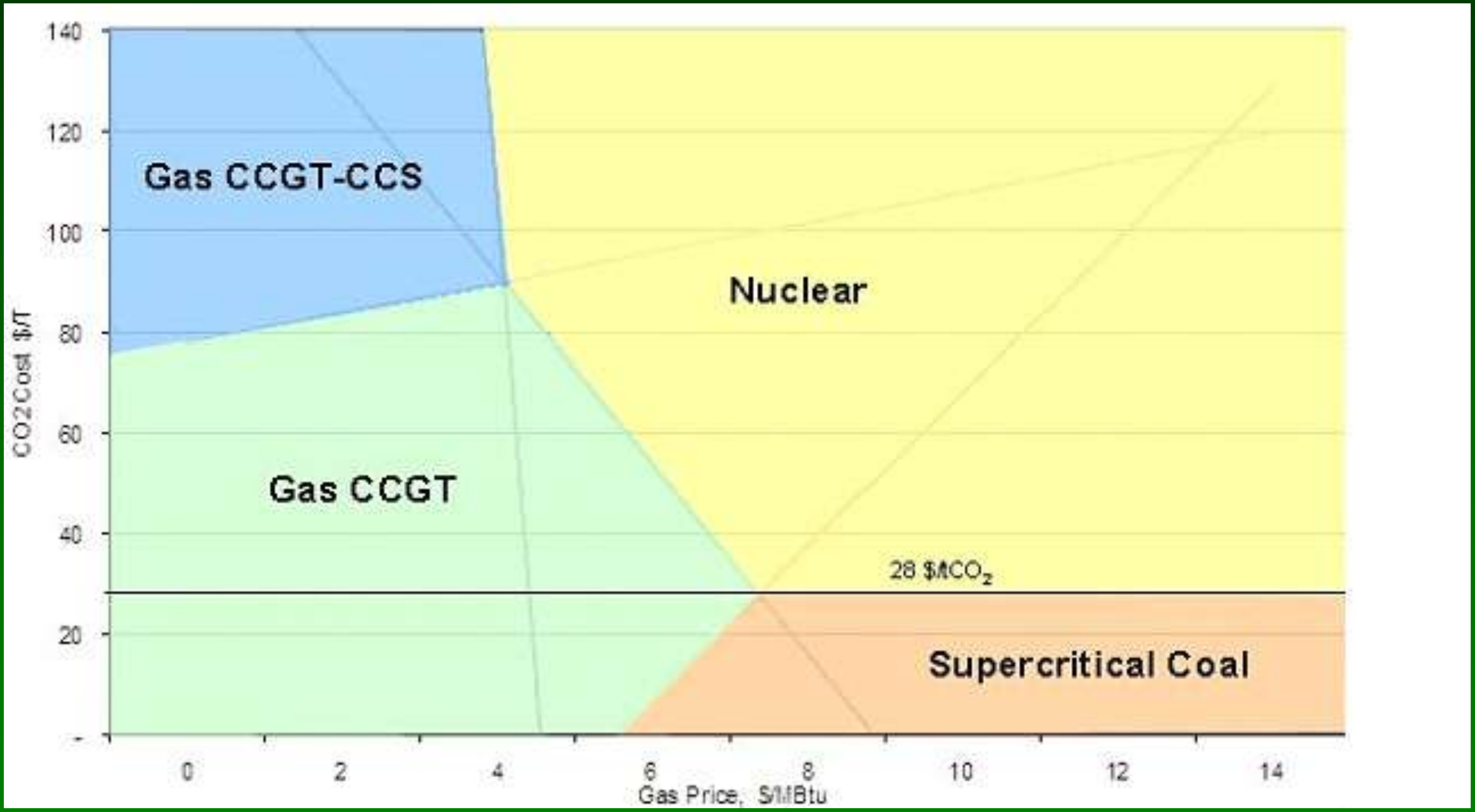
Important Considerations for Cost Estimates

- Variability
- Uncertainty
- Bias

Variability



Uncertainty
Khesghi *et al*, SPE 139716-PP, 2010



Bias

- Most people doing the cost estimates have a vested interest in seeing their technology being successful
- People analyzing the competitive technologies are low-balling costs, so we have to

Bias
Comparing Air Capture to CCS

- Factored estimate costing approach
  - Total CAPEX = (Major equip cost) x (factor)
- For CCS, used 4.5
- Report stated: "A more appropriate capital cost factor, treating a first-of-a-kind air capture facility like any new plant commercializing a new chemical process, would be at least 6."
- For air capture, used 4.5

Take-Aways

- The cost estimates we put out are used by many people in many ways
- Some users may twist cost estimates to fit their agenda, but we cannot control that
- As a user, my wish is for objective, transparent (unbiased) cost estimates that quantify the uncertainty and clearly state the design basis
- Most users would like consistency across the cost estimates for the various energy supply and carbon mitigation technologies, but this is a very difficult goal to achieve

Contact Information

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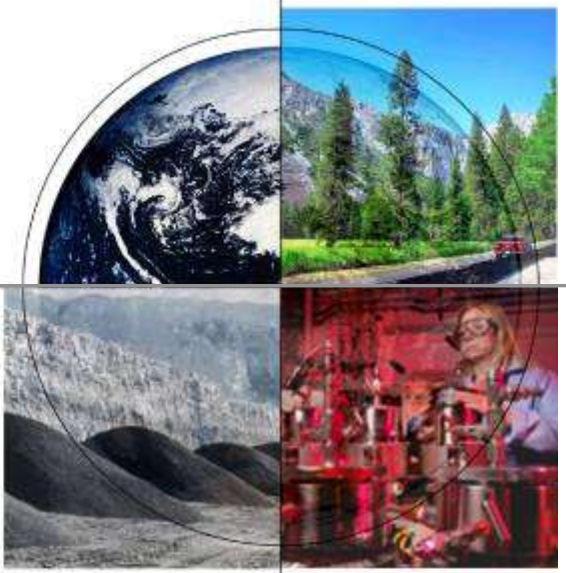
NATIONAL ENERGY TECHNOLOGY LABORATORY



Audiences & Uses for CCS Cost Estimates

Government Respondent

IEA CCS Cost Workshop
March 22, 2011
Paris, France

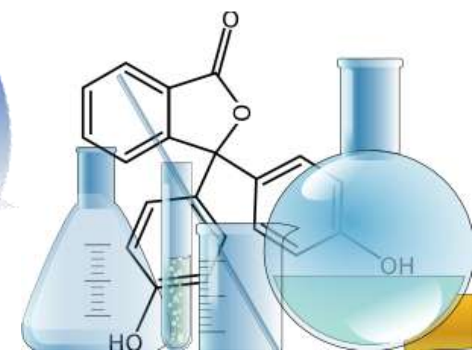
Major Audiences for CCS Cost Estimates

Consumers & Utilities:

1. ***Drive Electricity Demand***
2. ***Cost-Conscious***
3. ***Create/Equilibrate Feedback***

Regulators & Policymakers:

1. ***Span Diverse Industries***
2. ***Create Effective Legislation***
3. ***Balance Societal Impact***

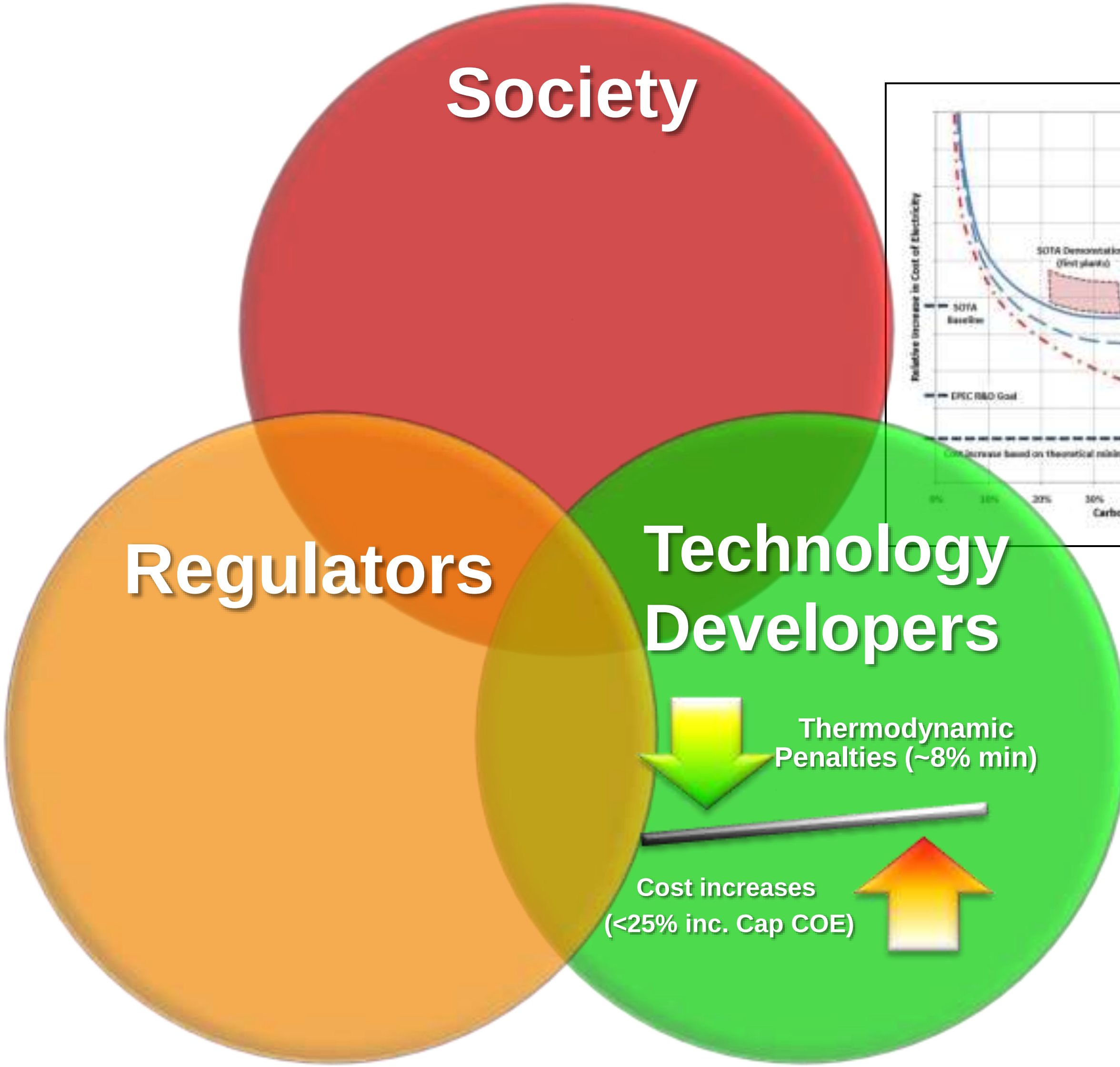


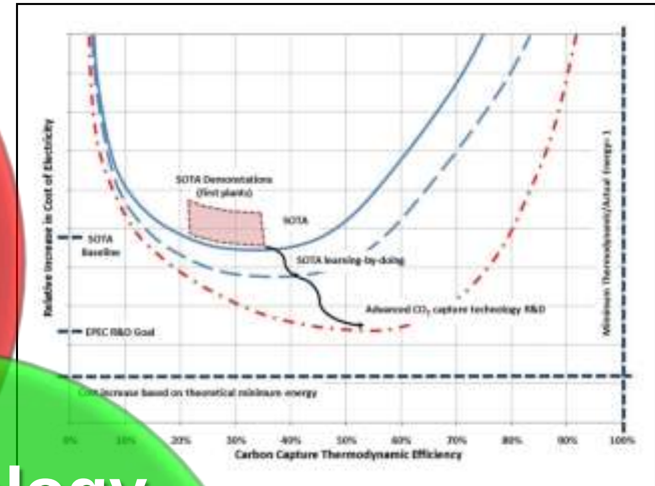
Capture & Sequestration Technology Developers:

1. ***Characterize Performance***
2. ***Increase Efficiency***
3. ***Drive Down Costs***

** Images Courtesy of www.clker.com*

Intricate Balancing Act

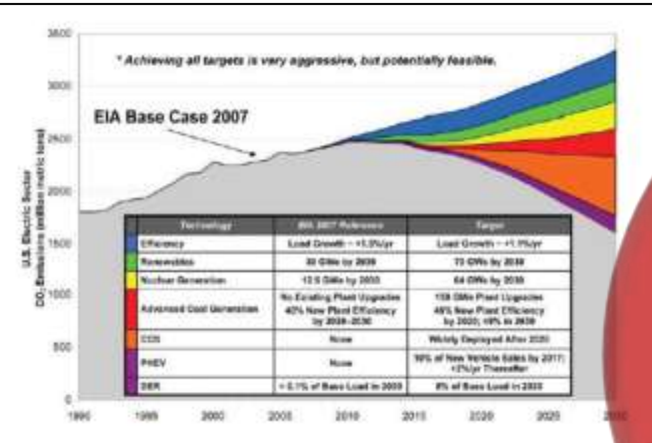


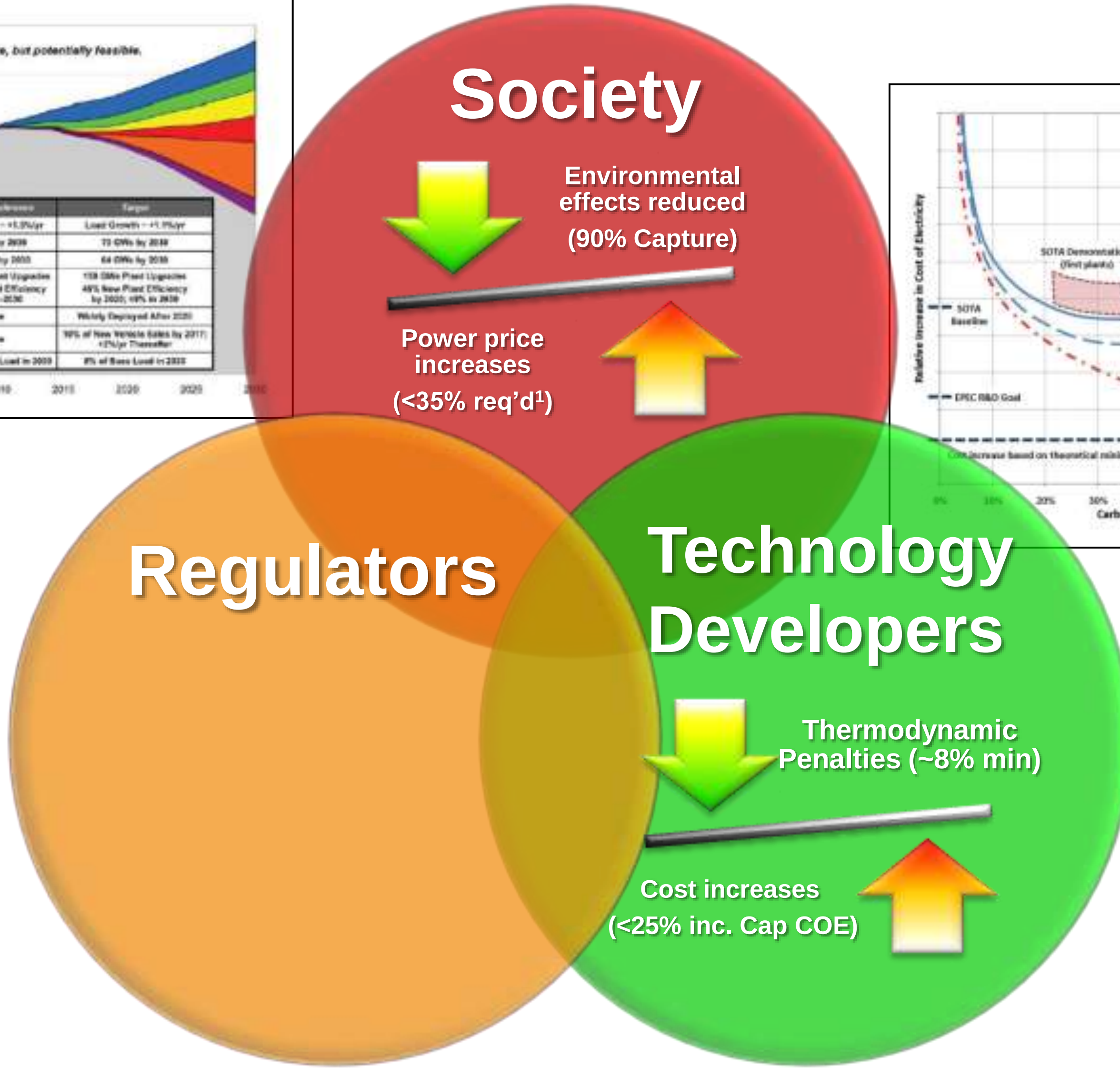


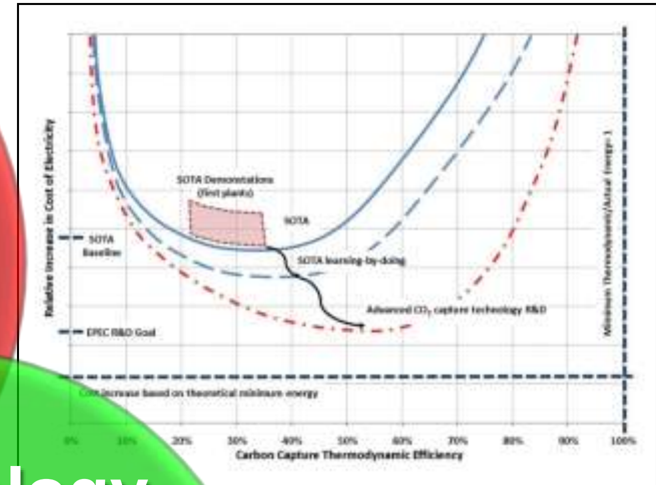
Note 1: NETL Carbon Capture Goal

** Images from www.clker.com, EPRI and NETL CCS Roadmap*

Intricate Balancing Act







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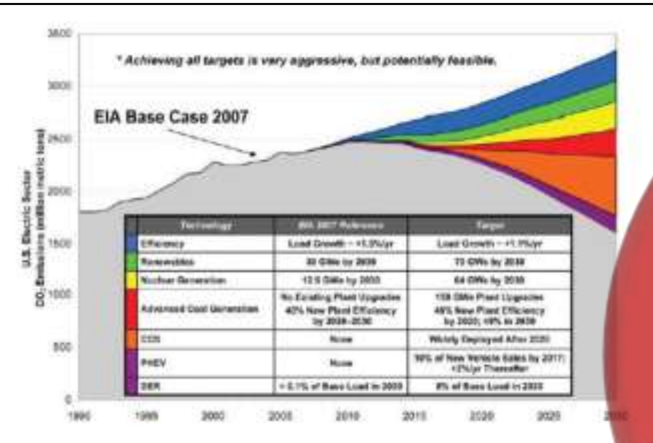
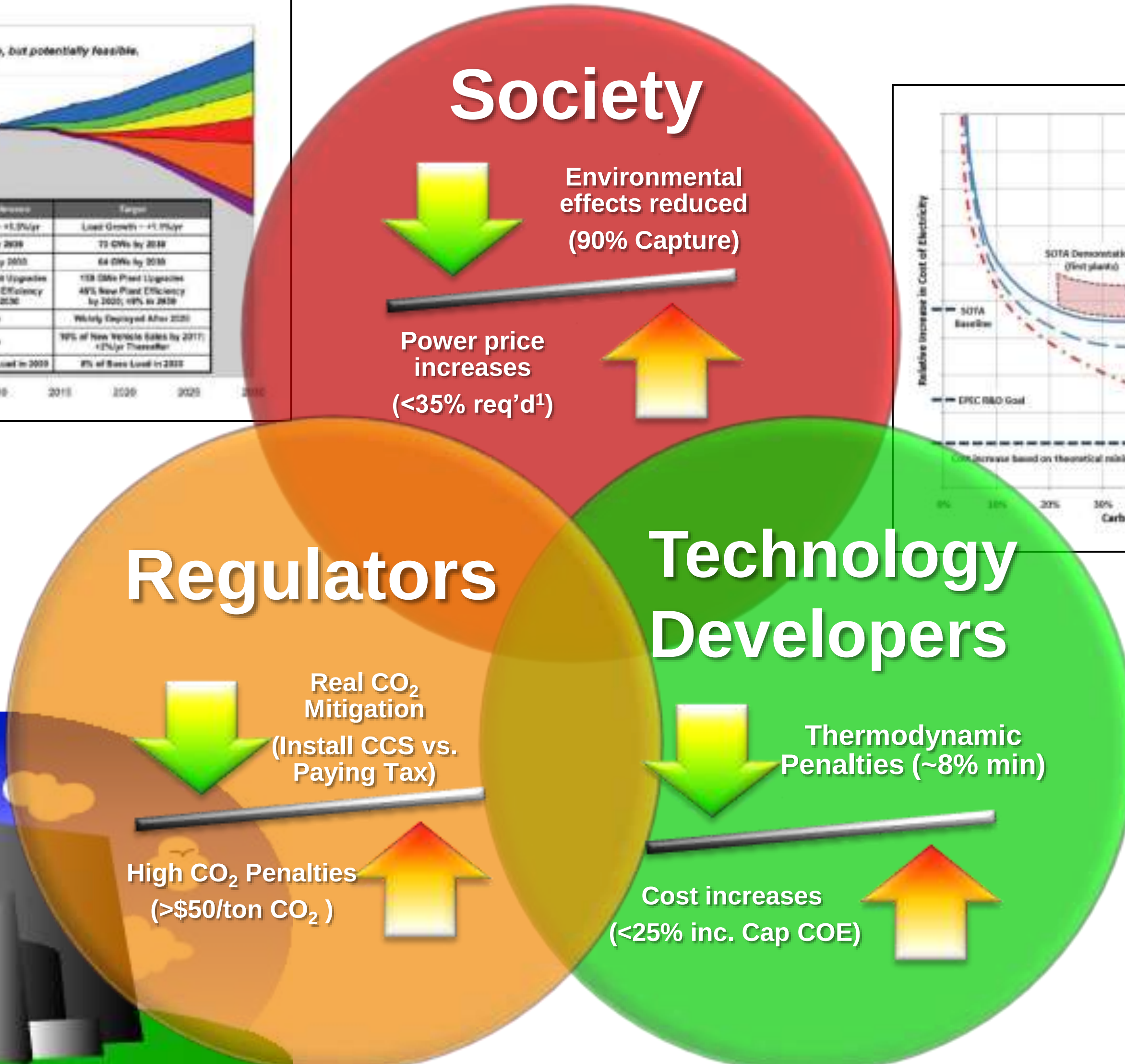
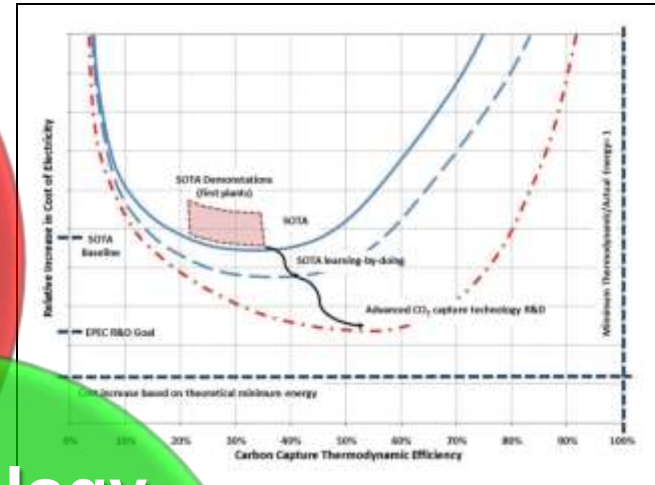
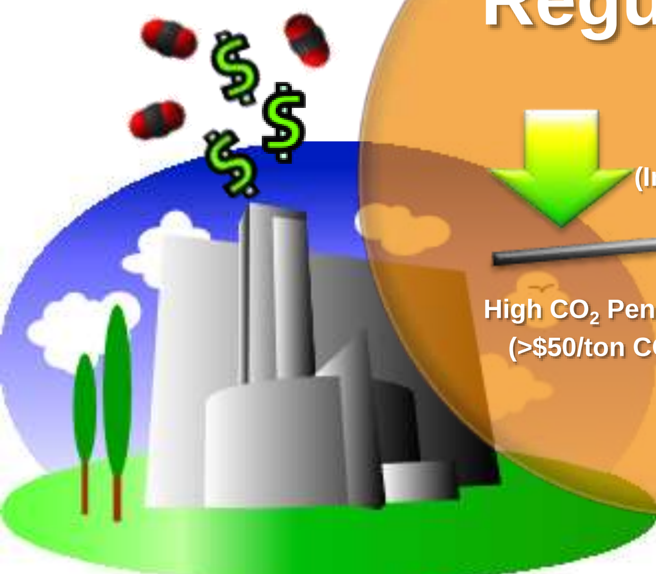






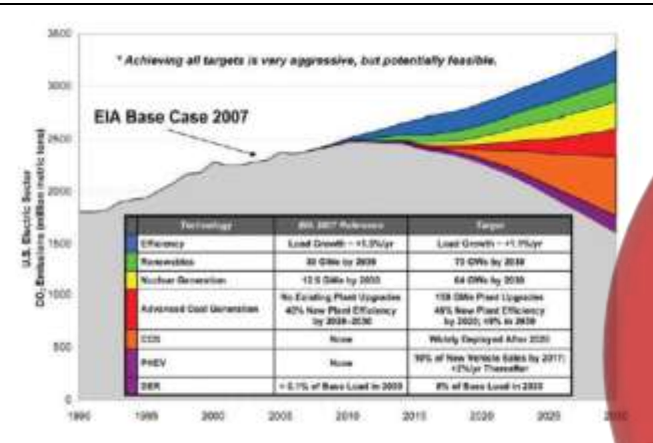


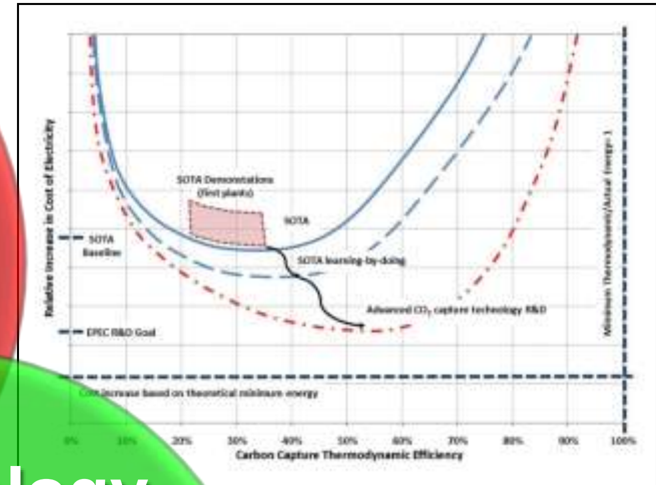
NATIONAL ENERGY TECHNOLOGY LABORATORY

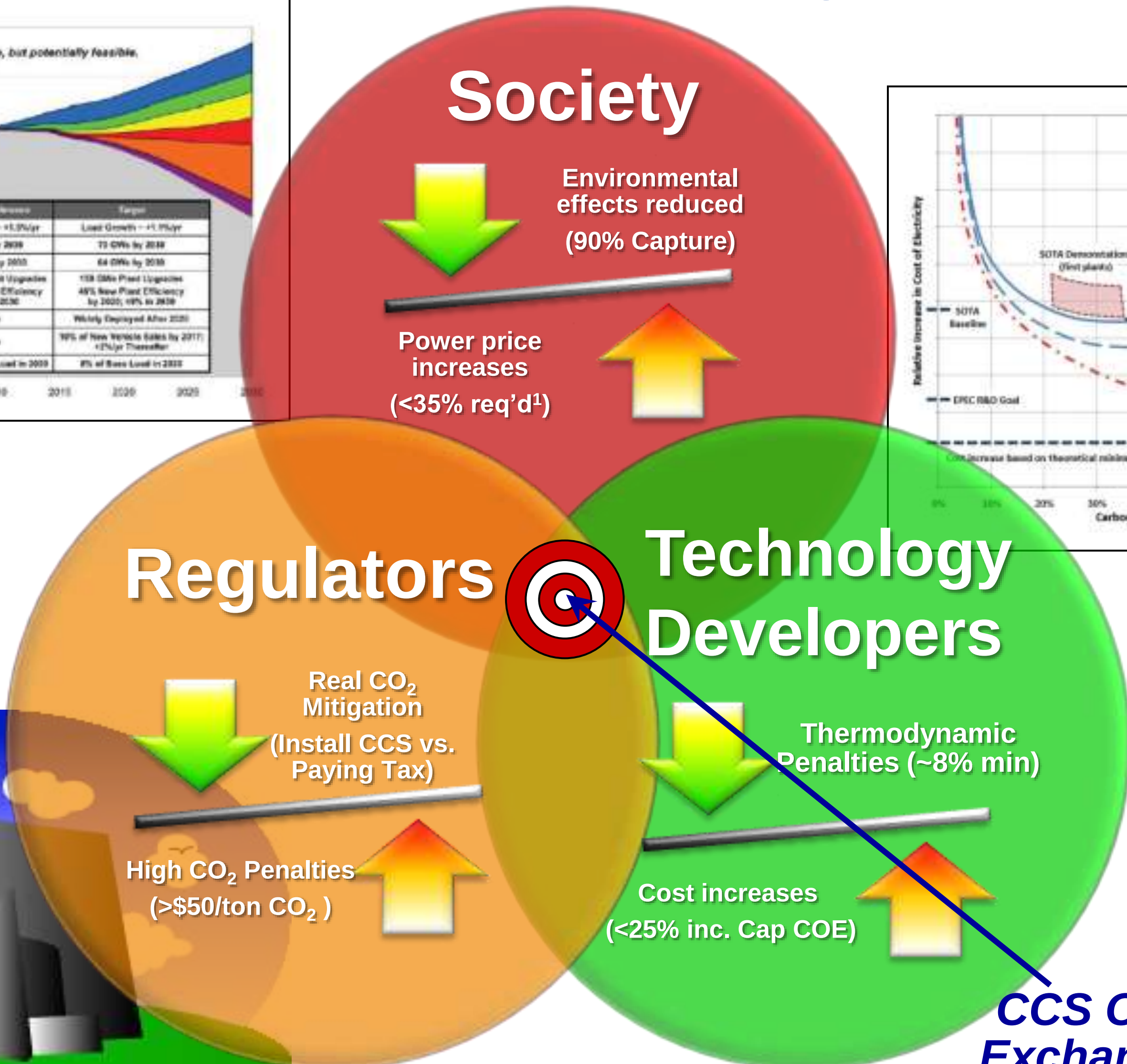
Note 1: NETL Carbon Capture Goal

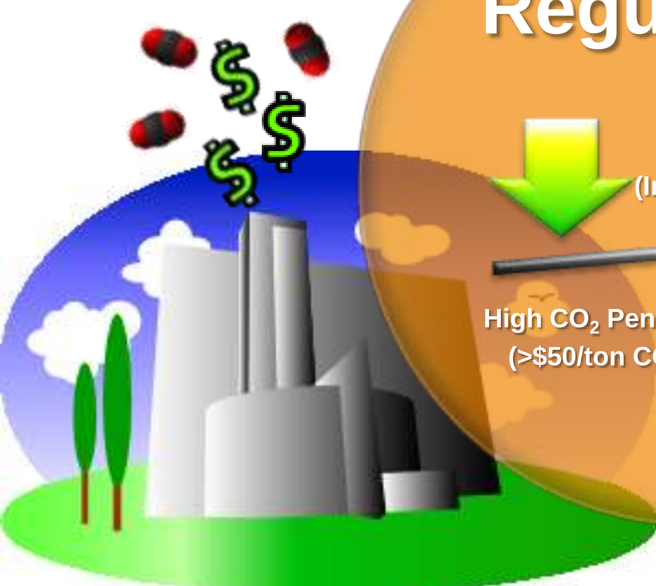
** Images from www.clker.com, EPRI and NETL CCS Roadmap*

Intricate Balancing Act









CCS Cost Information Exchange is Crucial for Balanced Solutions

**Note 1: NETL Carbon Capture Goal*

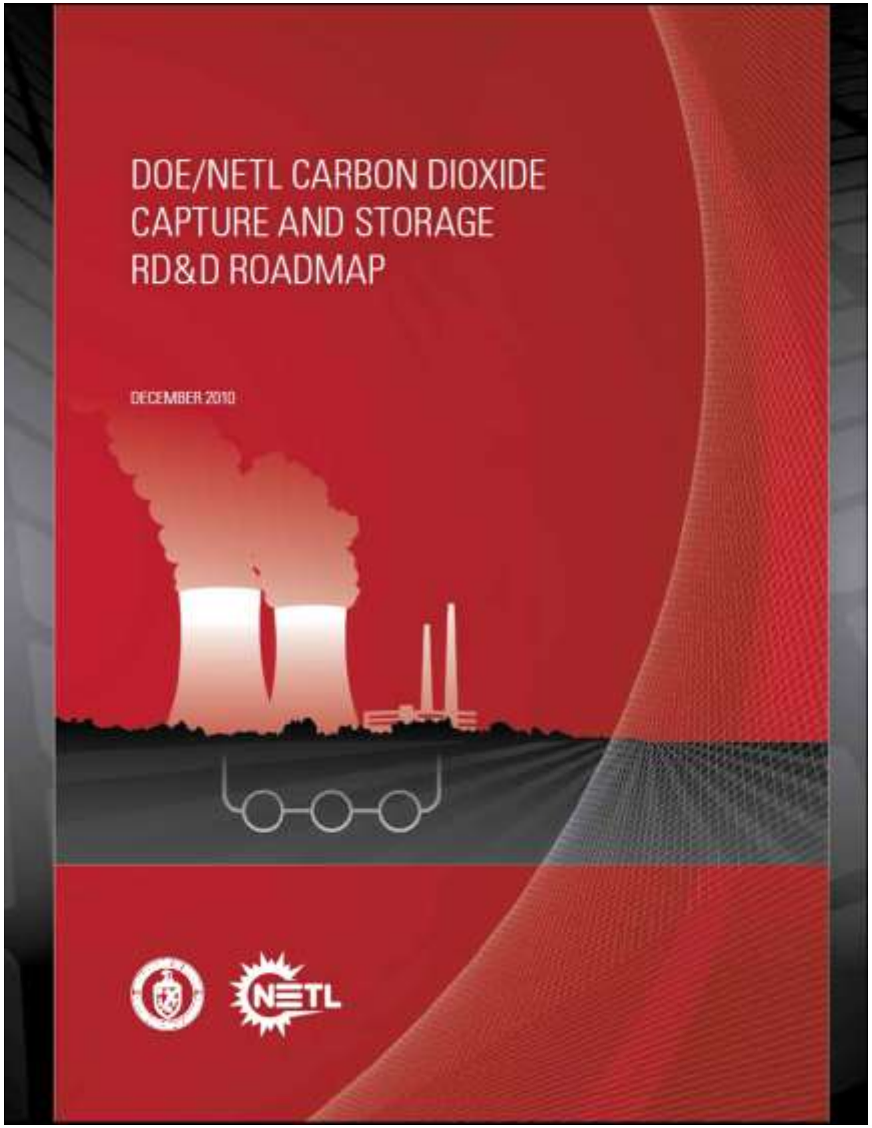
** Images from www.clker.com, EPRI and NETL CCS Roadmap*

Thank You

Please visit:

http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CCSRoadmap.pdf

For Additional Information



CCS COST WORKSHOP

March 22-23, 2011
International Energy Agency (IEA) Paris, France

Lars Strömberg
Vattenfall AB

Pulverized coal plant Lippendorf

Buggenum IGCC plant

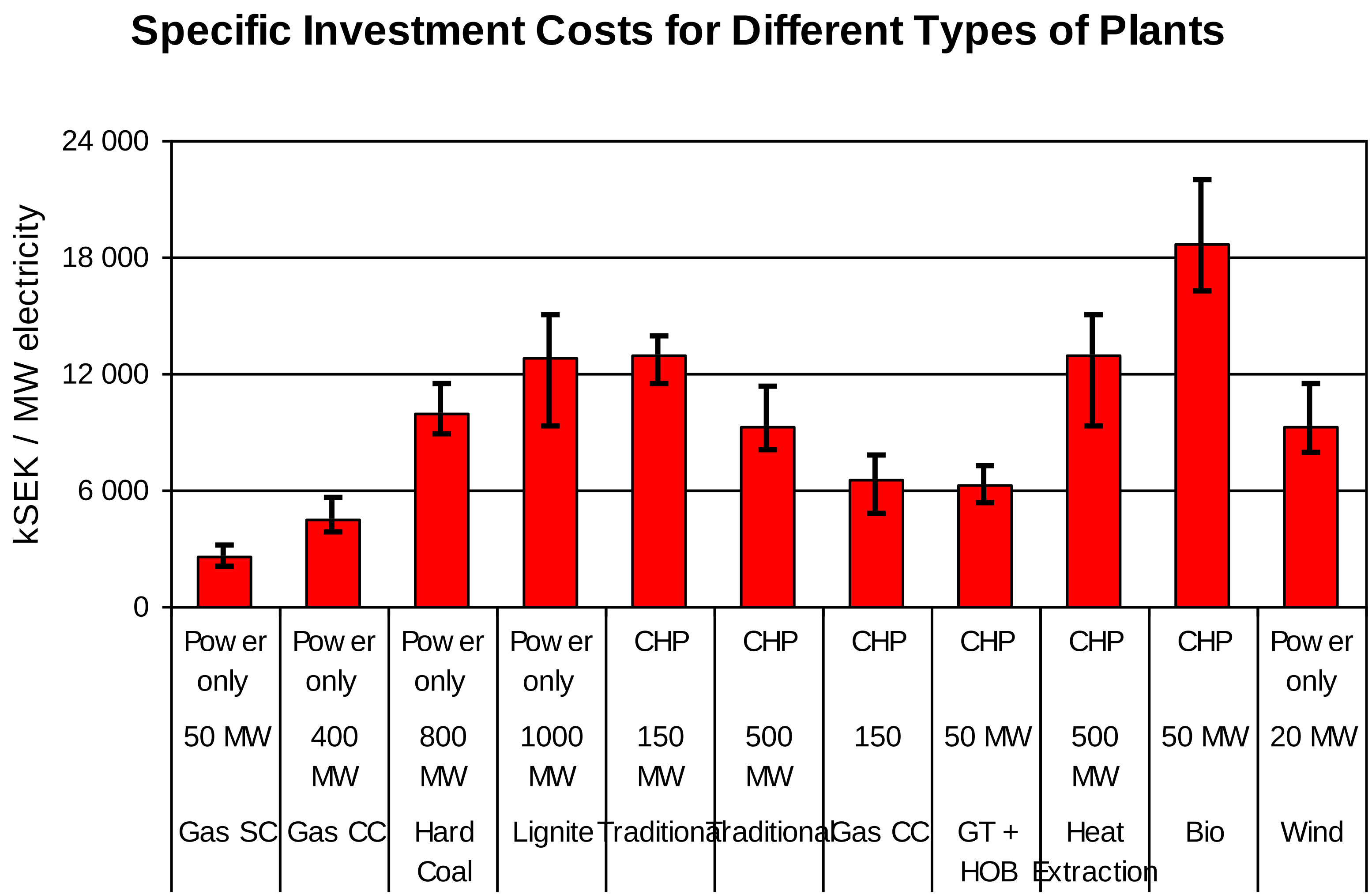
VATTENFALL

Cost of a Power Plant

- We are the fourth largest European power generating company
- We operate a large number of power plants, Coal, Nuclear, Hydro, Wind, Biomass, Gas and …
- At present we build three large coal fired power blocks in the 1000MW class and a 1200 MW CCGT.
- We have just recently finalized two complete FEED studies on full scale CCS plants demonstrating IGCC with pre combustion capture and PC supercritical oxy fuel technology

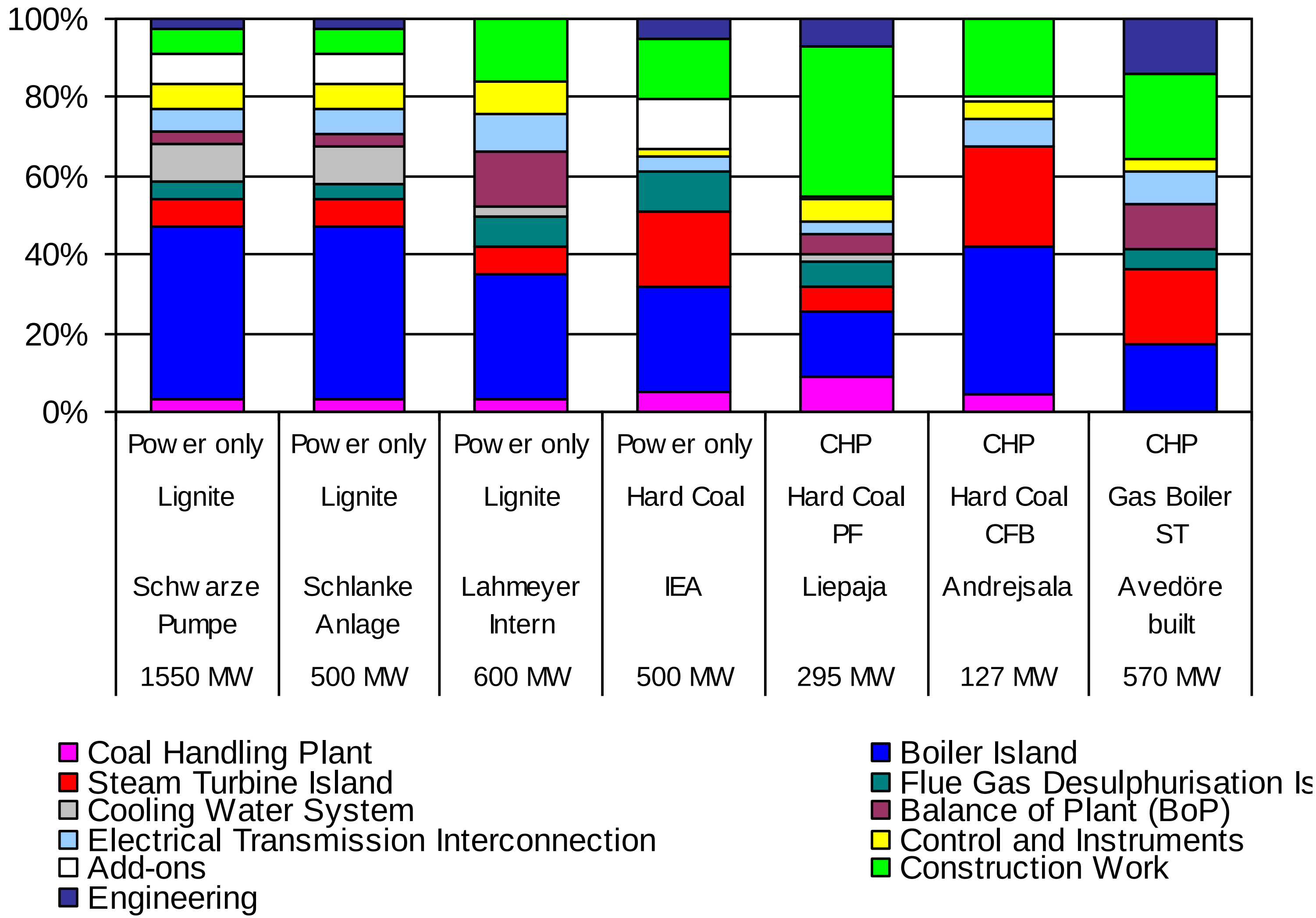
- We know what a Power plant cost
  - To build
  - To operate and maintain

Total investment cost for power plants 2005
(Error bars represent 95 % confidence interval)

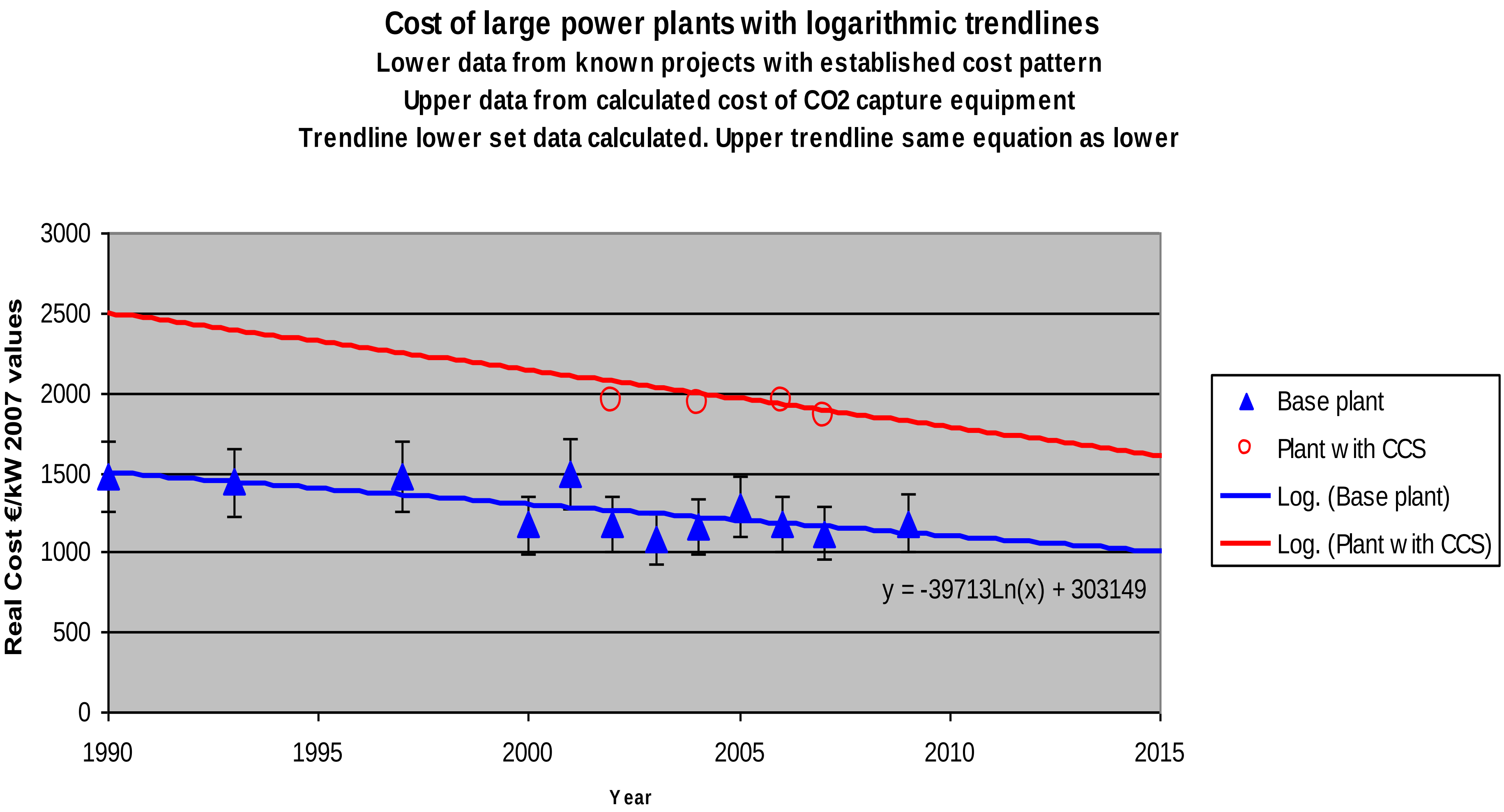


VATTENFALL

Cost distribution for different power plants – case study



Investment costs for large power plants



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View on Oxyfuel Pilot Plant

Investment costs for CCGT

Source: Gas Turbine World

VATTENFALL

The user of cost study information

- We do not need this for ourselves. We hopefully know what we are doing. We know what the Jänschwalde demo or the IGCC in Eemshaven costs, including competing technologies

- “Others” though need this for their
  - Policy work
  - Research
  - Strategic work in other businesses

- Indirectly we need the “others” work and we need that they have correct information and that it becomes public

- We need to help to make the data
  - As correct as possible
  - Understandable

Cost modeling

- Too many use this tool for either, push their own technology, or other marketing purposes.
- It seem there is a considerable difference between Europe and the USA, not only concerning our deregulated market, but several other cost factors
- An investment decision is never, ever based on a general study.
- They might be used for discussions and food for thought

VATTENFALL

CCS demonstration plant Jänschwalde Unit G

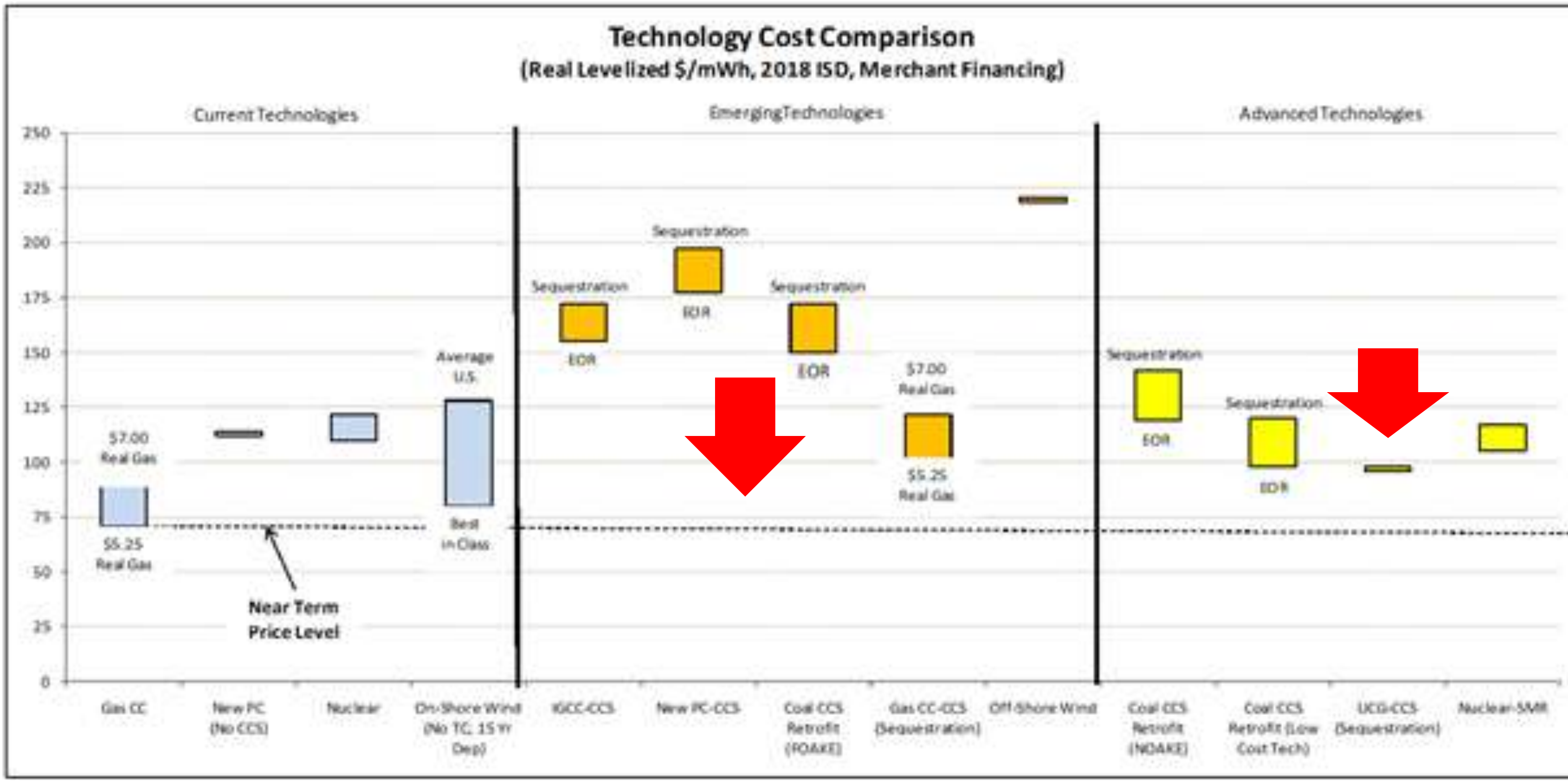
VATTENFALL

Audiences and Uses for CCS Cost Estimates

IEA CCS Cost Workshop
Paris, March 22, 2010

Response by John Thompson
Clean Air Task Force

CCS costs too much… but then, so do all the other near zero carbon options.



Real levelized cost metric escalates from 2018 at 2.5% annually.

Note: These are US costs. Absolute costs will be much lower in China, as will be the "spread" among the different technologies.

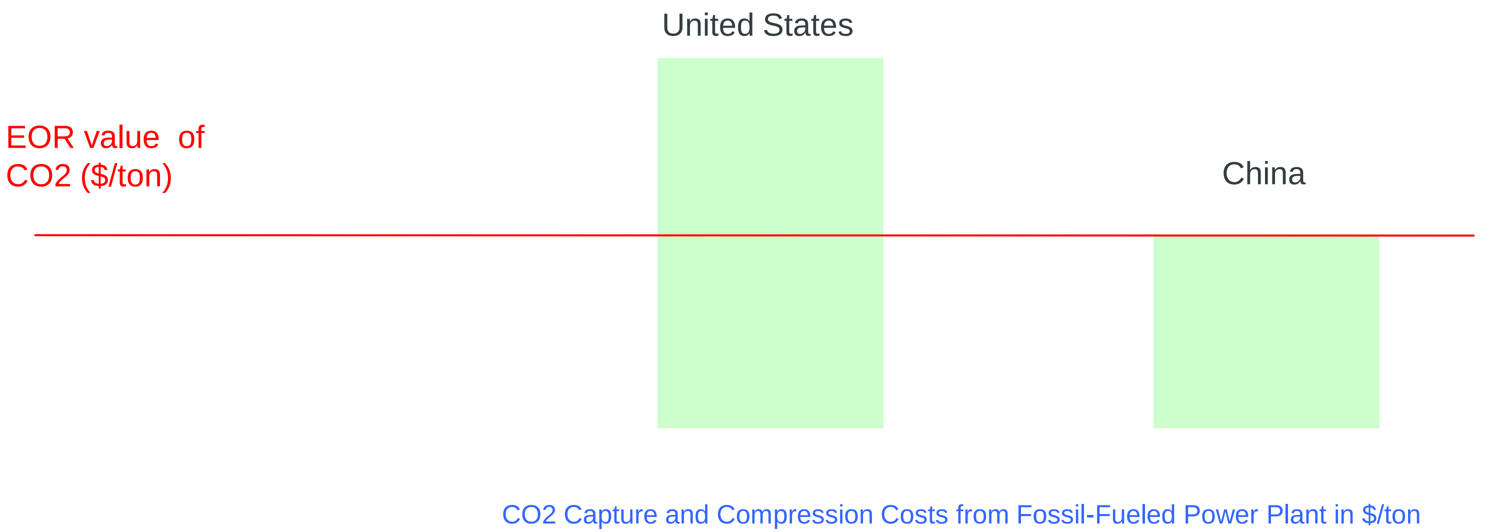
Paradox

- Can’t lower costs without building the “Nth” plant, but can’t build N plants because government won’t provide subsidies for more than a handful of projects.

- Must find niches where many more CCS projects can be deployed without incentives.

Post-Combustion Unit at Huaneng Shanghai Shidongkou.

Straw Man- CCS EOR Projects are Economic in China with Little or No Subsidy.



- The global price of oil establishes the value of carbon dioxide for EOR.
  - Therefore, the value of carbon dioxide for EOR is the same whether it is conducted in China, Australia, North America, or the EU.

- But the cost of capturing and compressing carbon dioxide from a fossil-fueled power plant is NOT uniform across the world. It's vastly cheaper in China due to faster construction schedules and cheaper inputs.

Implications

- Deploy first CCS projects in China, potentially moving through the learning curve years sooner than conventional “West Deploys First” strategies assume.

- Priorities
  - Facilitate EOR in China
  - Form West-China CCS business partnerships that will build CCS projects globally

Methods and Measures for CCS Costs

Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

Presentation to the
CCS Cost Workshop
Paris, France

March 22, 2011

Outline of Talk

- What measures of CCS cost are most useful?
- What methods are used to quantify these costs (and their uncertainties)?
- How consistent are the costing methods and assumptions used by different organizations?
- How can the CCS community improve the quantification and reporting of CCS costs?

Déjà vu

E.S. Rubin, Carnegie Mellon

From GHGT-6, October 2002:

Many Factors Affect CCS Costs

- Choice of Power Plant and CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; *e.g.*,
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO_2 only vs. all GHGs)
  - Power plant only vs. partial or complete fuel cycle
- Time Frame of Interest
  - First-of-a-kind plant vs. n^{th} plant
  - Current technology vs. future systems
  - Consideration of technological "learning"

E.S. Rubin, Carnegie Mellon

Measures of CCS cost

E.S. Rubin, Carnegie Mellon

Recent CCS Cost Estimates

- 2005: IPCC Special Report on CCS
- 2007: Rubin, et al., *Energy Policy*
- 2007: EPRI Report No. 1014223
- 2007: DOE/NETL Report 2007/1281
- 2007: MIT *Future of Coal* Report
- 2008: EPRI Report No. 1018329
- 2009: Chen & Rubin, *Energy Policy*
- 2009: ENCAP Report D.1.2.6
- 2009: IEAGHG Report 2009/TR-3
- 2009: EPRI Report No. 1017495
- 2010: Carnegie Mellon IECM v. 6.4
- 2010: UK DECC, Mott MacDonald Report
- 2010: Kheshgi, et al., SPE 139716-PP
- 2010: DOE/NETL Report 2010/1397
- 2010: DOE EIA Cost Update Report
- 2011: OECD/IEA Working Paper
- 2011: Global CCS Institute Update

E.S. Rubin, Carnegie Mellon

Measures of CCS Cost

- Cost of CO_2 avoided
- Cost of CO_2 captured
- Added cost of electricity
- Capital cost
- Dispatch (variable) cost

E.S. Rubin, Carnegie Mellon

Dollars per Ton

- This is the metric most commonly used in technical and policy forums to quantify the cost of CCS (as well as other methods of reducing carbon emissions)
- Also the measure most easily misunderstood, misleading and most often misapplied

E.S. Rubin, Carnegie Mellon

Similar Units, Different Meanings

- Cost of CO_2 Avoided (\$/t CO_2)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(t\ CO_2/MWh)_{ref} - (t\ CO_2/MWh)_{ccs}}$$

- Cost of CO_2 Captured (\$/t CO_2)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(t\ CO_2/MWh)_{ccs,\ produced} - (t\ CO_2/MWh)_{ccs}}$$

- Cost of CO_2 Abated (Reduced) (\$/t CO_2)

$$= \frac{(\$\ NPV)_{ccs} - (\$\ NPV)_{reference}}{(t\ CO_2)_{ref} - (t\ CO_2)_{ccs}}$$

E.S. Rubin, Carnegie Mellon

Cost of CO_2 Avoided

- Cost of CO_2 Avoided (\$/t CO_2)

$$= \frac{(COE)_{ccs} - (COE)_{reference}}{(t\ CO_2/MWh)_{ref} - (t\ CO_2/MWh)_{ccs}}$$

- This is the measure most frequently used to quantify the cost of CCS
- It should (but often does not) include the full cost of CCS, i.e., capture, transport and storage (because emissions are not avoided unless/until the CO_2 is sequestered)
- It is a relative cost measure that is very sensitive to the choice of reference plant without CCS

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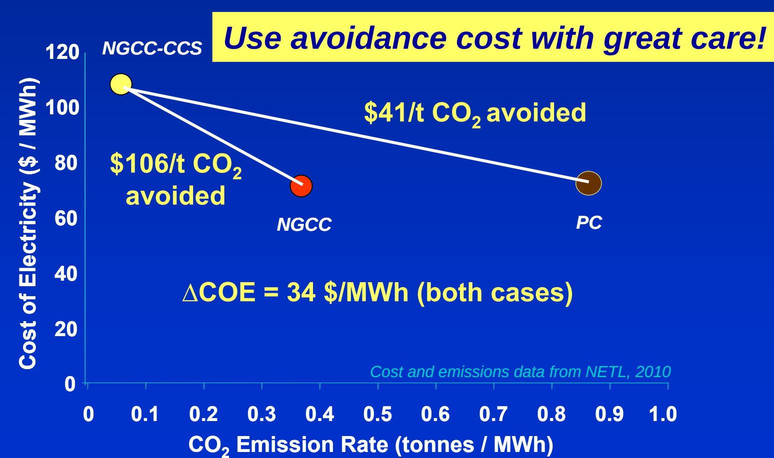
Cost of CO_2 avoided is sensitive to assumed reference plant w/o CCS

- *Q: What is the cost of CCS for an NGCC plant?*



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Cost of Electricity (COE)

$$\text{COE (\$/MWh)} = \frac{\text{(TCC)(FCF)} + \text{FOM}}{\text{(CF)(8760)(MW)}} + \text{VOM} + \text{(HR)(FC)}$$

TCC = Total capital cost ($)
FCF = Fixed charge factor (fraction)
FOM = Fixed operating & maintenance costs ($/yr)
VOM = Variable O& M costs, excluding fuel cost ($/MWh)
HR = Power plant heat rate (MJ/MWh)
FC = Unit fuel cost ($/MJ)
CF = Annual average capacity factor (fraction)
MW = Net power plant capacity (MW)

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COE Comes in Different Flavors

- Year-by-year COE
  - Uses a discounted cash flow analysis with parameter values specified for each year of plant construction and operation
- First year COE
  - Uses parameter values for first year of operation
- Levelized COE
  - Uniform annual value giving the same net present value as the year-by-year case

Levelized COE

- This is the most common method of reporting COE. Also used to calculate the cost of CO_2 avoided.
- LCOE implies that parameters in the COE equation (such as FCF and CF) reflect their levelized values over the life of the plant.
- Annual O&M costs in the COE equation are multiplied by a "levelization factor" (LF) that is calculated from specified rates of inflation and real cost escalations over the life of the plant.
- Until recently most studies assumed LF = 1.0.

Many different parameters influence the cost of CCS !

Ten Ways to Reduce CCS Costs

(First presented at GHGT-6, Oct. 2002; Inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report \$/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume **all of the above !**

. . . and we have not yet considered the CCS technology!

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Methods for CCS cost estimates

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A Hierarchy of Methods

- Ask an expert
- Use published values
- Modify published values
- Derive new results from a model
- Commission a detailed engineering study

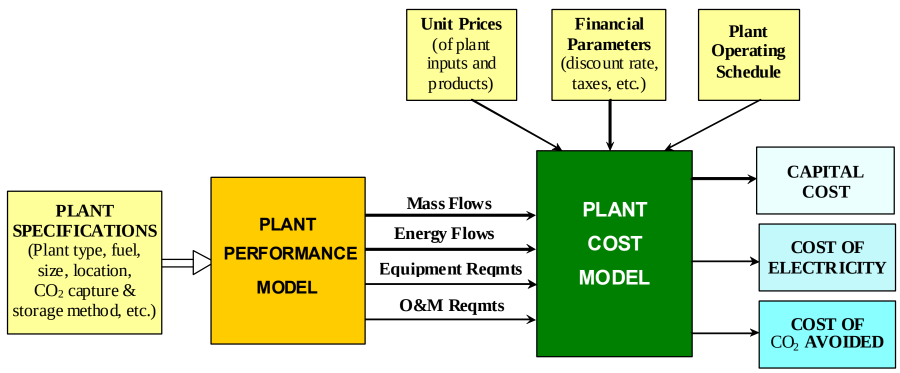
EPRI/AACE Categories of Cost Estimates

(and their attributes)

Item	Design-Estimate Effort	Project Contingency Range[a] (%)	Design Information Required	Cost Estimate Basis		
				Major Equipment	Other Materials	Labor
Class I (Similar to Amer. Assoc. of Cost Engineers (AACE) Class 5/4)	Simplified	30–50	General site conditions, geographic location and plant layout Process flow/operation diagram Product output capacities	By overall project or section-by-section based on capacity/cost graphs, ratio methods, and comparison with similar work completed by the contractor, with material adjusted to current cost indices and labor adjusted to site conditions.		
Class II (Similar to Amer. Assoc. of Cost Engineers Class 3)	Preliminary	15–30	As for Type Class I plus engineering specifics, e.g.: Major equipment specifications Preliminary P&I[b] flow diagrams	Recent purchase costs (including freight) adjusted to current cost index	By ratio to major equipment costs on plant parameters	Labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates
Class III (Similar to Amer. Assoc. of Cost Engineers Class 3/2)	Detailed	10–20	A complete process design Engineering design usually 20–40% complete Project construction schedule Contractual conditions and local labor conditions	Firm quotations adjusted for possible price escalation with some critical items committed	Firm unit cost quotes (or current billing costs) based on detailed quantity take-off	Estimated man-hour units (including assessment) using expected labor rate for each job classification
				Pertinent taxes and freight included		
Class IV (Similar to Amer. Assoc. of Cost Engineers Class 1)	Finalized	5–10	As for Class III, with engineering essentially complete	As for Class III, with most items committed	As for Class III, with material on approximately 100% firm basis	As for Class III, some actual field labor productivity may be available

[a] Expressed as a percentage of the total of process capital, engineering and home office fees, and process contingency.

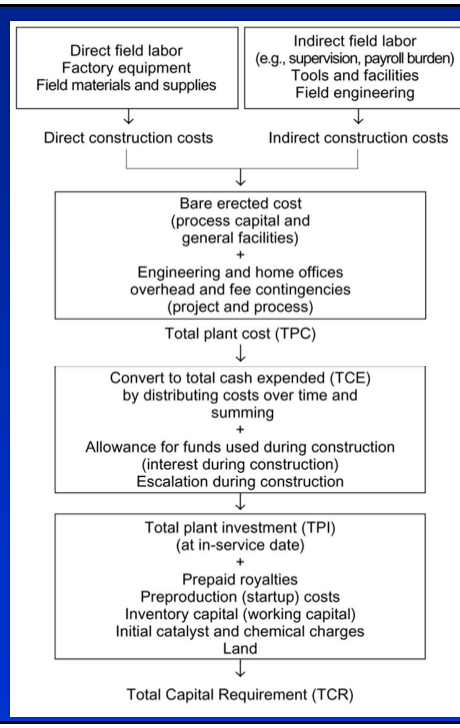
Framework for Cost Estimation



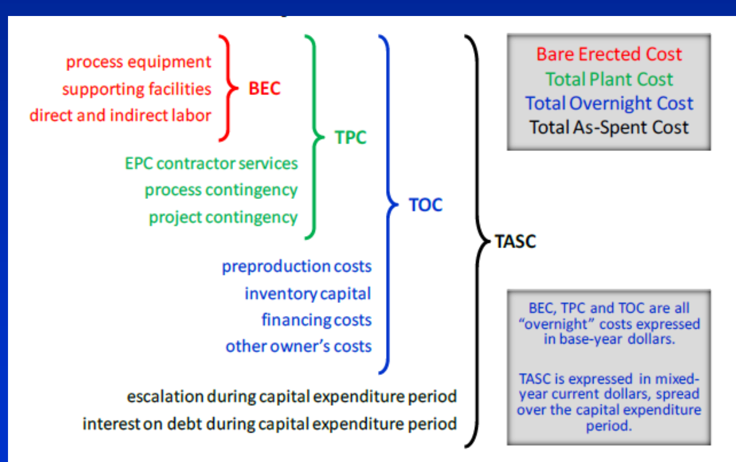
Current Status

- Individual organizations have developed detailed procedures and guidelines for calculating power plant costs (capital, O&M, COE) in a consistent fashion
- However, there are significant differences in the costing methods used by different organizations concerned with CO_2 capture and storage

EPRI Capital Cost Elements



DOE/NETL Capital Cost Elements



Capital Cost Elements in Recent Studies

EPRI TAG (2009)	USDOE/NETL (2007)	USDOE/NETL (2010)	USDOE/EIA (2010)
Process facilities capital	Bare erected cost (BEC)	Bare erected cost (BEC)	Civil Structural Material & Installation
General facilities capital	Eng. & Home Office Fees	Eng. & Home Office Fees	Mechanical Equip. Supply & Installation
Eng'g, home office, overhead & fees	Project Contingency Cost	Project Contingency Cost	Electrical/I&C Supply and Installation
Contingencies—project and process	Process Contingency Cost	Process Contingency Cost	Project Indirects
Total plant cost (TPC)	**Total plant cost (TPC)**	**Total plant cost (TPC)**	EPC Cost before Contingency and Fee
AFUDC (interest & escalation)		Pre-Production Costs	Fee and Contingency
Total plant investment (TPI)		Inventory Capital	**Total Project EPC**
Owner's costs: royalties, preproduction costs, Inventory capital, Initial catalyst and chemicals, Land		Financing costs	Owner's Costs (excl. project finance)
		Other owner's costs	**Total Project Cost (excl. finance)**
Total Capital Requirement (TCR)		**Total overnight cost (TOC)**	

IEA GHG (2009)	ENCAP (2009)	UK DECC (2010)
Direct materials	EPC costs	Pre-licencing costs, Technical and design
Labour and other site costs	Owner's costs	Regulatory + licencing + public enquiry
Engineering fees	**Total Investment**	Eng'g, procurement & construction (EPC)
Contingencies		Infrastructure / connection costs
Total plant cost (TPC)		**Total Capital Cost (excluded IDC)**
Construction interest		
Owner's costs		
Working capital		
Start-up costs		
Total Capital Requirement (TCR)		

No consistent set of cost categories or nomenclature across studies

Elements of "Owner's Costs" in Several Recent Studies

USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI TAG (2009)	IEA GHG (2009)	UK DECC (2010)
(None)	Preproduction (Start-Up) costs	Preproduction (Start-Up) costs	Feasibility studies	(None)
	Working capital	Prepaid royalties	Obtaining permits	
	Inventory capital	Inventory capital	Arranging financing	
	Financing cost	Initial catalyst/chem.	Other misc. costs	
	Land	Land	Land purchase	
	Other			

No consistent set of cost categories or nomenclature across studies

O&M Cost Elements in Recent Studies

Category	USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI TAG (2009)
Fixed O&M	Operating labor	Operating labor	Operating labor
	Maintenance –labor	Maintenance –labor	Maintenance costs
	Admin. & support labor	Admin. & support labor	Overhead charges (admin & support labor)
		Property taxes and insurance	
Variable O&M (excl. fuel)	Maintenance – material	Maintenance – material	Maintenance costs
	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)
	Waste disposal	Waste disposal	Waste disposal
	Co- or by-product credit	Co- or by-product credit	Co- or by-product credit
	CO2 transport and storage	CO2 transport and storage	CO2 transport and storage

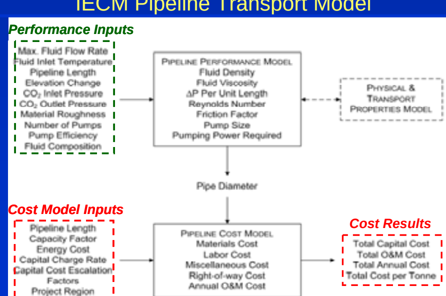
No consistent set of cost categories or nomenclature across studies

Category	IEA GHG (2009)	UK DECC (2010)
Fixed O&M	Operating labour	Operating labour
	Indicative cost	Planned and unplanned maintenance (additional labour, spares and consumables)
	Administrative and support labour	
	Insurance and local property taxes	Through life capital maintenance
	Maintenance cost	
Variable O&M (excl. fuel)	Consumables (water, chemicals, etc.)	Repair and maintenance costs
	By-products and wastes disposal	Residue disposal and treatment
	CO2 transport and storage	Connection & transmission charges
		Insurance
		CO2 transport and storage
		Carbon price

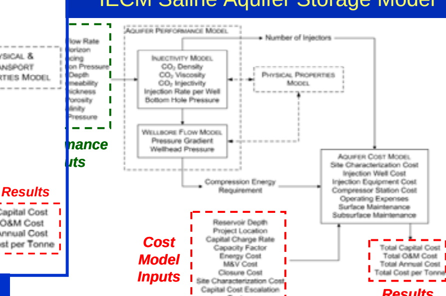
Transport and Storage Cost Models Also Differ in Scope and Complexity

- Most CCS cost estimates specify T&S costs as a lumped O&M cost.
- Some methods disaggregate T&S cost elements and/or employ more detailed performance and cost models to calculate costs.

IECM Pipeline Transport Model



IECM Saline Aquifer Storage Model



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Do We All Make the Same Assumptions?

- Different assumptions commonly reflect different circumstances or perspectives
- They can also reflect variability, uncertainty and biases (more on this later)

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Examples of Assumptions in Recent Studies

Parameter	USDOE/NETL 2007	USDOE/NETL 2010	EPRI 2009	IEA GHG 2009	UK DECC 2010
Plant Size (PC case)	550 MW (net)	550 MW (net)	750 MW (net)	800 MW (net)	1600 MW (gross)
Capacity Factor	85%	85%	85%	85% (yr 1= 60%)	varies yearly
Constant/Current $	Current	Current	Constant	Constant	Constant
Discount Rate	10%	10%	7.09%	8%	10%
Plant Book Life (yrs)	20	30	30	25	32-40 (FOAK) 35-45 (NOAK)
Capital Charge Factor					
no CCS	0.164	0.116	0.121	N/A	N/A
w/ CCS	0.175	0.124	0.121	N/A	N/A
Variable Cost Levelization Factor					
no CCS	1.2089 (coal) 1.1618 (other)	1.2676	1.00	1.00	N/A
- w/ CCS	1.2022 (coal) 1.1568 (other)	1.2676	1.00	1.00	N/A

N/A: not available

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DOE Cost Method Revisions Increased Reported CCS Costs

USDOE Baseline Bituminous Study (NETL 2007 vs. NETL rev. 2010)

Reported Cost in 2007$	**SCPC** (Case 11)	**SCPC+CCS** (Case 12)	**CCS Cost** (C12 - C11)
Bare Erected Cost ($/kW)	1286	2207	**921**
Bare Erected Cost, *rev* ($/kW)	1345	2239	**894**
% increase	***5%***	***1%***	***-3%***
Total Plant Cost ($/kW)	1575	2870	**1295**
Total As-Spent Capital, *rev* ($/kW)	2296	4070	**1774**
% increase	***46%***	***42%***	***37%***
LCOE ($/MWh)	63.3	114.8	**52**
LCOE, *rev* ($/MWh)	74.7	135.2	**61**
% increase	***18%***	***18%***	***17%***

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The Devil is in the Details

- Can we improve the reporting and transparency of costing methods and assumptions to improve the understanding of CCS costs?

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Uncertainty, Variability and Bias

Uncertainty

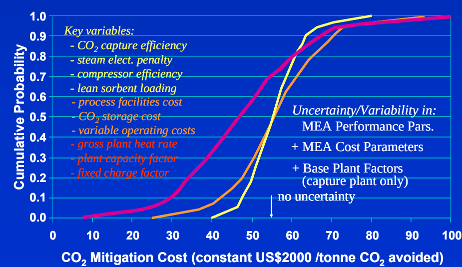
- This reflects a lack of knowledge about the precise value of parameters that affect CCS cost. Especially important for new capture processes at early stages of development.
- Cost methods may (in principle) account for uncertainties via assumptions and probability distributions for key performance, financial and cost factors (e.g., contingencies)
- Historical experience, expert elicitations and insights from relevant "learning curves" can help inform judgments

Technology Status	Process Contingency (% of Associated Process Capital)
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

AACE Guidelines

Variability

- This refers to differences in the value of a parameter across a collection of facilities, or at a single facility
- Can be expressed as a probability distribution function or (more simply) as a range of (known) values
- Cost methods can account for variability via parametric (sensitivity) analysis or a probabilistic analysis (as below)



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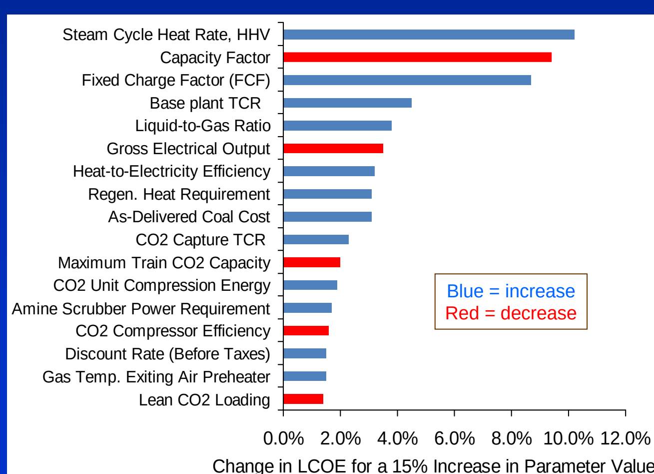
Important to Identify Key Parameters that Affect Results of Interest

Sensitivity of LCOE to a 15% increase in the nominal value of ~150 IECM parameters for a SCPC-CCS power plant.

17 parameters (shown here) changed LCOE by > 1% (other values constant)



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Bias

- Can be reflected in the project design specifications as well as in the choice of parameters and parameter values for cost estimates
- Can be hard to detect or “prove” since often depends on judgment. Independent (3rd party) evaluations can help identify areas and issues of concern.
- One example appears to be an optimistic assumption of levelized capacity factor in recent cost studies of U.S. coal-fired power plants

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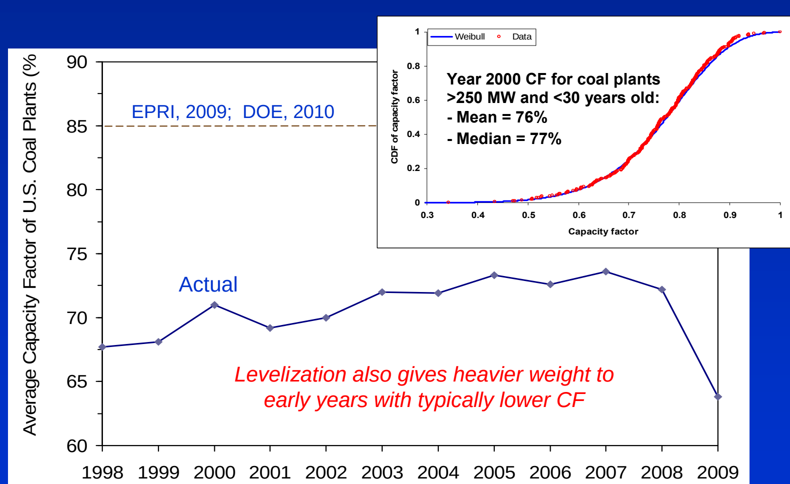
Actual vs. Assumed Capacity Factors for U.S. Coal Plants



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Closing Thoughts

- *Reminder*: The *true* costs of CCS are still unknown since we have yet to build and operate full-scale power plants with CCS
- This workshop, and potential follow-on meetings, can go a long way to improve the understanding and communication of CCS costs within the technical and policy communities
- Some topics/questions for discussion:
  - Can we improve the reporting, consistency and transparency of costing methods and assumptions?
  - Can we improve our methods of characterizing and incorporating uncertainties and variability?
  - Can we improve methods to compare CCS to other options?

Thank You

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CCS – Costing Methods and Measures

CCS Costs Workshop at IEA

Alstom, JF Leandri

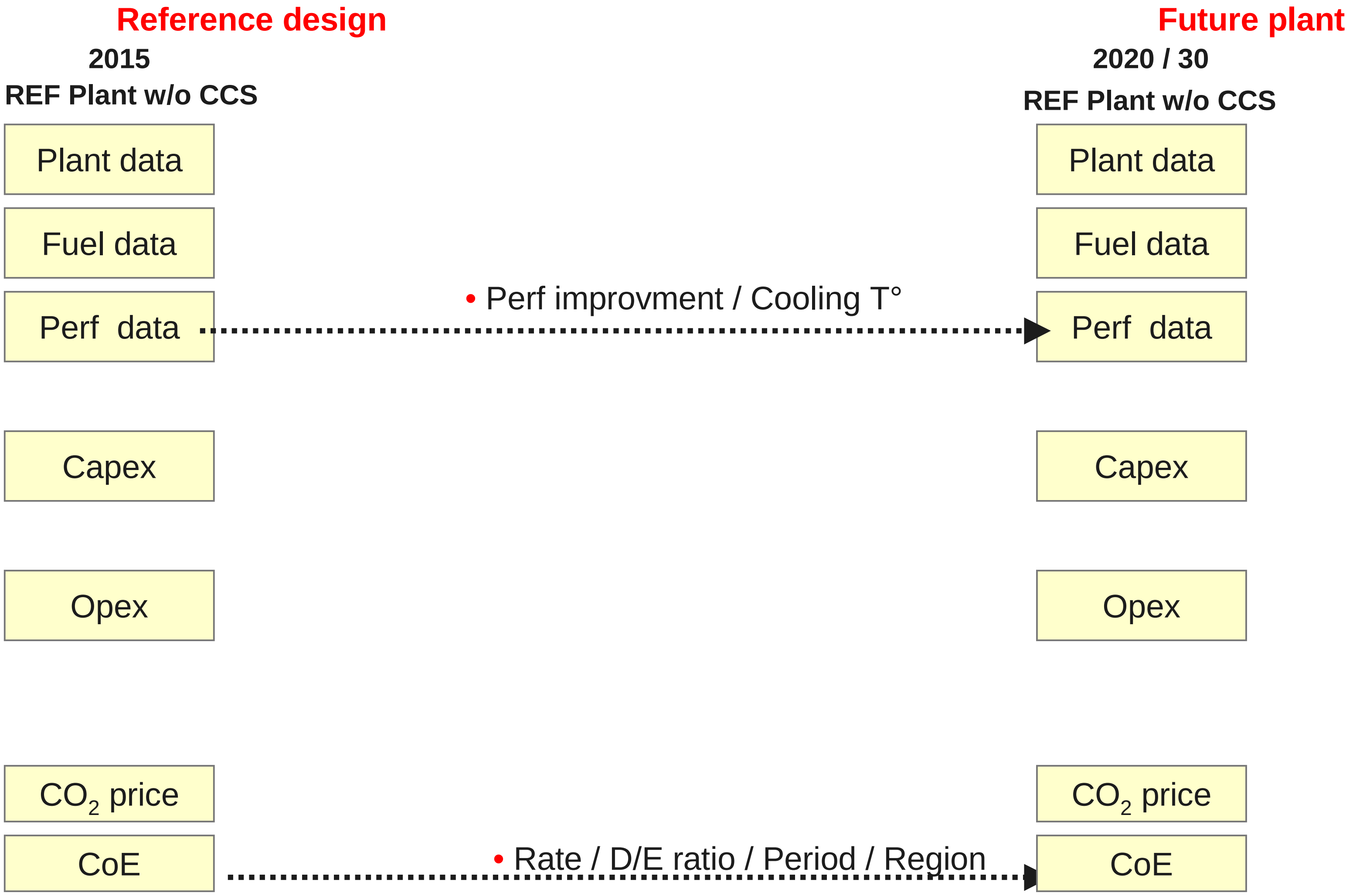
IEA Paris
22-23 March 2011

POWER | ALSTOM

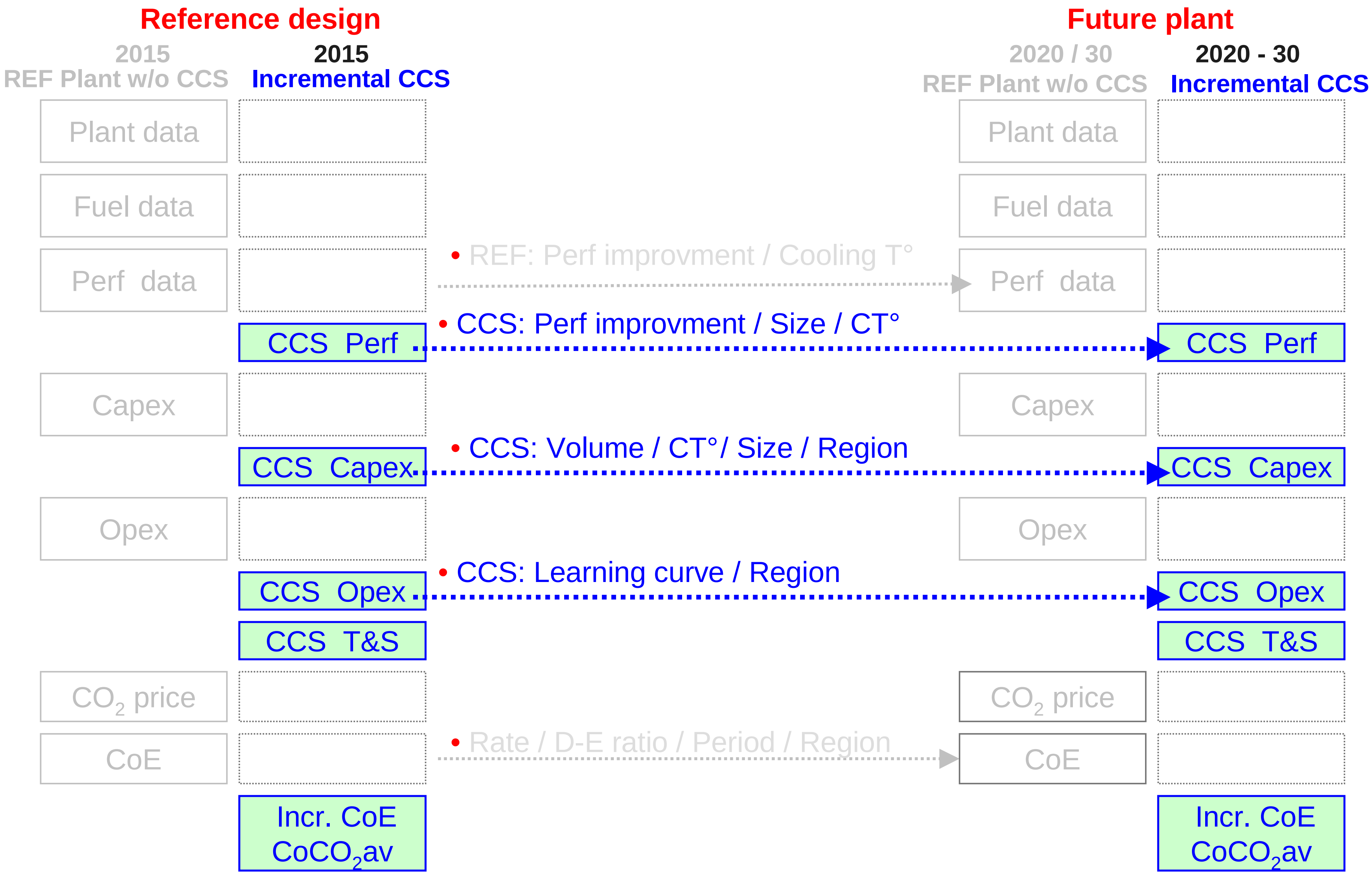
Objectives

1. Calculate a CoE 2010 or 2015 for CCS technology
2. Derive CoE for CCS technologies on long term (2030)
3. Evaluate competitiveness against other technologies using same costing methodology

Cost of Electricity
Costing methods – Conventional reference plant

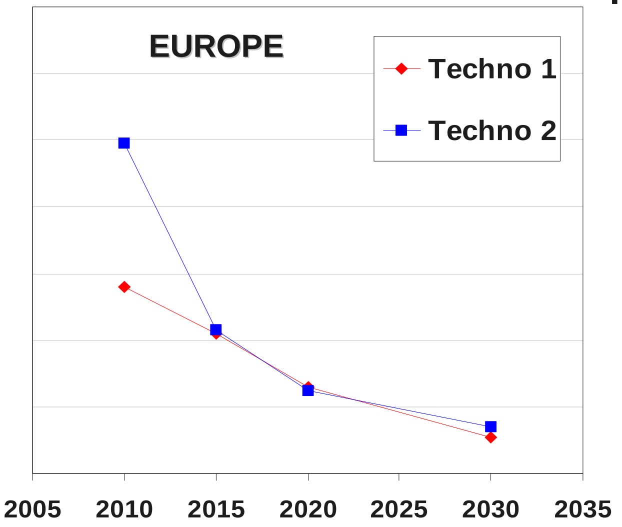


Cost of Electricity
Costing methods – CCS plant

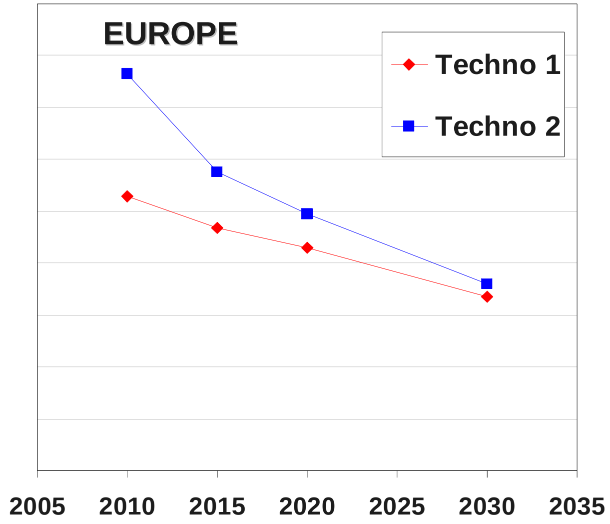


Cost of Electricity
Illustrative results 1/2

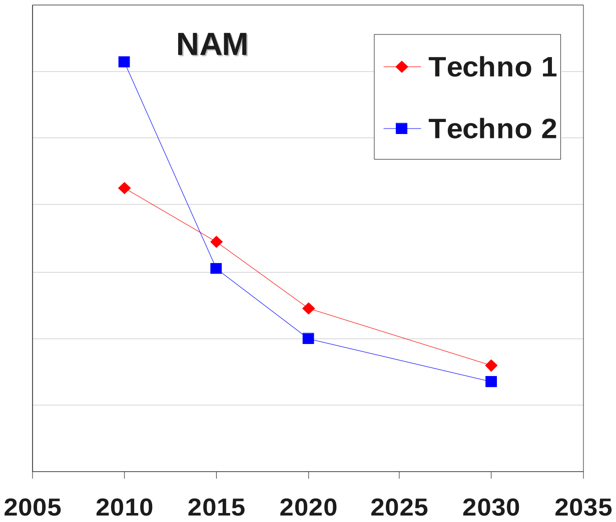
Energy Penalty ....**Capex, Opex…**



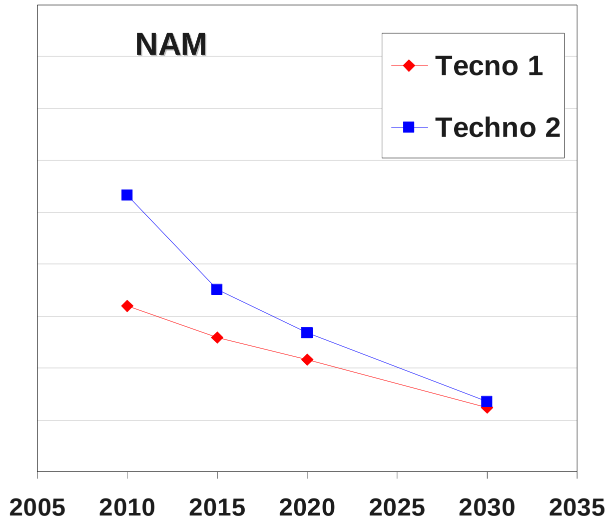
CoE **CoCO2**



Energy Penalty

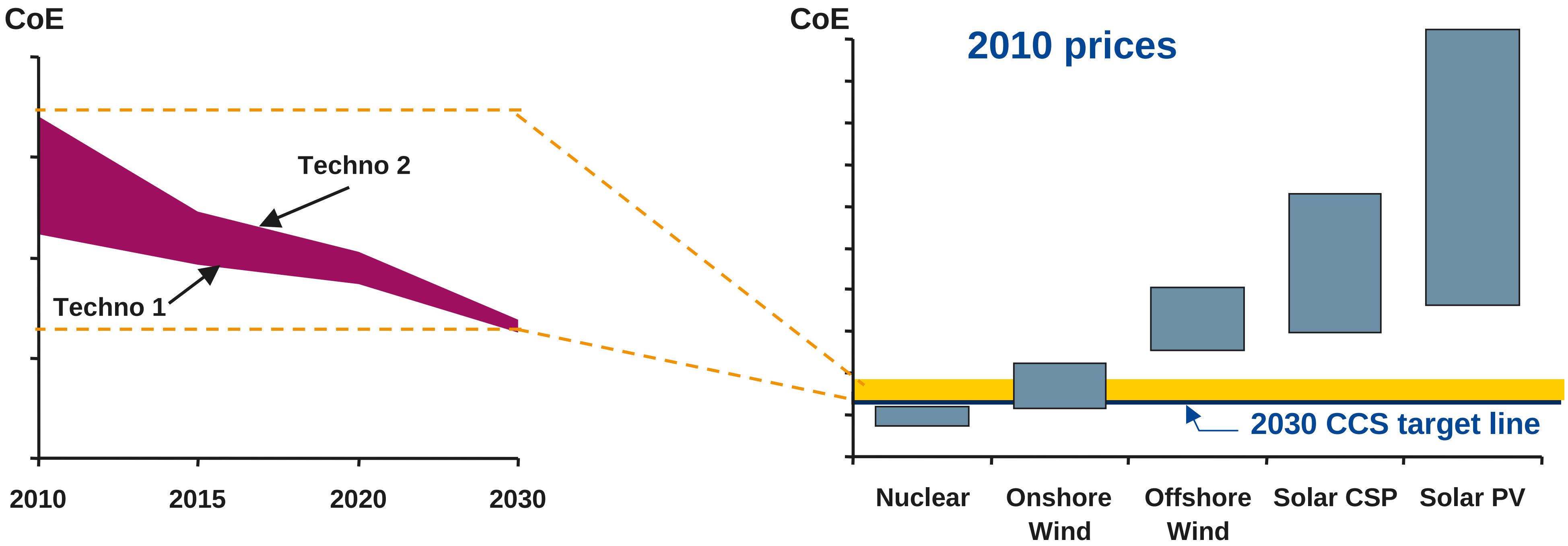


CoE



Cost of Electricity
Illustrative results 2/2

CoE of Coal with CCS vs. other decarbonised Power generation technologies - Europe



Source: Alstom

- CCS cost will decrease through learning effect
- No clear winner among CCS technologies
- CCS is competitive against all renewables

jfl

Cost of Electricity
Synthesis costing methods

ALSTOM

1. Formulate what are the objectives pursued and the corresponding metrix
   - ✓ Regions, years, fuels, technologies etc….
   - ✓ Comparing CCS technologies different from comparing CCS w other carbon free technologies

2. Clear definitions and visible assumptions and source of data
   - ✓ Macroeconomics
   - ✓ A cost is an opinion, to understand it we need to know the rationales behind it

3. Benchmark + Peer reviews

Appendix

CO_2 Capture Costing Methods and Measures
Utility Respondent
IEA CCS Cost Workshop 22 – 23 March 2011

Clas Ekström, Vattenfall

18th March 2011
Confidentiality - None (C1)

Assumptions and Boundary Conditions

- Reference/Baseline Power plants w/o CCS:
  - Own new-built, studied and/or planned power plants, state-of-the-art
- Concepts for power plants with CO_2 capture developed for same fuel, based on such reference plants.
  a) Same fuel input/live steam flow-rate, steam parameters and similar plant design (water-steam circle)
  b) Same gas turbine
  c) Exception: IGGC with capture and other technologies where there is no technical link between a reference plant and a plant with CO_2 capture
- Prices of Fuels, CO_2 Emission Allowances (EU), Sold Electricity:
  - Internally used price projections, different scenarios
- Financial boundary conditions:
  - Real or nominal interest rate
    - WACC (Weighted Average Capital Cost)
  - Economic lifetime
    - Often shorter than technical lifetime
- Calculations of:
  a) NPV and IRR
  b) Levelised Cost of Electricity (for which NPV = 0)
  c) CO_2 avoidance costs
- In particular if we compare a power plant w/o capture and a power plant with CO_2 capture, e. g. to calculate CO_2 avoidance costs, consistency is most important. Consistency and comparability is even more complicated when looking at different capture technologies.

Investment Costs

costs of all installations on the site to the fence
(excluding harbour and mining facilities but including coal yard and coal handling equipment).

EPC (Engineering, Procurement and Construction Costs)

EPC estimates from Equipment suppliers and/or from power utility company based on own plant projects for entire power plant and/or for entire process units

Owners Costs Contingencies

Heat & Mass Balances Design Parameters

- Fuel handling
- Boiler
- CO_2 Processing
- Balance Of Plant

Owners costs:
Planning,
Designing,
Commissioning
the plant

Contingencies

Alternative: When EPC cost estimates for entire process units can not be obtained

Requires access to extensive set(s) of detailed data

DIRECT COSTS

INDIRECT COSTS

Heat & Mass Balances Design Parameters

Equipment Costs

- Fuel handling
- Boiler
- CO_2 Processing

step-count exponential costing method using cost data from equipment suppliers and/or other available data

Installation Costs

Integrate Modules into Plant

piping/valves, civil works, instrumentations, electrical installations, insulations, paintings, steel structures, erections,

OSBL (outside battery limits).

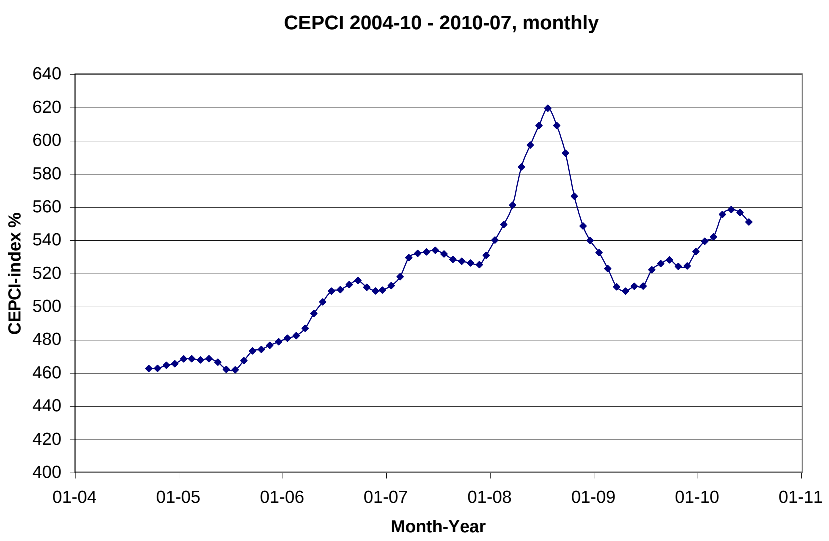
% of DIRECT COSTS

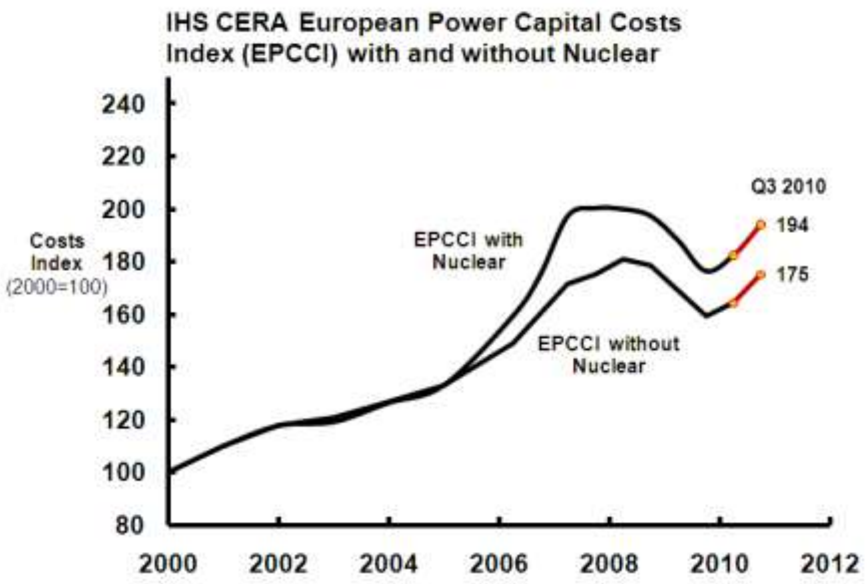
Yard Improvement, service facilities, engineering costs, building, sundries

Handling Volatility in Plant and Equipment Costs

Plant and equipment cost data - especially when using and/or updating cost estimates from earlier years - are adjusted to cost levels for actual time period by applying cost indexes like:

CEPCI Chemical Engineering Plant Cost Index





O&M Costs (Operation and maintenance costs)

O&M costs include all costs related to the operation and maintenance of the plant during the whole plant life.

Especially overhaul and to some extent spare parts will vary from year to year.

a) It is assumed that all operation and maintenance costs are equally high each year.
b) Significant overhauls are treated as re-investments at expected year

The O&M costs can be divided into:

- Fixed O&M costs (EUR/kWel gross or net per year, or as % of EPC costs)
- Variable O&M costs (EUR/MWhel gross or net)

Fixed O&M costs.

- For reference/baseline power plant w/o CCS, based on experiences from operation and maintenance of own plants.
- For power plants with CO_2 capture, differences compared to reference/baseline power plant w/o CCS estimated, often based on equipment vendor estimates

- Costs of personnel, administration. Often calculated
- Insurance; input often as % of EPC costs
- Maintenance, incl. spare parts and overhaul. Input often as % of EPC costs.

Variable O&M costs.

- Costs of consumables (water, limestone etc.) and disposal (ash, gypsum etc.)
- Often calculated

VATTENFALL

ECLIPSE ECONOMIC Modelling

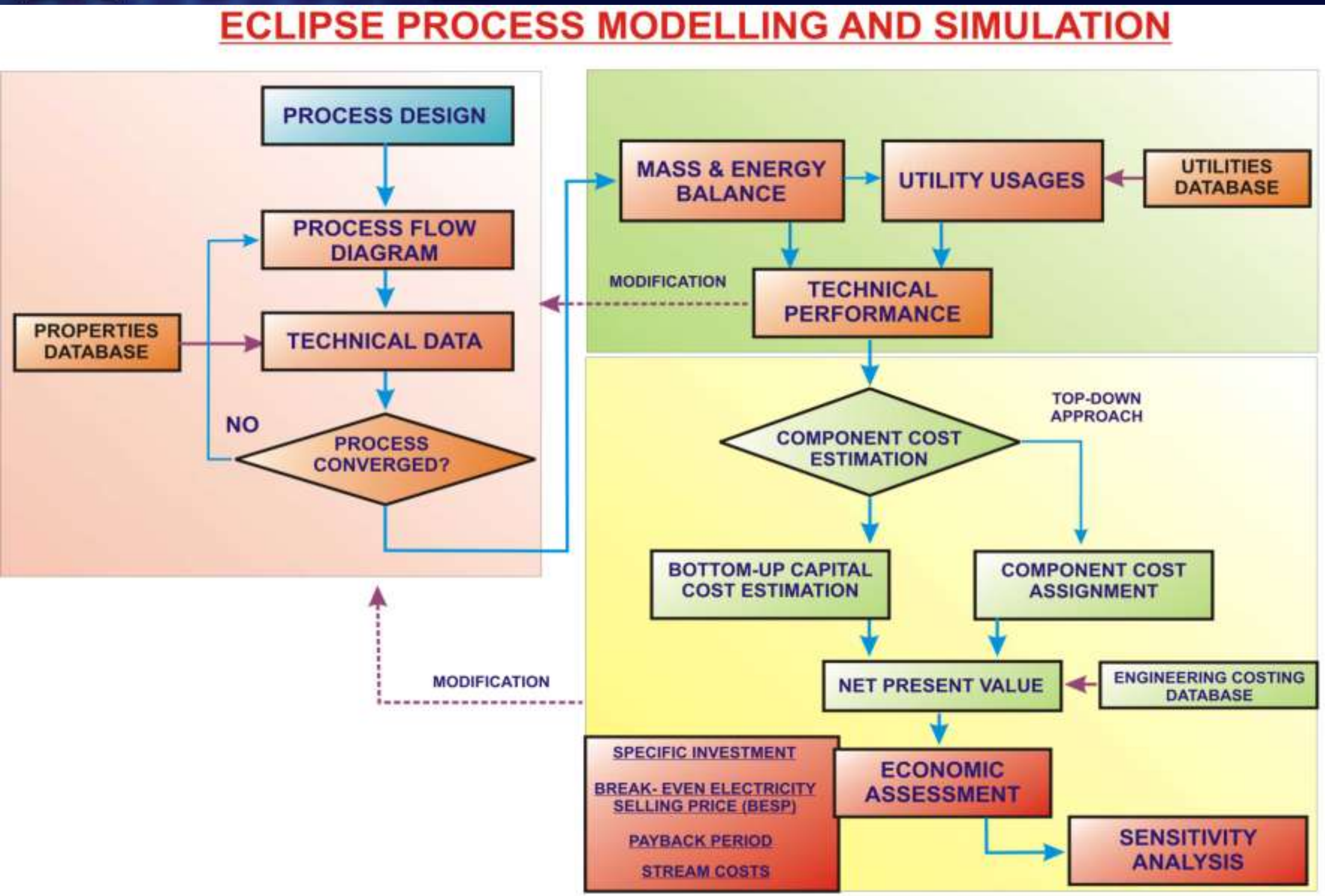
Sina Rezvani, Dipl.-Ing., MRes, PhD, CEng, MIEE, MIE

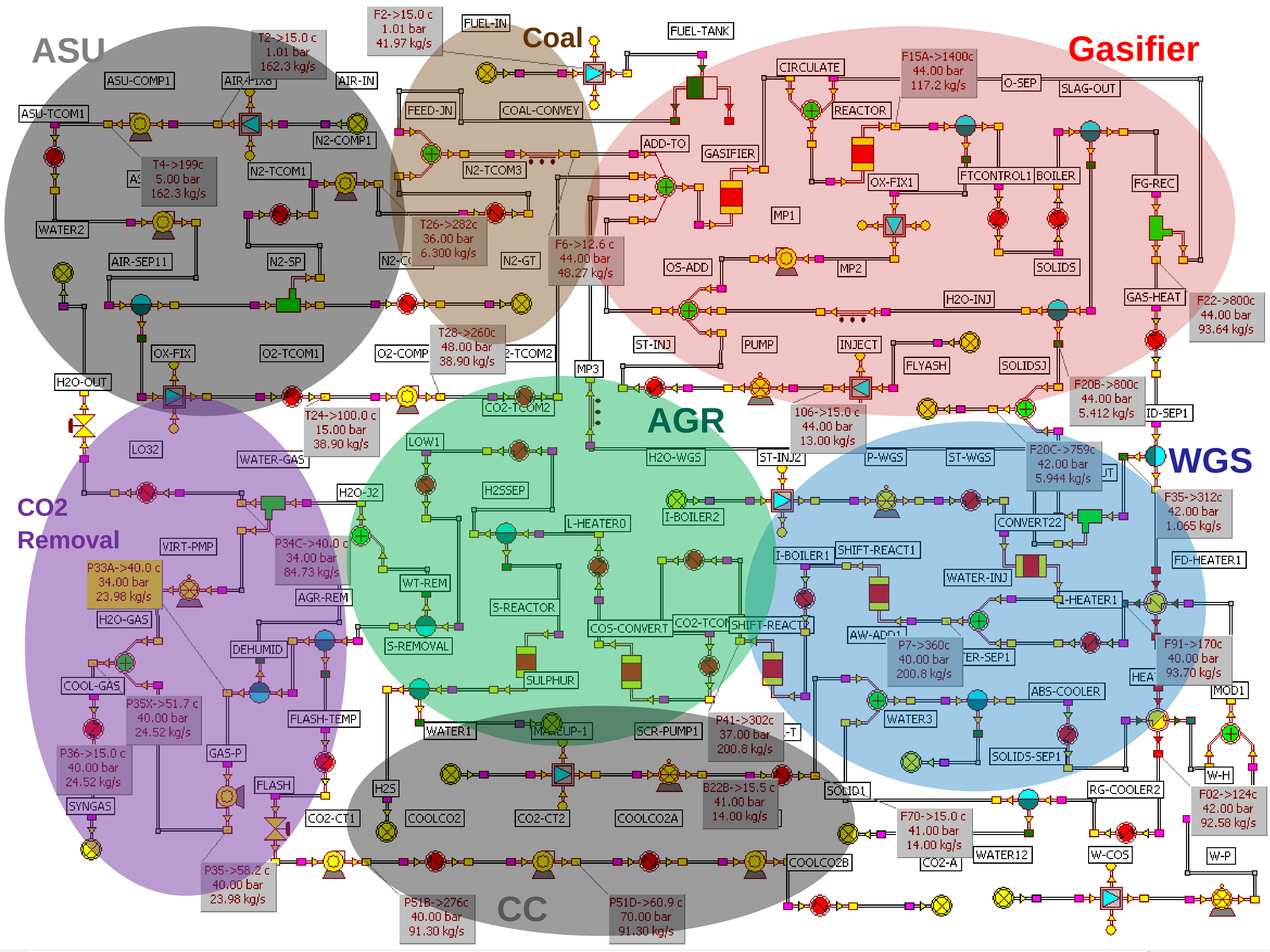
(University of Ulster, UK)

Total Cost Assessment

1. Exergy cost Analysis
   - Evaluation of the cost for each stream
   - Internal cost/ not market cost
2. Parametric estimation
   - Based on historical data
   - Cost Scaling (factors used to scale up/down costs)
   - Mathematical modelling of available key features
3. Factored Cost estimate/Bottom-up approach
   - Work breakdown structure
   - Allocation of costs to individual elements
4. Analogous system estimate/Top-down approach
   - Case based approach/inferential cost estimation of the entire system
   - Comparison and extrapolation
   - Cost adaptation and optimisation
   - Cost breakdown
5. Vendor quotes
   - Costs are obtained from vendors.

ECLIPSE Architecture

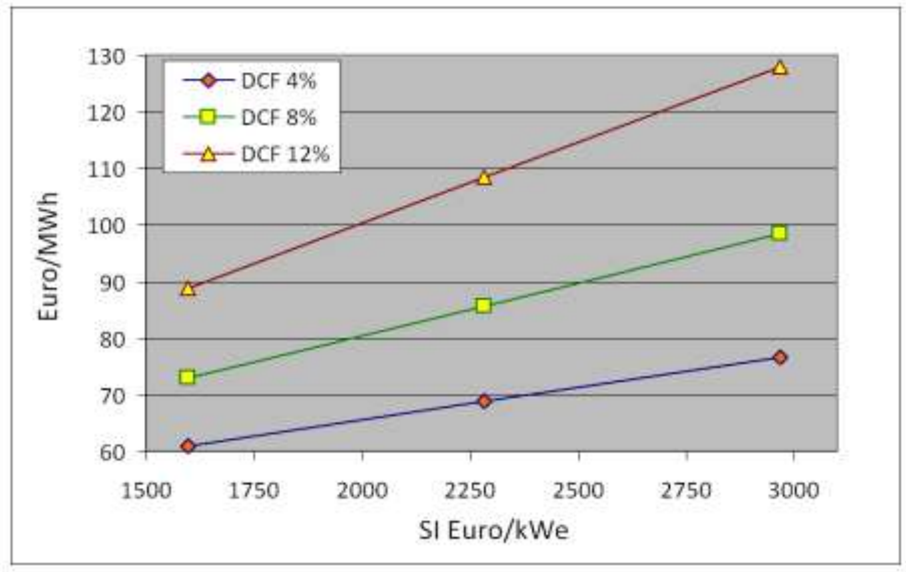


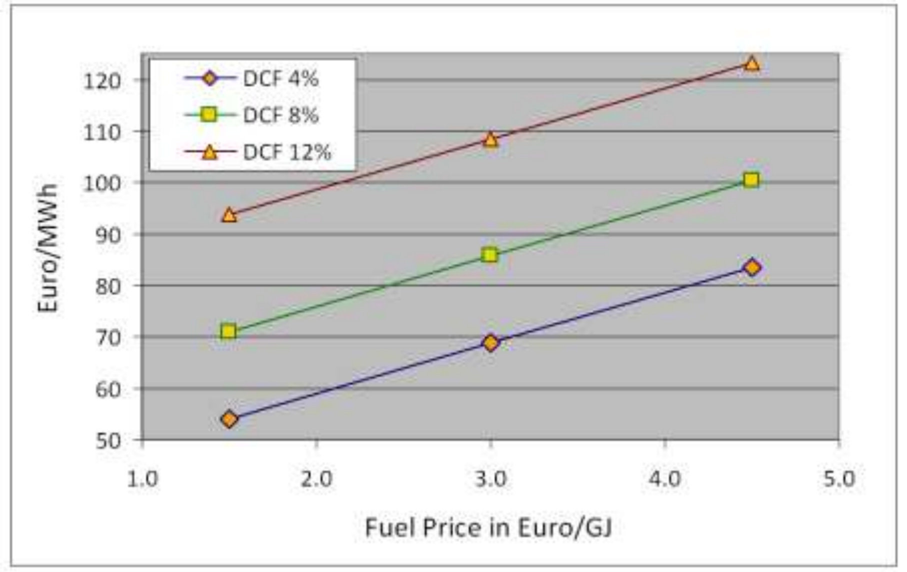


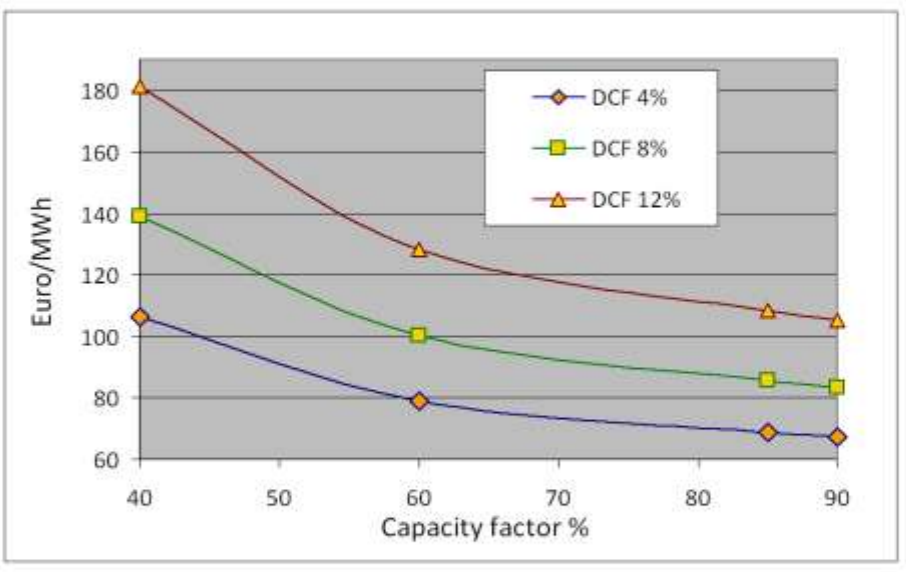
ASU
Coal
Gasifier
AGR
WGS
CO2 Removal
CC
F2->15.0 c
1.01 bar
41.97 kg/s
T2->15.0 c
1.01 bar
162.3 kg/s
T4->199c
5.00 bar
162.3 kg/s
T26->282c
36.00 bar
6.300 kg/s
F6->12.6 c
44.00 bar
48.27 kg/s
T28->260c
48.00 bar
38.90 kg/s
T24->100.0 c
15.00 bar
38.90 kg/s
F15A->1400c
44.00 bar
117.2 kg/s
F22->800c
44.00 bar
93.64 kg/s
F20B->800c
44.00 bar
5.412 kg/s
106->15.0 c
44.00 bar
13.00 kg/s
F20C->759c
42.00 bar
5.944 kg/s
F35->312c
42.00 bar
1.065 kg/s
P34C->40.0 c
34.00 bar
84.73 kg/s
P33A->40.0 c
34.00 bar
23.98 kg/s
P35X->51.7 c
40.00 bar
24.52 kg/s
P36->15.0 c
40.00 bar
24.52 kg/s
P35->58.2 c
40.00 bar
23.98 kg/s
P7->360c
40.00 bar
200.8 kg/s
F91->170c
40.00 bar
93.70 kg/s
P41->302c
37.00 bar
200.8 kg/s
B22B->15.5 c
41.00 bar
14.00 kg/s
F70->15.0 c
41.00 bar
14.00 kg/s
F02->124c
42.00 bar
92.58 kg/s
P51B->276c
40.00 bar
91.30 kg/s
P51D->60.9 c
70.00 bar
91.30 kg/s
ASU-COMP1
AIR-FIXS
AIR-IN
ASU-TCOM1
N2-COMP1
N2-TCOM1
WATER2
AIR-SEP11
N2-SP
OX-FIX
O2-TCOM1
O2-COMP
H2O-OUT
FUEL-IN
FUEL-TANK
FEED-JN
COAL-CONVEY
N2-TCOM3
N2-GT
2-TCOM2
MP3
ADD-TO
GASIFIER
CIRCULATE
REACTOR
O-SEP
SLAG-OUT
OX-FIX1
FTCONTROL1
BOILER
FG-REC
MP1
MP2
OS-ADD
SOLIDS
H2O-INJ
GAS-HEAT
ST-INJ
PUMP
INJECT
FLYASH
SOLIDSJ
ID-SEP1
CO2-TCOM2
LOW1
H2SSEP
H2O-WGS
ST-INJ2
P-WGS
ST-WGS
I-BOILER2
L-HEATER0
H2O-J2
WT-REM
S-REACTOR
S-REMOVAL
COS-CONVERT
CO2-TCOM
SHIFT-REACT2
SULPHUR
CONVERT22
I-BOILER1
SHIFT-REACT1
WATER-INJ
FD-HEATER1
L-HEATER1
AW-ADD1
ER-SEP1
ABS-COOLER
WATER3
SOLIDS-SEP1
MOD1
W-H
RG-COOLER2
W-COS
W-P
WATER12
CO2-A
SOLID1
LO32
WATER-GAS
VIRT-PMP
AGR-REM
H2O-GAS
DEHUMID
COOL-GAS
FLASH-TEMP
GAS-P
FLASH
SYNGAS
CO2-CT1
H2S
COOLCO2
CO2-CT2
COOLCO2A
COOLCO2B
WATER1
MAKEUP-1
SCR-PUMP1

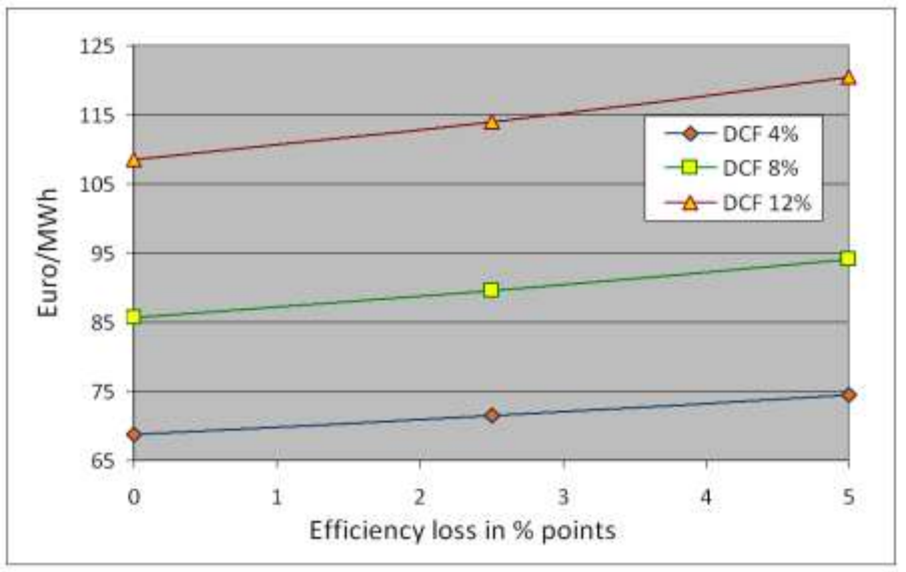
IGCC case studies

		NO CCS	H2-Rich gas	95% CCS	65% CCS	SNG +CCS
GT cost	M€	194.96	180.35	180.35	180.35	114.31
CCGT cost	M€	373.44	351.08	336.59	343.23	273.86
Gas gen. cost	M€	460.55	484.43	571.33	543.24	564.62
Syngas cost	€/GJ	6.67	7.34	8.09	7.58	9.36
Output net	GWh/a	3314.91	2857.05	2751.31	2982.74	2496.35
BESP	€/MWh	66.17	74.64	82.34	76.36	86.90


Euro/MWh
DCF 4%
DCF 8%
DCF 12%
SI Euro/kWe


Euro/MWh
DCF 4%
DCF 8%
DCF 12%
Fuel Price in Euro/GJ


Euro/MWh
DCF 4%
DCF 8%
DCF 12%
Capacity factor %


Euro/MWh
DCF 4%
DCF 8%
DCF 12%
Efficiency loss in % points

CARBON CAPTURE AND STORAGE

International Energy Agency

Keynote: CO_2 Capture Costs

CCS Costs Workshop, March 22 & 23, 2011, Paris

Matthias Finkenrath

CCS Unit, International Energy Agency

CARBON CAPTURE AND STORAGE

SCOPE

Summary of current status of **cost estimates** for **CO_2 capture** in **power plant** applications

OUTLINE

1 Early commercial plants

- Summary results from data analysis and reevaluation
- Variability (time, fuel source, power plant type, regional)
- Uncertainty and sensitivity
- Site-specific considerations

2 Demo plants

- Investment cost estimates

3 Retrofit

4 Potential future cost

- Learning curves, innovation, next generation

5 Capture applications with limited availability of data

6 Conclusions

EARLY COMMERCIAL PLANTS

- Data based on in-depth review for 2011 IEA Working Paper

Calibrated engineering study data of various institutions

- Carnegie Mellon University – CMU
- China-UK Near Zero Emissions Coal Initiative – NZEC
- CO_2 Capture Project – CCP
- Electric Power Research Institute – EPRI
- Global CCS Institute – GCCSI
- Greenhouse Gas Implementing Agreement – GHG IA
- National Energy Technology Laboratory – NETL
- Massachusetts Institute of Technology – MIT

Publication years & project locations

Organisation	CCP	CMU	EPRI	GCCSI	GHG IA	NETL	NZEC	MIT
Publication year(s)	2009	2007, 2009, 2010	2009	2009	2007, 2009	2008, 2010	2009	2007, 2009
Project location	EU	US	US	US	EU	US	CHN	US
Currency	USD	USD	USD	USD	USD, EUR	USD	CNY	USD

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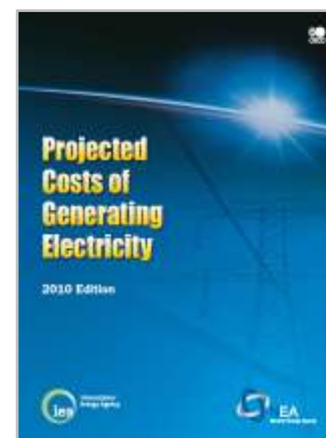
EARLY COMMERCIAL PLANTS

Scope of cost estimates and methodology

- Costing scope of published cost data recalibrated and costs updated to 2010 USD
- Only capture included, not transport and storage
- Focus on new-built power plants on a brown-field site
- Note: Some of the reviewed studies use the same engineering contractor or source for data

- Cost terminology and Levelized Cost of Electricity (LCOE) Methodology based on 2010 OECD Study:
  - Overnight costs key metric for capital costs
    (includes owner's cost, EPC costs, contingencies but no IDC)
  - Higher contingency for CCS vs. non-CCS plants
  - Same financial boundary conditions;
    fuel prices differ across regions
  - However, in contrast to OECD 2010 study,
    no CO_2 price is included



EARLY COMMERCIAL PLANTS

Average cost estimates across studies (2010 USD, OECD countries)

Fuel type	COAL			NG
Capture route	Post-combustion	Pre-combustion	Oxy-combustion	Post-combustion
Reference plant w/o capture	PC	IGCC (PC)	PC	NGCC
Net efficiency penalty (LHV, %-pts)	10.5	7.5	9.6	8.3
Overnight cost w/ capture (USD/kW)	3 808	3 714	3 959	1 715
Relative overnight cost increase	75%	44% (71%)	74%	82%
LCOE w/ capture (USD/MWh)	107	104	102	102
Relative LCOE increase	63%	39% (55%)	64%	33%
Cost of CO_2 avoided (USD/tCO_2)	58	43 (55)	52	80

Notes: Data cover only CO_2 capture and compression but not transportation and storage. The accuracy of feasibility study capital cost estimates is on average ±30%, hence for coal the variation in average overnight costs, LCOE and cost of CO_2 avoided between capture routes is within the uncertainty of the study. Underlying oxy-combustion data include some cases with CO_2 purities <97%. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

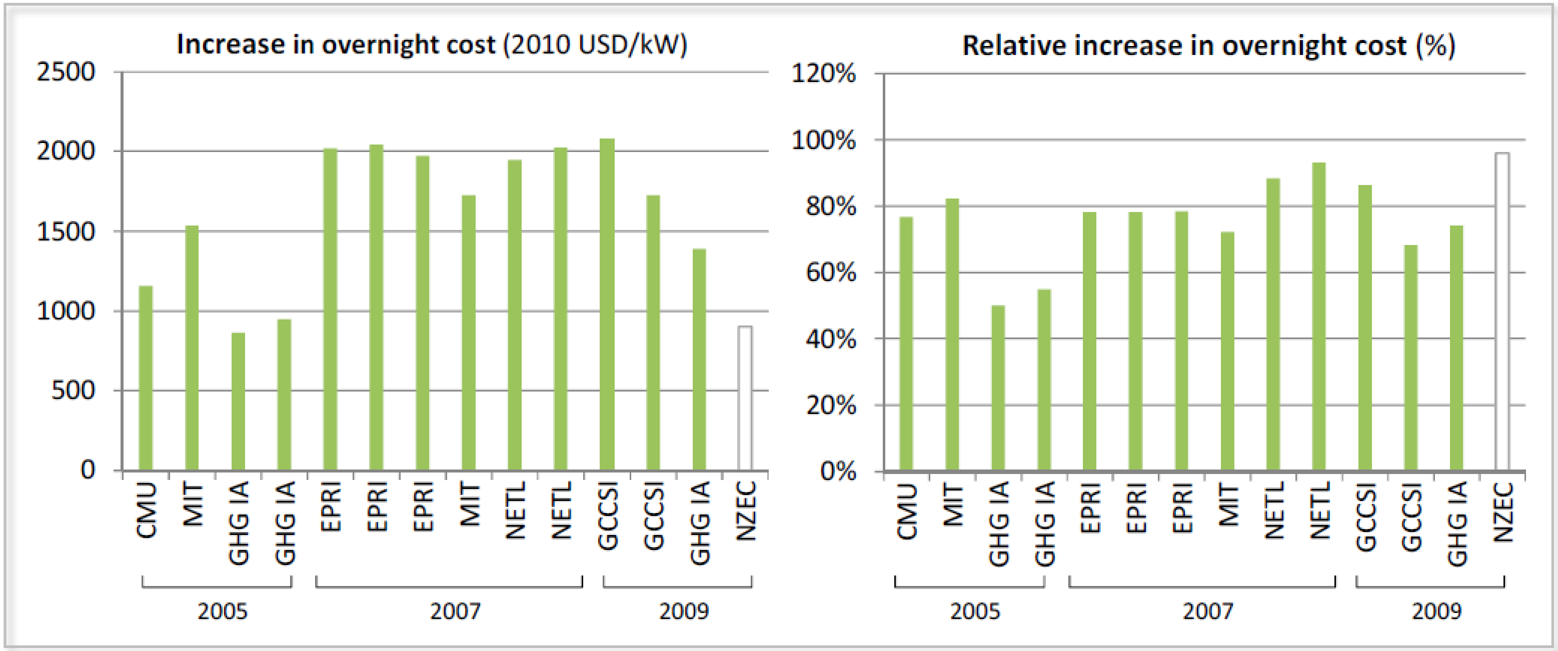
- Average overnight costs 3800 USD/kW for coal-fired power generation regardless of capture route (+74%), or 55 USD/tCO_2 cost of avoided
- For NGCC, on average 1 700 USD/kW (+82%), or 80 USD/tCO_2

CARBON CAPTURE AND STORAGE

EARLY COMMERCIAL PLANTS

Variability of cost estimates across studies

Example: Post-combustion capture from coal (with amines)



- Substantial variation of costs across studies and over time
- Relative cost increase appears slightly more stable
- Absolute costs in China estimated half of average OECD costs

EARLY COMMERCIAL PLANTS

Variability of cost estimates across studies (2010 USD, OECD countries)

Example: Oxy-combustion capture from coal

Specific fuel type	Bit coal		Sub-bit & Lignite		*Overall Average*
Power plant type	**USCPC**	**SCPC**	**SCPC**	**CFB**	
Number of cases included	2	3	3	2	
Net power output w/ capture (MW)	541	533	550	549	*543*
Net efficiency w/ capture, LHV (%)	35.0	31.2	31.2	31.2	*31.9*
Overnight cost w/ capture (USD/kW)	3 419	3 500	4 161	4 885	*3 959*
Relative increase in overnight cost	**62%**	**67%**	**75%**	**96%**	***74%***
Cost of CO_2 avoided (USD/tCO_2)	**50**	**45**	**49**	**69**	***52***

Notes: Data cover only CO_2 capture and compression but not transportation and storage. Overnight costs include owner's, EPC and contingency costs, but not IDC. A 15% contingency based on EPC cost is added for unforeseen technical or regulatory difficulties for CCS cases, compared to a 5% contingency applied for non-CCS cases. IDC is included in LCOE calculations. Fuel price assumptions differ between regions.

- Influence of fuel and power plant type can be significant
- Other factors include e.g. ambient conditions & cooling options
- Variability across studies depending on exact scope, different location or boundary conditions

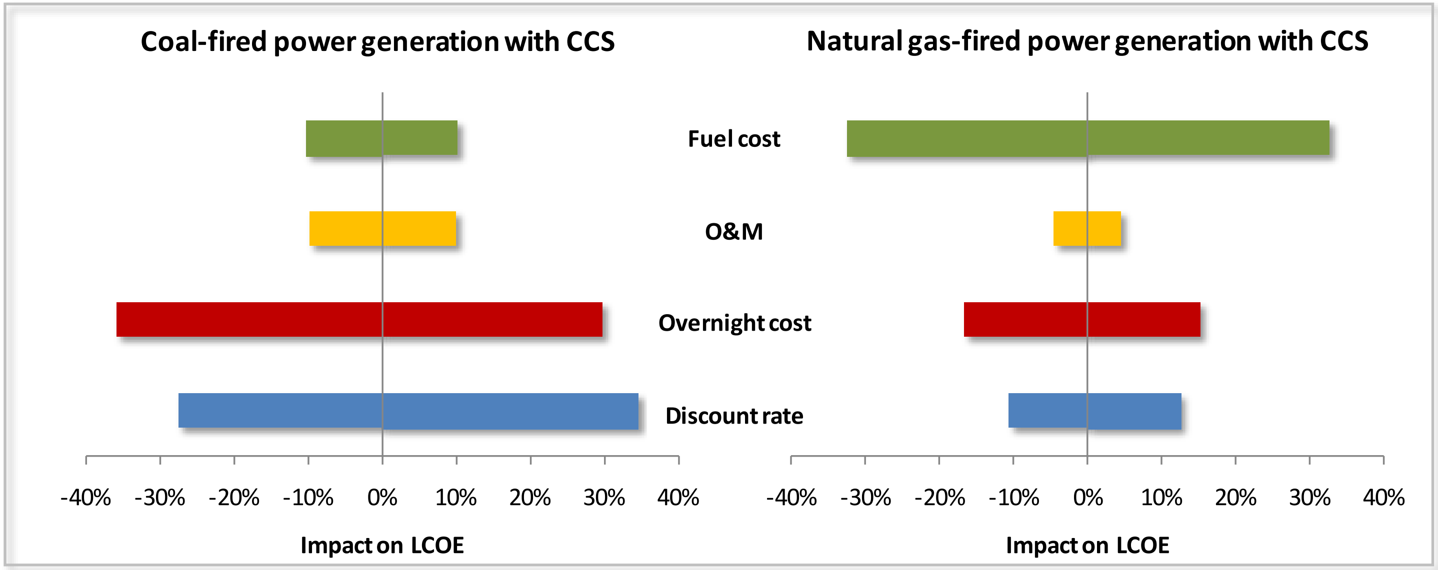
CARBON CAPTURE AND STORAGE

EARLY COMMERCIAL PLANTS

Accuracy of data and sensitivity of results

- Typical **accuracy** ranges of **feasibility study** cost estimates estimated by AACE -15% to -30% on the low side, and +20% to +50% on the high side
- **Significant sensitivity** of results to parameter assumptions

Impact of a ±50% variation in baseline assumptions on LCOE



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EARLY COMMERCIAL PLANTS

Variability of costs

Example: From generic to site-specific costs*

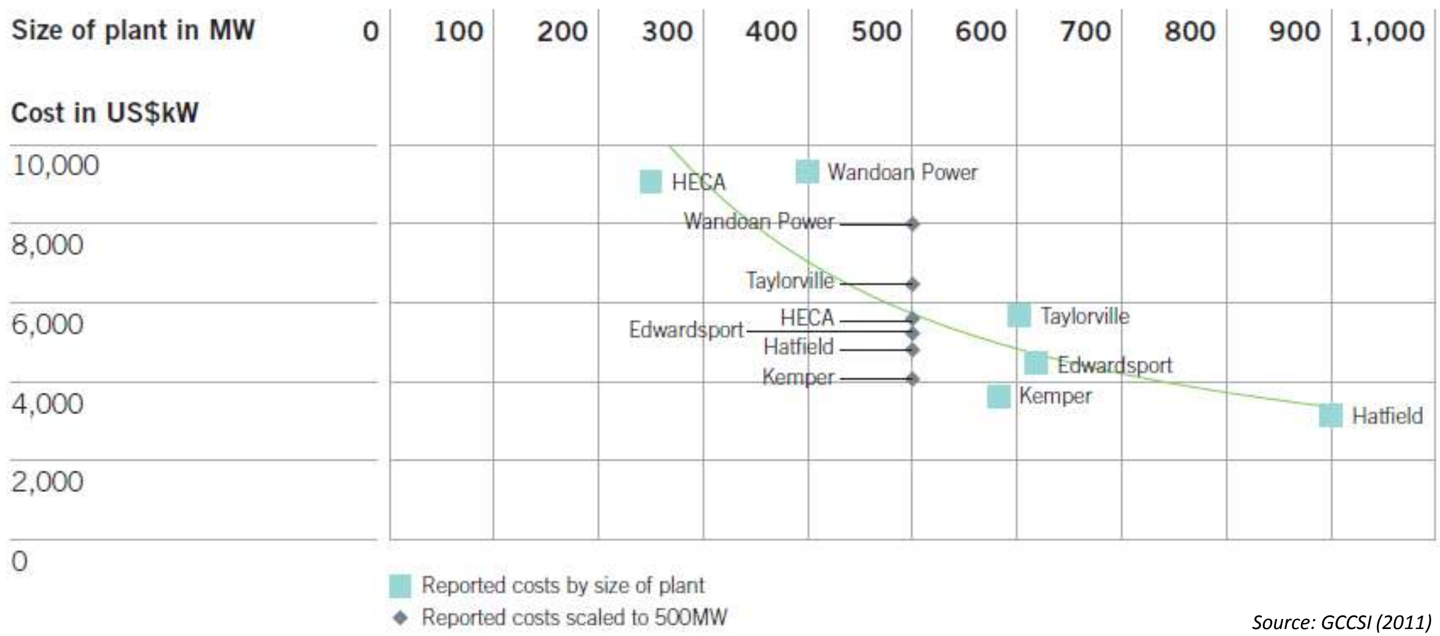
- Gassnova estimated costs for a **retrofit of post-combustion capture** to a natural gas power plant in a **rural area in Norway**
- **Project- and site- specific costs added 30% to EPC** (Engineering, Procurement and Construction) contract costs for the CO_2 capture plant
- The project- and site-specific costs included site preparation, connections for flue gas and other utilities, sea water cooling system, power supply, fire water supply, training of personnel, and miscellaneous other costs in the construction phase

** Personal communication with Tore Hatlen, Gassnova, 2011*

DEMO PLANTS

Example: Project investment costs for emerging IGCC projects
(from GCCSI, 2011)

Primarily greenfield facilities under or near construction (although some have been delayed), cost data updated to 2010 levels



Source: GCCSI (2011)

- Original cost data spread between 3 800 and 9 500 USD/kW
- Costs between 4 200 and 8 100 USD/kW after normalisation
- Investment requirements higher than for early commercial units

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FUTURE COST POTENTIAL

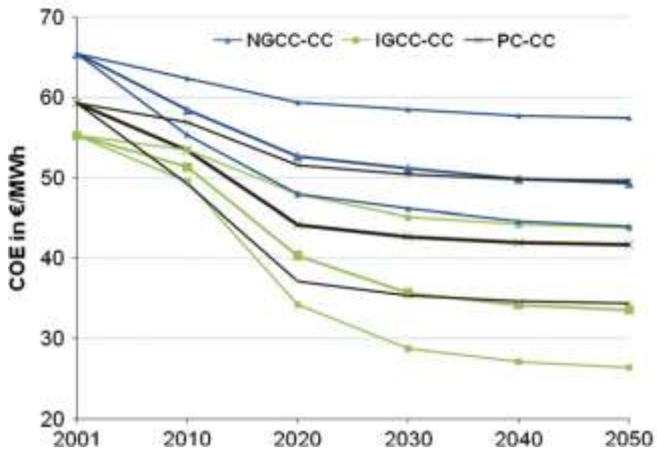
Estimates from historical experience curves for similar technologies

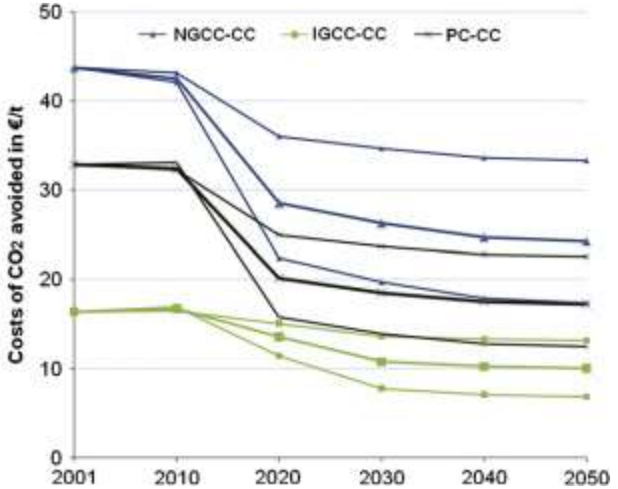
Percentage reduction in the cost of CO_2 capture after 100 GW of capacity

Technology	Capital cost	Total cost
NGCC, post-combustion	20	40
PC, post-combustion	15	26
IGCC, pre-combustion	15	20
Oxyfuel combustion	13	13

Source: Rubin et al. (2007)

Projections of COE and CO_2 mitigation costs (excluding T&S costs; CCC scenario)





Source: Van den Broek et al. (2010)

- Engineering-Economic Analysis and Historical Experience Curves suggests significant cost reduction potential over time

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RETROFIT

Cost considerations regarding retrofitting of power plants

- Feasibility and cost are **highly site-specific** (space, plant size, age, efficiency, existing pollution control systems, …)
- In general, **added LCOE is higher** than for a new-built:

  lower efficiency of existing power plants (larger energy penalty and higher capital cost per unit of capacity), plus added capital costs, performance penalties due to suboptimal integration
- **Cost per ton of CO_2 avoided increases** as a result of these higher costs, but abatement costs for retrofitting existing units is independent of the initial plant efficiency
- Studies indicate it is most cost-effective to **combine retrofit with a major plant repowering** for older subcritical plants, and apply retrofit alone for only to newer supercritical coal units

CARBON CAPTURE AND STORAGE

APPLICATIONS WITH LIMITED AVAILABILITY OF DATA

Examples of CO_2 capture applications from power generation with still limited availability of data

- Quantify differences between generic cost estimates and project- and site-specific costs of CO_2 capture projects
- Bioenergy with CCS (BECCS), given it's relevance in many global climate scenarios
- Broad analyses across technologies for CO_2 capture in non-OECD countries
- …

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CONCLUSIONS

- Considering uncertainties **no single technology outperforms** the alternative routes **for coal-fired power generation**
- For **near-term** CO_2 capture from **natural gas-fired power plants, post-combustion** CO_2 capture appears most attractive
- **Variability** between and **uncertainty** of costs remains **significant**
- The **relative increase** of cost compared to a plant without CO_2 capture often comparably stable across studies
- **Harmonisation** of costing methodologies and formats of reporting data is desirable in order to increase transparency
- **Additional analysis suggested** for e.g.
  - quantifying differences between generic cost estimates and project- and site-specific costs of CO_2 capture projects.
  - bioenergy with CCS (BECCS)
  - applications in non-OECD countries

CARBON CAPTURE AND STORAGE

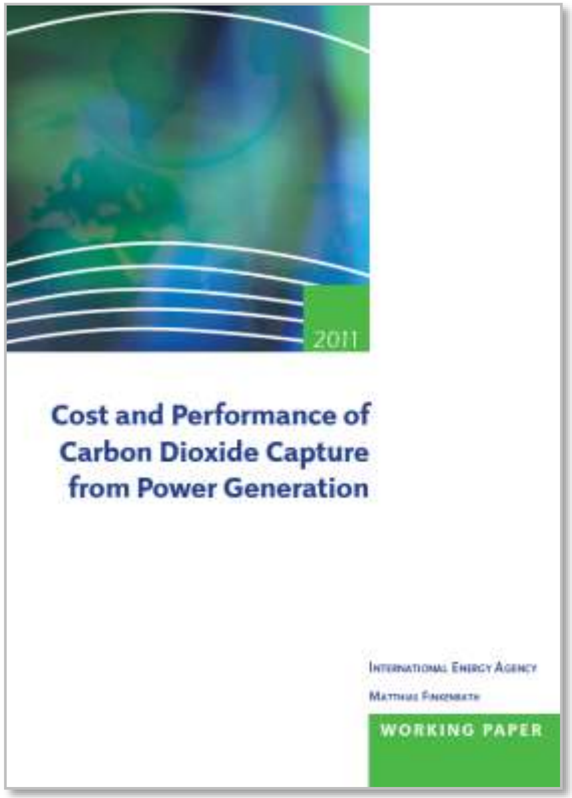
THANK YOU!

CARBON CAPTURE AND STORAGE

FURTHER INFORMATION

IEA 2011 Publication:

Cost and Performance of Carbon Dioxide Capture from Power Generation



Free download on IEA and OECD homepages:
www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2355
www.oecd-ilibrary.org/content/workingpaper/5kgggn8wk05l-en

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Status of CO_2 Capture Costs

EU Respondent

John Chamberlain

22nd March 2011

gasNatural fenosa

EU Studies

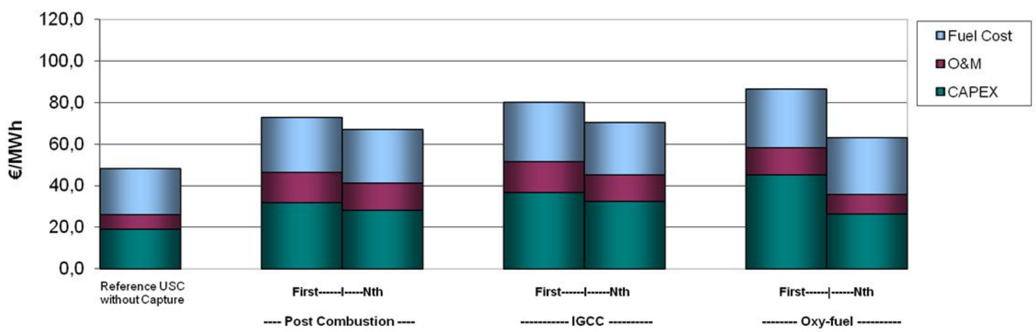
European Studies published in last few years – a selection

- DECC Mott MacDonald: "UK Electricity Generation Costs Update", June 2010
- Element Energy: "Potential for Application of CCS to UK Industry and Natural Gas Power Sectors", June 2010
- ENCAP: "Reference cases and guidelines for technology concepts", February 2008 & "Power systems evaluation and benchmarking. Public Version", February 2009
- McKinsey study: "Carbon Capture & Storage: Assessing the Economics", September 2008
- ZEP: "EU Demonstration Programme for CO_2 Capture and Storage (CCS): ZEP's Proposal", November 2008.

New European studies recently published

- ZEP The Costs of CO_2 Capture, Transport & Storage: post-demonstration CCS in the EU
- Alstom CCS cost study

Studies for new commercial power plants with CO_2 capture in Europe, based on new, actualized data



ZEP The Costs of CO_2 Capture, Transport & Storage, 2011

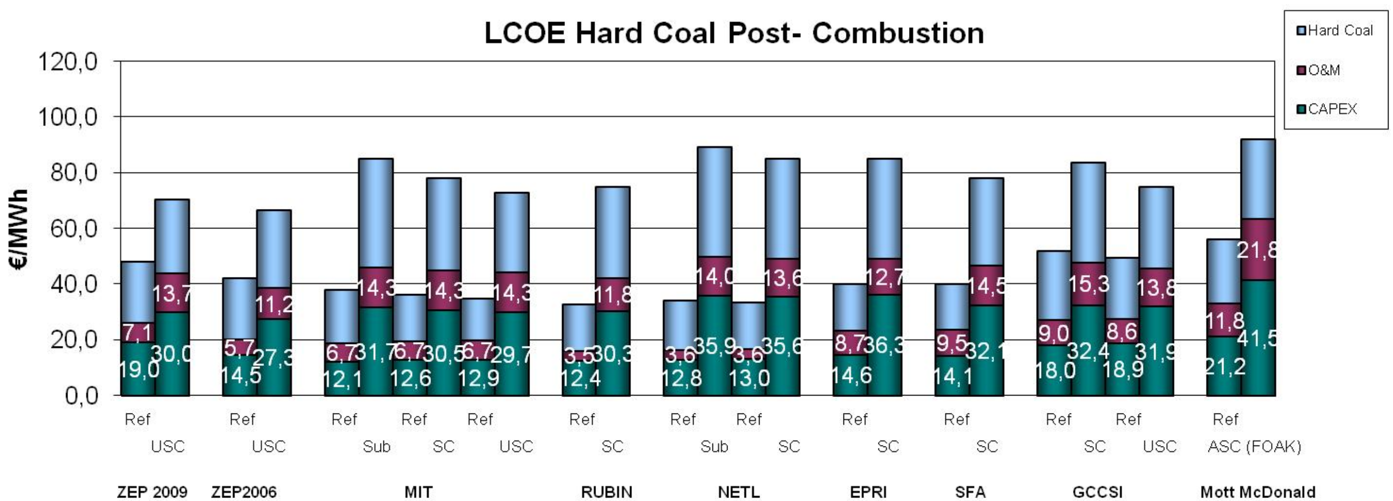
- Can we compare these results?
- What have we really learnt from these cost studies?

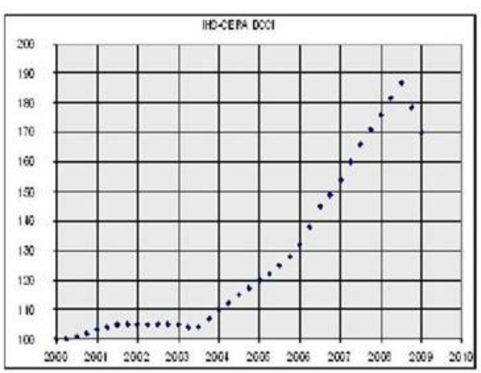
Status of CO_2 Capture Costs

Key Issues – “Best practices”

- **Cross comparisons between studies are not always possible.**
- **In each study there is a need to present upfront transparent boundary conditions**
  - **Technical: New build/retrofit, ambient site conditions, CO_2 quality and compression / processing issues, what is included in the plant costs, is it a true Greenfield?**
  - **Financial: Investment costs (Reference year, the cost index curve if applied), assumed plant life, operating regime, operation and maintenance costs and their escalations , fuel costs and their escalations, Interest costs and other charges**
  - **Reference Power plant design (MWs, efficiency, steam conditions, integration issues etc…**
  - **Capture power plants – capture rate, Efficiency drop….**

In each study all boundary conditions and Input Data needs to be clearly defined





Status of CO_2 Capture Costs

A reflection

- CCS is an emerging technology and historical experience with comparable processes suggests that significant cost improvements are achievable.
- Cost Studies provide a snapshot of the believed CCS costs at the time of the study.

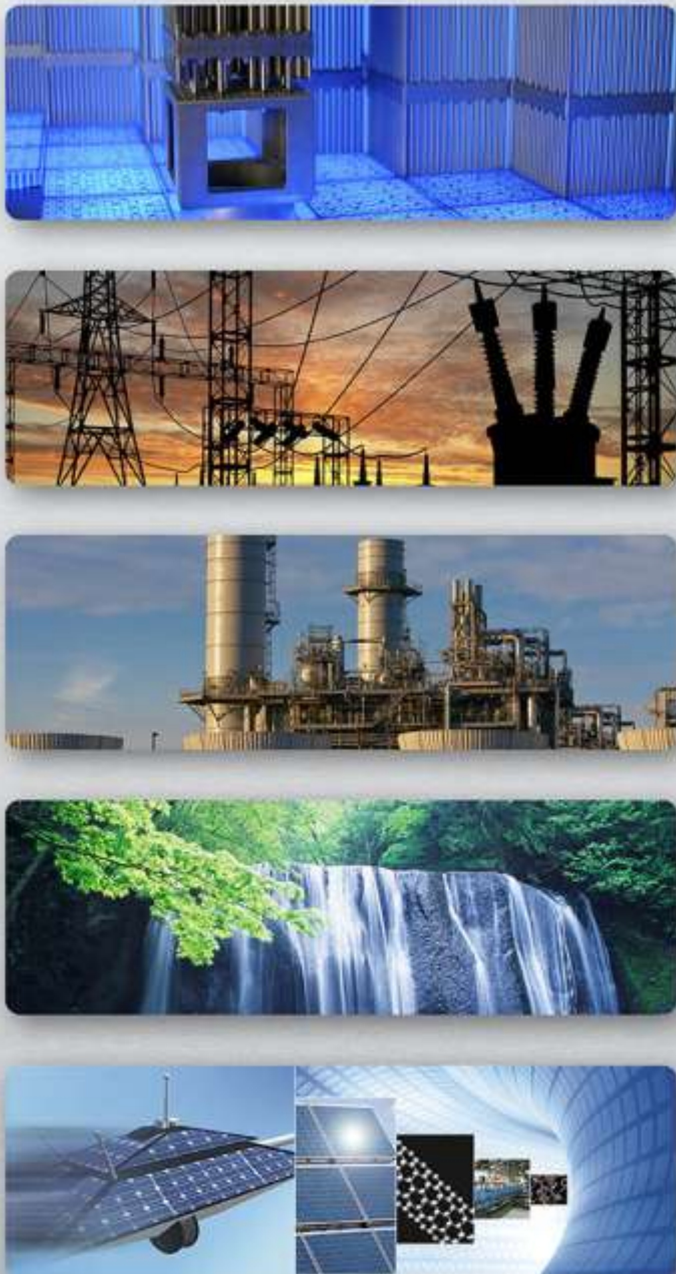
- Is actualizing data from some years ago, a good practice?
- Should more value be given to studies presenting new data based on current engineering knowledge & analysis? *- new data should have better capture plant data and consider issues such as plant integration?*
- Is there good data for plant retrofits?
- Standard CO_2 quality across different capture processes needs to be considered
- Instead of defining typical reference plant data etc.., should an open cost model be developed for others to use?

Is there a need to develop a open cost model for others to use?

Muchas gracias

Esta presentación es propiedad del Gas Natural Fenosa. Tanto su contenido temático como diseño gráfico es para uso exclusivo de su personal.

gasNatural fenosa



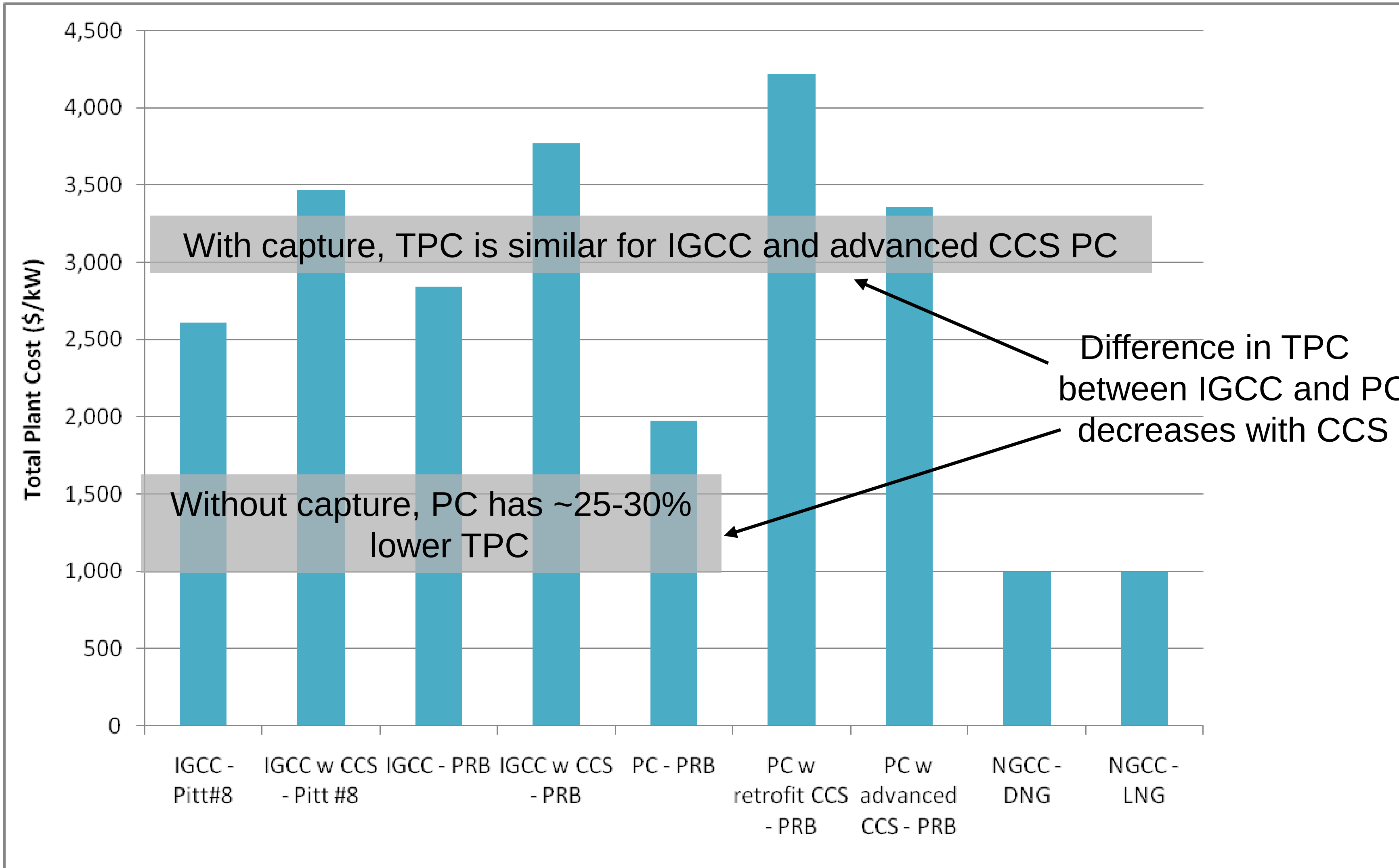
ELECTRIC POWER
RESEARCH INSTITUTE

Session 3:
Status of CO_2 Capture Costs
North American Response

George Booras (gbooras@epri.com)
Senior Project Manager
Advanced Generation

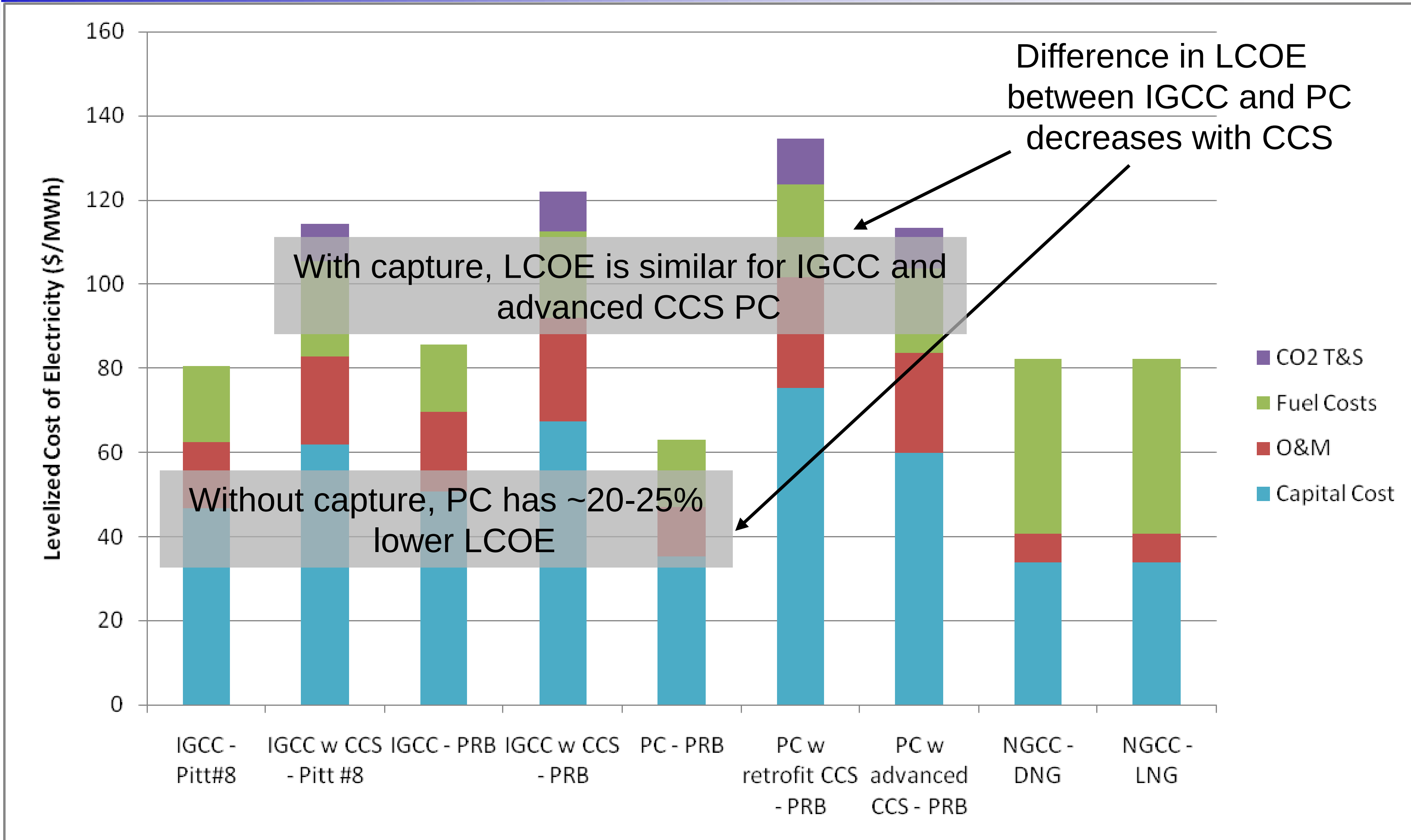
CCS Cost Workshop
International Energy Agency, Paris, France
March 22-23, 2011

Capital Cost Comparisons from EPRI Studies



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Levelized Cost of Electricity Comparisons

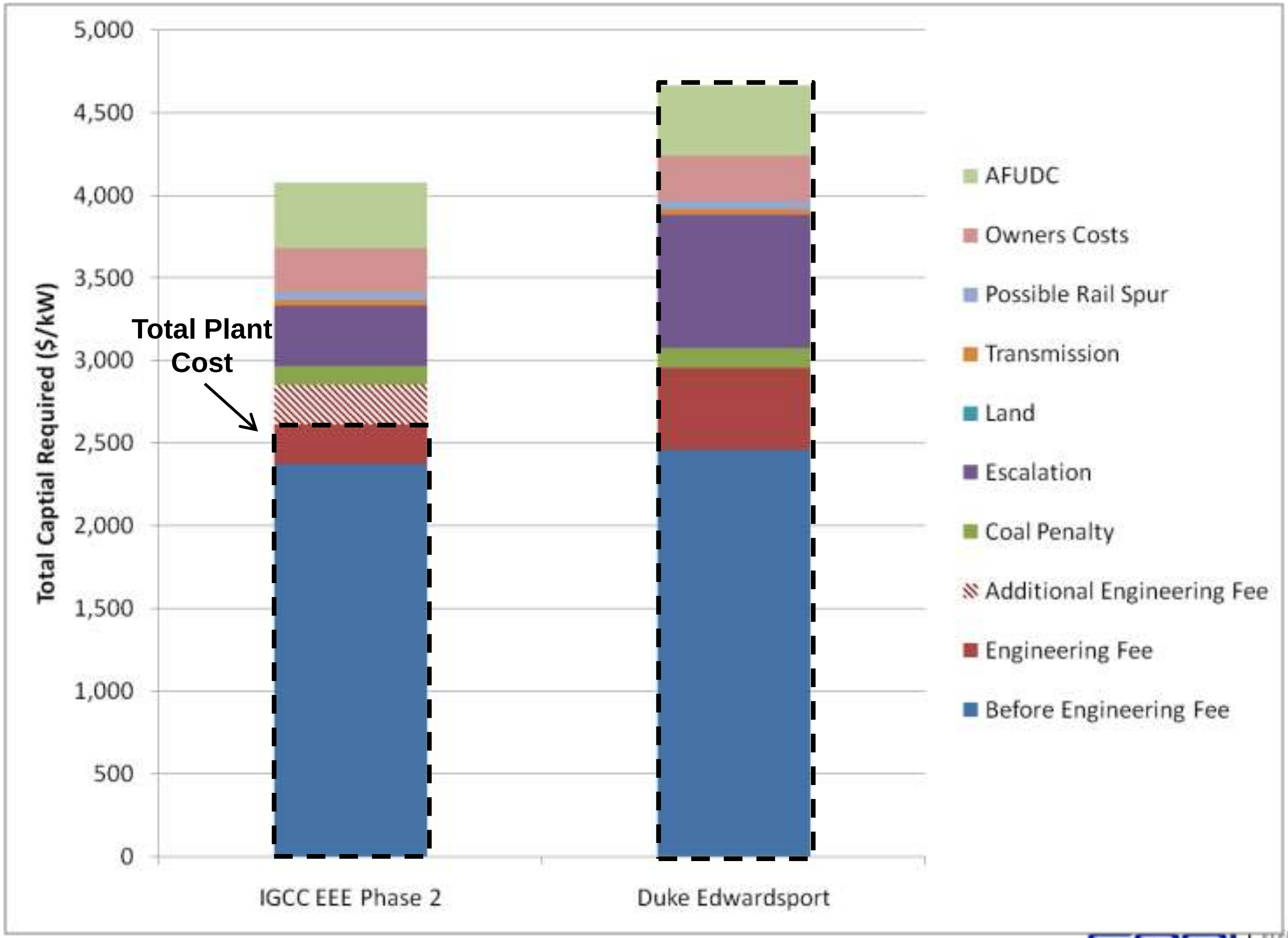


*NGCC shown for 40% capacity factor, $6/MMBtu gas

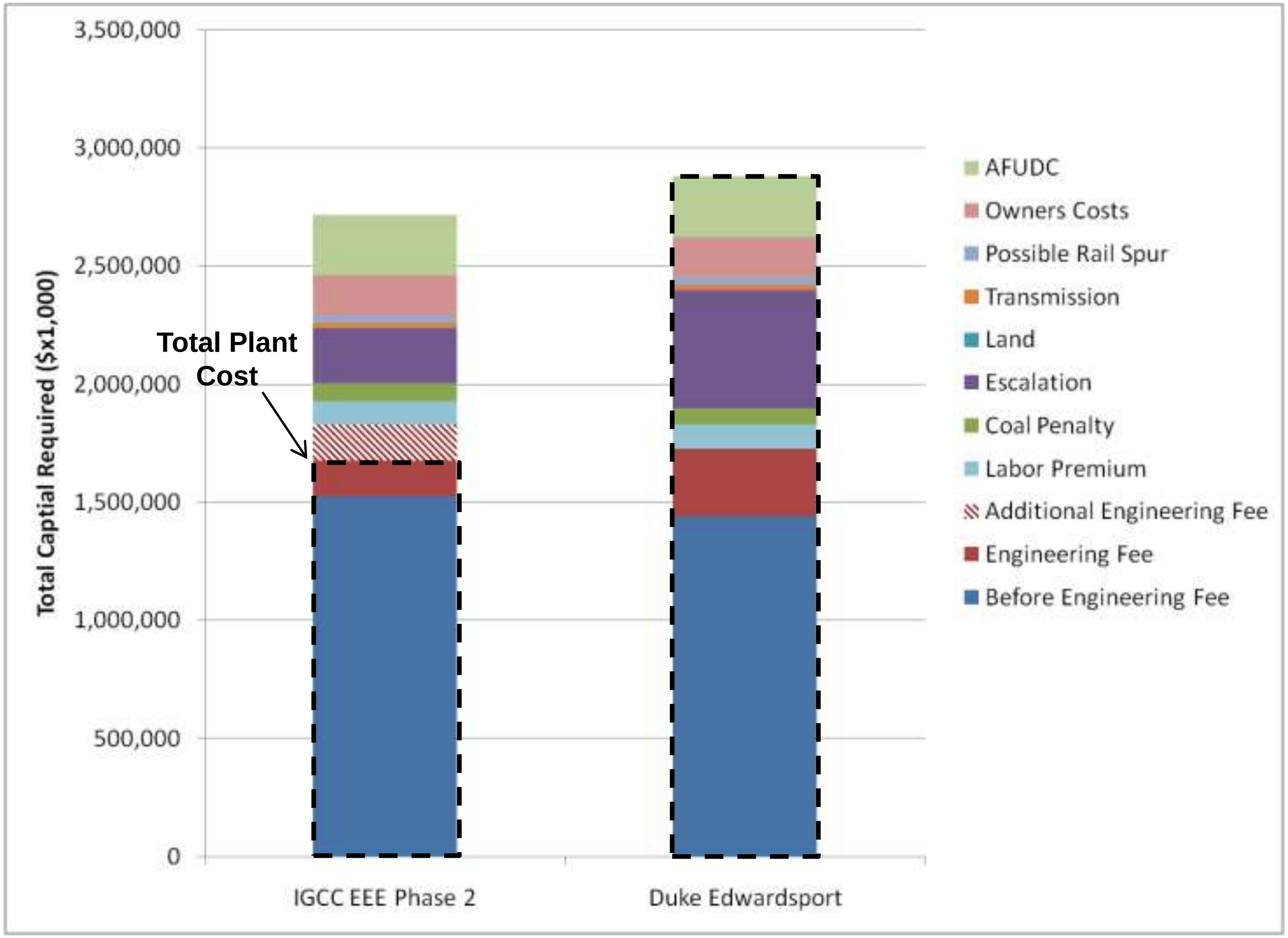
Comparison of EPRI Study Results with Reported IGCC Project Costs

- Duke Energy Indiana's Edwardsport IGCC project is based on bituminous coal, two GE Radiant Quench gasifiers, and GE 7F syngas combustion turbines. It does not include CO_2 capture.
- The latest filing of Duke Edwardsport costs was $2.88 billion for a 618 MW (net) plant, or $4,660/kW
- EPRI's IGCC EEE Phase 2 study estimates $2,612/kW (2Q'09 dollars) for a GE Radiant Quench gasifier IGCC plant without CO_2 capture, also based on bituminous coal
- Net plant output for the EEE study case was 641 MW

Total Capital Required Comparison - $/kW



Total Capital Required Comparison – $(000)



Observations

- On an absolute dollar basis, the Edwardsport costs are about 6% higher after adjustments for known design scope and other factors.
  - This can likely be attributed to additional scope differences for a first-of-a-kind plant compared to a mature plant.
- The key take-away from this analysis is that a major source of discrepancy in cost estimates is often what is actually included in the estimate.
  - Comparing an overnight cost estimate that does not include site specific costs, such as rail spurs or transmission interconnects, financing, or escalation to an all-in total capital requirement cost will result in inconsistencies and misunderstandings.

Remember: The Devil is in the Details

ELECTRIC POWER RESEARCH INSTITUTE

Together…Shaping the Future of Electricity

Carbon Capture Cost in China:
A look at reported costs from active capture projects

Prof. Zheng Li
Department of Thermal Engineering
Tsinghua BP Clean Energy Center
Tsinghua University, Beijing, China
2011-3-22

Capital costs for thermal power plants in China (EPPDI and CPECG, 2008)

	2004	2005	2006	2007
Type / capacity	Cost (2004 RMB/kW)	Cost (2005 RMB/kW)	Cost (2006 RMB/kW)	Cost (2007 RMB/kW)
Subcritical PC / 2x300MW	4853	4596	4292	4401
Supercritical PC / 2x600MW	4074	3919	3608	3643
Ultrasupercrit. PC / 2x1000MW	4128	3924	3604	3724
NGCC / 2x300MW, GE, 9F	3106	3060	3039	3155
NGCC / 2x180MW, GE, 9E	3137	2946	2912	2998

Response to page 6 about China

- Capital cost per KW been stable in RMB
- RMB vs. USD rate increases fast
- Electricity price is regulated in China and could cause difficulty in CCS deployment

Two demonstrations of post combustion capture

- Beijing: Huaneng Gaobeidian Power Plant, 3000t/a
  - Total consumptive cost is $25.3/ton CO2 captured
  - Capital cost not included
  - Source: Huang Bin. Applied Energy 87(2010) 3347-3354
- Shanghai: Huaneng Shidongkou Power Plant, 100kt/a
  - Actual capital cost 100M RMB vs. 160M RMB budgeted
  - Complete cost: RMB 300/tCO2 (=$45/tCO2)
  - No compression included

Additional Capture Cost Considerations

- Costs not fully representative for capture with integrated CCS
  - *Gaobeidian Power Plant* - **\$25.3/tonne** is **only operational cost**. Capital cost is not included. Operation **does not include compression**, and compression costs would be needed in a real, integrated CCS case
  - *Shidongkou Power Plant* - **\$45/tonne** cost of includes both capital cost and operational cost. Compression costs also not included.
- <u>Compression costs</u> - Under similar parameters to these plants, the compression costs are estimated to be **\$10/tonne**
- <u>Scale</u> - Both power plants use a small fraction of its flue gas. So the possible capital costs for water cooling systems, parasitic transformers, pumps, compressors and other additional facilities which are otherwise needed in a full size capture plant are not included.
- <u>NZEC</u> (2009) estimates point to costs of **\$42/t$CO_{2\ avoided}$** for similar post-combustion capture projects in China using amines. (taken from the IEA source…not clear if integrated CCS or just capture)
- <u>COACH</u> (2009) estimates: the **capture cost** was determined to be *€18/tCO_2* ***(~\$26/tCO_2)*** while the **cost avoided** was *€22/tCO_2* ***(~\$32/tCO_2)***

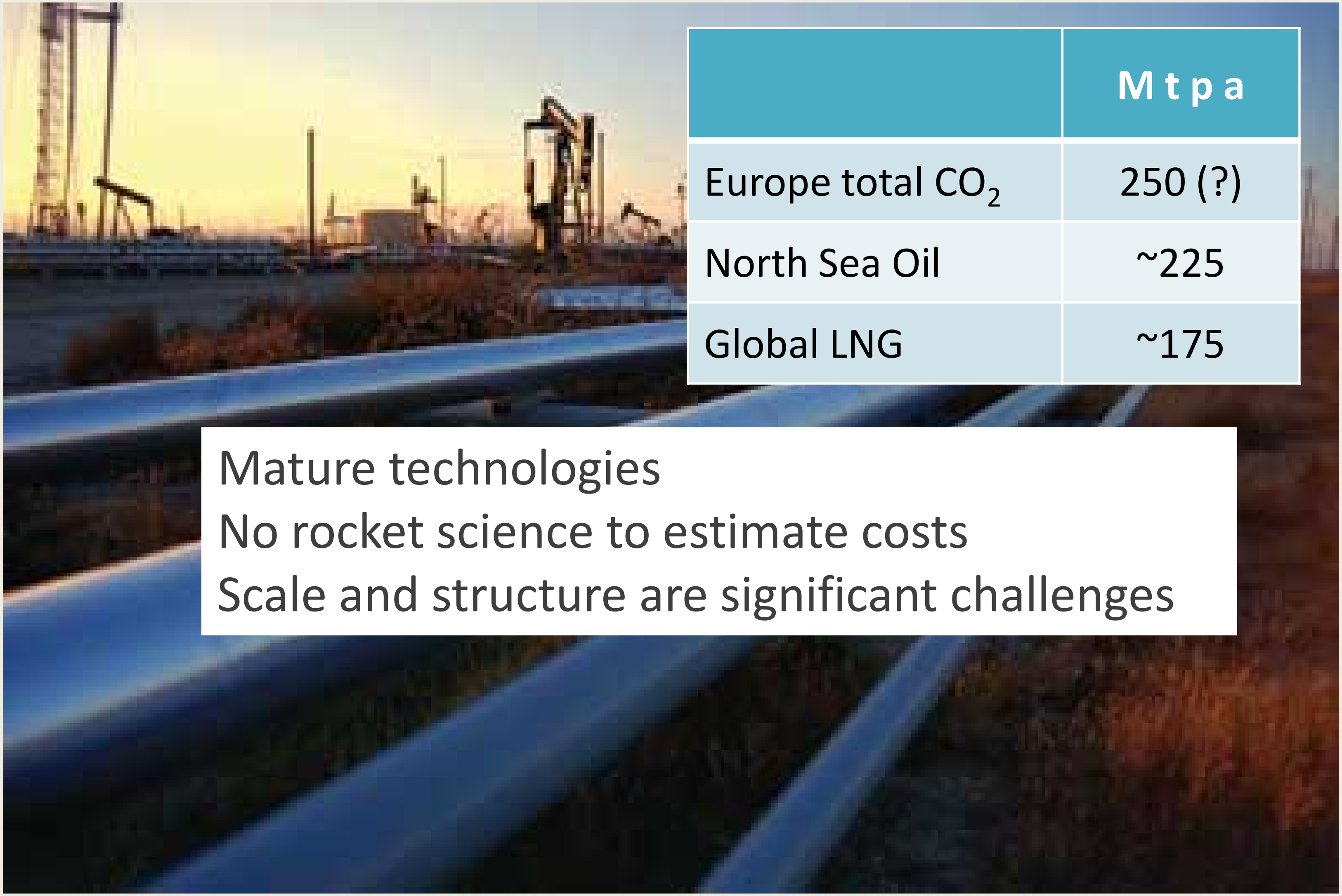
Keynote
Status of CO_2 Transport Costs

Paris 22nd-23rd March 2011

Per Arne Nilsson

panaware ab

What is the demand for transport of CO_2 in 2030?



	Mtpa
Europe total CO_2	250 (?)
North Sea Oil	~225
Global LNG	~175

Mature technologies
No rocket science to estimate costs
Scale and structure are significant challenges

Contents

Literature Review – Cost Comparisons

Report	Notes	Year	CAPEX (M€)	Distance (km)	Volume (Mtpa)	€/t
McKinsey&Co	Europe	2008	1,3 per km 24" onshore + 20% offshore	200-300		4 – 6
Pöyry for DTI	UK	2007	1,4 per km → 623 including boosters	444	7	5
NOGEPA (NL)	NL	2009	2,7 per km → 685	180/70	30	8 (incl storage)
IEAGHG	ship	2004	276	500	6	16
SINTEF/Statoil	ship/ energy	2006		750	1.3	18

A selection (1)

Pöyry for DTI 2007;
Analysis of carbon capture and storage, Cost supply curves for the UK

- elaborates cost of pipe and boosters, in two possible developments, “DC – Direct Connect” and “H&S – Hub- and Spoke”
- “...while the costs of using a Hub & Spoke network is slightly less than those for a Direct Connect network, the difference is marginal”
- transport cost ranges from 1 to 9 £/t are accounted for
- specific focus on optimizing transport and storage costs in the UK
- details reported for one specified source-to-sink case first as feeder and then in combination with other sources in an offshore spine
- no generic transport cost conclusions and limited detail on assumptions

A selection (2)

Netherlands Oil and Gas Exploration and Production Association, March 2009: Potential for CO_2 storage in depleted gas fields on the Netherlands Continental Shelf, Phase 2: Costs of transport and storage

- detailed account for the costs of transport of 20 Mtpa from Rotterdam and 10 Mtpa from Ijmuiden to the NCS
- specifies CAPEX and OPEX in detail and with clear assumptions
- pipeline distances are 180 km – 36” and 70 – 24” km’s tie-in, respectively
- design: 200 bar, operating pressure 160 bar, temperature -10 to +50 ºC, carbon steel
- pipeline capacity calculated with D’Arcy Weisbach formula
- detailed descriptions with rough CAPEX of routing, pipe laying, landfall, crossings, tie-ins and heating
- financial assumptions are specified, like project life time (30 yrs) and interest (6.5%)
- indicative transport and storage costs per ton stored CO_2

Approaches to transport cost estimation

Bottom-up

Detailed component cost built into dimensioning model for specific CCS cases

Focusing on material costs, operating expenses

Static view

<u>example</u>: Pöyry

Top-down

Analyzing ”the market”, potential capture projects coming on stream in a coordinated mode

Based on phased-in volumes, approximating required, optimal transport capacities

Focusing on total CAPEX

Dynamic volume development view, extrapolations

<u>example</u>: One North Sea, McKinsey&Co

Integrated

Bottom-up supply chain main cost components, CAPEX and OPEX

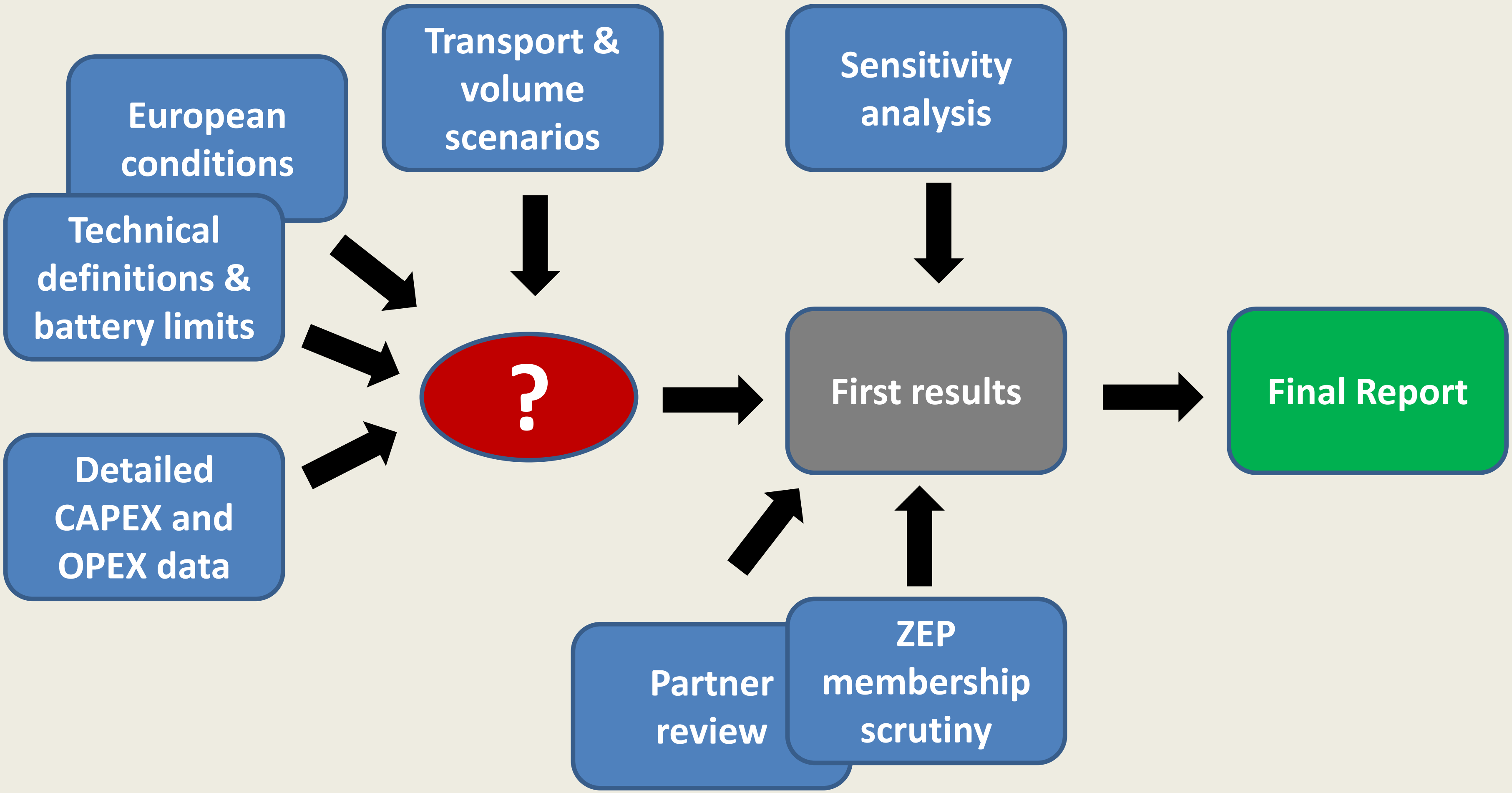
Simulated likely transport volume and network developments

Integrating network scenarios and component costs

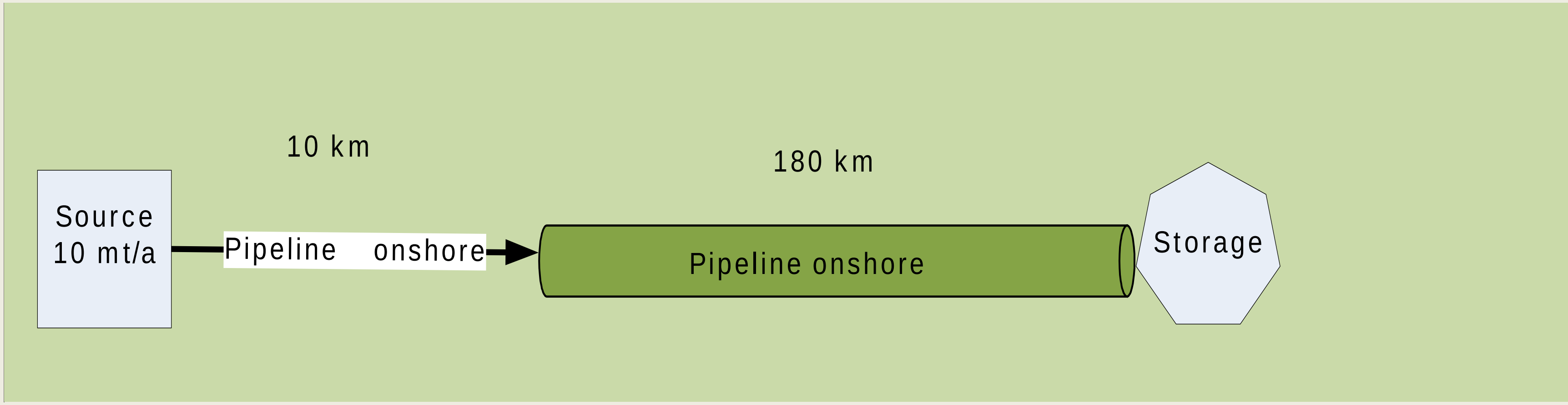
Dynamic view

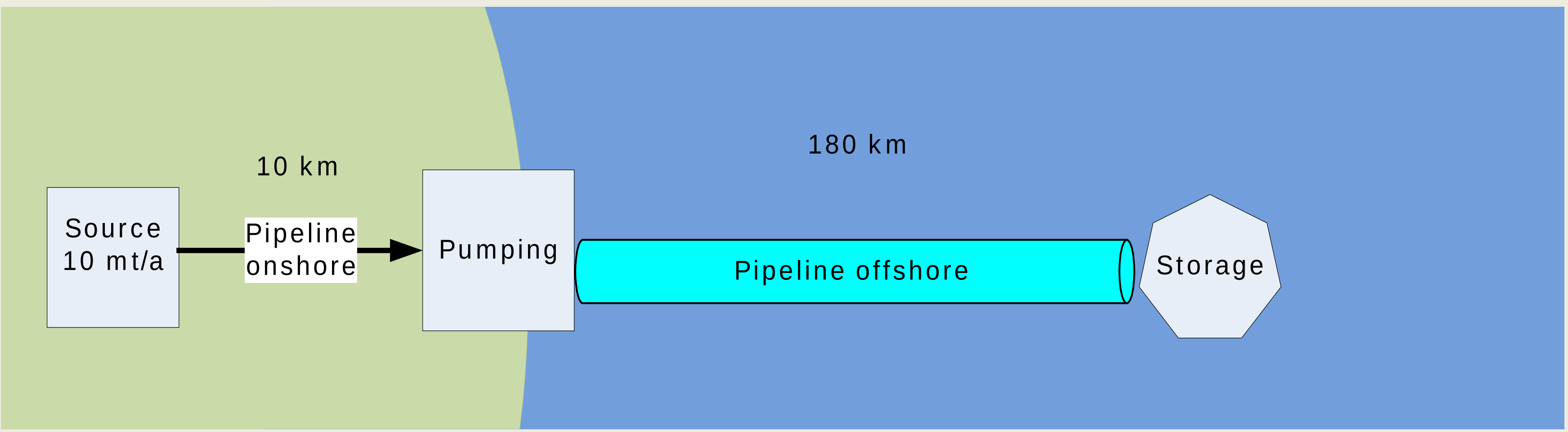
<u>example</u>: Netherlands, ZEP Transport Cost Report

ZEP: The costs of CO_2 transport – March 2011 Overview



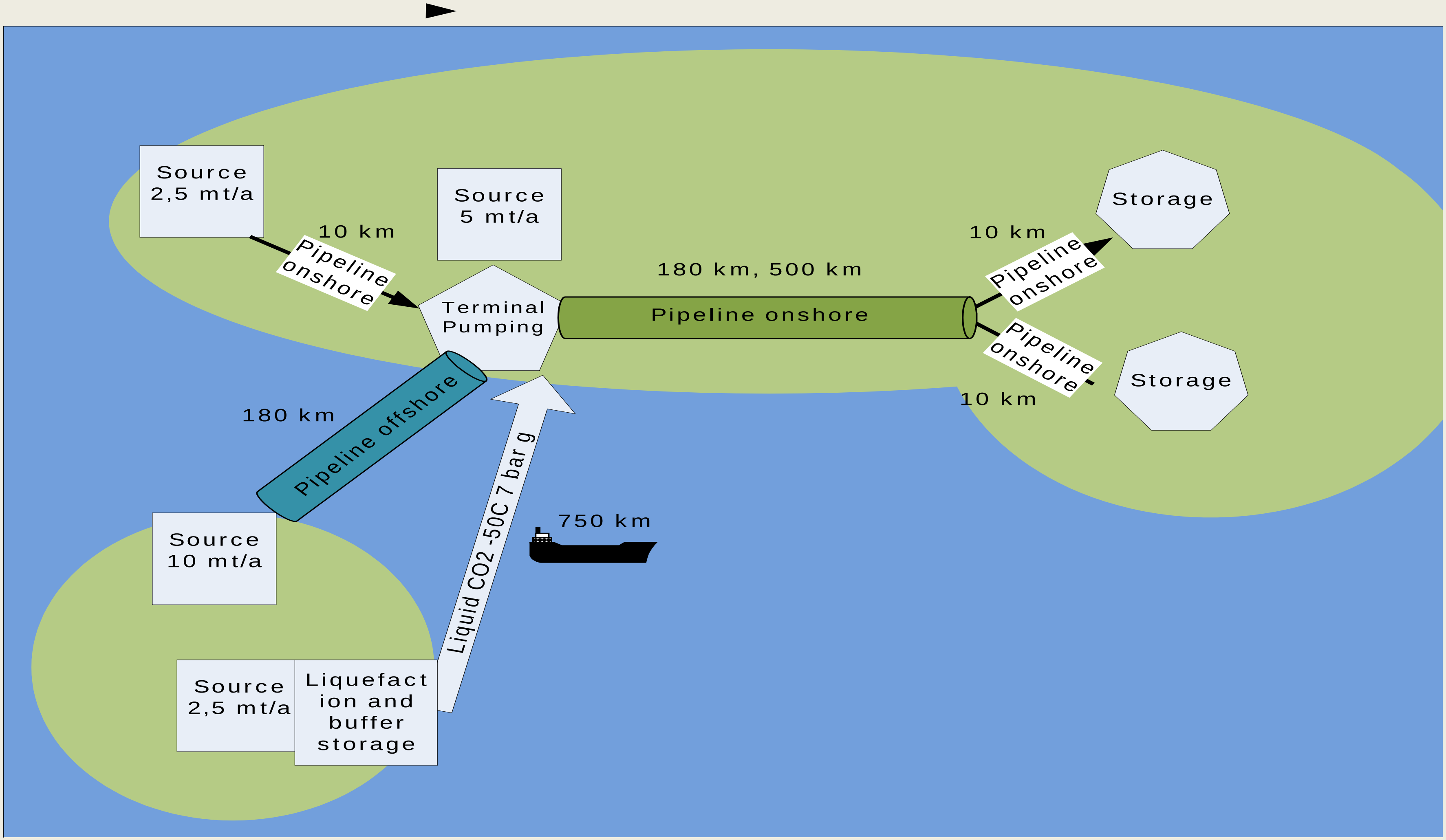
From one-to-one.....





Network 1 One-to-one onshore (1a) and offshore (1b) spine

....to complex networks

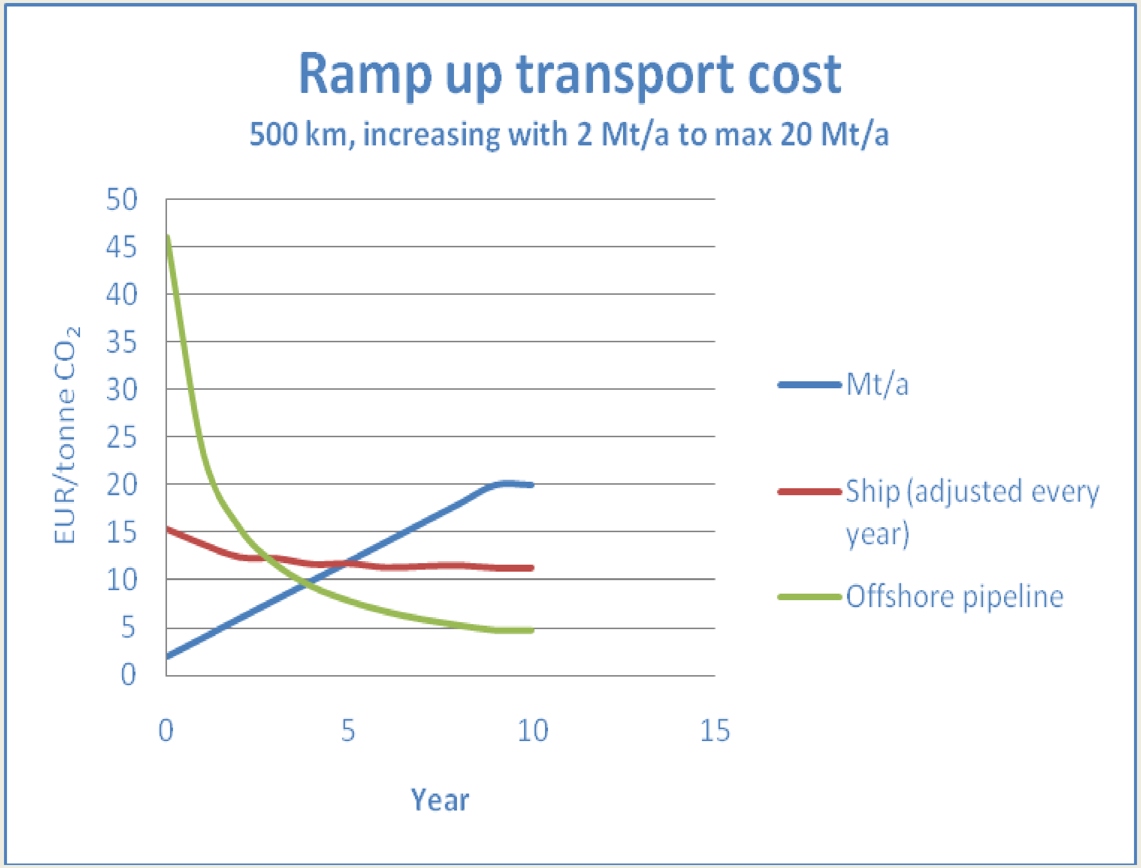


Network 7 Complex network with onshore pipeline spine of 180 km (a) and 500 km (b)

ZEP: The costs of CO_2 transport – March 2011
Key Results (2)

Net work	Volume	Source/s/	Transport						Store/s/	Cost
	Total		Feeder/s/		Spine		Distribution			
	(Mtpa)	(#*Mtpa)	(km)	Type	(km)	Type	(km)	Type	(#)	(EUR/t)
5 a	20	2*10	2*10	Onshore	180	Offshore	2*10	Offshore	2	**3,4**
5 b	20	2*10	2*10	Onshore	500	Offshore	2*10	Offshore	2	**6,0**
5 c	20	2*10	2*10	Onshore	750	Offshore	2*10	Offshore	2	**8,2**
5 d	20	2*10	2*10	Onshore	1,500	Offshore	2*10	Offshore	2	**16,3**
6 a	20	2*10	2*10	Onshore	180	Ship	2*10	Offshore	2	**11,1**
6 b	20	2*10	2*10	Onshore	500	Ship	2*10	Offshore	2	**12,2**
6 c	20	2*10	2*10	Onshore	750	Ship	2*10	Offshore	2	**13,2**
6 d	20	2*10	2*10	Onshore	1,500	Ship	2*10	Offshore	2	**16,1**
7		1*2.5	10	Onshore						
a	20	1*2.5	750	Ship	180	Onshore	2*10	Onshore	2	**5,1**
b		1*5	-	-	500	Onshore	2*10	Onshore	2	**7,2**
		1*10	180	Offshore						
8		1*2.5	10	Onshore						
a	20	1*2.5	750	Ship	180	Offshore	2*10	Offshore	2	**7,0**
b		1*5	-	-	500	Offshore	2*10	Offshore	2	**9,5**
		1*10	180	Offshore						

ZEP: The costs of CO_2 transport – March 2011
Key Results (4) – Volume Ramp-up Sensitivity



Transport cost EUR/tonne ramp-up case, 500 km and 20 Mtpa

Conclusions and Recommendations

Conclusions:

- Transport costs have been analyzed for different purposes
- Considerable convergence on €/t transport cost, significant variances on contents of cost, volumes and technical assumptions
- Transport costs are 7-12% of total CCS costs and with high certainty

Recommendations:

- Build on ZEP Transport Cost approach to evaluate Demonstration project candidates
- Commission an infrastructure study, combining volume and cost assumptions to suggest optimal infrastructure investments, starting now!
- Evaluate likely (transport) business models and tariffs to drive optimal development!

Schlumberger
Carbon Services

IEA CCS Cost Workshop
-*Storage Costs*

John Tombari

March 2011

(Some) Existing Studies

Studies have differing scope, methodology and Capex/Opex not split

- IPCC "Special Report on CCS"
  - 2005 ($0.5/ton to $8/ton)
- McKinsey: "CCS: Assessing the Economics"
  - September 2008, the 'original' baseline (4 – 12 Euro / ton)
- GCCSI
  - "The Global Status of CCS: 2010" ($3.2 – $6 per ton)
  - "Economic Assessment of CCSTechnologies: 2011 Update"
- National governments (in progress)
  - Many, often part of wider energy cost studies
- ZEP
  - "The Costs of CO_2 Capture, Transport & Storage" (completed but not yet published)

IPCC Special Report on CCS

Schlumberger
Carbon Services

2005

Representative estimates of the cost for storage in saline formations and depleted oil and gas fields are typically between 0.5–8 US$/t$CO_2$ injected. Monitoring costs of 0.1–0.3 US$/t$CO_2$ are additional. The lowest storage costs are for onshore, shallow, high permeability reservoirs, and/or storage sites where wells and infrastructure from existing oil and gas fields may be re-used.

Table SPM.5. 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US$/$CO_2$ avoided. All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 2.8-4.4 US$ GJ^{-1} and coal prices 1-1.5 US$ GJ^{-1} (Sections 5.9.5, 8.2.1, 8.2.2, 8.2.3, Tables 8.1 and 8.2).

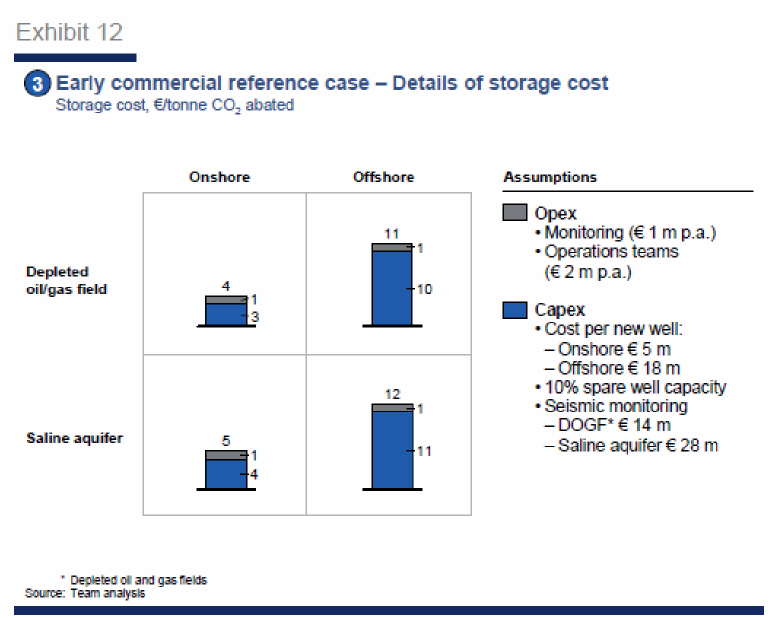
CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US$/t$CO_2$ net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US$/t$CO_2$ net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US$/t$CO_2$ net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US$/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr^{-1}.
Geological storage[a]	0.5-8 US$/t$CO_2$ net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US$/t$CO_2$ net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US$/t$CO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

[a] Over the long term, there may be additional costs for remediation and liabilities.

McKinsey: “CCS: Assessing the Economics”

Schlumberger Carbon Services

September 2008



Total storage cost is highly dependent on onshore versus offshore locations, due to an overall increase of equipment, exploration and site set-up/closure costs in the offshore case. Deep saline aquifers are, initially, likely to be more expensive than DOGF due to higher exploration and site mapping costs. Overall, the total onshore storage cost is estimated at € 4 per tonne CO_2 for DOGF and € 5 per tonne CO_2 for deep saline aquifers. But the cost increases significantly to € 11-12 per tonne CO_2 in the offshore case. Some 80-90 percent of that total cost is represented by capex (storage equipment, e.g. wells, pumps, platforms). Opex costs are assumed to be relatively low due to highly automated operations and the absence of pressure-boosting expenses (included within the capture and transport phases). [Exhibit 12]

GCCSI : The Global Status of CCS 2010

Schlumberger Carbon Services

- The economics of CO_2 storage is affected by the geology of the target storage formation. Without an appropriate storage site that is accessible by effective transport options, CCS may not be an appropriate option in certain circumstances. Nonetheless, in the technology cost studies recently released, storage costs contribute less than five per cent under ideal conditions, increasing to around 10 per cent for storage sites with 'poorer' geologic properties.

Table 14 Summary of recently completed CCS design cost studies

		POST-COMBUSTION			IGCC				OXYFUEL	NGCC	
		WORLEY PARSONS	DOE/ NETL	IEA[1]	WORLEY PARSONS (SHELL)	DOE/ NETL (SHELL)	DOE/ NETL (COP)	DOE/ NETL (GE)	WORLEY PARSONS	WORLEY PARSONS	DOE/ NETL
Base year[1,2]		2010	2007	2008	2010	2007	2007	2007	2010	2010	2007
Capacity	MW (net)	546	550	474	517	497	514	543	550	482	474
Total overnight cost	$/kW	4,701	3,570	3,838	4,632	3,904	3,466	3,334	4,430	1,964	1,497
O&M[3]	$/MWh	16	22	14	18				12	6	
Fuel cost	$/MWh	34	20	13	33	18	18	17	44	72	52
Capture rate	%	90	90	90	90	90	90	90	90	90	90
Efficiency[4]	%	27.2	26.2	34.8	32.0	31.2	31.0	32.6	29.3	43.7	42.8
Capacity factor	%	85	85	85	85	80	80	80	85	85	85
Lead time	Years	4	5	4	4	5	5	5	4	3	3
Lifetime	Years	30	30	40	30	30	30	30	30	30	30
Discount rate	%	8.8	9.1	10	8.8	9.1	9.1	9.1	8.8	8.8	9.1
Transport[5]	$/MWh	1	–	na	1	–	–	–	1	1	–
Storage[6]	$/$CO_2$	6	5.6	na	6	5.7	5.6	5.3	6	6	3.2
LCOE[7]	$/MWh	131	135	90	125	151	140	134	121	123	109
Avoided cost of CO_2[8]	$/tonne	81	87	~75	67	77	93	109	57	107	106

Timeline and costs for commercial storage (*US land DSA*)

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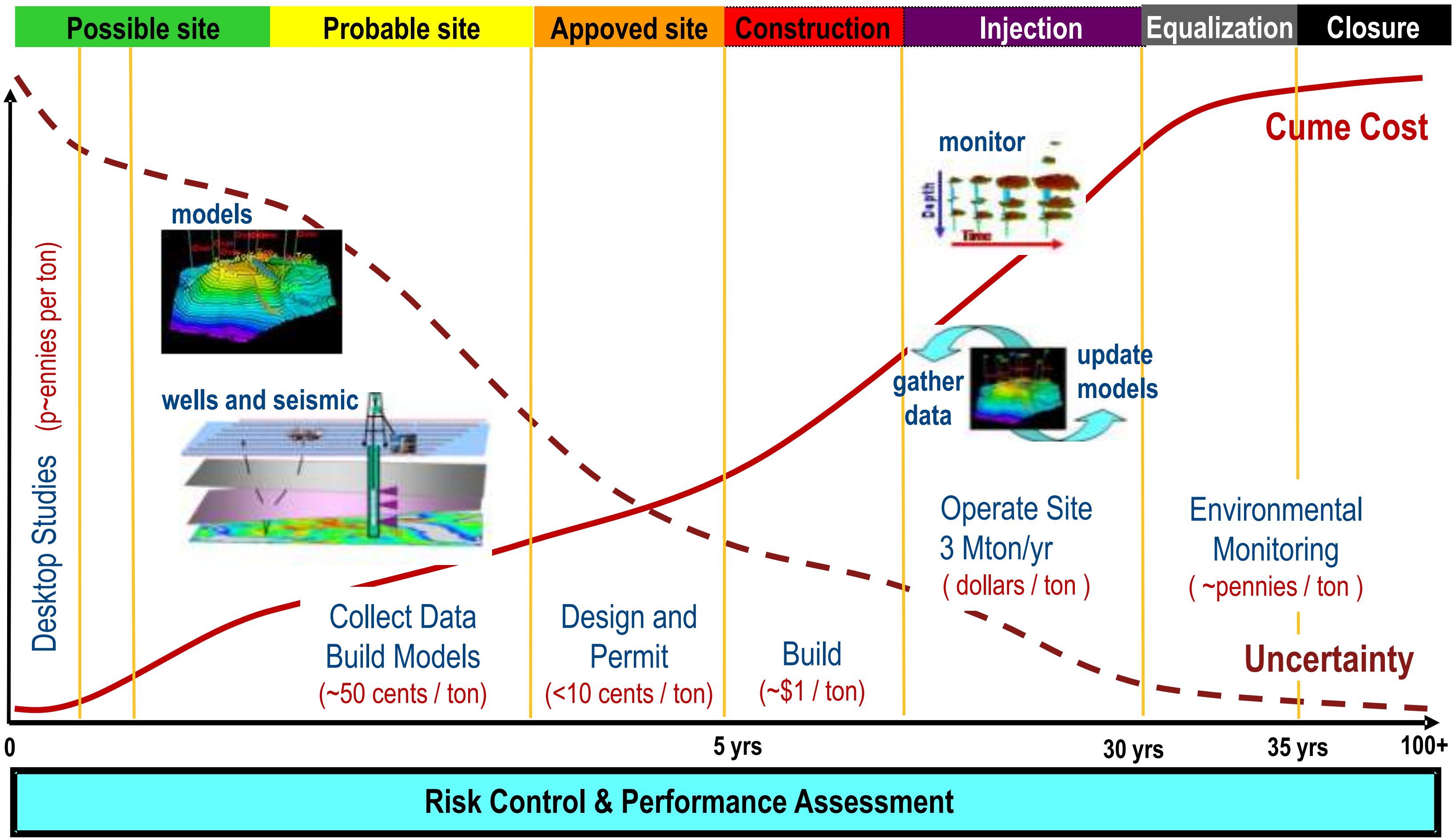

** Per ton estimates and total costs (in current day $USD) are based on 100Mton lifetime storage volume)*

Variables

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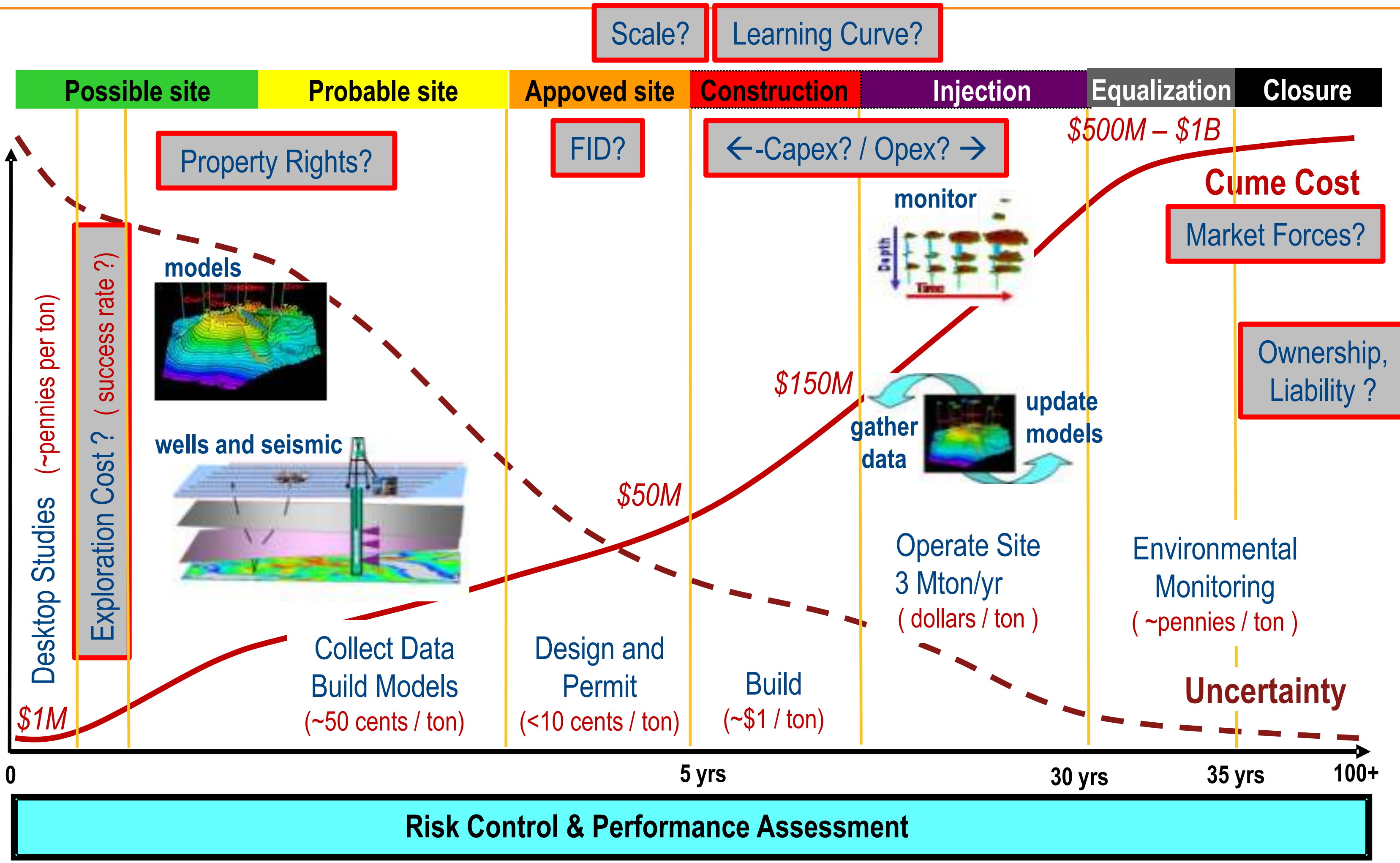
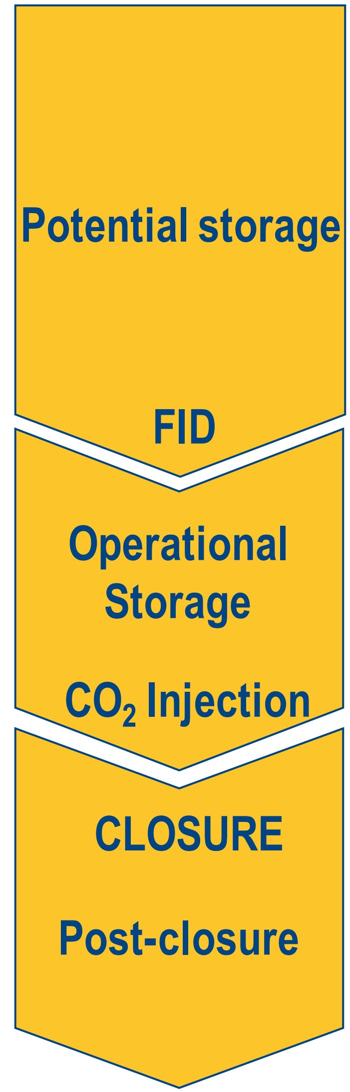


** Per ton estimates and total costs (in current day $USD) are based on 100Mton lifetime storage volume)*

Some conclusions

- Wide range in costs (factor of 10) result from:
  - Geology (depth, porosity, permeability, lithologic complexity)
  - Access (surface constraints, proximity to existing O&G locations)
  - Category: (land vs OS, oilfield, gasfield, depleted?, age?, available infrastructure?)
- Lowest cost category may be least available (large onshore O&G field)
- Confidence level needed for FID
- Major cost BEFORE Investment decision is exploration (seismic + drilling)
- Major cost AFTER decision is well construction
  - Could be spread across operating lifetime for large storage site
  - Monitoring costs are relatively small
- Main cost items to consider:
  - Characterization costs (seismic, appraisal wells), success rate
  - Size of reservoir – compared to volume of CO_2 to be stored
  - Number of wells – injectivity, redundancy, monitoring, maintenance!
  - Intensity of MMV (seismic + wells)
  - Offshore structure – surface or seabed
  - Cost of ownership, liability
  - Contingency



CCS Cost Workshop

IEA, 22-23 March 2011

Session 4: Status of CO2 Transport and Storage Costs

Transport expert respondent: Alastair Rennie, AMEC

Notes of points made-

1. Further to the previous discussions on the problem of CCS costs we should ask is the cost of CCS actually significant? Certainly it is an extra cost but it may not be a significant extra cost in the context of volatile energy costs, high baseload intermittent renewables and nuclear power, and security of supply.

2. The designing of a transport & storage solution starts with the local context. Fundamentally is CO_2 emission or the use of CCS a non avoidable cost? How will the CCS plants compete in the market (the set of foreseen incentives, and competitive supply with old and alternative new plant) and as generators in merit order? The answers give the scale and utilisation parameters for the transport & storage system.

3. Transport costs are absolutely dominated by scale economies, as shown earlier, so the unit costs are extremely sensitive to the number x size of sources. Besides transport distance as a cost factor, a high reliability of storage is also essential for lower costs by good asset utilisation and risk reduction.

4. It may be that, beyond a simple single source to single store system, the direct cost of transport is not that relevant to overall CCS costs for a generator and use of quoted low amortised capital costs should be treated with caution. This is because of the common costs in a system and the tendency for a natural monopoly in transport to occur, in part due to the advantages of higher than minimum capacity. There is also a need for generators to have a very low risk storage solution, which in may imply having multiple storage options at financial close to enable the infrastructure investment. The combination of these, regulatory requirements, the wish not to own such assets, and treatment of incentives means that generators may see transport costs as a service tariff per year and per unit transported.

5. Cost reduction for transport without the commercial pull of EOR requires regulator or Government measures to reduce the risk costs of investment in infrastructure. A big issue is the cost of capital for these assets. Governments may wish to avoid risks associated with investment in right sized transport and storage, but they should be engaged to enable lower costs to the public incentives for at least “first of a kind” plants and encourage further industry commitment.

CO_2 Storage costs

ZEP & IEAGHG

for CCS Costs Workshop
at IEA in Paris on March 22-23

Wilfried Maas (Shell)
ZEP Storage cost workgroup lead

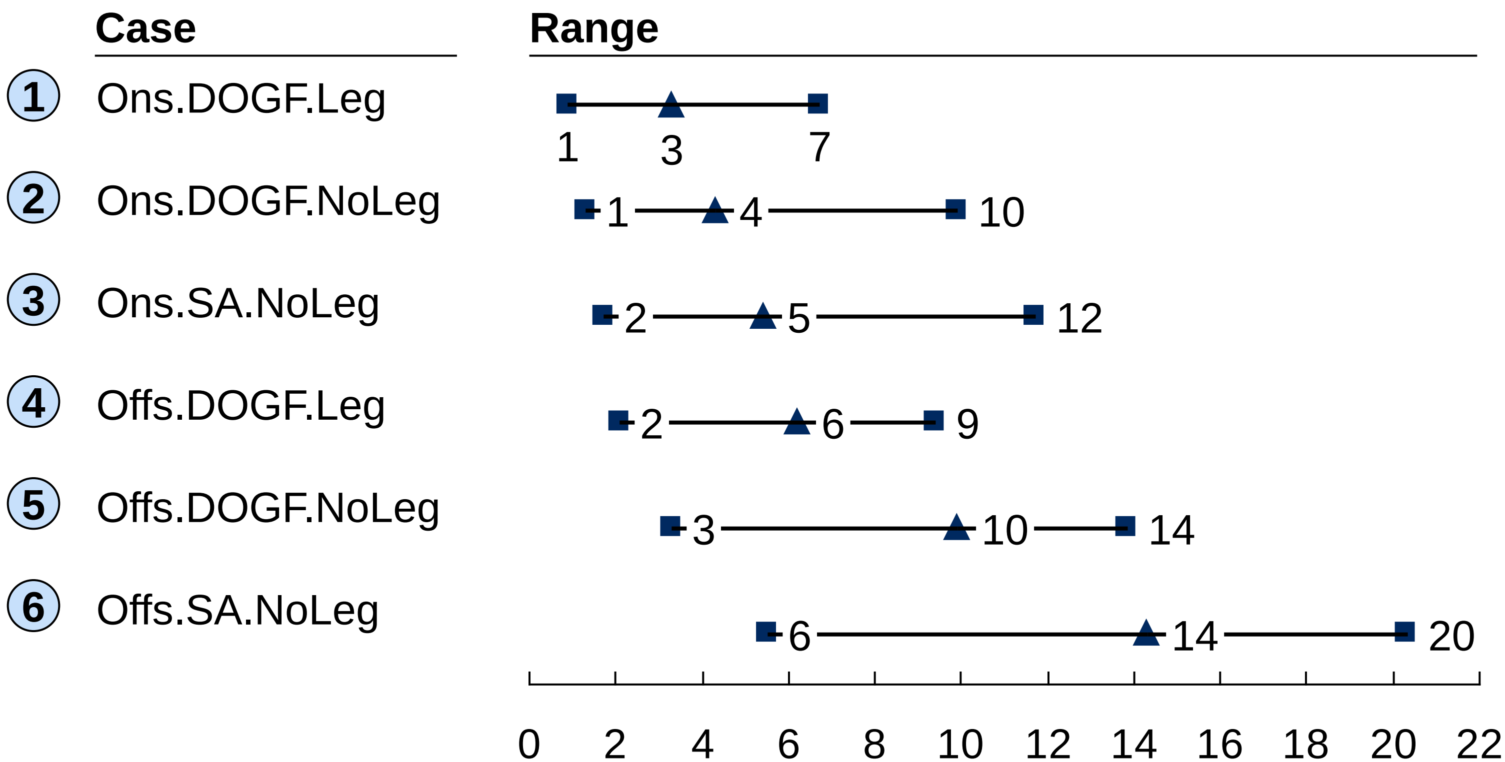
Full report can be downloaded at
http://www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html

Updated January 14, 2011

Storage costs differ per case, with the widest range and highest costs with offshore aquifers

€/ton CO_2 stored

Low
Medium
High



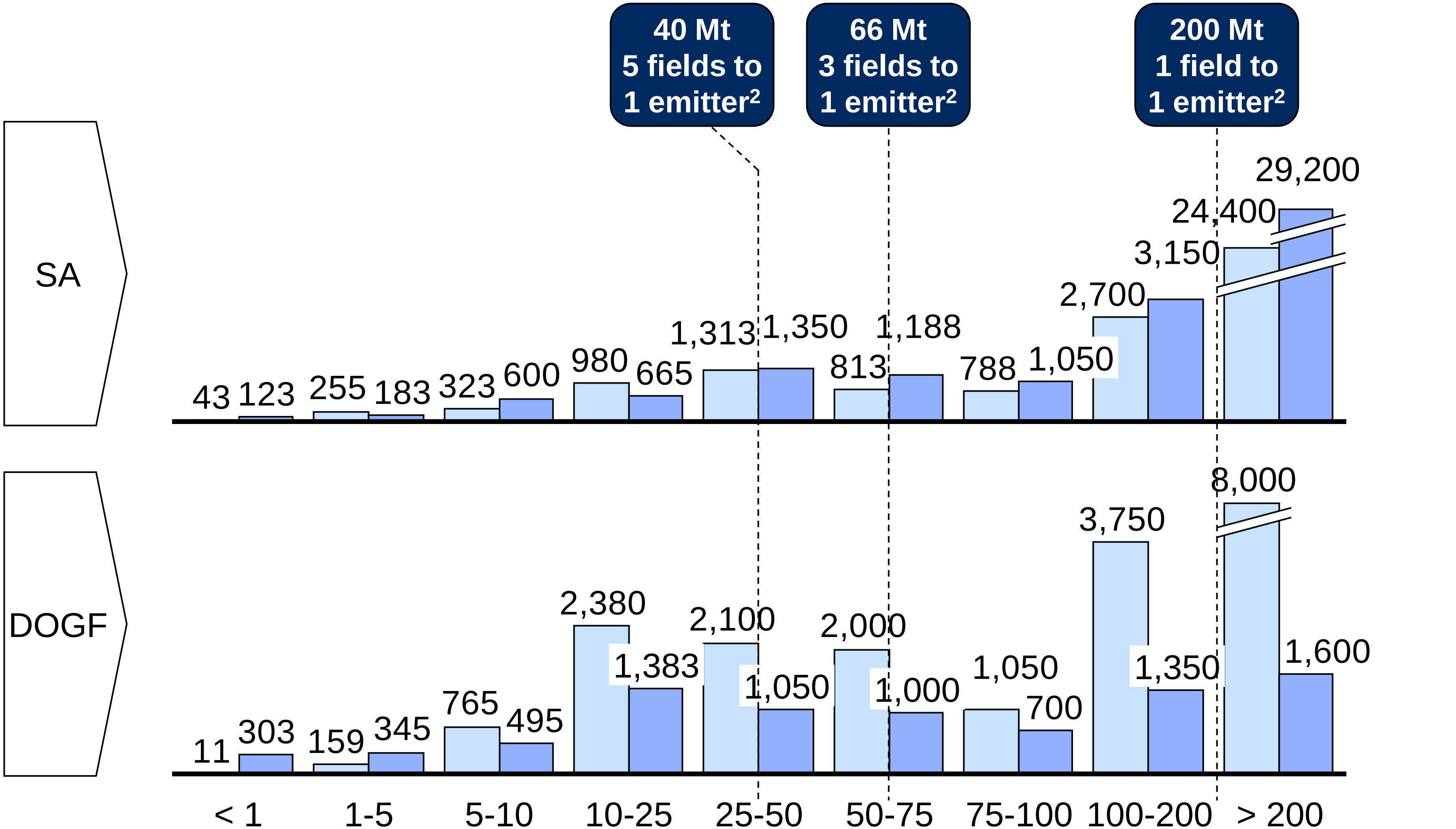
Ranges driven by setting Field capacity, Well injection rate and Liability transfer costs to low, medium and high scenarios[1]

1 In terms of cost

SOURCE: Team analysis

Field sizes vary strongly so three sensitivity ranges for field sizes have been taken

Total storage volume[1] per category of field size (in Mt CO_2 storage capacity) in Europe



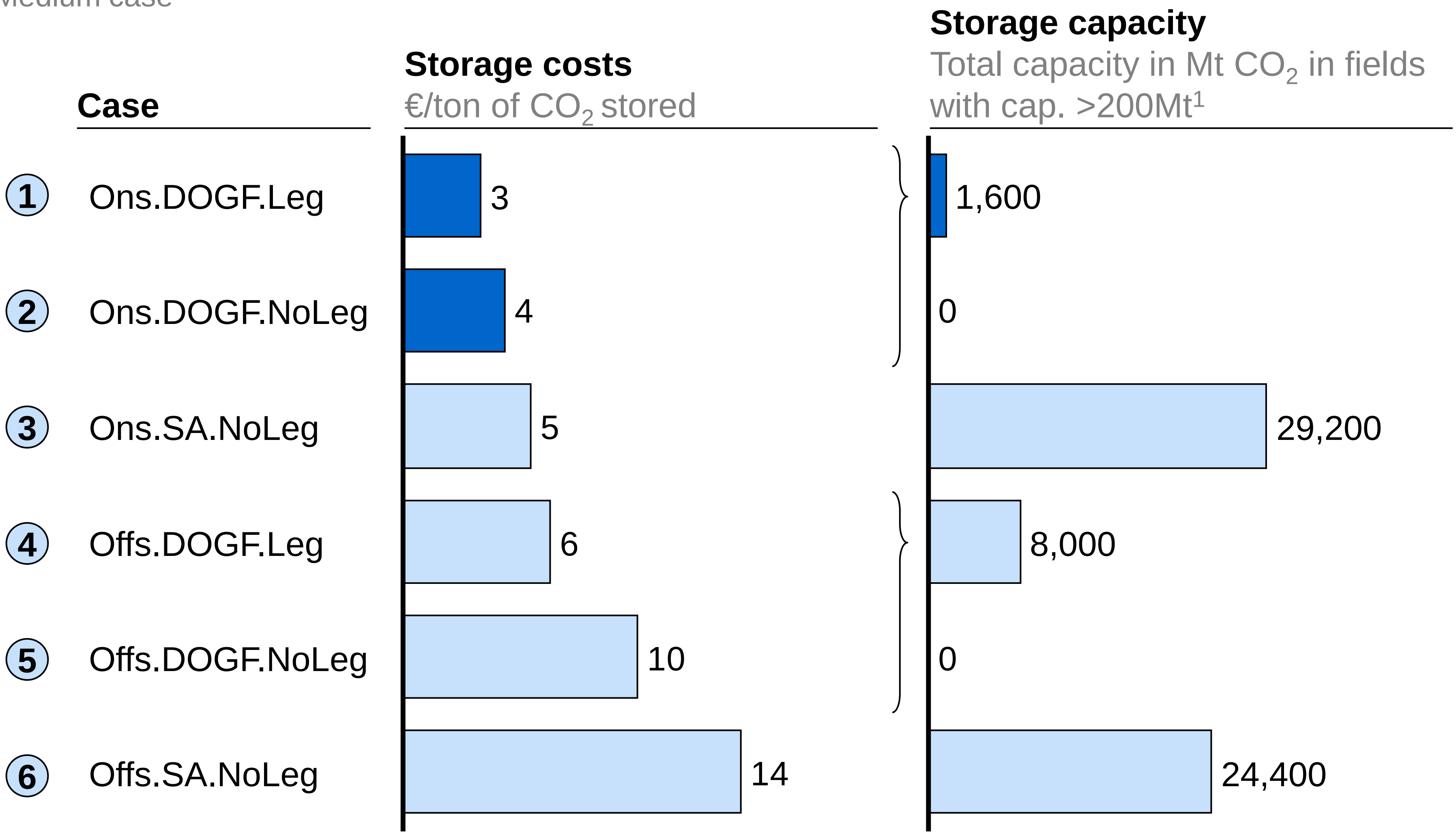
1 Total storage volume is an approximation, based on multiplying number of fields per category with the midpoint of the field size range of the category

2 Typical emitter requires 200Mt of storage in its economic lifetime

SOURCE: Geocapacity Final Report, EU project no. SES6-518318, team analysis

Cheapest field types are also the rarest

Medium case

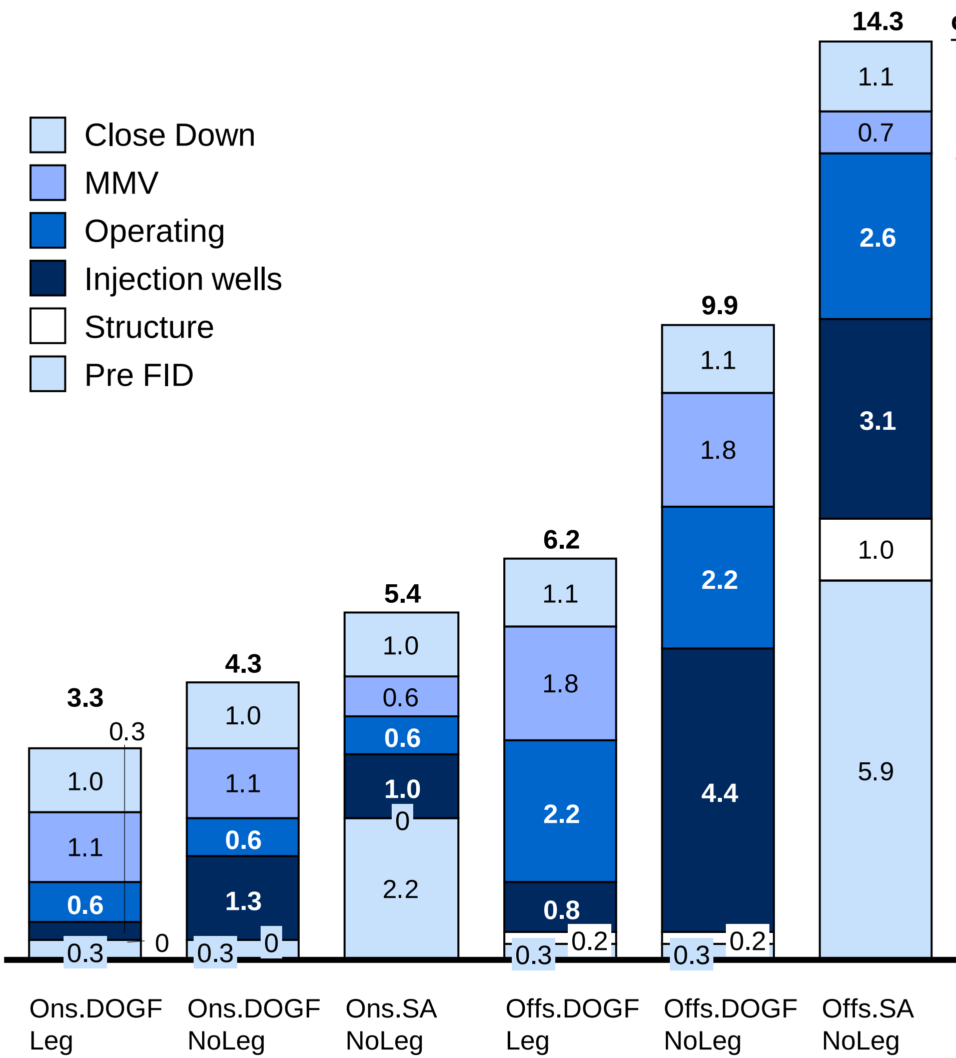


1 Typical emitter requires 200Mt of storage in its economic lifetime

SOURCE: Geocapacity Final Report, EU project no. SES6-518318, team analysis

Breakdown of cost components – medium scenarios for all 6 cases

€/ton CO_2 stored



Cost component	Description
Close down	▪ Decommissioning ▪ Liability transfer
MMV	▪ Including Opex, new observation wells and post-closure monitoring ▪ Final seismic survey
Operating	▪ Operations and maintenance
Injection wells	▪ New and re-used injection wells ▪ Legacy well remediation
Structure	▪ Platform new/ re-use
Pre FID	▪ Modeling/ Logging costs ▪ Seismic survey ▪ Injection testing ▪ New exploration wells ▪ Permitting

1 Pre FID excludes MMV baseline costs. Pre FID costs are high for SA due to seismic survey costs
2 Because SA needs initial seismic survey, MMV baseline costs and total MMV are lower for SA. Higher Pre FID for SA thus partially offset by lower MMV.

SOURCE: Team analysis

Key insights

1. Type and location of field is the main determinant of costs; onshore is cheaper than offshore, DOGF is cheaper than SA
2. The cheapest forms of storage (big onshore DOGF) are also the least available, because these are rare
3. High Pre FID costs for Aquifers reflect higher need of exploration compared to DOGF and risk of spending money on exploring SA that are deselected later. A risk-reward mechanism will need to be in place for companies to go after the large aquifer potential
4. Well costs are ~40-70% of total costs, sensitivities corresponding to well capital costs have highest impact. Resulting wide cost ranges are driven more by (geo)physical variation than by uncertainty around estimating resulting costs

- **Back up**

Methodology of CO_2 Storage cost computation model

1 **Early commercial phase as basis**	▪ Starting point of the model is the **early commercial phase** – Demonstration phase is modeled as a special situation – Mature commercial phase is assumed to be similar to the early commercial phase, i.e. it is assumed that there is only a low learning rate. This is because of the re-utilisation of existing technologies from the mature E&P industry
2 **Six discrete, realistic cases**	▪ The model computes CO_2 storage costs for **six discrete cases**, based on **Industry experience**, and varying on **three dimensions**: – Onshore vs. Offshore fields – Depleted Oil/Gas Field vs. Saline Aquifer – Legacy wells present vs. no legacy wells present[1]
3 **High number of parameters and sensitivity ranges**	▪ **26 parameters** are modeled to determine the CO_2 storage cost ▪ For **8 of these parameters**, sensitivity ranges have been run since these have a **material effect** on the outcome
4 **All costs annualized**	▪ All costs are **annualized** with the weighted average cost of capital, taking into account the time value of costs
5 **Costs in €/ton CO_2 stored**	▪ The model computes the CO_2 storage costs in Euro per ton CO_2 **stored**, not per ton CO_2 abated. This ensures neutrality for different capture technologies ▪ The scope is Europe, for other regions global variations in costs need to be taken into account (e.g. rig costs). However the trends between the six cases are expected to be the same

1 SA fields have no legacy wells, so the three dimensions result in 6 discrete cases

SOURCE: Team analysis

Assumptions and sensitivities for the 8 key cost drivers

Cost driver	Medium case assumption	Sensitivities	Rationale
▪ Field capacity	66Mt per field	▪ 200Mt per field ▪ 40Mt per field	▪ Based on Geocapacity data
▪ Well injection rate	0.8 Mt/year per well	▪ 2.5 Mt/year ▪ 0.2 Mt/year[1]	▪ See deep dive page
▪ Liability transfer costs	€ 1.00 per ton CO_2 stored	▪ € 0.20 ▪ € 2.00	▪ Rough estimate of liability transfer cost ▪ Wide ranges reflect uncertainty
▪ WACC	8%	▪ 6% ▪ 10%	▪ Same range as previous (September 2008) study
▪ Well depth	2000 meters	▪ 1000m ▪ 3000m	▪ Well costs strongly dependant on depth[2]
▪ Well completion costs	Based on industry experience, offshore cost three times onshore cost	▪ -50% ▪ +50%	▪ Ranges based on actual project experience
▪ # Observation wells	1 for onshore; nil for offshore	▪ 2 for onshore; 1 for offshore	▪ 1 well extra to better monitor the field
▪ # Exploration wells	4 for SA; nil for DOGF	▪ 2 for SA, nil for DOGF ▪ 7 for SA, nil for DOGF	▪ DOGF are known, therefore no sensitivities needed ▪ SA reflects expected exploration success rate

1 0.2 Mt/yr not modeled for offshore cases, as costs would become to high to be viable
2 Supercritical state of CO_2 occurs at depths of 700-800 meter

SOURCE: Geocapacity Final Report, EU project no. SES6-518318 , team analysis

Sample model output

CCS Model - Control panel

Scenario switch: Medium

Switches	Manual override	Active scenario value
Field/plant capacity multiplier		0.33x
Injection rate (Mt/yr)		Medium
Liability transfer (EUR / tonne stored)		Medium
WACC		Medium
Depth		Medium
Well completion costs / well (EUR m)		Medium
Average CO2 production (Mt/yr)		Medium
Lifetime		Medium
New Exploration wells		Medium
New Observation wells		Medium
Permitting		Medium
Learning rate		Medium
Booster (half the years, double the wells)		No

Storage - calculation sheet

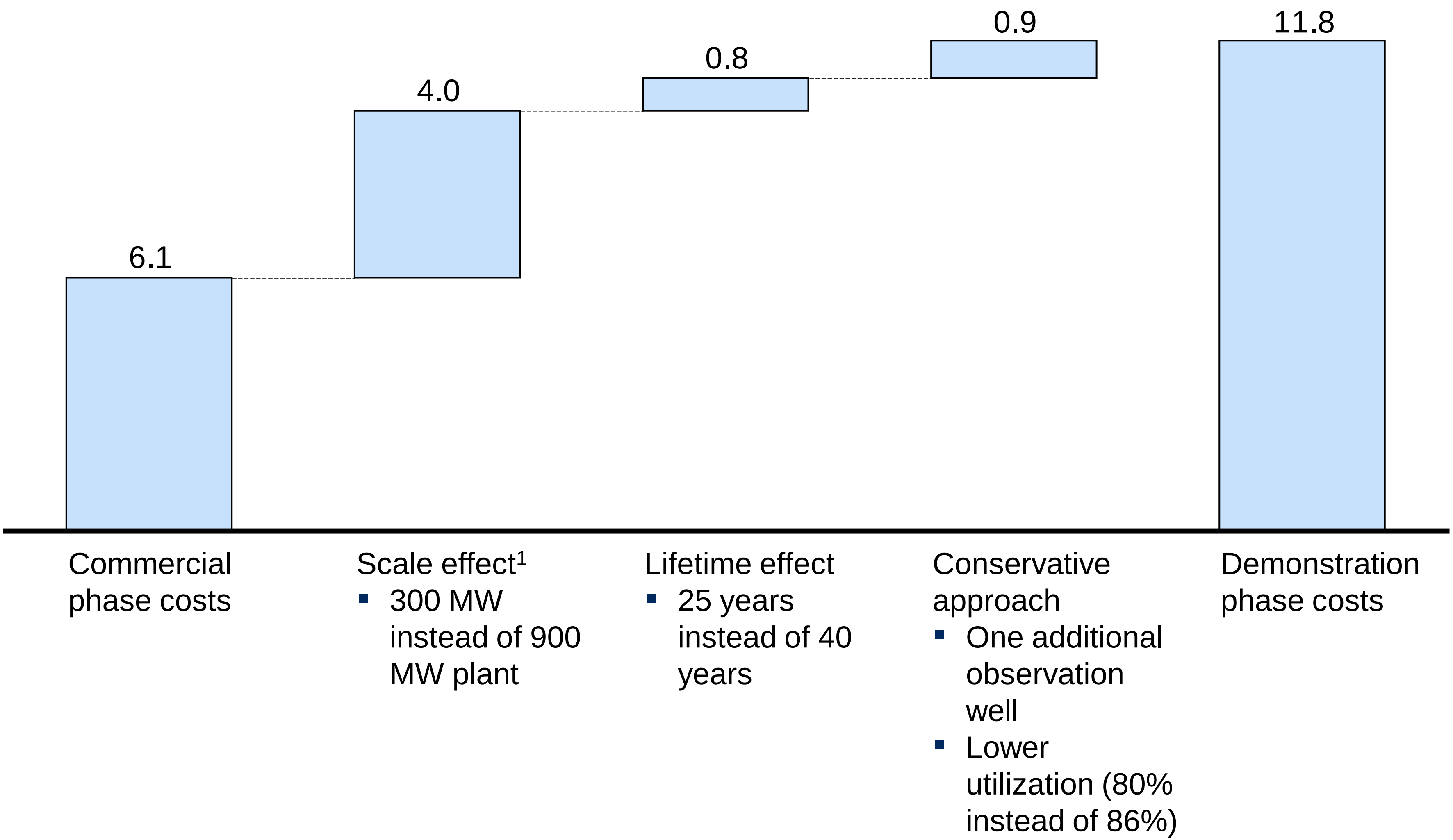
	Settings	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Location		Onshore	Onshore	Onshore	Offshore	Offshore	Offshore
Type		DGF	DGF	Aquifer	DOGF	DOGF	Aquifer
Data quality		Data-Rich	Data-Rich	Data-Poor	Data-Rich	Data-Rich	Data-Poor
Legacy Wells		Yes	No	No	Yes	No	No
Capacity and number of wells							
Lifetime (years)	Medium	40	40	40	40	40	40
Average CO2 production (Mt/yr)	Medium	1.7	1.7	1.7	1.7	1.7	1.7
CO2 avoided (Mt/yr)		1.2	1.2	1.2	1.2	1.2	1.2
Field/plant capacity multiplier	0.3x	0.3x	0.3x	0.3x	0.3x	0.3x	0.3x
Total capacity needed (Mt)		66	66	66	66	66	66
Well capacity (Mt)		32	32	32	32	32	32
New Exploration wells	Medium	0	0	4	0	0	4
New Observation wells	Medium	1	1	1	0	0	0
New Injection wells		0	4	3	0	4	3
Costs							
CapEx (EURm)							
Modelling / Logging costs		3	3	6	3	3	6
Seismic survey		0	0	9	0	0	22
Injection testing		1	1	1	1	1	1
New exploration wells		0	0	26	0	0	87
Permitting	Medium	1	1	1	1	1	1
Prestudy costs		5	5	43	5	5	116
MMV baseline		10	10	1	23	23	1
New injection wells		0	26	17	0	87	58
Re-used injection wells		3	0	1	9	0	3
New observation wells		6	6	6	0	0	0
Legacy well remediation		3	1	1	6	0	0
Platform new/re-use		0	0	0	4	4	19
Commercial-phase set-up costs		21	43	26	42	113	81
Close-down costs discount factor		21.7	21.7	21.7	21.7	21.7	21.7
Decommissioning (discounted)		0	0	0	0	1	1
Final seismic survey (discounted)		0	0	0	1	1	1
Post-closure monitoring (discounted)		0	0	0	0	0	0
Close-down costs		1	1	1	1	2	2
Learning rate	Medium	0%	0%	0%	0%	0%	0%
Total CapEx		**27**	**48**	**70**	**48**	**120**	**199**
Annualized CapEx (driven by WACC)	Medium	2	4	6	4	10	17
OpEx (EUR m)							
Operations & Maintenance		1.0	1.0	1.0	3.6	3.6	4.2
Liability transfer (EUR m)		1.7	1.7	1.7	1.7	1.7	1.7
MMV recurring costs		0.4	0.4	0.4	1.0	1.0	1.0
Learning rate	Medium	0%	0%	0%	0%	0%	0%
Total OpEx (EUR/yr)		**3.1**	**3.1**	**3.1**	**6.3**	**6.3**	**6.9**
CO2 Storage costs (EUR / tonne stored)		**3.3**	**4.3**	**5.4**	**6.2**	**9.9**	**14.3**

SOURCE: Team analysis

For any demonstration phase project, costs will be significantly higher – Example case 3 (Ons.SA.NoLeg) medium scenario

ILLUSTRATIVE

€/ton CO_2 stored



1 Scale effect has been taken as factor 2 rather than 3 since absolute scale effect is mitigated somewhat by expected ‘cherrypicking’ of storage fields

SOURCE: Team analysis

Assumptions on other parameters (1/2)

Cost driver	Assumption	Why no sensitivities
▪ Re-use of exploration wells	One out of three exploration wells is re-usable as injection well; others are not located correctly, do not match the injection depth, etc.	1 Sensitivity range would be small as cost driver is small
▪ Utilization	Utilization is 86%, implying a peak production of 116% average	
▪ Contingency wells	10% of the required number of injection wells is added as contingency, with a minimum of one per field	
▪ Well retooling cost	Re-tooling legacy wells as exploration wells, or exploration wells as injection wells, costs 10% of building the required well from scratch	
▪ Operations & Maintenance	4% of CapEx costs for platform and new wells	2 Sensitivity range would be small as cost driver is well understood from E&P experience
▪ Injection testing	Fixed cost per field	
▪ Modeling / logging costs	Fixed cost per field, SA costs ~2 times as high as DOGF	
▪ Seismic survey costs + MMV Baseline	Fixed cost per field, offshore costs ~2 times as high as onshore. In addition, at end of economic life, final seismic survey is performed prior to handover (costs discounted for time value of money)	
▪ MMV recurring costs	Fixed cost per field, offshore costs ~2 times as high as onshore	

SOURCE: Team analysis

Assumptions on other parameters (2/2)

Cost driver	Assumption	Why no sensitivities
Permitting costs	€ 1M per project	1 Sensitivity range would be small as cost driver is small
Well remediation costs	Provision ranging from nil to 60% of new well costs, based on chances of risky wells and costs to handle them.	
Platform costs	For offshore there are platform costs; SA is assumed to require a new platform, DOGF is assumed to require refurbishment of an existing platform	
Decommissioning	15% of CapEx of all operational wells and CapEx of platform	
Post-closure monitoring	20 years after closure, at 10% of yearly MMV expenses during first 40 years	
Economic life	40 years, demonstration phase 25 years. In line with Capture assumptions;	2 Sensitivity range would be too small as cost driver is well understood from E&P experience
Learning rate	0% as CO_2 storage technologies are well known and builds on oil& gas industry experience[1]	
Exchange rate	1.387 USD/EUR (as of October 6, 2010)	
Plant CO_2 yearly captured	CO_2 captured is assumed to be 5Mt per year. Variation in the amount captured is implicitly modeled by variation in storage field capacity as a sensitivity	Sensitivity modeled with other parameter

1 Deep dive slide on positive learning rate is included in backup

SOURCE: Team analysis

Sensitivities – Example: case 6 (Offs.SA.NoLeg) medium scenario

Parameters used on ranges page

Sensitivity of cost[1]

€/ton CO_2 stored

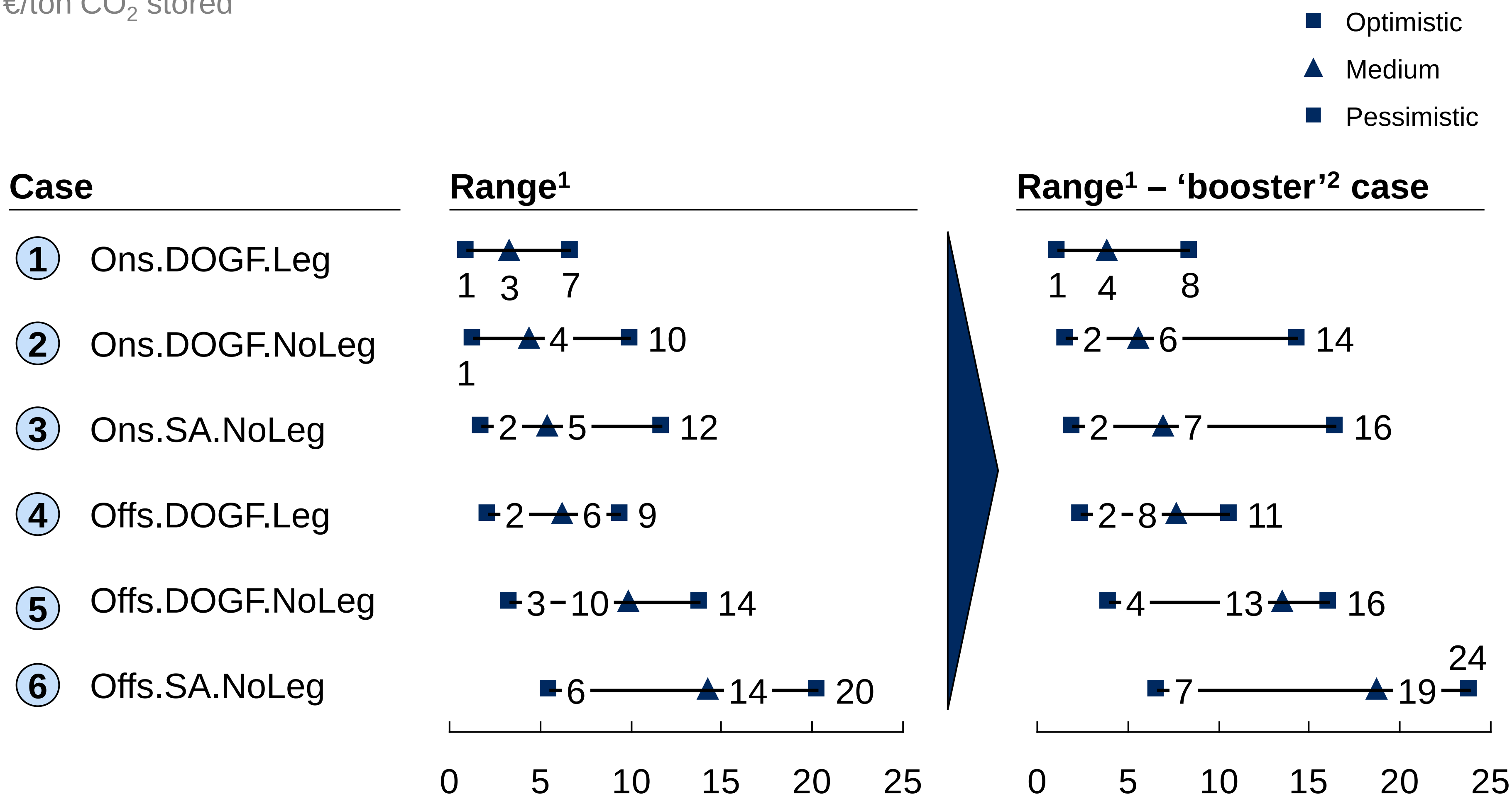
Parameter	Low	High	Sensitivity range	Medium
Medium scenario		14.3		
Field capacity	-5.2	5.0	200 – 40Mt[4]	66Mt[4]
Well Injection Rate	-3.3	0	100 – 8 Mt	32 Mt
Liability	-0.8	1.0	€ 0.2 – 2/ton CO_2	€ 1/ton CO_2
Well completion	-3.8	3.8	+/- 50 %	100 %
Depth	-4.8	4.8	1000 – 3000 m	2000 m
WACC[2]	-2.0	2.2	6% – 10%	8%
New observation wells	0	1.1	1 – 2 wells	1 well
New exploration wells	-1.5	2.3	2-7 wells	4 wells
Total[3]	-11.5	40.5		

1 The sensitivity denotes the individual effect of ranging a parameter on the total cost in medium scenario
2 Weighted Average Cost of Capital
3 Parts do not add to total. Combined effect of variables is larger due to interdependencies
4 High scenario is 1 emitter to 1 field, medium scenario is 1 emitter to 3 field, low scenario is 1 emitter to 5 fields

SOURCE: Team analysis

Doubling wells and halving lifetime increases storage costs by ~20-25%

€/ton CO_2 stored



1 Well injection capacity, Field capacity and Liability transfer costs set to most high, medium and low scenario in terms of costs

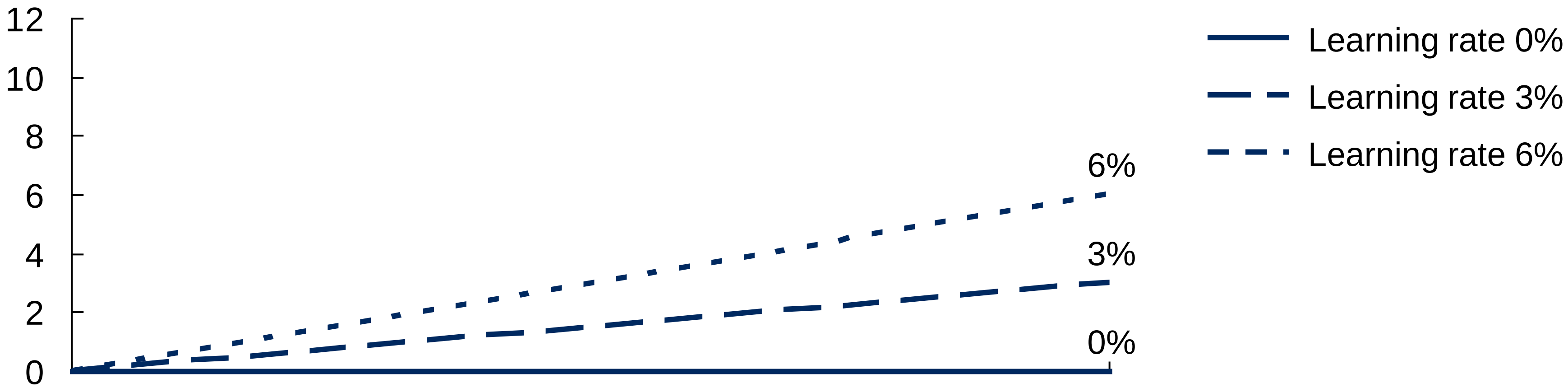
2 ‘Half the years, twice the wells’; therefore assumes 20 years (vs. 40 years) and half the well capacity (in order to double the number of wells)

SOURCE: Team analysis

The learning rate does not materially impact the cost of storage

Cost decrease due to learning rate

Percentage



Effect of learning rate per case

€/ton CO_2 stored

	Ons.DOGF. Leg	Ons.DOGF. NoLeg	Ons.SA. NoLeg	Offs. DOGF. Leg	Offs. DOGF. NoLeg	Offs.SA. NoLeg
3%	0.098	0.130	0.163	0.187	0.297	0.428
6%	0.195	0.261	0.326	0.374	0.593	0.856

For all cases, learning rate is one of the or the **smallest sensitivity effect**

SOURCE: Team analysis

Global Storage Resource Analysis for Policymakers

Neil Wildgust
Project Manager – Geological Storage

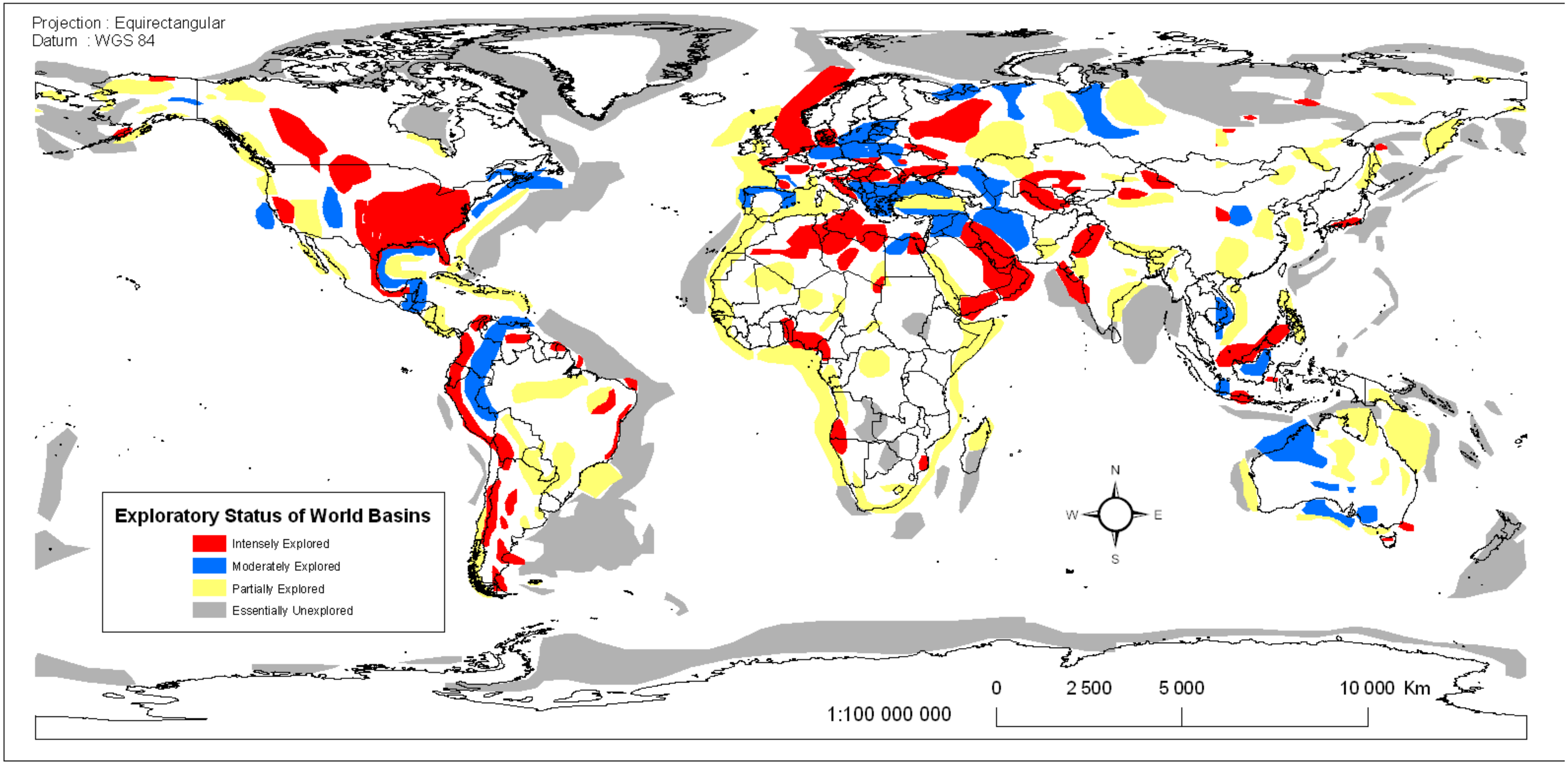
IEA CCS Costs Workshop

Paris, 22nd – 23rd March 2011

Introduction

- Study being undertaken by Geogreen, and funded by GCCSI, commenced 2010, in progress
- Primary objective - Alert policymakers to the scale, cost and timing of the storage resource assessment, required to enable deployment of commercial-scale CCS projects by 2020: 20 projects envisaged by G8 Leaders, and 100 projects in IEA CCS Roadmap.

Basin Exploration level



Estimated project time line

Deep Saline Formation	IEA GHG Timing min	IEA GHG Timing max
Phase 1 Desk Based assessment	0.5	1
Licensing Exploration Permit	1	2
Phase 2 Site confirmation & characterization	1	4
Phase 2 Injection Test	1	4
Bankable		
Licensing Demo	1	2
Phase 3: Construction and Start up	1	3
Injection & Storage Demo	1	5
Bankable		
Detail design Commercial	1	2
Licensing Commercial	1	3
Phase 4: Construction and Start up	1	3
Injection & Storage Commercial	5	50
Closure		

Depleted Oil and Gas Field	IEA GHG Timing min	IEA GHG Timing max
Phase 1 Desk Based assessment	0.5	1
Licensing Injection Test	0.5	2
Phase 2 Site confirmation & characterization	0.5	1
Phase 2 Injection Test	0	0.5
Bankable		
Detail design Commercial	1	2
Licensing Commercial	1	3
Phase 4: Construction & Well integrity check	1	3
Injection & Storage Commercial	5	50
Closure		

CO2 - EOR	IEA GHG Timing min	IEA GHG Timing max
Phase 1 Desk Based assessment	0.5	1
Licensing EOR Test	0.1	0.5
Phase 2 Construction and Well assessment	0.5	1
Phase 2 Injection Test	0	0.5
Bankable		
Detail design Commercial	1	2
Licensing Commercial	0.5	1
Phase 4: Construction & Well integrity check	1	3
Injection & Storage	5	10
Closure		

DSF Bankability workflow

Type of study	Phase	Major costs items
National based *Non exclusive surveys*	Phase 0 Screening	First desktop studies
Project based *Exclusive surveys*	Phase 1 Desk Based assessment	Desktop studies, where possible seismic reprocessing and existin logs analysis (inluding communication on project)
	Licensing Exploration Permit	Admistrative engineering and follow-up
	Phase 2 Site confirmation & characterization	Studies and engineering for this phase (including monitoring actio equipments and monitoring (soil, gravimetric, Insar))
		Seismic acquisitions 2D
		Seismic acquisitions 3D (on CO_2 future plume only)
		Civil Engineering
		Drilling CO_2 well with rotary rig (including 20% contingency includi Mob/demob)
	Licensing Injection test	Injection test permitting
	Phase 2 Injection Test	Studies and monitoring
		Injection test duration
		CO_2 injection cost
Bankable		

How many project will be bankable in 2015? in 2050?

Projects data base

Phase 0 Screening

Phase 1 Desk Based assessment

Licensing Exploration Permit

Phase 2 Site confirmation & characterization

Licensing injection test

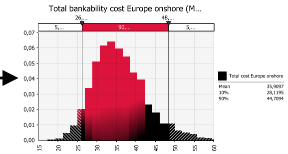
Phase 2 Injection Test

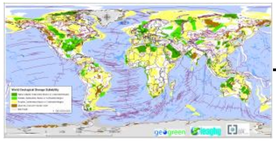
Number of projects financed in 2020

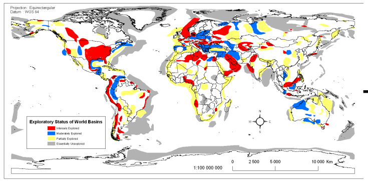
Development time model

cost

How many projects to finance to match development objectives?

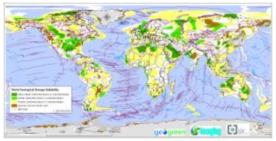




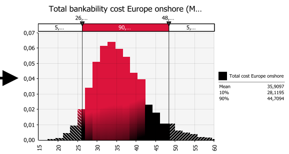


Development time model + success rate to 2015

cost



Number of projects to finance to achieve 2050 objective

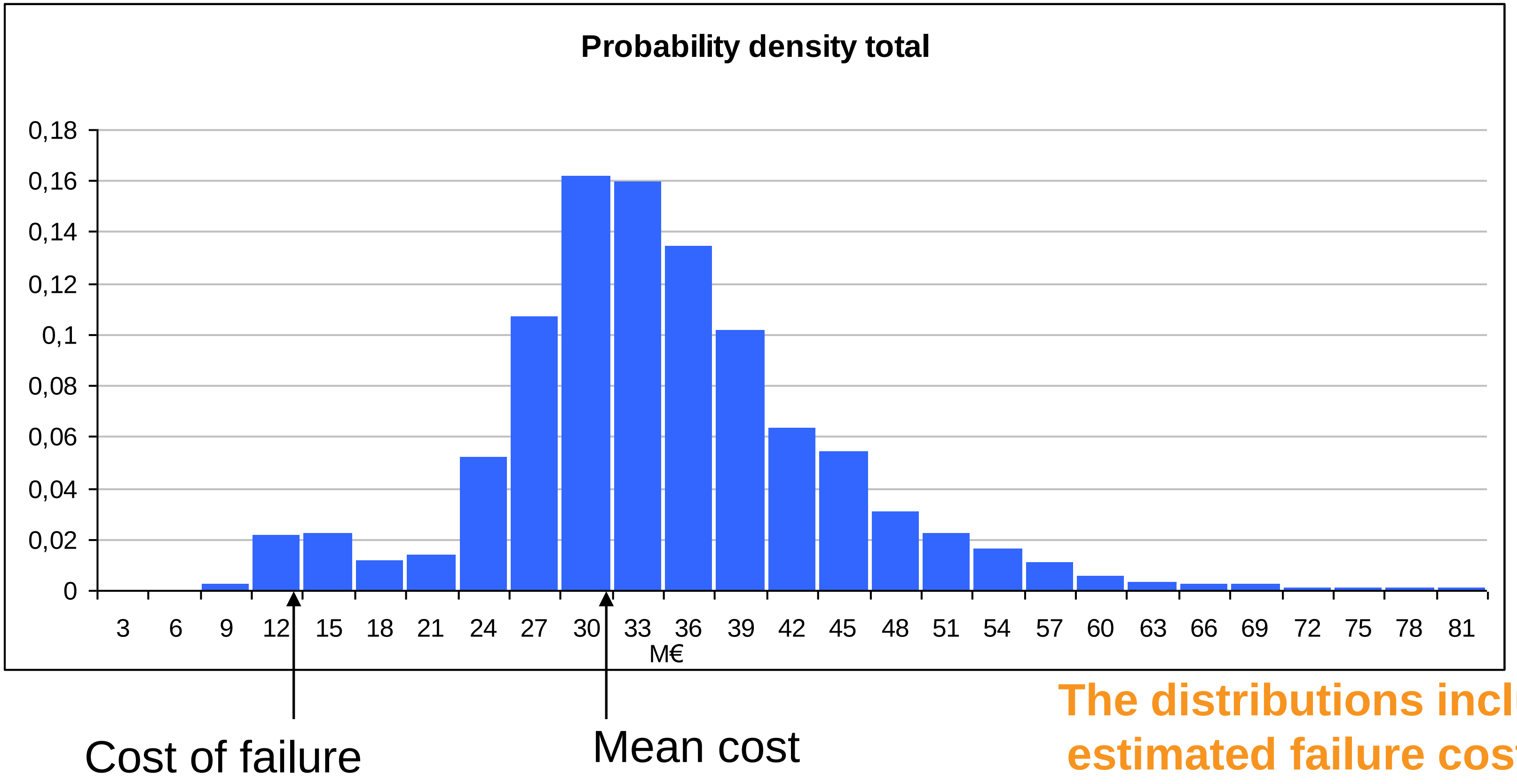


CO_2 sources data base

Development needs in 2030 - 2050

DFS European project cost

Total cost distribution for onshore bankability for an intensely explored area



The distributions includes estimated failure costs of data acquisition, wells…

Costs – key points

- Cost models are considered for onshore and offshore storage options both in Deep Saline Formations and Depleted Oil and Gas Fields
- Take account of failed storage sites
- Numerous possibilities for each site to reach a successful path
- Cost models include an assessment of the economic uncertainties of project bankability

- Draft Report delivered March 2011

Thank you

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