How UK thermal power plant cleaned up their act......for what future?

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65th Energy Science Lecture, University House, University of Leeds
20th September 2016

Presentation Overview

- The growth of coal fired power stations in the UK from 1950 onwards
- Typical coal analysis and combustion characteristics
- The 1980’s acid rain debate and the introduction of SOx and NOx control
- Fundamentals of NOx emission control
- Low NOx burner design and development
- The early 1990 changes in the electricity generation industry
- Large Combustion Plant Directive 2001/80/EC
- Developments in the industry in the 2000’s
- The closure of coal plant by 2025
- Where now for the UK electricity industry

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Coal fired electricity generation in the UK pre 1950

- 1920’s ….over 480 authorised suppliers of electricity in England and Wales
  - Generating and supplying electricity at a variety of voltages and frequencies
  - Typical plant sizes around 10MW
  - Most coal fired plant were of the mechanical grate design; first pulverised fuel boiler tested in the USA in 1918
  - Pulverised fuel approach accepted in the UK a decade or so later

- Electricity Supply Act 1926 created a central authority, the Central Electricity Board, to promote a national transmission system operating at 132kV
  - Transmission system largely completed by the end of 1935

- Electricity Act 1947 brought the distribution and supply activities of 560 separate organisations in England and Wales under state control and integrated them into 12 regional Area Boards ..British Electricity Authority (B.E A) formed; name changed to Central Electricity Authority in 1954

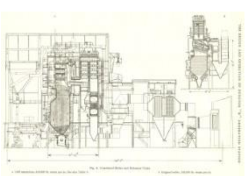
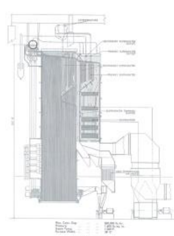
UK Coal Fired Boiler Development …1949 to 1963

1949	1956	1958	1959	1962	1963
50MW Dunston	100MW Castle Donnington	120MW Blyth A	200MW High Marnham	275MW Blyth B	550MW Thorpe Marsh
42 bar 454/454°C	103 bar 565/565°C	103 bar 538/538°C	162 bar 565/538°C	159 bar 568/568°C	159 bar 568/568°C
Two 50 MW sets, first with both reheat steam cycle and turbo-alternators unitized with the boiler	Six off units, at the time the largest power station in Europe, with a cost of £30m	Four off units. In total 44 units of this type built across the country	Europe's first 1GW power station. Later units at West Thurrock, Willington B and Kincardine…11 in total	Two 275 MW units	The prototype for all large modern coal fired power stations in the UK; four units in total

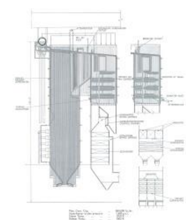
1957





The Electricity Act 1957 established the Central Electricity Generating Board (CEGB) and the Electricity Council. The CEGB took over the duties of generation and transmission from the CEA




The Supercritical Experiment

- Work began in 1962, with generation commencing in 1964, at Drakelow C on
  - Two 350 MWe John Thompson boilers

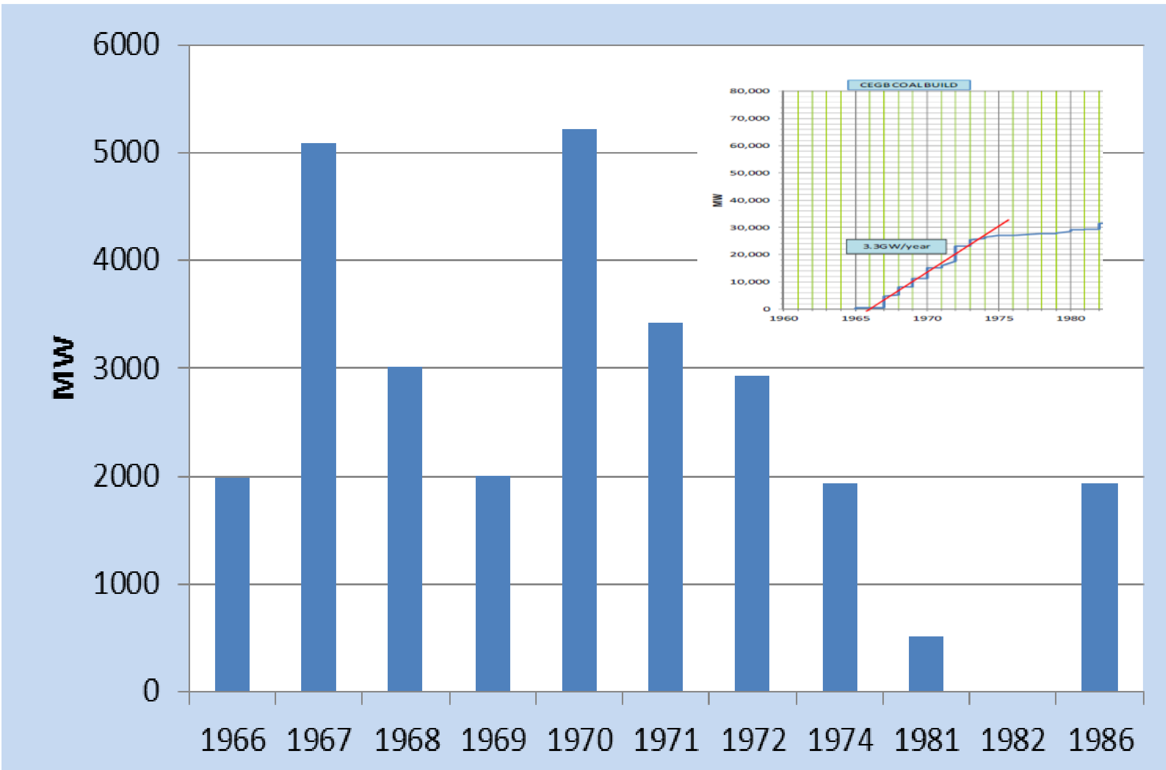
    158.5 bar, 593 deg C superheat, 565 deg C reheat
  - Two 375 MWe Babcock and Wilcox boilers

    240 bar, similar temperatures
  - The first supercritical boiler design in the UK

- Although the implementation, from a business case perspective just about broke even, the decision to go ahead was based on the need to stimulate design development and the production of low cost high temperature steels.
- There were many problems associated with the plant design
  - Boiler flue gas leakage
  - Metallurgical issues with the high temperature materials
  - Corrosion issues
- The experience damaged the reputation of supercritical boilers in the UK and no more were ever built…there was more success in Europe and supercritical designs became the norm from the 1970’s onward

..and then…..the 60's "Dash for Coal"

- All based around the Thorpe Marsh prototype design
- 1974 saw the introduction of the first opposed wall fired boiler design ..Drax



Year	Station	Installed Capacity (MW)
1966	Ferrybridge C	1,995
1967	Eggborough	1,960
1967	West Burton	1,972
1967	Cockenzie	1,152
1968	Ratcliffe	2,000
1968	Tilbury B	1,020
1969	Cottam	2,008
1970	Kingsnorth	1,940
1970	Ironbridge	970
1970	Longannet	2,304
1971	Fiddler's Ferry	1,961
1971	Aberthaw	1,455
1972	Rugeley	1,006
1972	Didcot A	1,925
1974	Drax A	1,935
1981	Kilroot	520
1986	Drax B	1,935

Boilermakers	
Babcock & Wilcox	22
Foster Wheeler / John Brown	14
ICL	12
Foster Wheeler	4
John Thompson	4
Clarke Chapman	1

Turbine suppliers	
Parsons	20
AEI	9
EE	12
GEC	16

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Typical UK Fuel Supply specification

- Castle Donnington Fuel Supply specification

	1	2	3	4	5
		Range of 95% of supplies			
	Typical Basic Fuel	Limits	Typical High Moisture Fuel	Typical High Ash Fuel	Limits of 100% Supplies
Proximate Analysis Moisture inherent … % Moisture free … %	} 14.0	5.5 - 18.0	18.0	6.7	Max. 20
Ash … … … %	14.0	5.2 - 23.0	6.4	23.0	Max. 23
Volcanic matter … … %	29.0	27.0 - 34.0	28.0	27.6	Min. 25
Fixed carbon … … …	43.0	36.5 - 49.5	47.6	42.7	---
Sulphur … … … %	1.5	0.6 - 2.5	0.8	0.7	Max. 2.7
Phosphorus … … %	0.02	0.001 - 0.05	0.01	0.03	Max. 0.07
Chlorine … … … %	0.3	0.01 - 0.5	0.30	0.50	Max. 0.7
Gross Calorific Value … …	10350	9500 – 11500	11030	10220	Min. 9000
Net Calorific Value (B.Thu/lb) …	9850	9000 – 11000	10470	9820	---
Ash in Reducing Atmosphere Initial Deformation °C … …	11500	1100 – 1285	1180	1150	Min. 1050
Fusion Temperature °C …	1200	1150 - 1375	1250	1220	Min. 1100

- East Midlands coal …..a typical UK coal.. (over 800 UK coal mines in operation)
  - No Nitrogen specification ….NOx emissions not a design consideration
  - Typical nitrogen level 1.5% and Fuel Ratio (FC/VM) 1.48
  - Sulphur level in East Midlands coal low relative to other UK coal…2.5 to 2.7% not atypical

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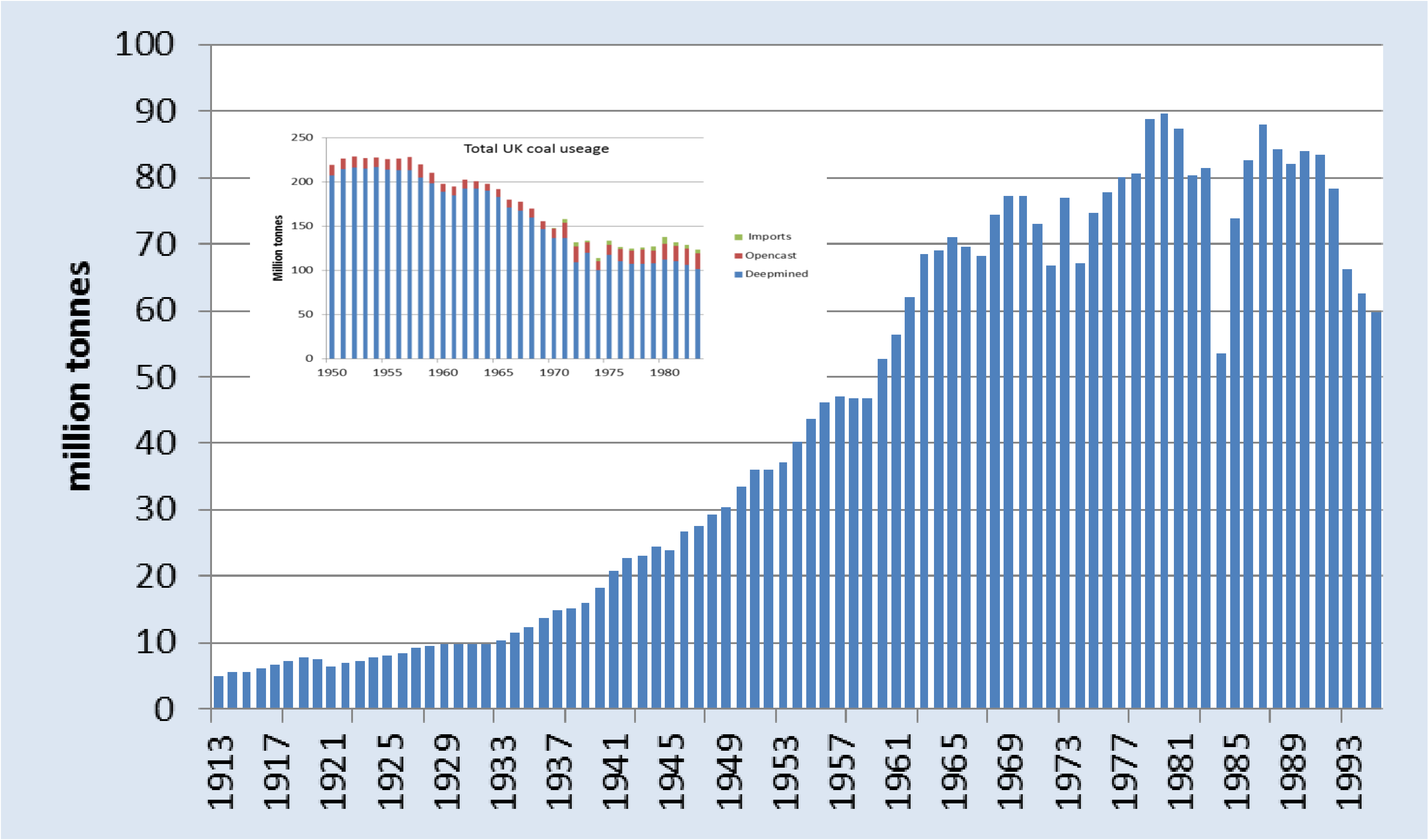
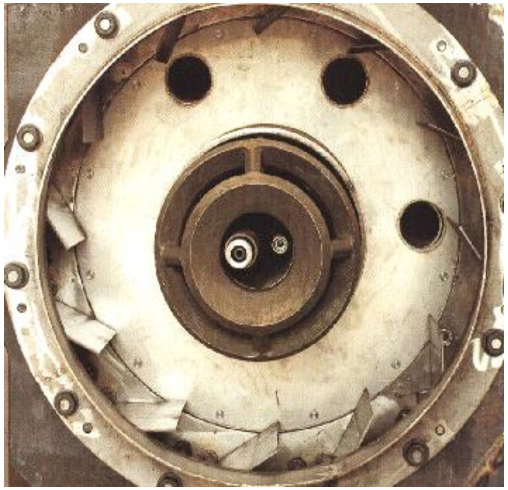
UK coal used in electricity generation



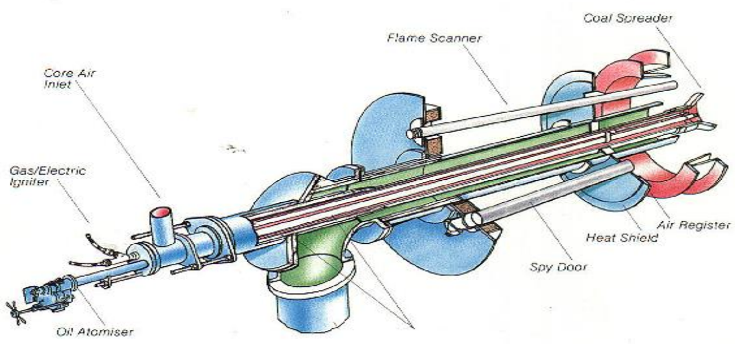
Boiler / Combustion Basic Design principles

- The basic driving force parameters in the design evolution were overall efficiency and cost
- As such the trend was to design the combustion chamber to be compact, and as size increases the design became relatively more compact e.g. Ferrybridge is single wall fired and has a residence time of ~1.2 seconds from top row of burners to the furnace exit; Drax is opposed wall fired, with a division wall, and has a residence time of ~1 second……more intense hotter combustion.
- Accordingly, the majority of wall fired boiler designs used circular coal burners, designed for fast mixing and high combustion efficiency
  - NOx emission levels never a design consideration
  - Designed for high volatile bituminous coals, evolving in size and operational features as plant size increased



Conventional Circular Coal Burner : Typical Combustion Performance

- Typical Combustion Performance
  - NOx emissions of 1000 - 1700 mg /Nm^3 @ 6% oxygen
    - Drax ~ 1270 – 1415 mg /Nm^3
    - Ferrybridge ~ 1100 mg/Nm3
    - Cockenzie ~ 900 to 1000 mg/Nm3



  - CO emissions of less than 100 vppm
  - Carbon in flyash approximately 1 – 2%
  - GCV Loss approximately 0.2 – 0.4%
  - Overall plant efficiency between 33 – 37%
  - With a 1.0% sulphur coal typical SOx levels 2200 mg/Nm3

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Acid Rain…and its effects…UK denial

- In 1980, the UK produced 26.2% of total European Community (EC) large plant SO_2 emissions, 3,883 kt/year, and 26.7% of total community large plant NOx emissions (1016 kt / year)

- In 1982 FRG recognised the link between plant emissions and German forest die-back….despite UK protestations….. and pressed for EC action against " The Dirty Man of Europe"

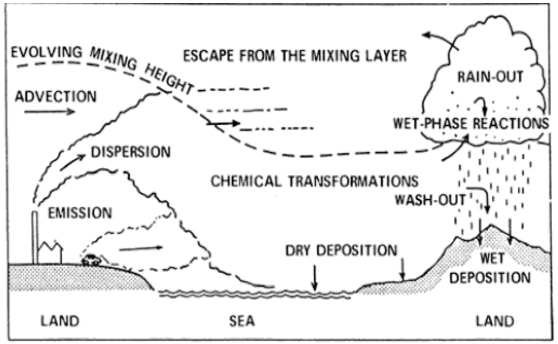


Fig. 1.1. Processes involved in the deposition of atmospheric pollutants.

- ~ 80% of electricity generation in the UK from coal fired plant

- In December 1983 the EC introduced COM (83)704, for new and existing combustion plants, calling for 60% SO_2 reduction and 40% NOx and dust reduction by 1995

Acid Rain…and its effects…UK denial

- The principles behind COM (83) 704 were debated for five years
  - Within the EC, environmental policy at loggerheads with energy policy
  - UK continued to question the EC approach
    - Questioned the scientific evidence on acid rain
    - Costs of FGD retrofit and NOx reduction prohibitive could not be justified
    - SO_2 and NOx reduction technologies unproven on UK coal and in UK boiler applications
- UK government position
  - To achieve 30 per cent reduction on 1980 levels of SO_2 and NOx emissions by the end of 1990s,
  - "….. although the very substantial expenditure required to install flue gas desulphurisation plant at existing power stations could not be justified while scientific knowledge was developing and environmental benefits remained unclear"

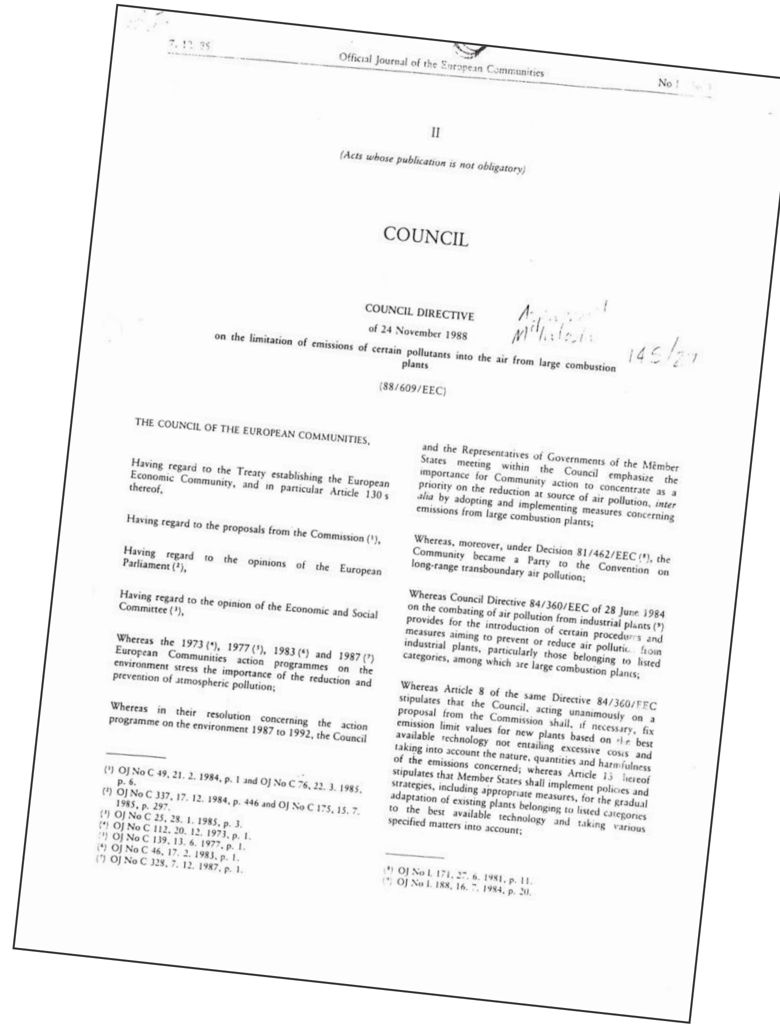
Acid Rain…and its effects….UK acceptance

- In 1986 the UK accepted the scientific evidence for the first time
  - Over three years the CEGB planned to ”*spend over £20M investigating sulphur reduction in coal, desulphurising flue gas, fluidised-bed combustors, furnace burners with reduced outputs of oxides of nitrogen, and coal gasifiers with reduced emissions”*
  - CEGB recommended FGD installation at Drax (part of a 6GW retrofit package) and on future new coal fired stations, albeit with a notably restrained timeline….ultimately Drax FGD initiated in 1988, operational 1995, also Ratcliffe had FGD installed in the early 1990’s
  - CEGB initiated a series of three year trials on NOx reduction, principally to determine the feasibility of NOx reduction with UK coal on UK plant

CENTRAL ELECTRICITY GENERATING BOARD

Acid Rain…and its effects….UK acceptance

- Large Combustion Plant Directive (LCPD) eventually adopted in November 1988….88/609/EEC
  - BATNEEC for new large combustion plant
  - SO_2 …20% reduction of 1980 levels from large combustion plant (3883 ktonnes) by 1993, 40% reduction by 1998, 60% reduction by 2003
  - NOx ..20% reduction of 1980 levels from large combustion plant (1016 ktonnes) by 1993, 40% reduction by 1998
    - Individual plant NOx level of 650 mg/Nm3, aligned with FRG and US retrofit plant requirements, adopted by the CEGB



7. 12. 88 Official Journal of the European Communities No L

II

(Acts whose publication is not obligatory)

COUNCIL

COUNCIL DIRECTIVE

of 24 November 1988

on the limitation of emissions of certain pollutants into the air from large combustion plants

(88/609/EEC)

THE COUNCIL OF THE EUROPEAN COMMUNITIES,

Having regard to the Treaty establishing the European Economic Community, and in particular Article 130 s thereof,

Having regard to the proposals from the Commission (1),

Having regard to the opinions of the European Parliament (2),

Having regard to the opinion of the Economic and Social Committee (3),

Whereas the 1973 (4), 1977 (5), 1983 (6) and 1987 (7) European Communities action programmes on the environment stress the importance of the reduction and prevention of atmospheric pollution;

Whereas in their resolution concerning the action programme on the environment 1987 to 1992, the Council and the Representatives of Governments of the Member States meeting within the Council emphasize the importance for Community action to concentrate as a priority on the reduction at source of air pollution, *inter alia* by adopting and implementing measures concerning emissions from large combustion plants;

Whereas, moreover, under Decision 81/462/EEC (8), the Community became a Party to the Convention on long-range transboundary air pollution;

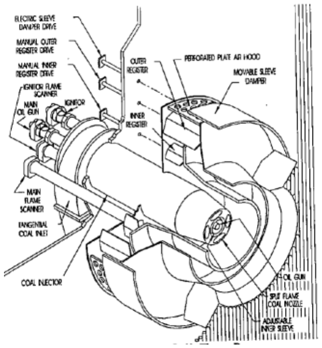
Whereas Council Directive 84/360/EEC of 28 June 1984 on the combating of air pollution from industrial plants (9) provides for the introduction of certain procedures and measures aiming to prevent or reduce air pollution from industrial plants, particularly those belonging to listed categories, among which are large combustion plants;

Whereas Article 8 of the same Directive 84/360/EEC stipulates that the Council, acting unanimously on a proposal from the Commission shall, if necessary, fix emission limit values for new plants based on the best available technology not entailing excessive costs and taking into account the nature, quantities and harmfulness of the emissions concerned; whereas Article 13 thereof stipulates that Member States shall implement policies and strategies, including appropriate measures, for the gradual adaptation of existing plants belonging to listed categories to the best available technology and taking various specified matters into account;

(1) OJ No C 49, 21. 2. 1984, p. 1 and OJ No C 76, 22. 3. 1985, p. 6.
(2) OJ No C 337, 17. 12. 1984, p. 446 and OJ No C 175, 15. 7. 1985, p. 297.
(3) OJ No C 25, 28. 1. 1985, p. 3.
(4) OJ No C 112, 20. 12. 1973, p. 1.
(5) OJ No C 139, 13. 6. 1977, p. 1.
(6) OJ No C 46, 17. 2. 1983, p. 1.
(7) OJ No C 328, 7. 12. 1987, p. 1.
(8) OJ No L 171, 27. 6. 1981, p. 11.
(9) OJ No L 188, 16. 7. 1984, p. 20.

The three UK NOx plant trials

- The plant selected by the CEGB for the series of 3 year trials were



  - **Eggborough**, 500MWe front wall fired boiler

    Foster Wheeler burners, based on existing US technology

  - **Fiddler's Ferry**, 500MWe tangential fired boiler

    ICL / Alstom burners, based on existing US technology

  - **Drax**, 660MWe opposed wall fired boiler

    Doosan Babcock UK developed technology

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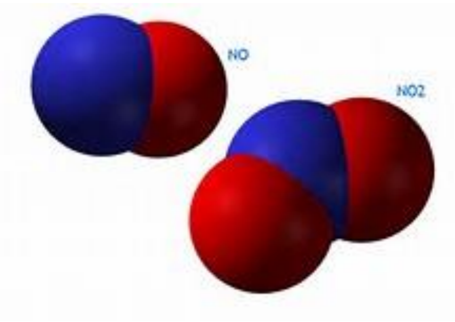
NOx – Nitrogen Oxides

- Nitrogen oxides (NOx) formed during the combustion of pulverised coal are mainly nitric oxide (NO) and nitrogen dioxide (NO_2)



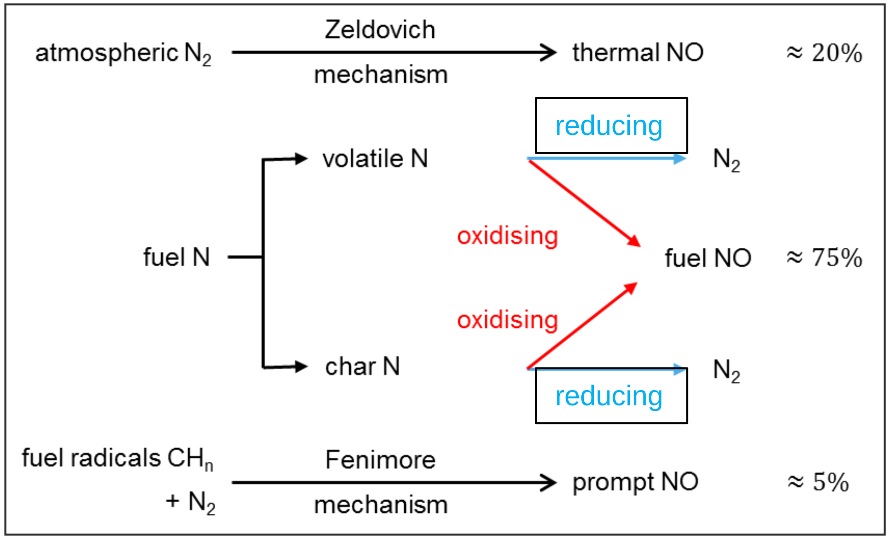
- Typical flue gases contain 90-95% NO and 5-10% of NO_2

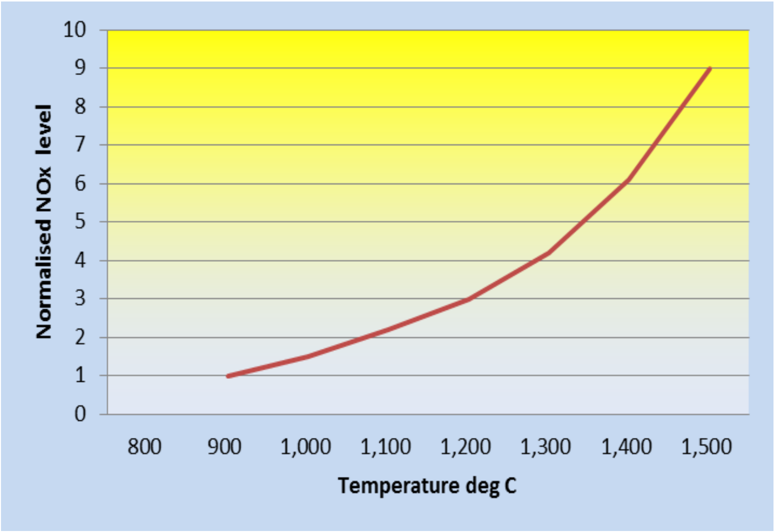
- A very small percentage of nitrous oxides (N_2O) are also formed in pulverised combustion ; higher percentages of this greenhouse gas are formed in lower temperature combustion processes

- Together NO and NO_2
  - promote ozone (O_3) formation in the lower troposphere which becomes the primary component of photochemical smog and which is itself a greenhouse gas
  - participate in ozone depletion in the stratosphere, increasing ground level UV-B radiation which in turn contributes to global warming and climate change

NOx Formation in Pulverised Coal Fired Boilers

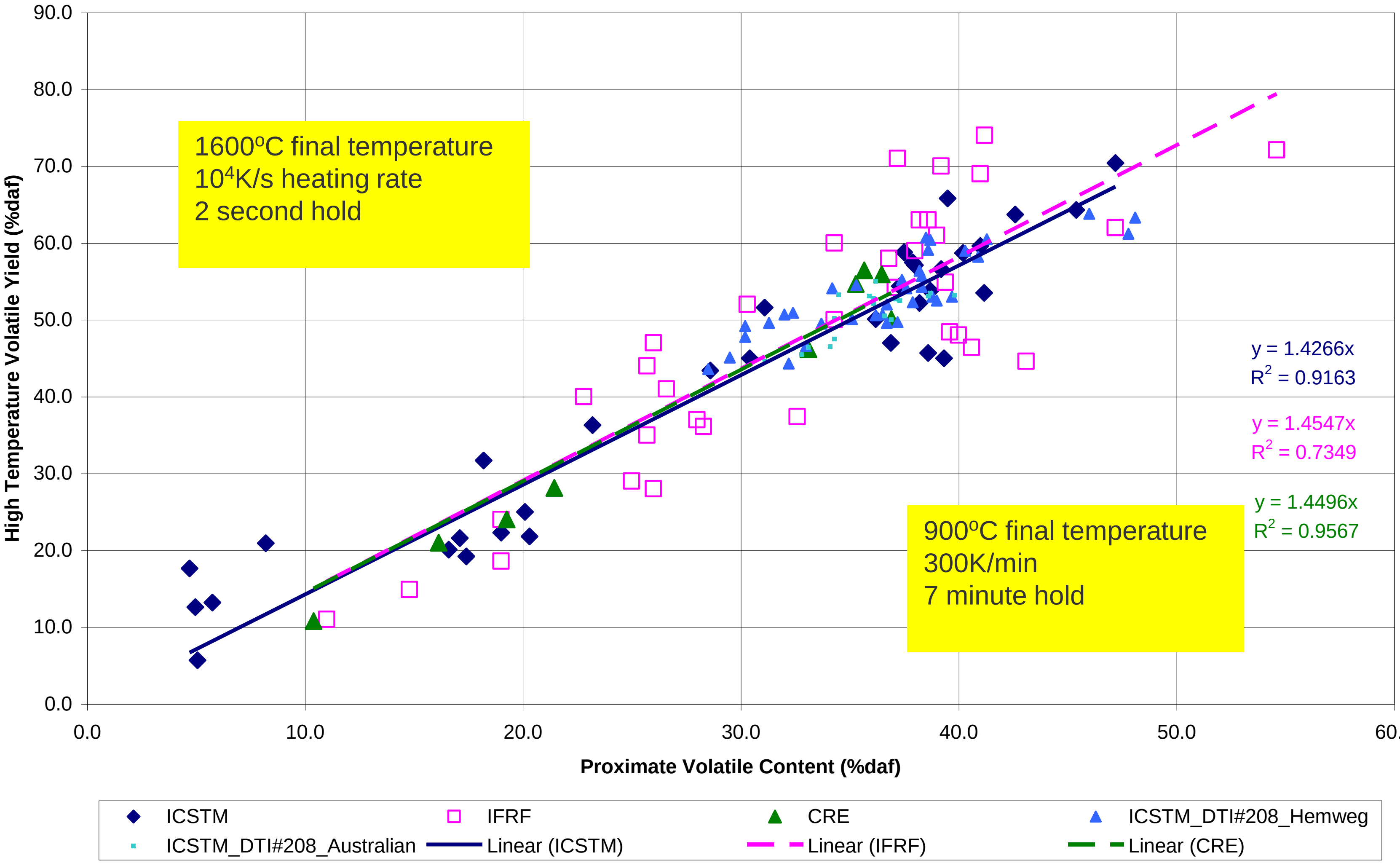
- NOx formation in boilers comes from three different routes
  - Thermal NOx from the nitrogen molecules in the air as the air is oxidized at high temperature
  - Fuel NOx from the nitrogen in the fuel as it is released in the volatiles and from the burning char
  - Prompt NOx from interactions between partly burned fuel and air nitrogen





- Fuel and Thermal NOx formation routes dominate in pulverised coal fired boilers

Volatile Yield Characteristics



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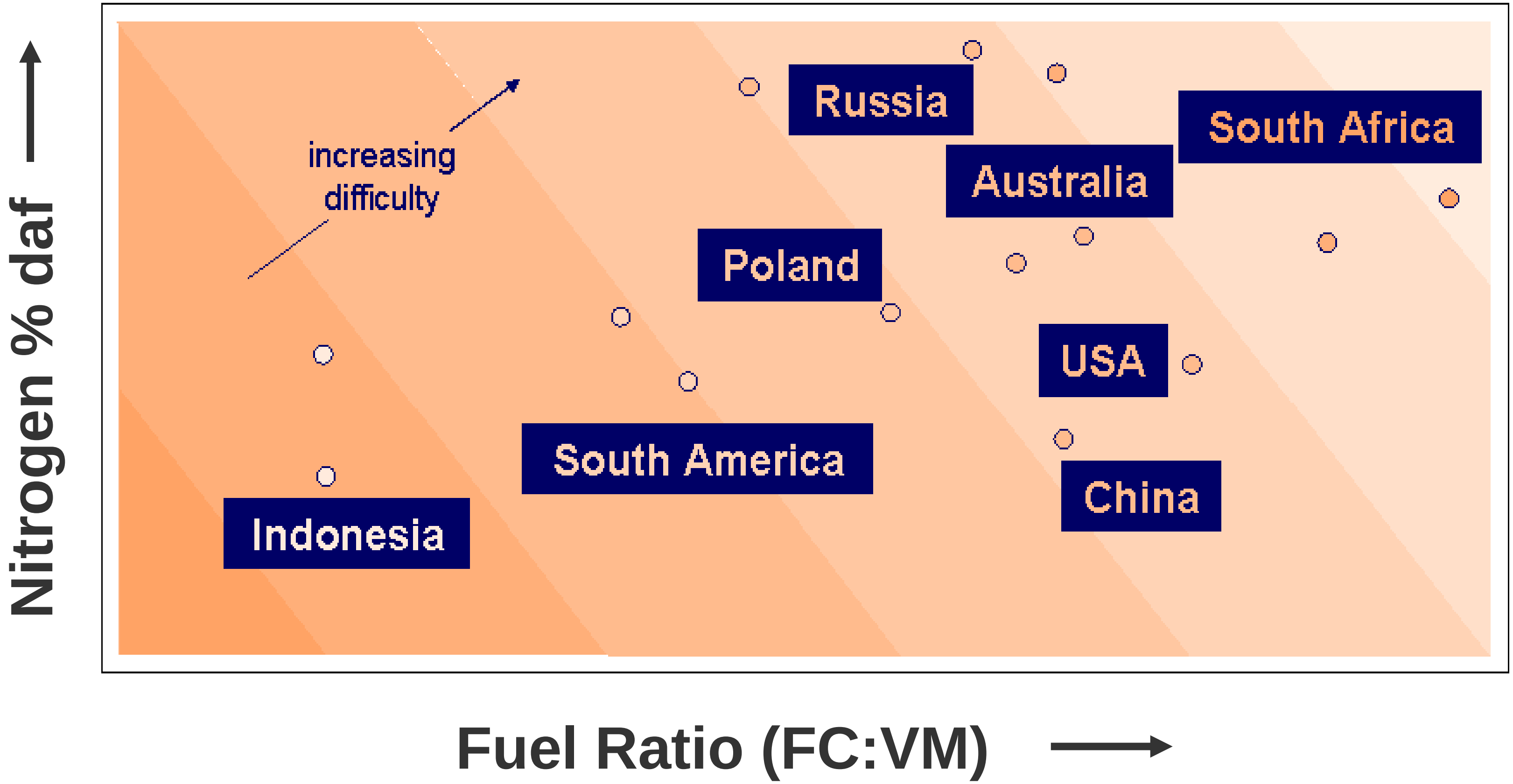
NOx – Differing Degree of Difficulty according to Coal Type



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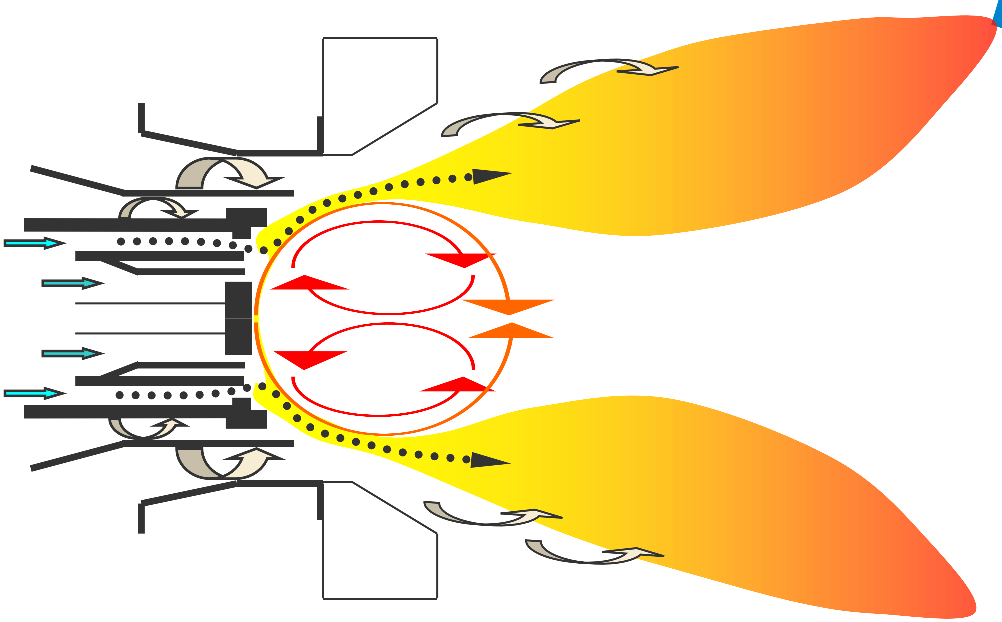
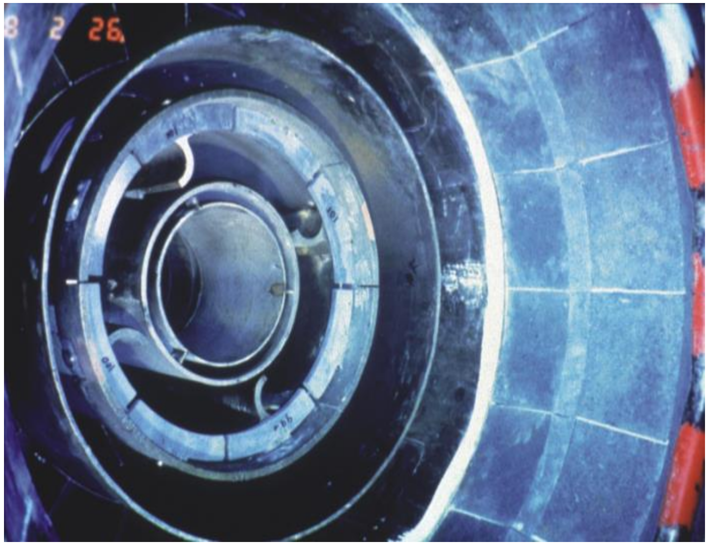
Low NOx coal burners – design requirements

- Maximise devolatilisation of the fuel and therefore maximise early fuel nitrogen release
- Provide an initial oxygen deficient zone which restricts both the conversion of evolved fuel nitrogen to NOx and the formation of thermal NOx
- Delayed mixing of fuel and air which suppresses temperature throughout the flame length and restricts thermal NOx performance
- Later provision of sufficient oxygen rich residence time which ensure burnout and minimise flame length, with no flame impingement
- Adequate fuel fineness to assist with the early evolution of fuel nitrogen and enable burnout to progress to acceptable levels
- Ensure outer oxidising flame envelope to minimise any potential for side wall corrosion ….coal high chlorine content fears





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Low NOx Coal Burners – Practical considerations in the 1980's

- Minimise the requirement for any changes to the existing burner throat opening and FD fan head
  - more efficient swirl generation

- Minimise the amount and complexity of moving parts to improve mechanical integrity
  - fixed vane swirl generation with bypass for swirl adjustment

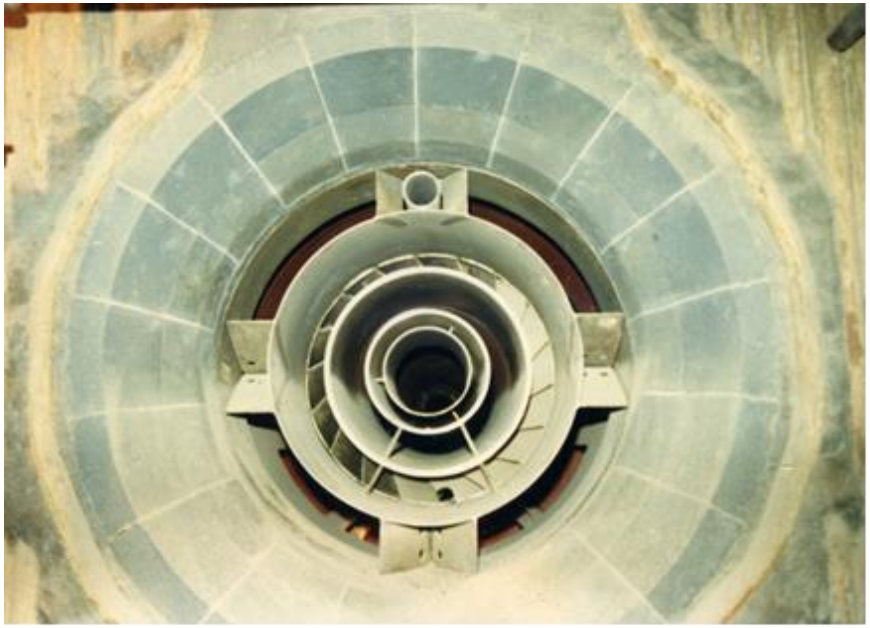
- Elimination of high wear mechanical flame stabilisation devices (coal impellers) and improved turndown
  - aerodynamic flame stabilisation by promotion of internal recirculation of furnace gases by incorporation of adequate core and primary air tube bluff body

- During the course of burner development additional features were incorporated
  - adjustment of the fuel stream to enhance staging and ignition characteristics
    - inlet elbow design
    - introduction of fuel collectors
  - enhanced flame root stabilisation
    - via a flameholder

Doosan Babcock low NOx burner development

Through 1985

- FH industrial boiler in Renfrew converted to a burner test facility
  - Two 12MW burners installed….1/3rd geometric scale of the Drax burner…so called Mark I design



Doosan Babcock low NOx burner development

August / September 1986

- Two 37MW Mark I low NOx burners installed in Ferrybridge Power Station
  - One burner in centre of top row…primarily for mechanical integrity assessment
  - One burner in wing burner position of bottom row
    - Dedicated monitored air supply installed
    - Flame probing ports installed along side wall to enable assessment of flame structure to be made
  - Standard circular register burner in opposite wing position also studied
    - Dedicated air supply
    - Flame probing ports also installed

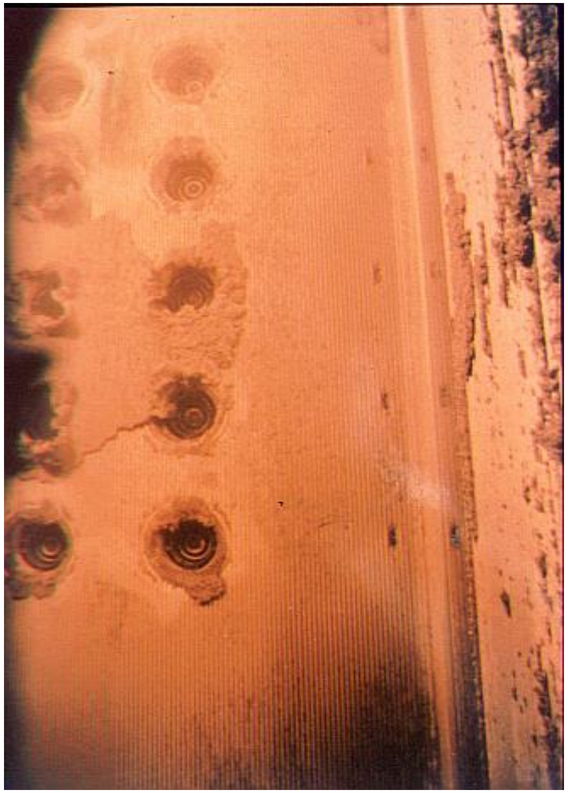
October to December 1986

- Low NOx and Circular register burners probed and tested over the operational range in Ferrybridge
- Sufficient confidence in burner performance obtained to proceed with full 60 burner installation in Drax Unit 6

Doosan Babcock low NOx burner development

April to June 1987

- Full boiler complement of sixty Mark I burners installed in Drax Unit 6
- Minimum boiler / pressure part modifications



July to September 1987

- Proving and testing of Mark I design in Drax
- Initial results showed 25 to 30% NOx reduction
  - From 1414 mg/Nm3 to around 1000mg/Nm3

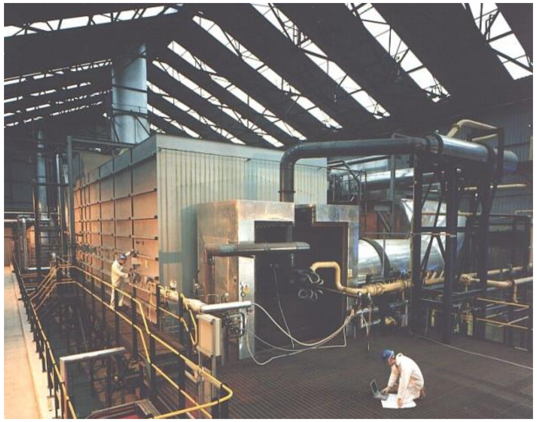
- But ….NOx reduction could not be maintained for any length of time due to ash / slag build up in the burner zone / area

- Extensive series of in furnace probing using water cooled video probe
  - Slag build up was associated with two features
    - The bluff bodies in the tertiary air stream
    - The refractory tile design of the burner throat opening

Doosan Babcock low NOx burner development

September 1987 to September 1989

- Concerns over
  - Scaling of low NOx burners from 12 MW to 37MW
  - Representativeness of temperature levels in the FH industrial boiler led Doosan Babcock to invest in a full scale single burner test facility



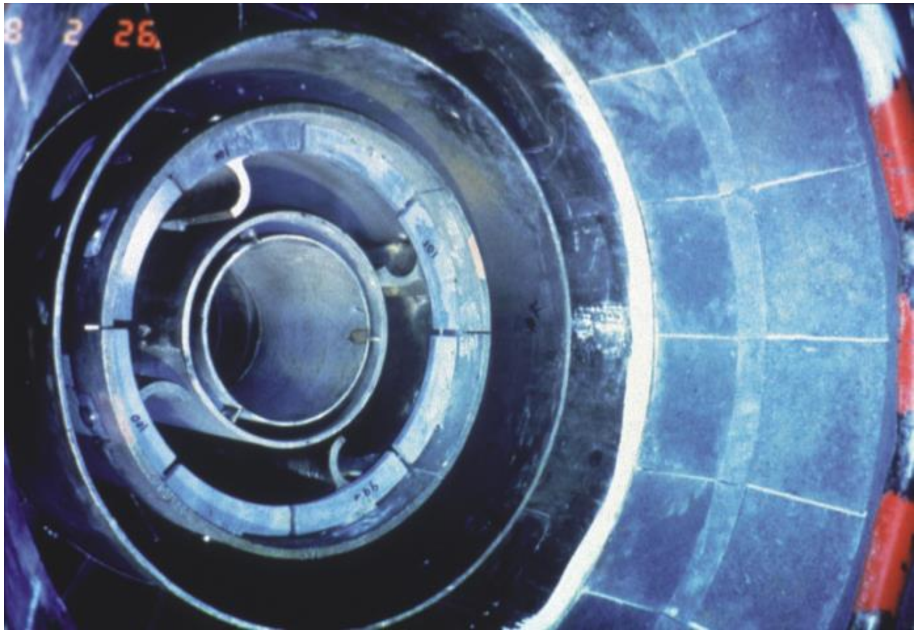
- Designed to be capable of testing single burners, up to 50MW thermal hear input, on coal, HFO or natural gas
  - Representative residence times
  - Representative time temperature history
  - In flame probing capability
  - Capable of on line (i.e. via mill) or offline (via storage bunker) coal firing

- Burner testing of
  - Circular register burner
  - Mark II low NOx burner ..simple variant of Mark I design with tertiary air bluff bodies replaced by tertiary air swirl
  - Mark III low NOx burner

Doosan Babcock low NOx burner development

September 1987 to September 1989 (contd.)

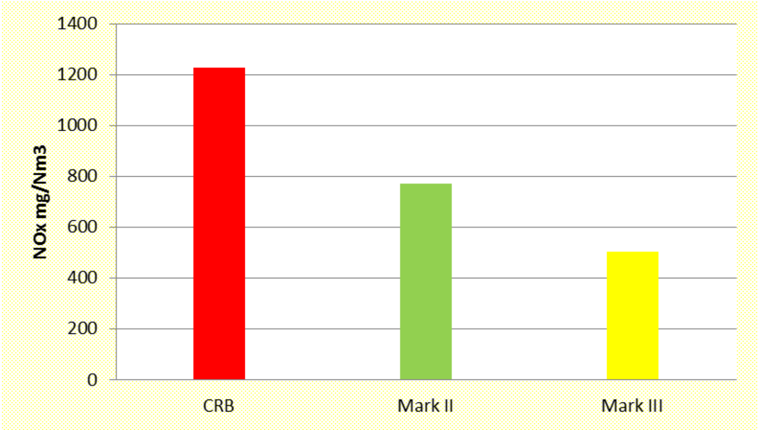
- In parallel with burner development / proving, an extensive investigation into slag build up in burner quarls was undertaken
- Leading front edge tube concept developed
  - No refractory on front face of burner (tile protected by water tube)
  - Minimum refractory tile thickness, compatible with mechanical strength
  - High conductivity tile material (silicon carbide)



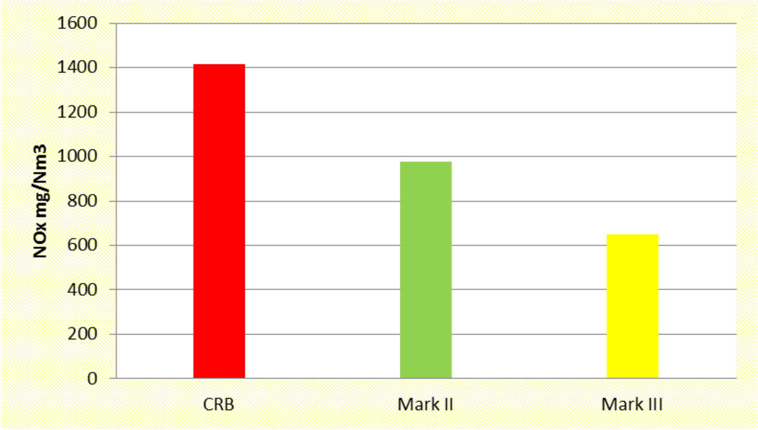
Doosan Babcock low NOx burner development

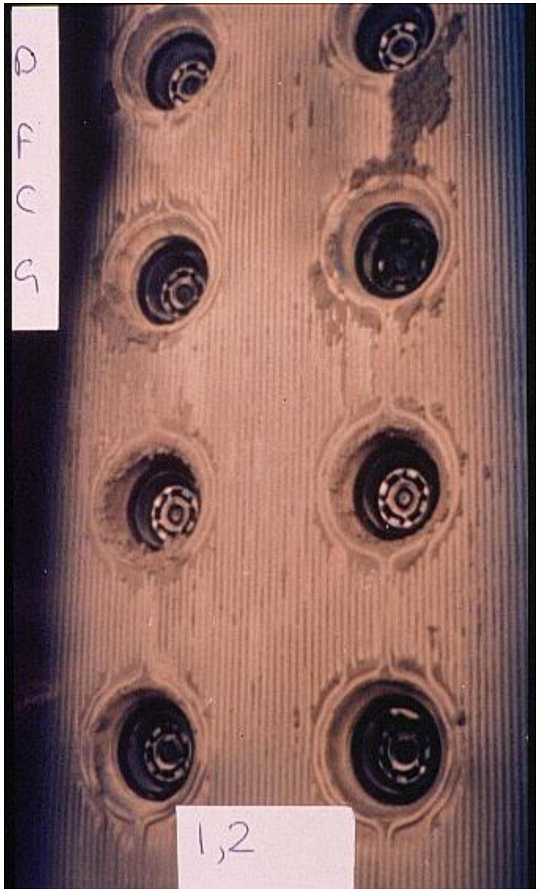
September 1987 to September 1989

Large Scale Test Facility



Drax Unit 6

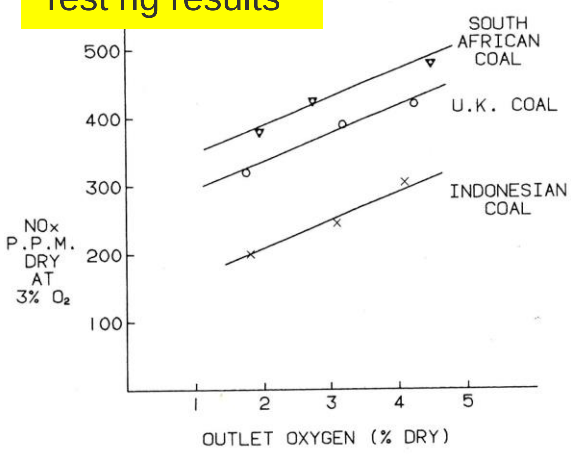


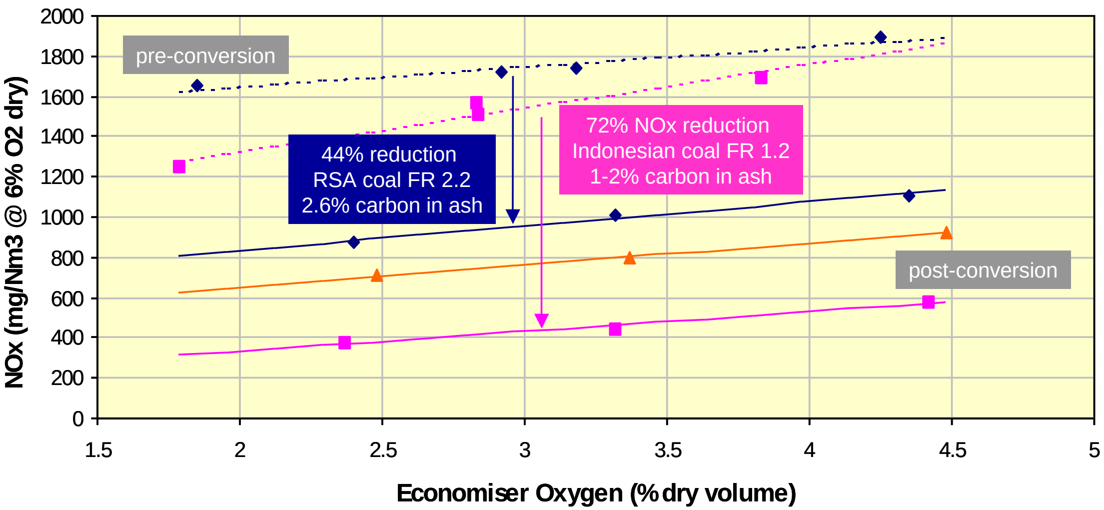


- Mark III design proven, giving confidence that 650mg/Nm3 could be achieved in a single stage mode of operation in UK plant for UK coals

Low NOx burners ..effect of coal quality

Test rig results





Plant Data
Castle Peak B

UK Low NOx burner retrofit programme ..1990's

- The CEGB 3 year trial, initiated in 1986, to "determine the feasibility of NOx reduction, with UK coal and on UK plant" on

  - Drax
  - Eggborough
  - Fiddler's Ferry

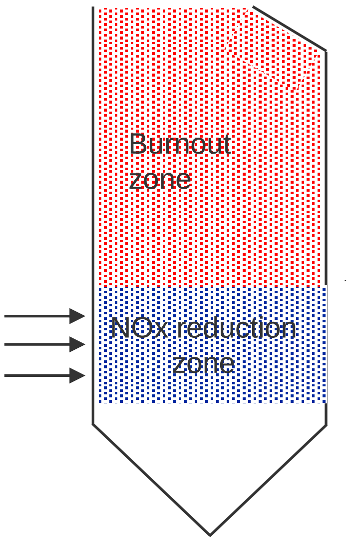
  demonstrated that acceptable levels of NOx reduction (to meet 88/609/EEC) could be achieved

- However, it isn't just a matter of replacing burners; the NOx reduction process effectively reduces the burnout time for the fuel and results in an increase in carbon in fly ash

DOOSAN

UK Low NOx burner retrofit programme ..1990's

- To minimise the increase, and also control CO levels, attention has to be paid to
  - Air distribution improvements – windbox and individual burners, and air inleakage
  - Fuel distribution measurement and improvement
  - Mill product fineness optimisation – classifier adjustment
  - Burner optimisation – systematic examination of all available burner settings
- Evaluation of "baseline " combustion performance of each individual plant (and boiler) required to optimise low NOx burner system performance
- The majority of the 1960 built coal fired fleet converted to low NOx burner operation in the 1990's



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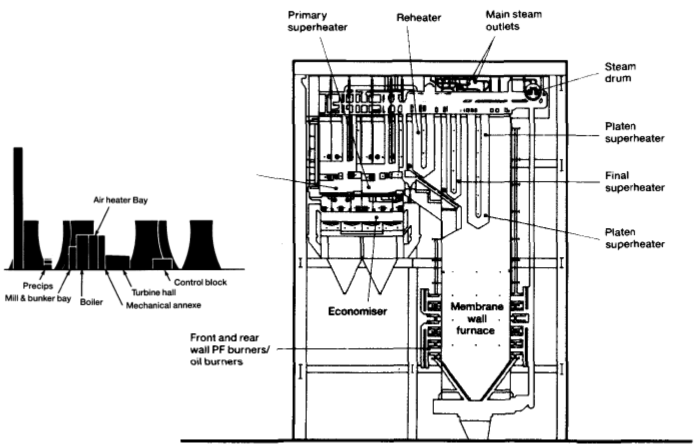
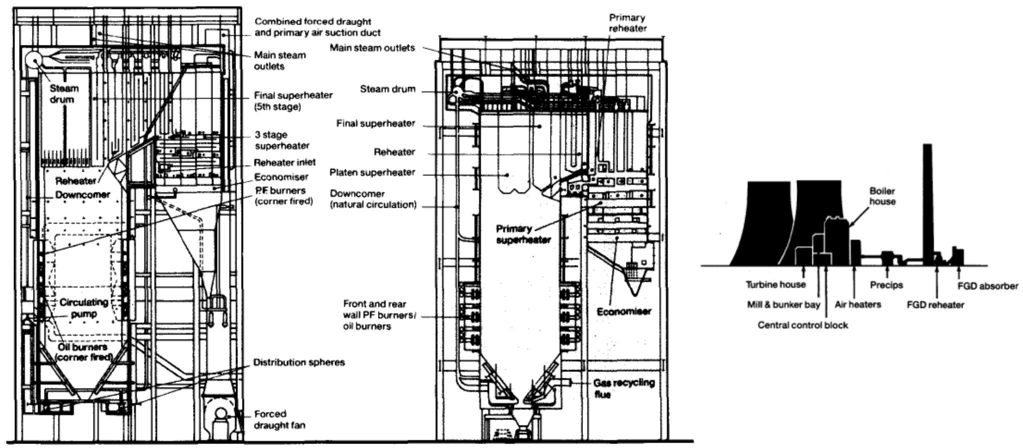
And also in the early 1990's…..

- CEGB privatised
  - Three generating companies National Power, PowerGen, Nuclear Electric
  - Transmission activities allocated to the National Grid Company

And also in the early 1990's…..

- In late 1984 the CEGB began studies on the design and parameters for future coal fired stations
  - Reflect international trends in the past decade
  - Achieve capital and generation cost savings, with a shorter construction period
- The CEGB decided that its objectives could be best achieved by increasing the unit size from 660MWe to 900MW, subcritical, 180 bar, 568 / 568 deg C
- Both remaining UK boilermakers involved in developing designs

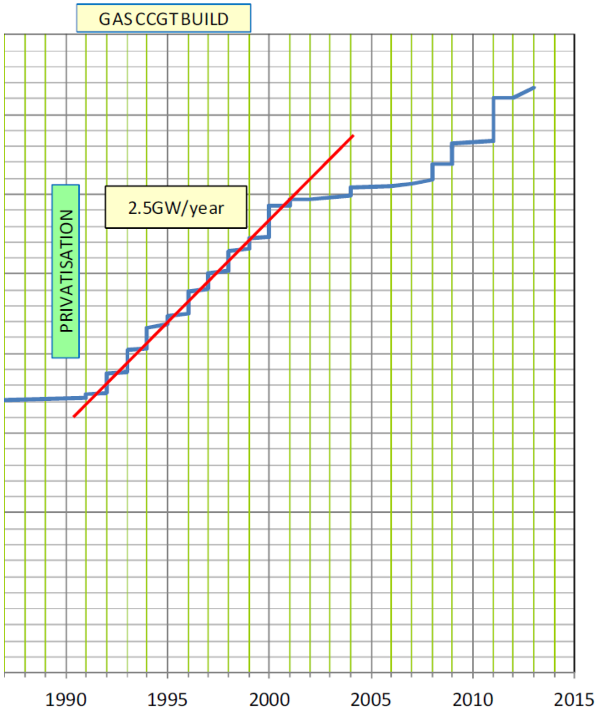




- *1988 CEGB paper "..It is clear….the nation faces a shortage of electricity….in the mid 1990's..this is to be averted by the dual policy of a small family of PWR stations and new coal fired stations using the 900MW units. The industry is ready, able and well prepared to meet the challenge"*

And also in the early 1990's…..

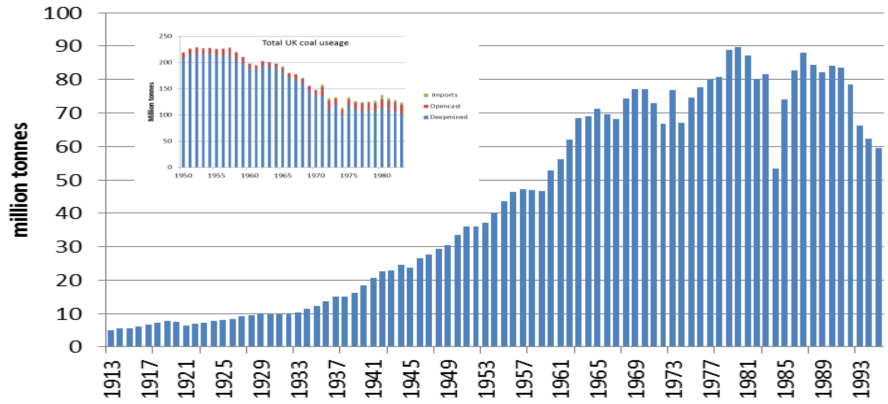
- Ban on using Natural Gas for power generation lifted..sparked a dash for gas

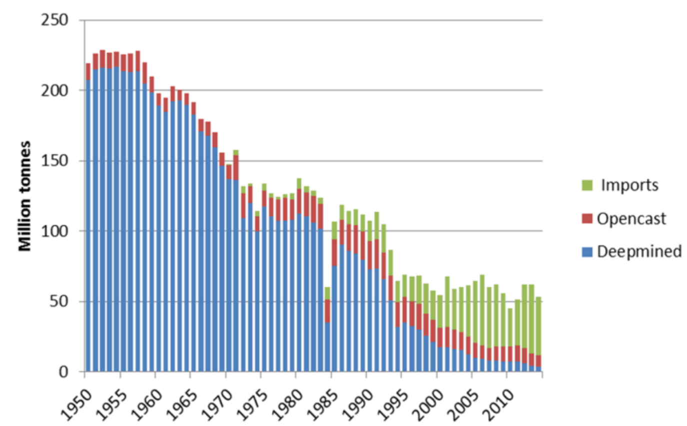


- Two coal fired units at Didcot converted to combined natural gas / coal firing in 1996
- Order placed for Cottam conversion cancelled on UK government instruction

And also in the early 1990's…..

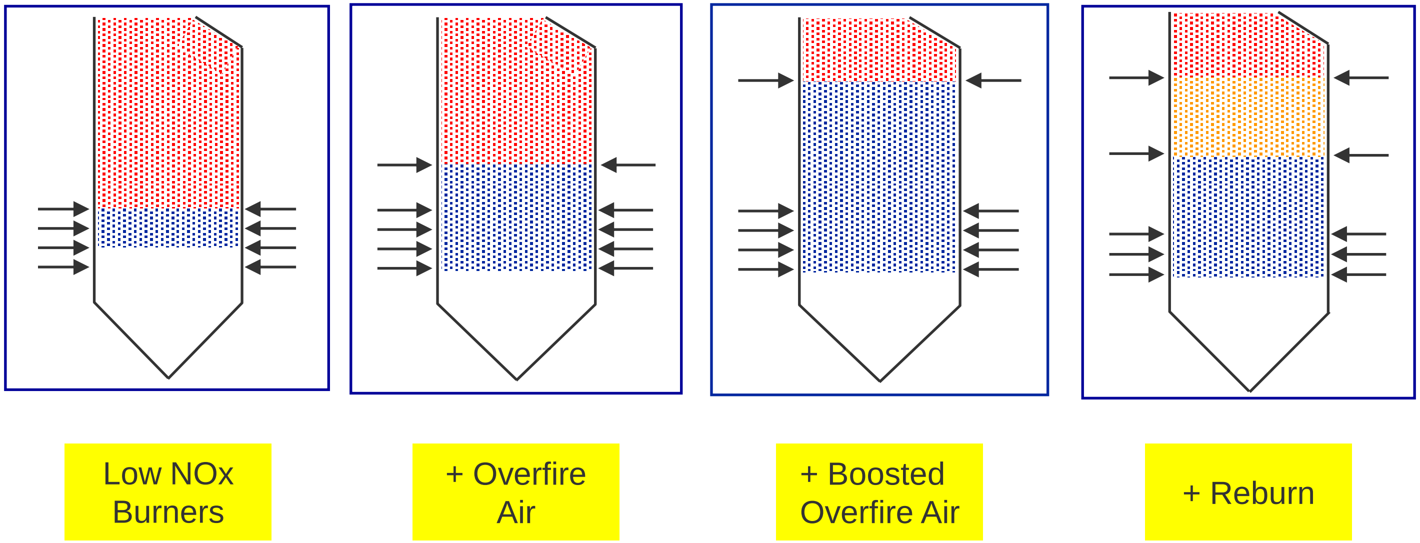
- Pressure on high UK coal prices led to increasing use of imports, aided by
  - Selective use of low Sulphur coals from a SOx emission perspective
  - Selective use of high volatile coals from a NOx emission perspective



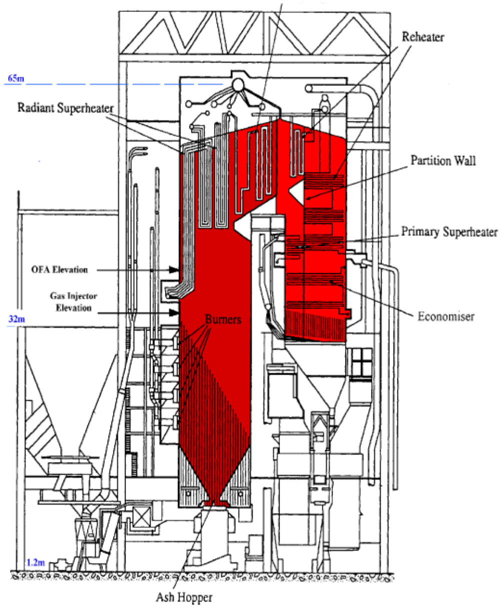


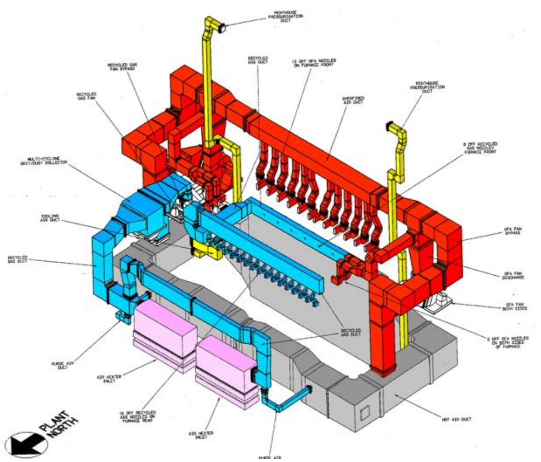
And also in the early 1990's…..

- Selective use of high volatile coals from a NOx emission perspective
  - Imported coals also have little or no chlorine
    – Introduces the possibility of using air staging techniques, in addition to low Nox burners, to further reduce NOx emissions

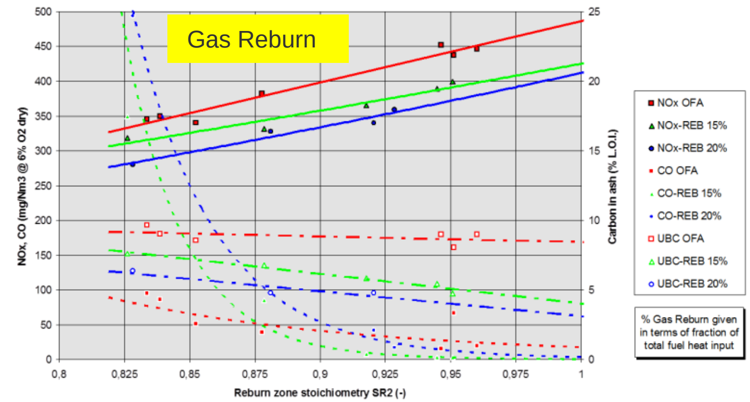


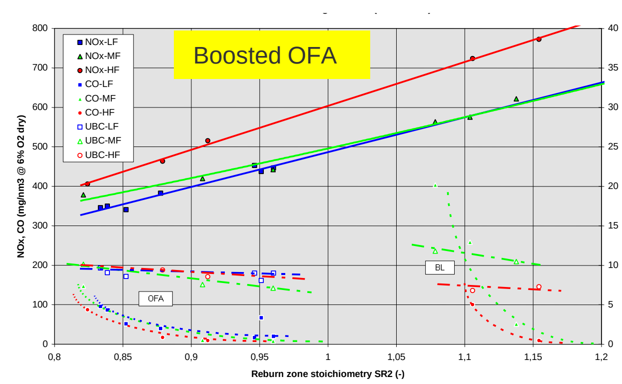
Gas Reburn – Longannet Unit 2





- EU Thermie funded project initiated in 1996, commissioned 1997/1998
- Tests on both UK and imported coal





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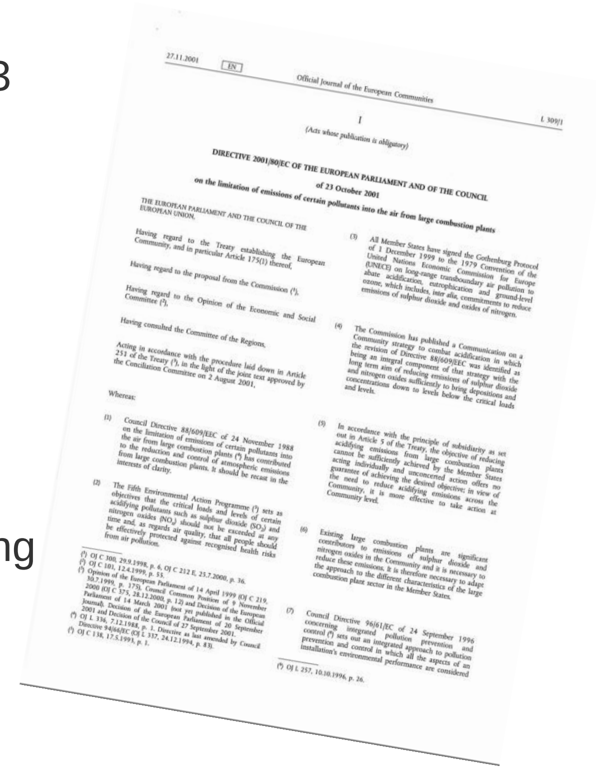
Large Combustion Plant Directive 2001/80/EC

- Replaced "old" LCP Directive first agreed in 1988
- Introduced into the European Parliament and Council on 23 October 2001, and transposed and enacted into member state law 27 November 2002
- For existing plant in operation prior to 27 November 2003, compliance with Emission Limit Values (ELV's) by 01 January 2008. For coal fired boilers these are
  - SO_2 < 400 mg/Nm3
  - NOx < 500 mg/Nm3
  - Dust < 50 mg/Nm3
- In the period 01 January 2008 to 31 December 2016 existing plant can
  - Comply with more stringent ELV's
    - SO_2 < 200 mg/Nm3
    - NOx < 200 mg/Nm3
    - Dust < 20 mg/Nm3
  - Participate in the member state's National Emission Reduction Plan (NERP) limited overall emissions (based on a year 2000 operating basis) from the plants included in the national plan
  - "Opt out" if the plant is considered to have limited life time left..defined as 20,000 operating hours post 01 January 2008


27.11.2001 EN Official Journal of the European Communities L 309/1

I

(Acts whose publication is obligatory)

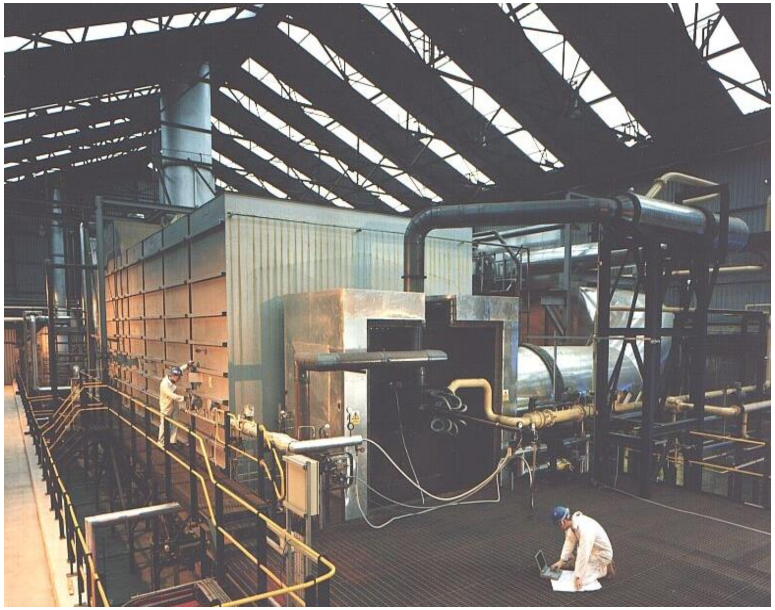
DIRECTIVE 2001/80/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 23 October 2001

on the limitation of emissions of certain pollutants into the air from large combustion plants

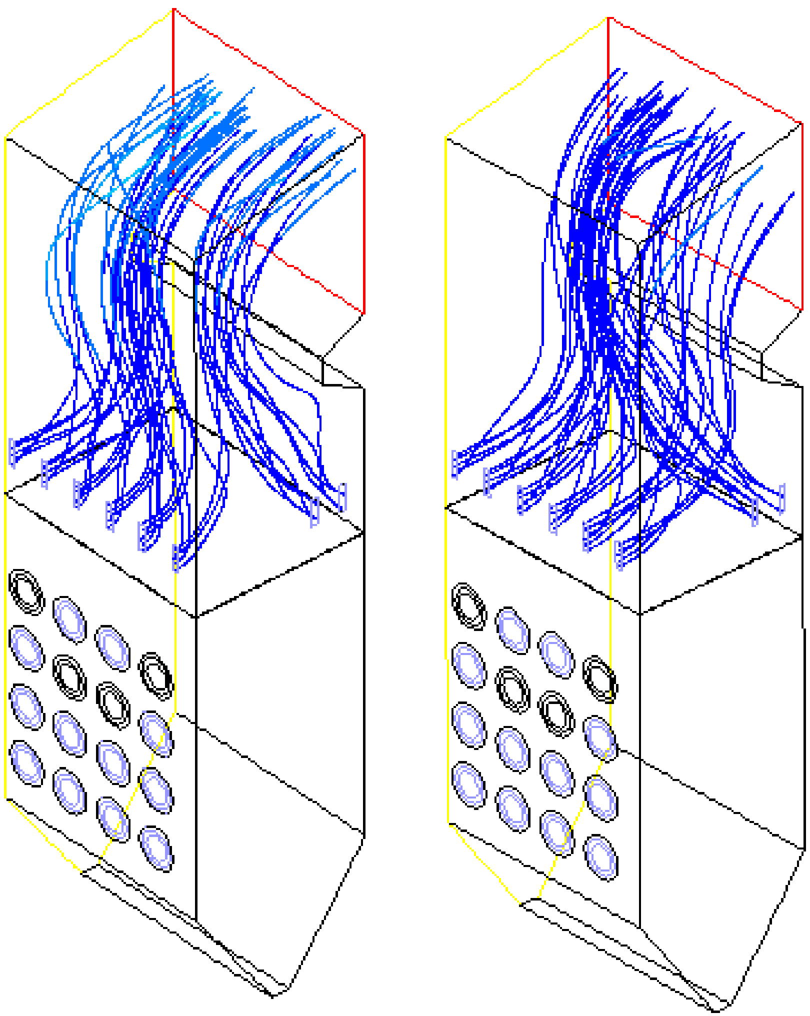
Doosan Babcock Burner Test Facility upgrade

- The original 50 MWt capacity Doosan Babcock single burner test facility built in the late 1980s was replaced a decade later with a 70 MWt capacity facility for the development of larger burners, for the new build overseas boiler market
- The larger facility was retrofitted with an overfire air capability to support burner development / proving in a two stage combustion environment, in support of 2001/80/EC compliance
  - Test burner size is 40 MWt in order to provide a meaningful staged residence time
  - Design rules developed for plant application



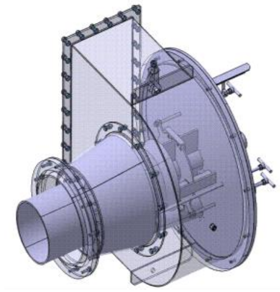
Phase II of the UK NOx reduction programme..the 2000's

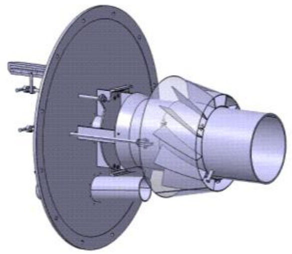
- Air staging became the "Technology of Choice" for compliance with 2001/80/EC
  - Experience overseas ...USA, Europe..although generally not boosted
  - To maintain acceptable carbon in ash levels in the "tight" UK furnace designs boosting the overfire air injection pressure offered a solution
  - Air staging is an inherent part of T fired boiler technology
  - Test rig demonstration
  - The Longannet and VL reburn demonstrations further justified the application of the technology
- Elevation of overfire air ports relative to the combustion zone key
- The overfire air ports are designed to promote efficient mixing of the overfire air and combustion flue gases leaving the burner zone



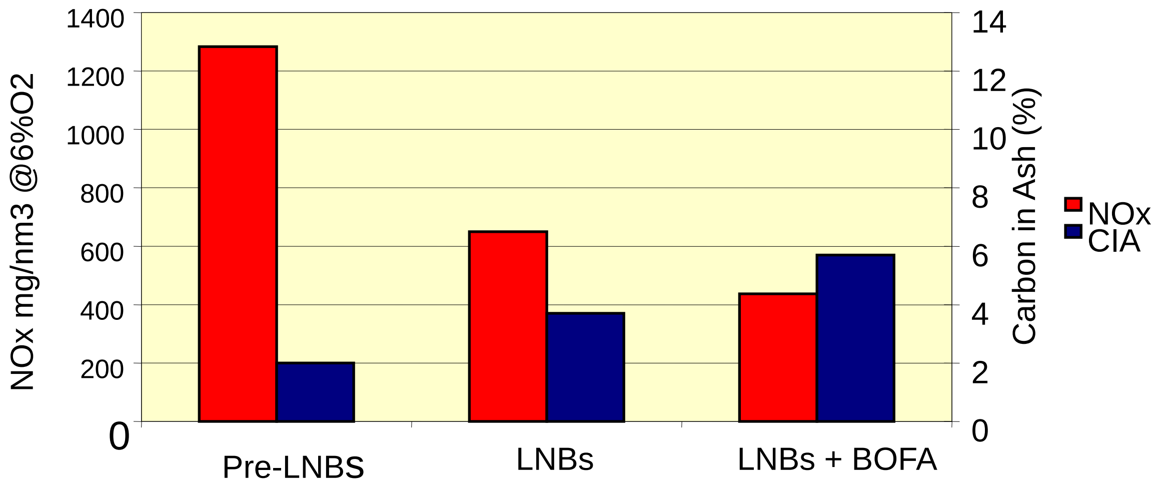
Typical BOFA application

- Twin stream design of over fire air port
  - Inner / outer stream control damper for air split control
  - Inner stream unswirled for penetration
  - Outer stream swirled for cross stream mixing





- Typical BOFA application..Drax Unit 1



- By the end of 2008 all UK coal plant were NOx compliant, and all but four had installed FGD plant

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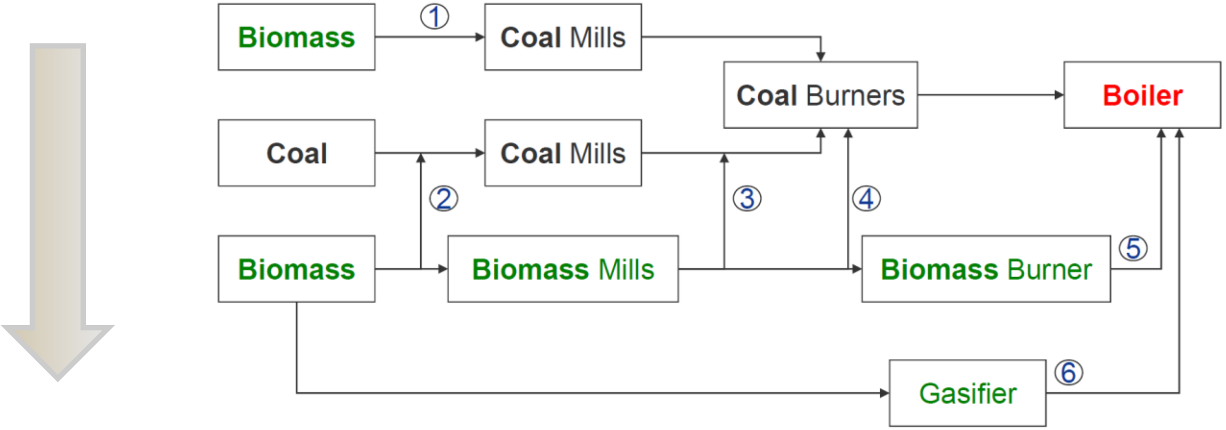
DOOSAN

And also in the 2000's……

- The Renewables Obligation introduced in April 2002 provided significant financial incentives to the generators of electricity from renewable sources
- The co firing of biomass in existing coal fired boilers was eligible, and most generators got involved
- Generally up to 10% biomass could be fired through the existing combustion system, depending on the mill type
- Range of options available, from co firing to full biomass conversion



Dedicated 100% Biomass Conversions

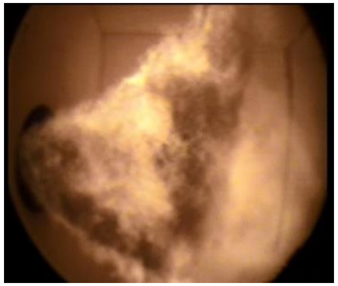
- **Drax**….three of the six 660 MWe units now converted to dedicated biomass, possibility of a fourth under consideration

- **Ironbridge**…..the two 500MWe units fully converted between April and October 2013, with the intention of maximising operational hours on biomass prior to LCPD closure in November 2015

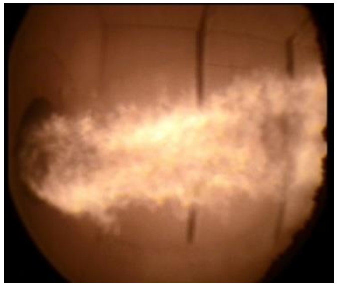
Two other coal fired units are also involved in dedicated biomass conversion

- **Uskmouth** ..three units total capacity 383MWe, plant was closed by SSE in May 2014, who have converted to 100% biomass

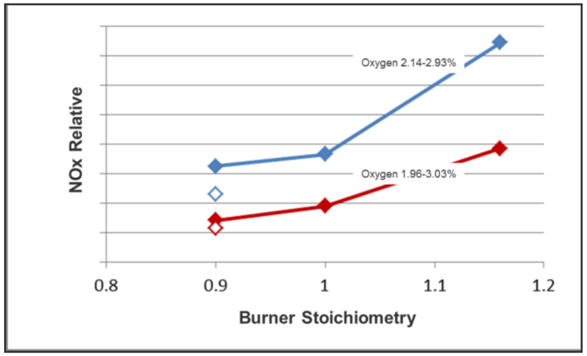
- **Lynemouth**…. the three 140MWe units were awarded a Contract for Difference in December 2015 for converting this power station to biomass. Lynemouth will receive the CfD subsidies until at least 2027. Doosan Babcock is currently undertaking the biomass conversion on the plant



Unstaged burner

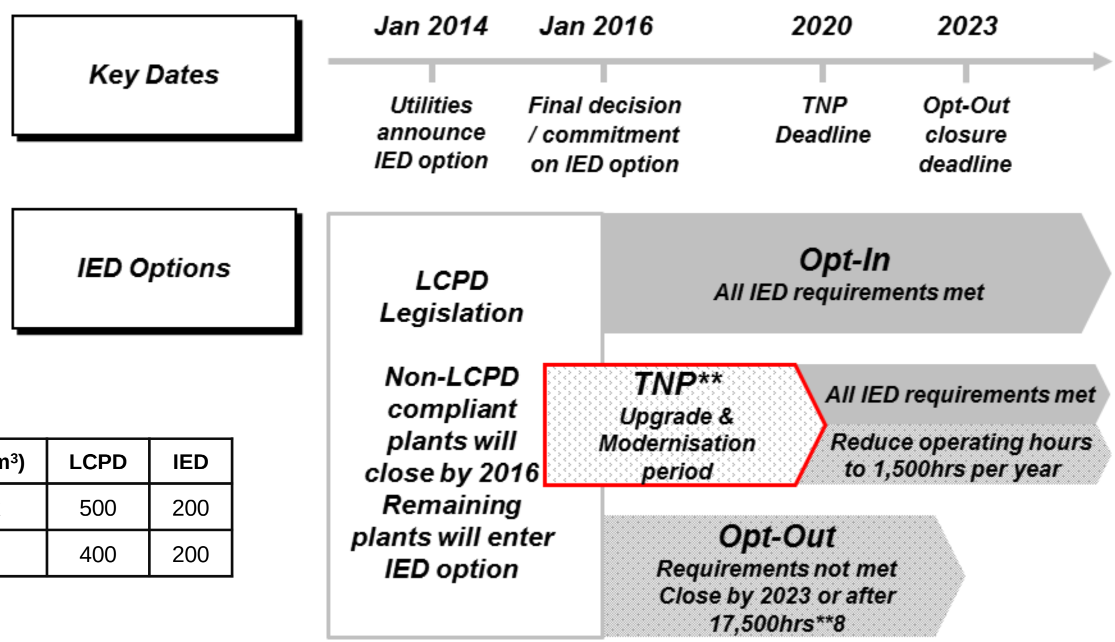


Low NOx burner



And also in the 2000's……

- In November 2005 EC launched a review of European legislation on industrial emissions
- The Industrial Emissions Directive (IED) which came into force on 06 January 2011 replaces the Large Combustion Plant Directive (LCPD) and brings together all other European emission reduction legislation
- All plants that do not comply with LCPD must close by 2016. Plants that remain open will then be subject to the more stringent IED emission limits
- Operators must choose one of the three IED options by Jan 2016



(mg/Nm³)	LCPD	IED
NOx	500	200
SOx	400	200

In 2016, the remaining five coal plant have all chosen the TNP option

Drax
Ratcliffe
West Burton
Cottam
Aberthaw
Kilroot

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DOOSAN

…18 November 2015…..

- The UK Government announce plans to close all coal-fired power stations by 2025 and restrict their use by 2023

- Amber Rudd

  - *"We are tackling a legacy of underinvestment and ageing power stations which we need to replace with alternatives that are reliable, good value for money, and help to reduce our emissions.*
  - *It cannot be satisfactory for an advanced economy like the UK to be relying on polluting, carbon intensive 50-year-old coal-fired power stations.*
  - *Let me be clear: this is not the future.*
  - *We need to build a new energy infrastructure, fit for the 21st century.*
  - *Our determination to cut carbon emissions as cost effectively as possible is crystal clear and this step will make us one of the first developed countries to commit to taking coal off our system"*

- The Government said it will consult early 2016 on when to close all coal-fired power stations. The consultation will set out proposals to close unabated coal-fired power stations by 2025 - and restrict use from 2023

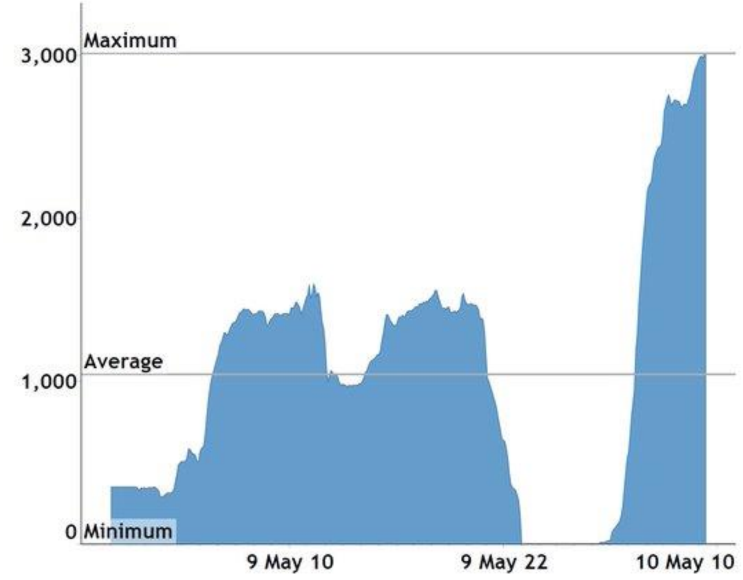
…..May 2016…..

- Coal generation fell to a record low in May 2016, supplying just 1TWh of power during the month, according to the Department for Business, Energy and Industrial Strategy (BEIS)

- Coal generation was down by 72 per cent year-on-year during the second quarter of 2016 at 4.3TWh. Its share of total output fell to 6.8 per cent – the lowest level in 21 years

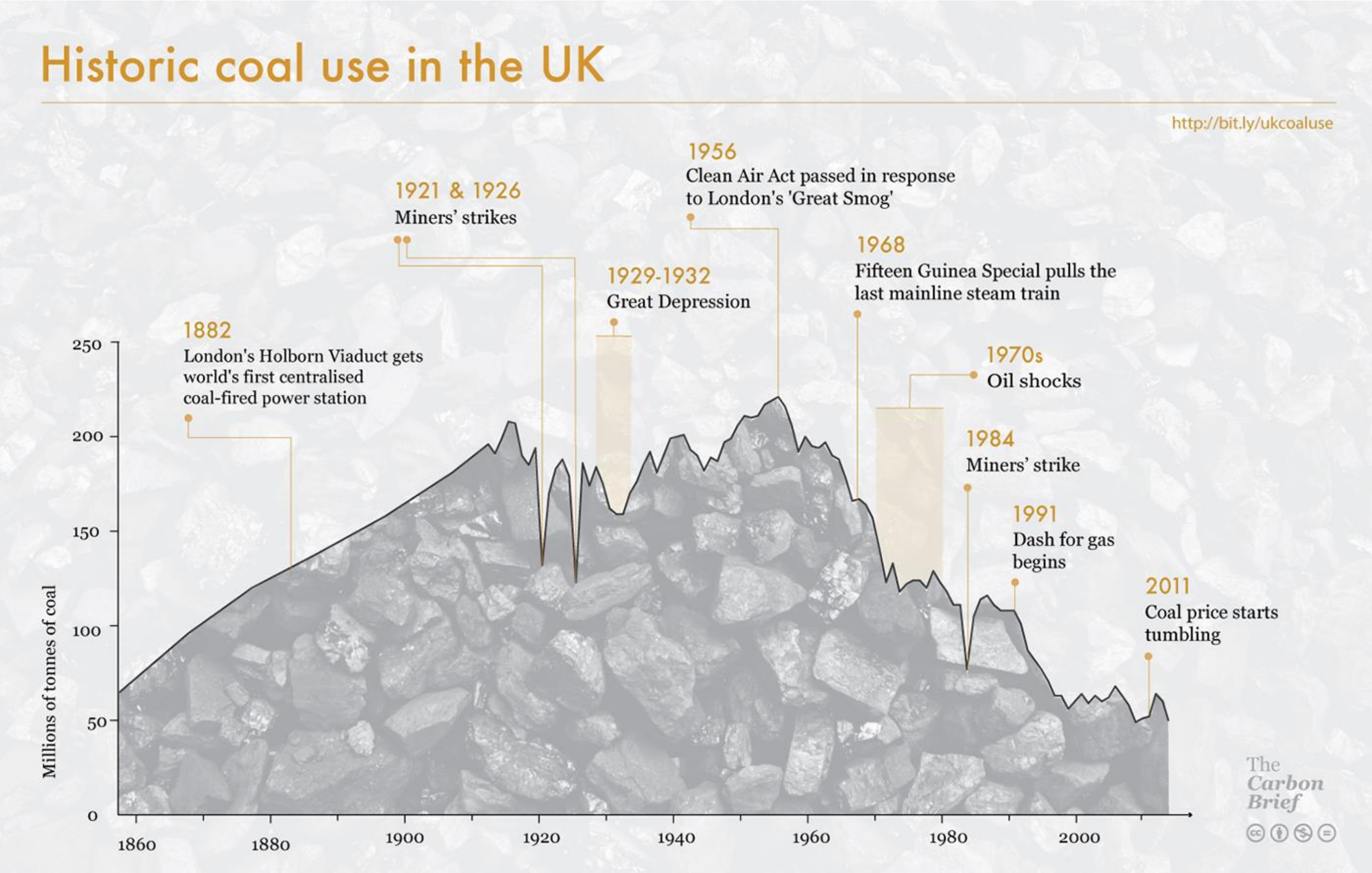
- No electricity from coal was generated Tuesday morning 10 May 2016, for what is believed to be the first time since the 19th century, in a major milestone in the decline of coal as a power source

- This was the first time there had been no electricity production from coal since the era of central electricity generation began with the construction of the UK's first coal plant in 1882



The Decline of Coal in the UK

- The world's first coal superpower, the U.K., now produces less power from coal than it has since at least 1850.



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Looking into the future

- Doosan Babcock's market environment is changing

  - *50% of UK coal capacity closed since 2007 and post 2025 no coal*
  - *37% share value (100bn€) lost 2008-13 by 5 utilities supplying 60% of Europe's electricity*
  - *150% increase in renewable generation in UK in the last 4 years, with further increases planned*
  - *Installed solar power has doubled globally 7 times in the past 10 years, wind 4 times*
  - *Environmental targets require clean generation across heat and transport as well as electricity*
  - *Renewables, distributed generation and energy storage are all being considered as solutions*

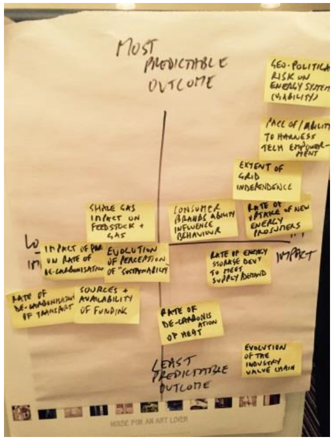
- To deliver a sustainable future Doosan Babcock requires to adapt, from a business perspective, to the changing market environment

- To this end, Doosan Babcock identified key questions to be addressed in a Scenario Planning exercise

  - *The energy (electricity, heat and transport) scenarios in the UK may change as increasing decarbonisation occurs, combined with potential changes in demand side management technology and capability, what are the resultant changes in our energy landscape that we might expect to see on this pathway between now and 2025?*

    - *Given these changes what products, technologies and resources should Doosan Babcock be investing in to deliver a sustainable future?*

Uncertainty Ranking Matrix



Most predictable outcome

Low impact

High impact

Geo-political risk on energy systems (viability)

Pace of, and ability to, harness technological empowerment

Extent of grid independence

Rate of uptake of new energy prosumers

Shale gas impact on feedstock and gas

Consumer brands availability influence behaviour

Impact of Paris on rate of decarbonisation

Evolution of perception of Sustainability

Rate of energy storage development to meet supply / demand

Sources and availability of funding

Rate of decarbonisation of transport

Rate of decarbonisation of heat

Energy as a pawn in political relationship

Evolution of the Industry value chain

Evolution of energy flow management

Impact of government incentives on investment decisions

Least predictable outcome

Scenarios for UK Energy System Evolution

Zero emissions a reality

A Brand New "Business As Usual"

UK desire to meet ambitious, internationally binding emissions targets drive A New BAU. The government continues to promote centralised electricity generation infrastructure, with large generation assets supplying the National Grid.

Smart Life

UK desire to meet ambitious, internationally binding emissions targets drive Smart Life. The government introduces policies which **support innovation in, and generation from, small scale renewable generation technologies and energy storage. Decarbonisation of heat and transport increases.**

Centralised — Evolution of energy management flow — **Decentralised/ Localised**

Government and society appetite for zero emissions

World events lead to an inward-looking national government with security of supply and affordability as priorities. UK retrenches to fossil fuels.

Groundhog Day

Governments fail to agree internationally binding targets on emissions. UK government provides no clear energy policy. Technological innovation enables regional energy hubs for distributed generation to begin playing a more significant role in the energy mix.

Dragons Slay Dinosaurs

Failing to meet emission targets

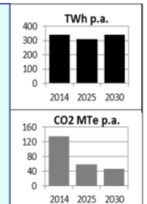
Scenario Power Profiles

Zero emissions a reality

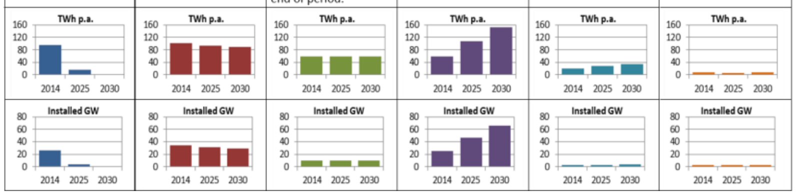
Centralised ——— Evolution of energy management flow ——— **Decentralised**

Government and society appetite for zero emissions

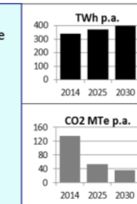
- UK desire to meet ambitious, internationally binding emissions targets drive A New BAU.
- The government continues to promote centralised electricity generation infrastructure, with large generation assets supplying the National Grid.
- Emissions legislation accelerates coal closures.
- Large renewable installations dominate the generation mix, balanced by gas and large scale storage.
- New build CCGT plant will require CCS. New plant will potentially be located close to industrial clusters to facilitate carbon storage.
- Electricity demand falls initially as energy efficiency measures are mandated but recover to 2014 levels as transport becomes electrified.



Coal	Gas	Nuclear	Renewables	Imports	Distributed Generation
Closures accelerate, driven by emissions legislation.	Existing assets are sweated. Some new build (replacement plant) with CCS.	Existing assets are life extended to 2028 and beyond. Potential for a single new build station to come on line towards end of period.	Significant new build installations, supplemented by energy storage.	Imports increase, but remain minority part of the supply mix.	Remains stable at 2014 levels.

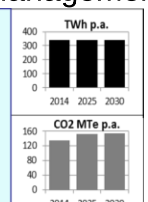


- UK desire to meet ambitious, internationally binding emissions targets drive Smart Life.
- The government introduces policies which support innovation in, and generation from, small scale renewable generation technologies and energy storage. Decarbonisation of heat and transport increases.
- Distributed generation and "energy to energy" systems at local (building) level dominate the generation mix.
- Commercial buildings lead , followed by residential scale – public opinion is shouting "DIIMBY!"
- A new wave of fast moving, large players offer "Power Plus" solutions - new business models to which the Internet of Things and smart devices are central.
- Public pressure leads to the government outlawing shale gas.
- Electricity demand rises significantly, driven by decarbonisation of heat & transport.

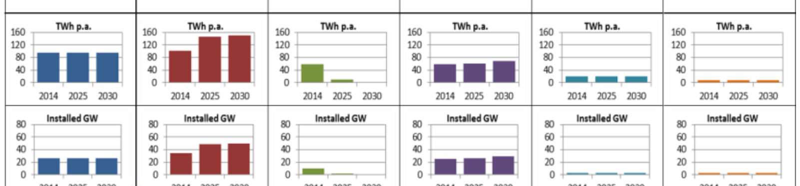


Coal	Gas	Nuclear	Renewables	Imports	Distributed Generation
Closures accelerate, driven by emissions legislation.	Remains an important part of the generation mix. Some new build (replacement plant) with CCS to maintain capacity.	No new build. Existing assets close gradually over period 2019-2028 per current scheduled closure dates.	Significant new build installations.	Imports increase, but remain minority part of the supply mix.	Accelerated growth in supported by government policy and public demand. Commercial operations lead, followed by the domestic sector.

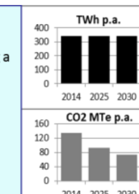
- World events lead to an inward-looking national government with security of supply and affordability as priorities. UK retrenches to fossil fuels.
- Lack of focus on emissions creates an effective moratorium on CCS and renewables.
- World events, perhaps in the form of a natural disaster or terrorist attack, lead to early closure of the nuclear fleet
- In general existing assets are sweated, with investment in new gas and USC coal to close the gap left by nuclear.
- Energy generation remains centralised, with large generation assets supplying the National Grid.
- Electricity demand remains stable at 2014 levels with heat and transport making no additional demand on electricity.



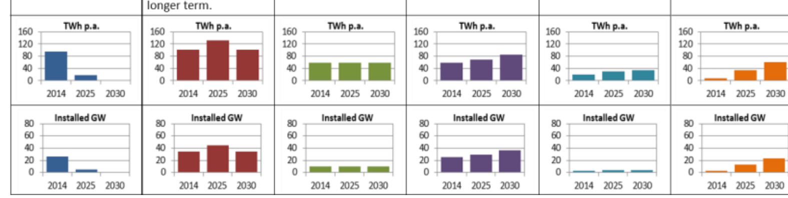
Coal	Gas	Nuclear	Renewables	Imports	Distributed Generation
Regeneration of coal via life extension of existing assets and new build.	Existing assets are sweated. New build replaces lost nuclear capacity.	World events lead to early closure of fleet.	Minimal new build.	Remains stable.	Remains stable.



- Governments fail to agree internationally binding targets on emissions. UK government provides no clear energy policy.
- Technological innovation enables regional energy hubs for distributed generation to begin playing a more significant role in the energy mix.
- Electricity demand remains stable at 2014 levels.
- Utilities cancel nuclear new build plans. No investment in coal.
- Gas is competitive and dominates the generation mix, followed by large renewables installations.
- Electric / hydrogen transport increases and heat demand is secured through local CHP, electricity and gas.



Coal	Gas	Nuclear	Renewables	Imports	Distributed Generation
Coal assets close, pushed out by gas and regional distributed generation.	Significant new build in the period to 2025. Rise in distributed generation reduces need for capacity longer term.	Existing assets are life extended to 2028 and beyond.	Limited renewables as part of energy hubs.	Imports increase, but remain minority part of the supply mix.	Distributed generation growth facilitated by technological innovation and economics.



Failing to meet emission targets

DOOSAN

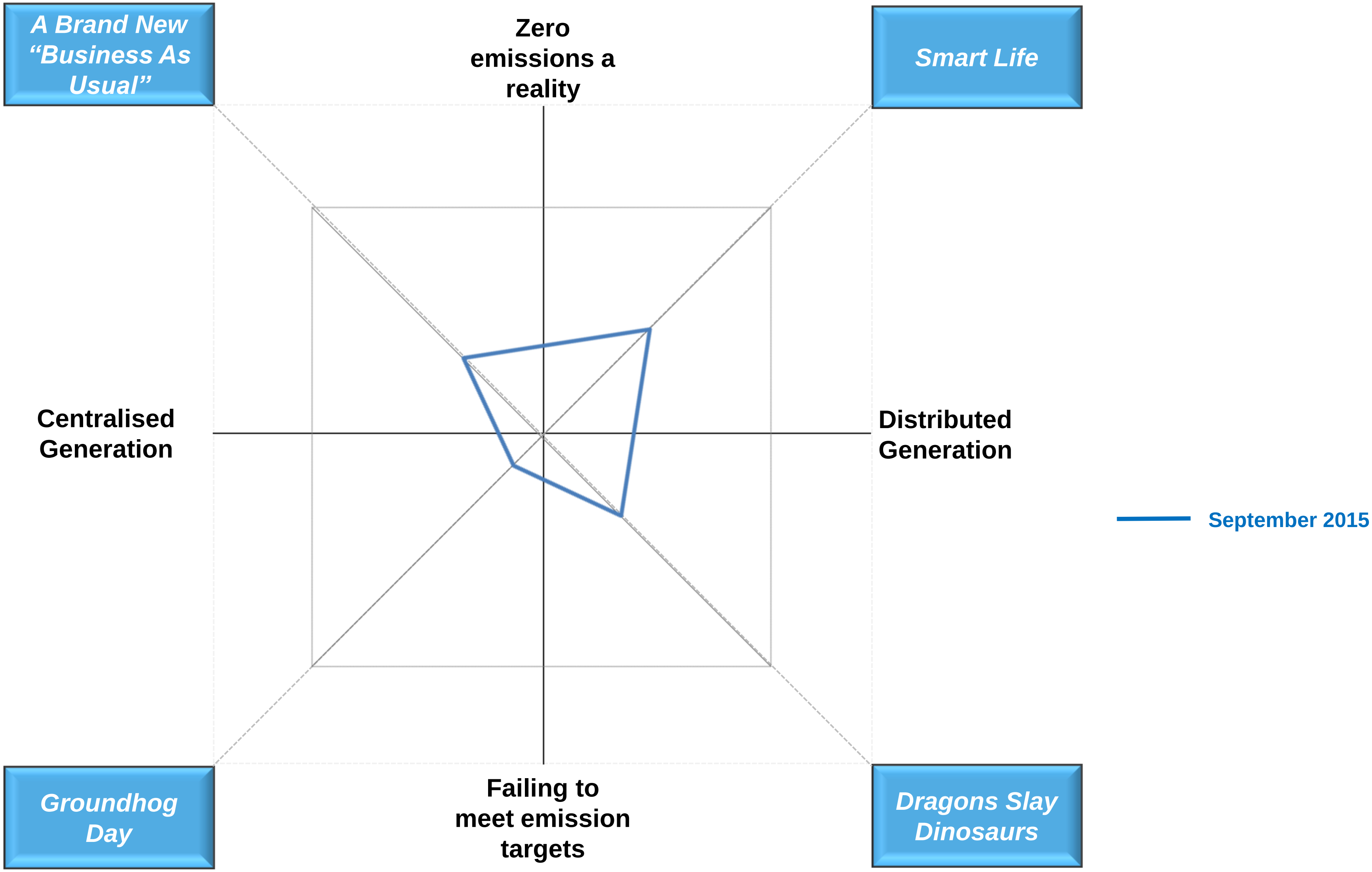
Early Warning Indicators – September 2015

Indicator	Current Comments	Smart Life	Dragons Slay Dinosaurs	Brand New BAU	Groundhog
Environmental Commitments	• Renewable energy outstrips coal for first time in UK electricity mix • COP21 participants indicate INDCs are moving closer to a 2 degree scenario	◕	○	●	○
Energy Affordability	• Developer Claims UK Solar Has Hit Grid Parity	◕	◑	○	○
Security of Supply	• UK guarantees £2bn nuclear plant deal as China investment announced • Fast pace of power plant closures threatens UK electricity grid • Eggborough coal plant closure worsens UK power crunch	◔	◔	◔	◔
Energy Demand	• SSI closure	○	○	◔	○
Key Regulation Changes	• CBI warning over renewables subsidies	○	◑	○	◑
Key events / must haves	• Government will seek to close all coal units in UK by 2023	●	◑	●	○
What are the main Utilities / Suppliers doing	• Drax pulls out of £1bn carbon capture project • National Grid CEO: Large Power Stations For Baseload Power Is Outdated • Shell pulls out of Arctic	◔	◑	○	◔
First mover indicators	• Osborne poaches Labour peer to lead rail and energy overhaul • UK's small energy suppliers gain market share from 'big six' • Balcombe 'fracking village' to go 100 per cent solar power	◕	◑	◔	○
		15	11	11	4

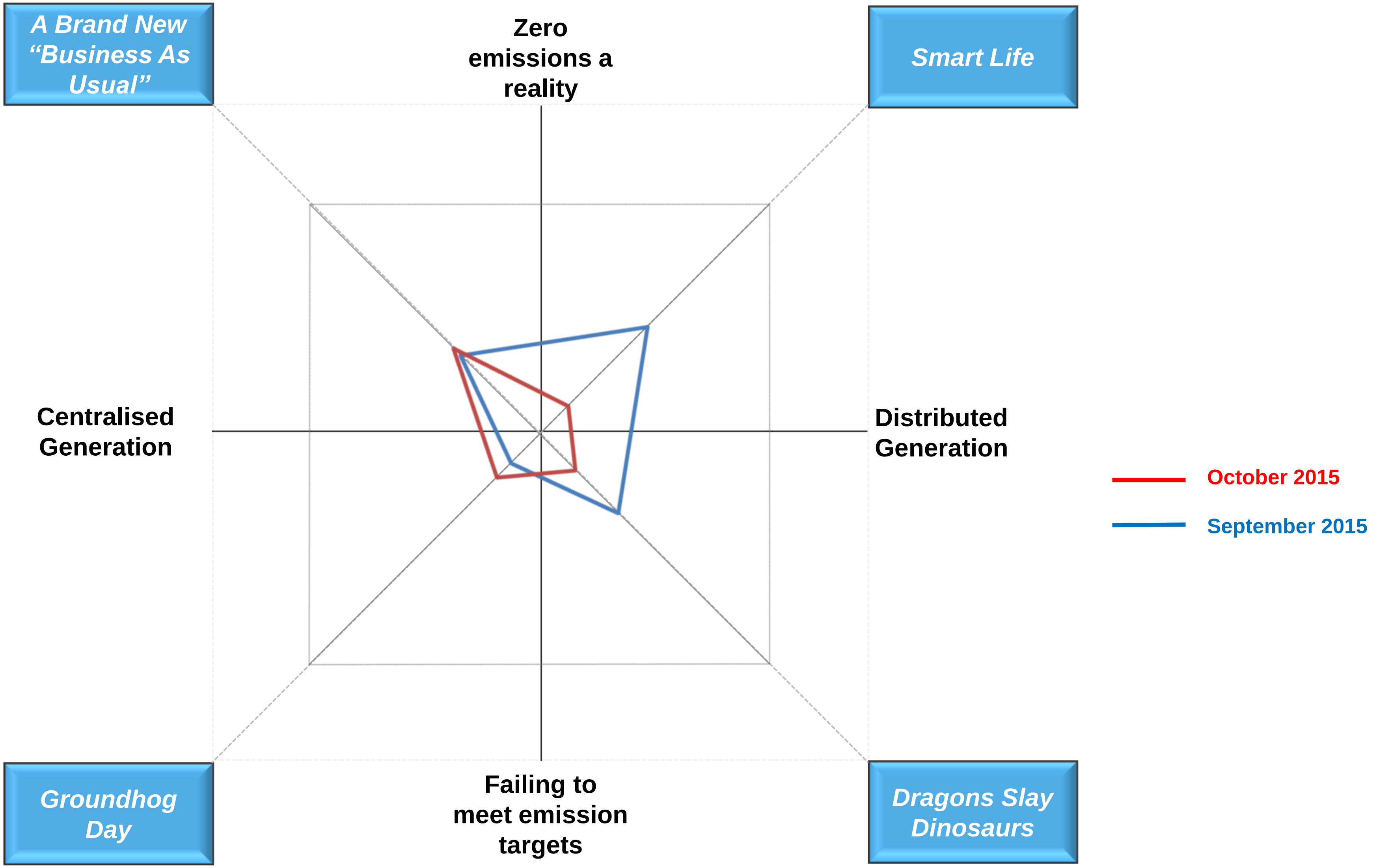
Scoring

No pull in scenario direction	0	1	2	3	4	Indicator strongly supporting scenario
	○	◔	◑	◕	●	

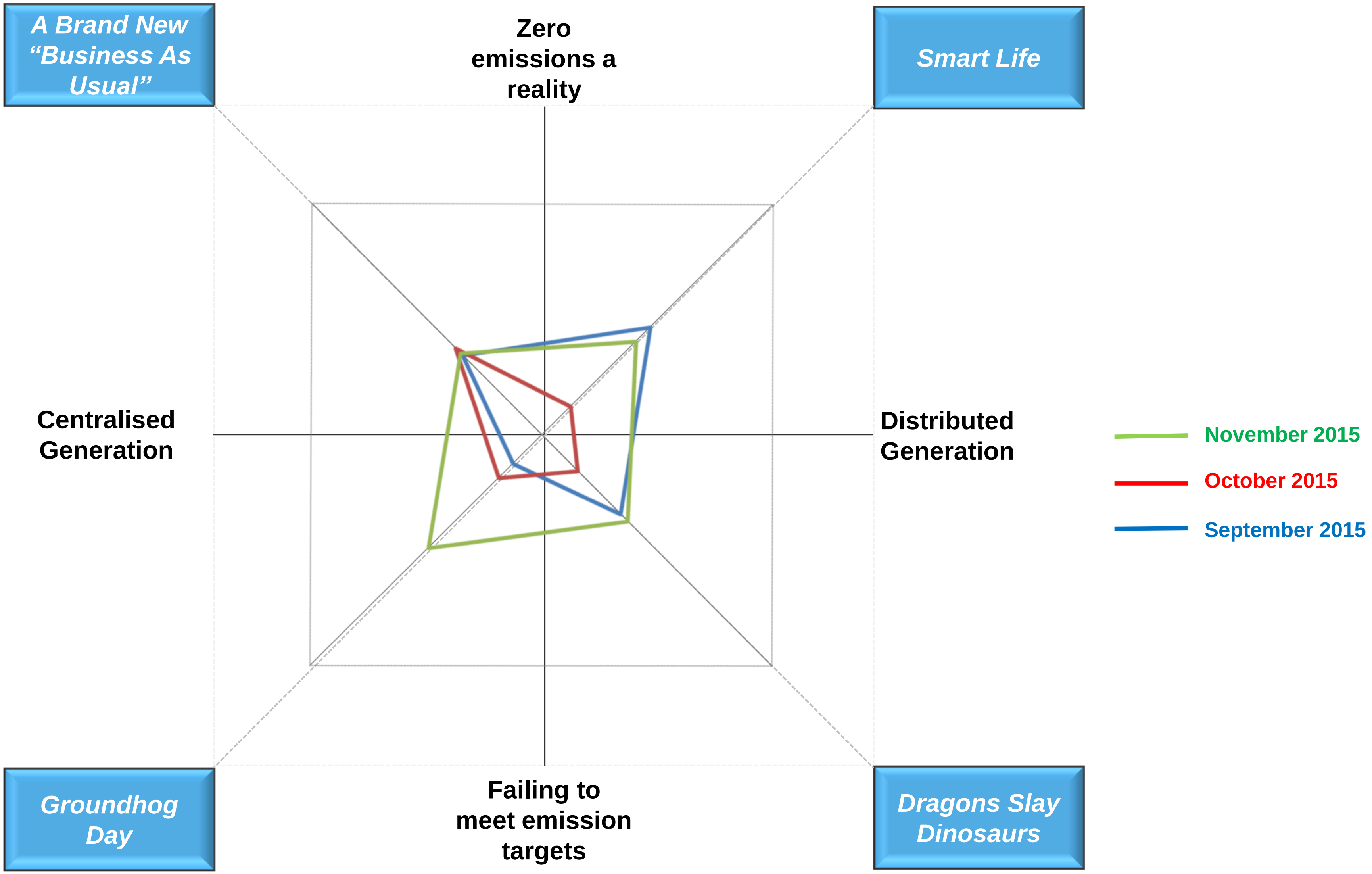
EWI Output – September 2015



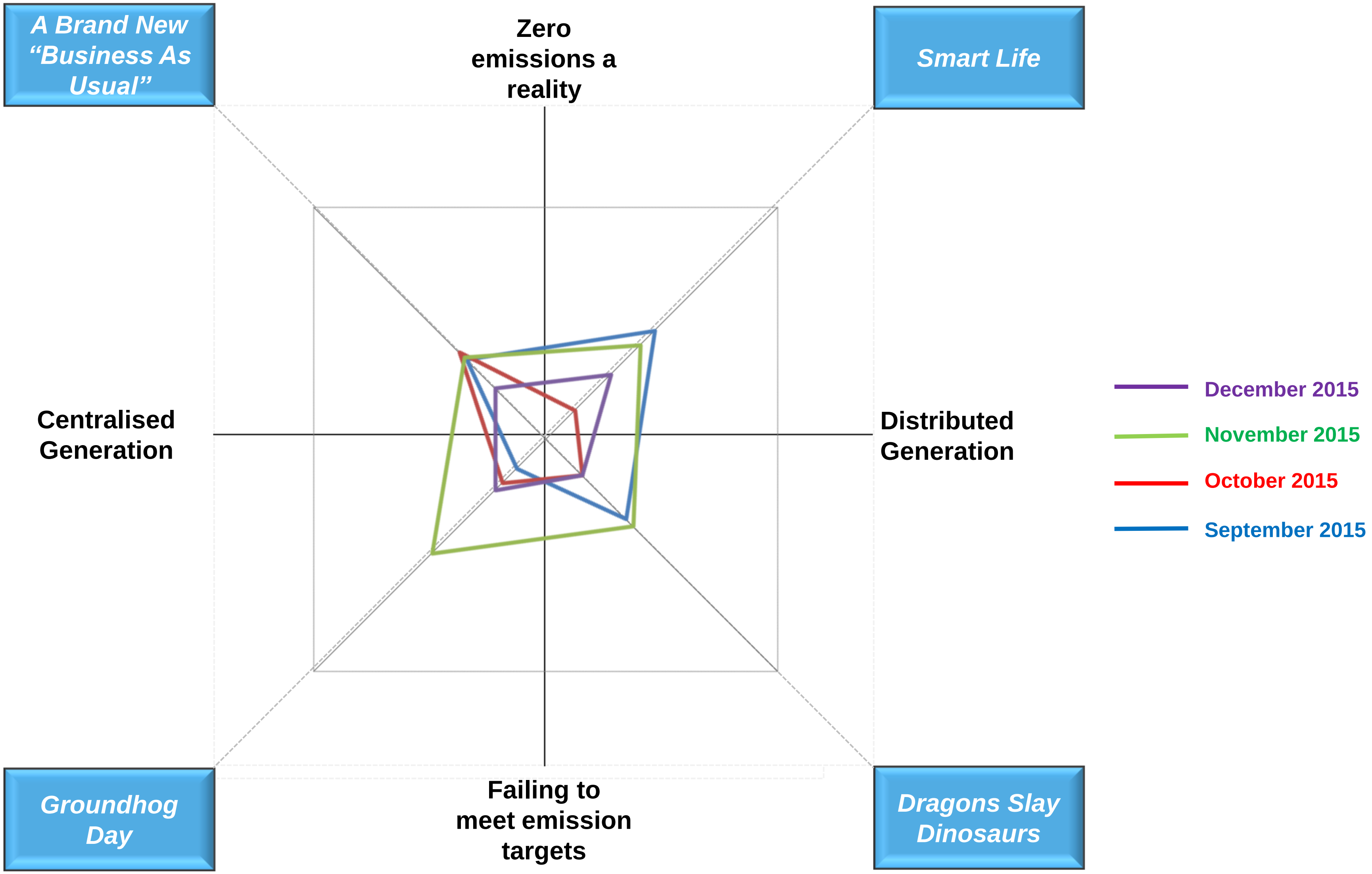
EWI Output – October 2015



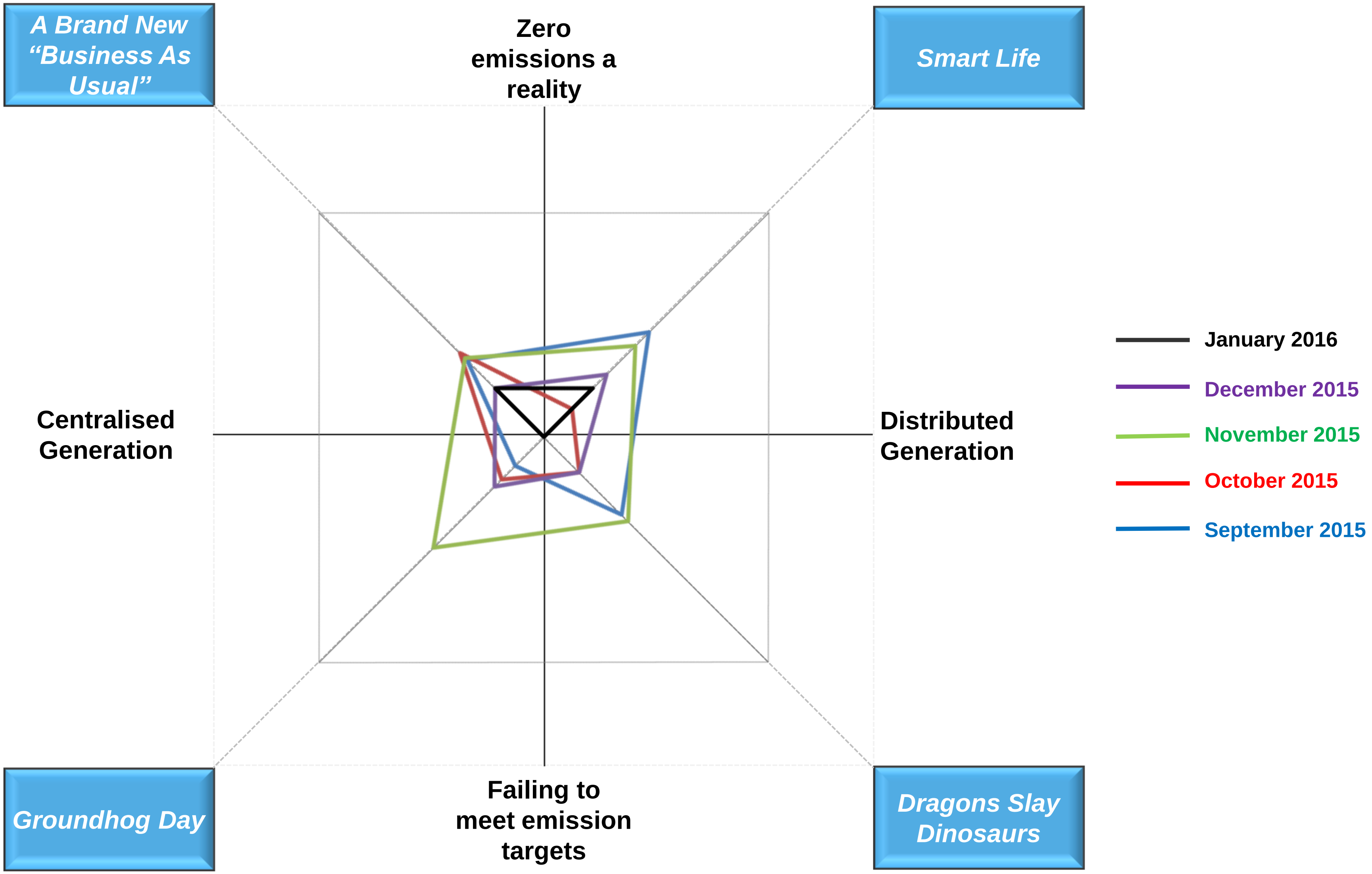
EWI Output – November 2015



EWI Output – December 2015

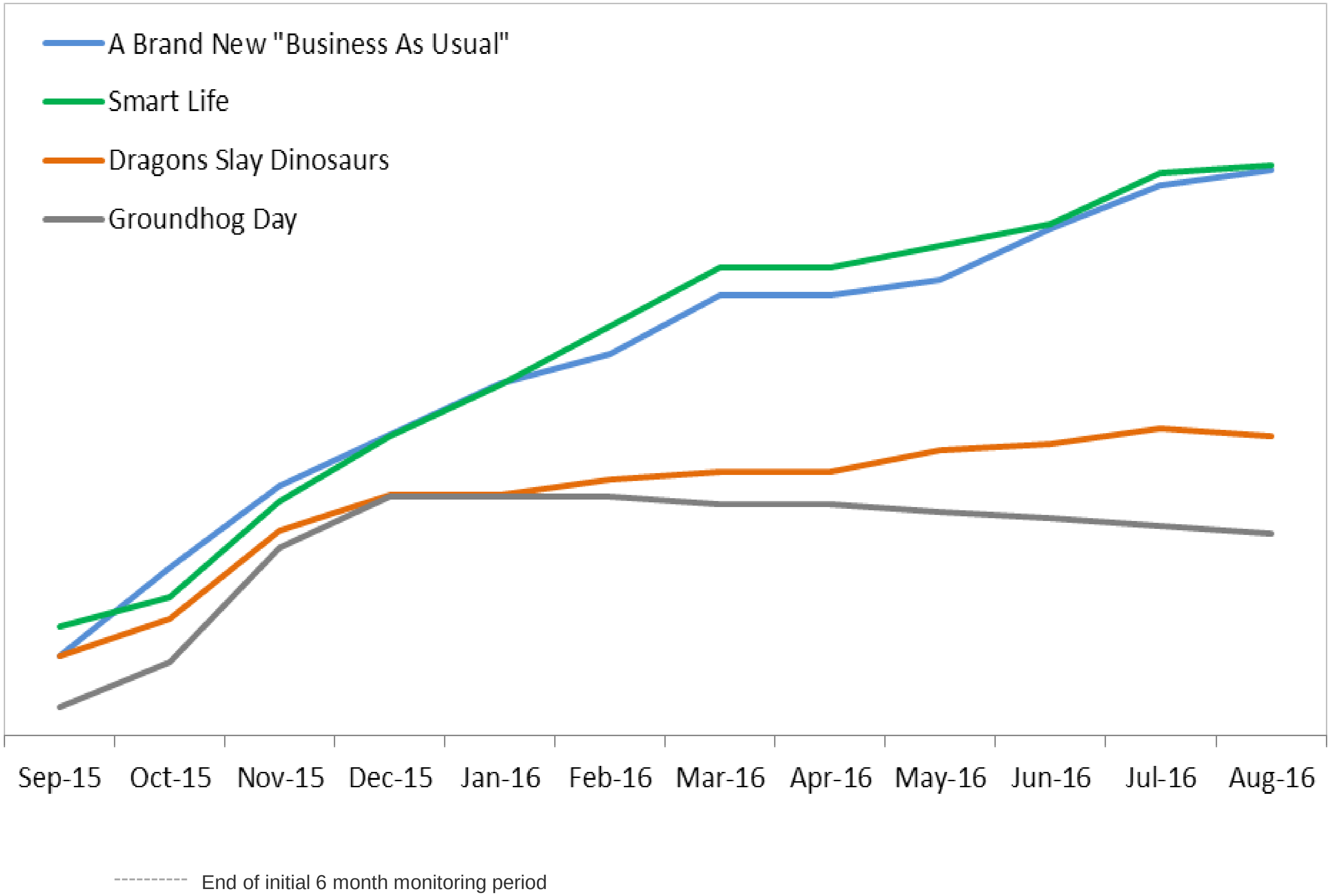


EWI Output – January 2016



Early Warning Indicators – August 2016

Cumulative Monthly Indicators



Conclusions

- The first line of my opening slide
  - " 1920's ….over 480 authorised suppliers of electricity in England and Wales

- The focus on large centralised thermal and nuclear plant for electricity generation reduced this number somewhat => "Big 6" generators

- However, the UK has seen a step change in the past ten years or so in the sources of electricity generation, driven by renewables
  - In 2011, 230,000 solar power projects in the UK, total installed generating capacity of 750 MW. In April 2016 almost 10GW of solar power installed, 22GW predicted by 2020
  - At August 2016, there are 6,938 wind turbines in the UK with a total installed capacity of over 14GW
  - National Grid recognising that the generation and demand landscape is changing and now recognising energy storage as a factor going forward

- Despite the huge investment , and the experience gained, over the last thirty years in cleaning up emissions from coal fired plant, and in improving efficiency, the possibility of new coal fired plant (even with carbon capture) being built in the UK and Western Europe seems remote today.

- It is hard to imagine today the disruptive event necessary to restore coal to its former glory as an electricity production source in the UK…………