The evolution of a major power grid

Philip J. Lloyd

Abstract— Seven years ago, the UK depended on coal-fired power to a large extent. Since then, the contribution of coal to the supply has been driven to a very low level. Some of the coal-fired stations have been converted to biomass, using imported wood pellets. Most have been replaced by combined-cycle gas turbine stations that are inherently more efficient and also, using natural gas as the fuel, less carbon intensive than coal. Nuclear makes a stable contribution, and hydropower and pumped storage make small contributions. Wind power has grown, and there were periods when it contributed over 8000MW to the grid - but also periods when it contributed less than 100MW. Latterly solar has entered the supply mix. These moves are tracked using the 5-minute data of Gridwatch, which also allows an assessment of the impact of non-dispatchable power on grid performance. Solar power appears to present particular challenges. The role of interconnections to Europe is also significant in the overall supply picture. These results are discussed in terms of plans to increase the nuclear contribution significantly in the near future, and the implications these findings might have for South Africa's desire to reduce its reliance on coal power for generation of electricity.

Index Terms— **Power grid, UK electricity, Gridwatch**

1 INTRODUCTION

The power generation technology employed worldwide is changing relatively rapidly. The limits of steam boilers were probably achieved a decade ago, when ultrasupercritical boilers first came into use. Operated at 300 bar, with steam temperatures of 600ºC, they had efficiencies of over 45%. [1] The earlier boilers typically had efficiencies of less than 35%.

The disconnect between oil, coal and gas prices, caused by the shale gas revolution in the US and the subsequent drop in gas prices, has led to a wider application of combined cycle gas turbine [CCGT] technology, which has an efficiency closer to 60%. In addition, being fired with natural gas rather than coal, CCGT technology produces less carbon dioxide than coal-fired steam boilers.

Also non-dispatchable sources such as wind turbines, photovoltaic cells and solar-thermal boilers have reached industrial scale, although their reliability is not yet at the low-risk level of traditional generation (for instance, some 108 wind turbines offshore Britain have recently reported to have suffered blade failure in less than 3 years since installation [2]). The cost of generation from these sources has fallen dramatically, and storage processes are being developed to improve the dispatchability of this form of power. Indeed, thermal storage allied to solar thermal boilers are approaching the dispatchability of conventional power stations at a comparable cost.[3]

These various forms of generation are placing new demands on the transmission and distribution of power. South Africa has been considering changing its generation and transmission model for some years now, but has made little progress. There is still a monolithic utility, and, to its considerable credit, it continues to deliver high-quality power reliably. The costs of doing so have, however, risen rapidly. Worse, the utility has no say in the costing of non-dispatchable renewable energy, of which it is the sole buyer. It is presently paying about three times more than the average cost of production in the rest of its system. Those costs therefore have to be recouped directly from the customer, who blame the utility rather than the national policy of making the utility the sole distributor. As the fraction of non-dispatchable renewable energy in the total supply rises, so the costs increase disproportionately.

Other nations are adapting the newer technologies with varying degrees of success. Germany, which long relied on nuclear power to provide base load, is closing its nuclear plant and growing the renewable component of the system in a programme known as *Energiewende*.[4] Until recently, this enjoyed widespread support, but in 2017 it proved a stumbling block in the formation of a ruling coalition in Germany. Domestic electricity prices have risen rapidly, and are now the second-most expensive in the European Union.

The United Kingdom has also embraced the new technologies with determination. As recently as 2012, coal-fired power stations provided nearly 40% of Britain's power, today they provide less than 10% and there are periods when they are all closed.

This paper therefore looks at how the British power supply has changed in recent years, to see if there are any guides to how the South African generation system may adapt to the new technologies and achieve the Government's stated aim of reducing our greenhouse gas emissions.

2 METHODOLOGY

Data on the performance of the British supply and demand were downloaded from the Gridwatch site.[5] Data on the total demand and the generation by coal, open and combined cycle gas turbines, nuclear, wind, pumped storage, hydropower, biomass, oil-fired and solar, and the flows down interconnections, are recorded every five minutes. The service started operation in May 2011, so annual data were

P.Lloyd, Energy Institute, Cape Peninsula University of Technology, P O Box 1906 Bellville 7535, South Africa (e-mail: lloydp@cput.ac.za).

downloaded ending in May 2012, 2013, 2014, 2015, 2016 and 2017.

The data, while very extensive, suffered from some imperfections, namely:

- Spurious demand readings. These comprised typically less than 10 per year, and claimed demands far in excess of the known capacity of the grid. All records related to such spurious demands were deleted.
- Stationary demand readings. Several thousand times a year, the recording system showed no change in the demand or any of the supplies for several consecutive 5-minute periods. All records related to these stationary readings were deleted
- Spurious supply readings. These amounted to perhaps five a year, and were identified via a plot of the distribution. Records more than 10% above the known capacity of the particular technology were deleted.

The cleaning process obviously destroyed the continuity of the data, but with over 105 000 data points per year, it was not felt to be very serious. Over 95% of the data survived this process. Fig 1 illustrates the relative completeness, in terms of the number of 5-minute gaps that were introduced as a result of the process.

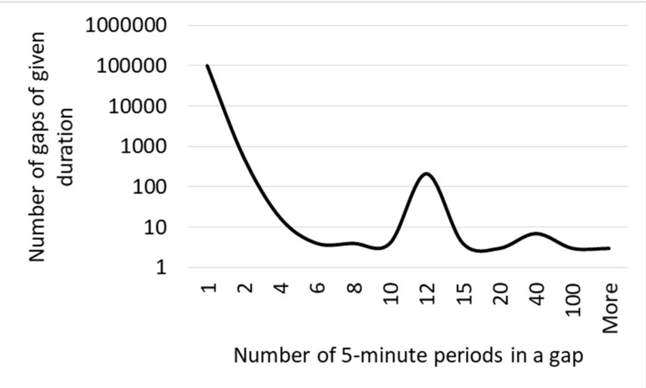

Fig. 1 Distribution of gaps in 2012 data base as a result of the cleaning process.

There were some 500 cases where there was 2x5 minutes between readings and 200 where there was 12x5 minutes between readings. All other gaps were much less frequent. It could be concluded that the data base was sufficiently complete for analysis to proceed.

3 ANALYSIS

3.1 Supply and demand

The supply-demand balance is shown in Table 1. It was questionable whether measuring all inputs to the grid would be sufficiently accurate to be able to match the demand, but the test of this question left no doubt – it was indeed possible, as the final row in Table 1 clearly indicates.

Table 1 The supply/demand balance, 2012 to 2017

	2012	2013	2014	2015	2016	2017
Demand	36722	36717	35135	34085	32421	32325
Coal	13781	15359	13173	10163	5700	2609
Ccgt	12469	9340	8509	10158	11660	14843
Nuclear	7105	7463	7391	7003	7337	7704
Wind	1273	1782	2393	2464	2524	2785
Hydro	457	339	437	435	439	411
Pumped	342	328	326	313	312	327
Biomass	40	441	520	917	1692	1594
Ocgt	4	2	1	1	1	2
Oil	2	2	0	1	0	0
Solar	0	0	0	0	0	462
French_ict	547	903	1523	1678	1655	795
Dutch_ict	420	688	799	905	918	810
Irish_ict	-167	-222	-159	-87	12	24
EW_ict	0	-79	-304	-226	-44	61
Total	36274	36347	34610	33725	32207	32427
% demand	98.8	99.0	98.5	98.9	99.3	100.3

Cctg combined cycle gas turbine; Octg open cycle gas turbne; ict Interconnector

3.1.1 Demand

The UK demand has fallen by about 10% since 2012. Much of this is the result of higher efficiency driven by higher prices; some of it is a reflection of economic slowdown; some of it may be a move away from electrical to gas space heating. Fig.2 shows how the peak demand has changed year by year.

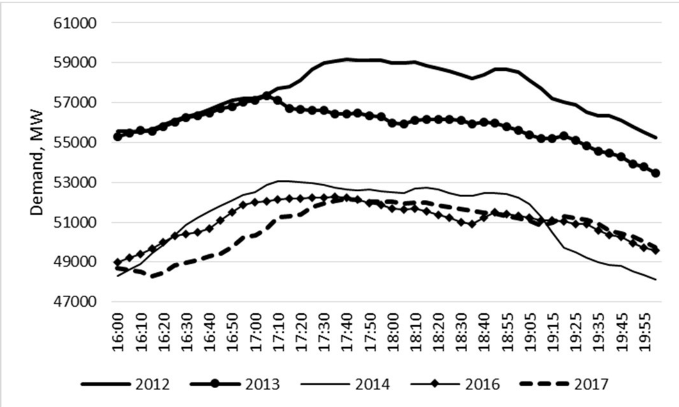

Fig.2 Change in peak demand in winter in U.K.

It is usually found between 4 and 6p.m.on a winter's evening. It has also dropped by about 10% since 2012. From the timing, it is most likely to be a domestic load. The drop in demand in the face of a rising population strongly suggests a change in space heating technology.

3.1.2 Coal

In 2012 coal provided nearly half the peak winter energy demand. By mid-summer that year, its contribution had dropped to less than 5% of its peak. There was a similar pattern in 2013. In 2014, the coal contribution to the winter peak was less than 40% of the demand but it contributed about 15% of the summer demand. By 2015, coal made up less than a third of the peak winter demand and supplied less than 10% of the summer demand. The next winter, coal's share was only a quarter of the peak winter demand, and during the summer there was a period when no coal-fired stations operated.

By 2017, coal made up only about 20% of the winter peak, and the stations were silent during many summer days, being operated only during the morning and evening peaks in demand

3.1.3 CCGT

Britain had about 24GW of CCGT installed in 2012, which proved adequate until 2017 when a further 2 GW was built. The load factor dropped from 2102 to 2016, which appeared to be due to the rising cost of gas during this period, and the steady decline in the UK's own reserves. However, growing confidence in the supplies from elsewhere have enabled greater reliance on CCGT as the base load provider of choice. Today it supplies over half the peak winter demand.

The confidence in imported supply is surprising. Britain's own reserves in the North Sea today make up about 40% of the supply and declining; Russia and Western Europe provide about 45% and about 15% arrives in the form of liquefied natural gas [LNG] from elsewhere.

3.1.4 Nuclear

Britain has about 9GW of nuclear power, and it operates at about 80% load factor throughout the year. Refueling appeared to take place during summer and autumn months, when load factors fell to below 50%, but winter and spring at close to 90% load soon made up for that.

3.1.5 Wind

As Table 1 indicates, the contribution of wind to the annual supply more than doubled from 2012 to 2017. Interestingly, the variability of the supple, as measured by the relative standard deviation of the average supply varied very little. This is illustrated in Fig.3, which shows how the frequency of large changes in output varied by quite a small amount as the capacity increased. There were over 100 000 5-minute periods each year when the total output from wind varied by less than ±150MW.

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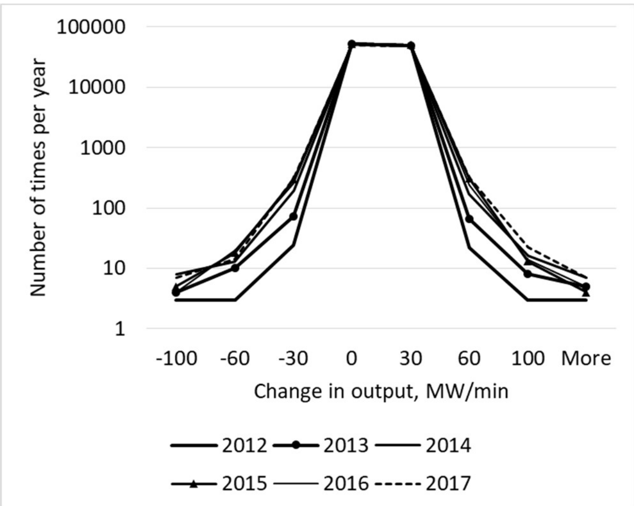

Fig 3. Variation in output from all wind turbines over 5 minutes, from 2012 to 2017

3.1.6 Pumped storage

Britain has over 2000MW of pumped storage. About one-third of the time, it makes no contribution to the supply. It is quite frequently called upon to provide between 200 and 400MW, but for about 25 days a year it provides over 1000MW. Fig.4 shows the performance over two typical years, 2015 and 2017:

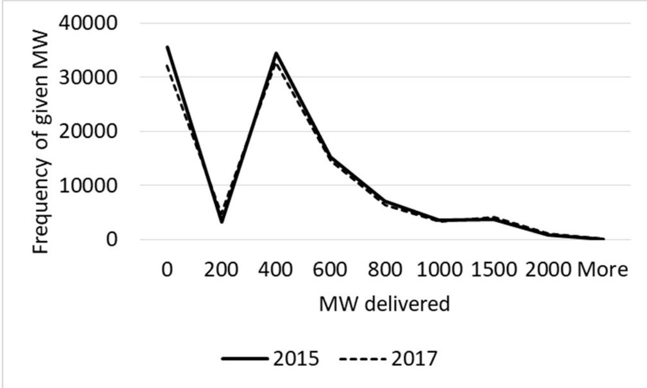

Fig.4 Deliveries from pumped storage, 2015 and 2017.

3.1.7 Hydropower

Britain has about 1200MW of hydropower. It is operated at an annual average load factor of about 35%, and only contributes over 1000MW for about 2% of the year. 35% of the year it makes no contribution whatsoever. The reasons for this level of performance are not clear.

3.1.8 Biomass

As Table 1 illustrates, there has been a rapid growth in the consumption of biomass for power generation. To date, six originally coal-fired stations have been converted to burn imported wood pellets. Some 63Mt of pellets are required annually, which are sourced primarily from the US and Eastern Europe. At the end of 2017, there was about 2500MW of capacity, and the average load factor during the year was about 65%.

The programme has not been without its critics. [6] The deforestation necessary supply the pellets may have a greater effect than the carbon dioxide from coal combustion.

3.1.9 Solar

Nearly 9GW of solar photovoltaics were added to the grid from November 2016. In the seven months of operation, through till the end of May 2017, much of the time the insolation was very low and it is therefore not surprising that the average contribution was only 480MW. There was, however, a brief period in May 2017 when the solar input was over 8GW.

To try to get a better picture of solar power, the data for May 2017 to May 2018 were assessed. It appeared to be more complete than the data for other sources, but still suffered from some problems. For instance, on 2018-03-19 at 12:52 it suddenly appeared to drop 4480MW. However, the rest of the grid was unchanged, even the frequency, so this had to be an artefact.

The power delivered was only significant for a small fraction of the time of operation:

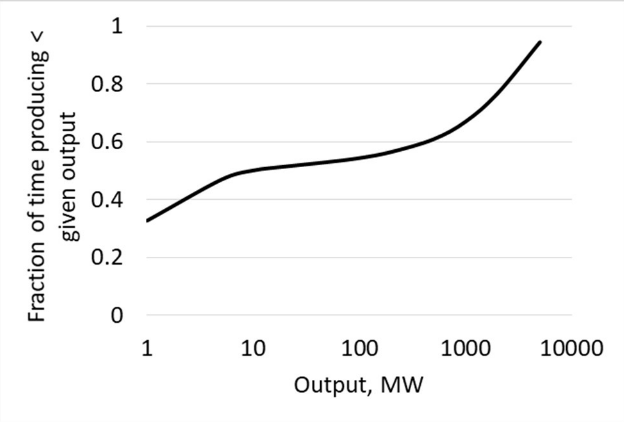

Fig.5 Fraction of time solar gave power

Over half the time it gave less than 10 MW; about 5% of the time it yielded between 5000 and 8600 MW. It also had an unusual ramp rate behaviour:

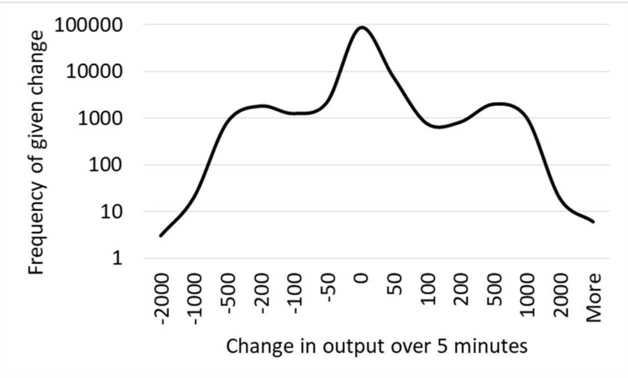

Fig 6. Variation in solar output over 5 minutes during 2018

The "shoulders" indicate that several thousand times a year there would be changes in output of the order of 1000 MW in five minutes, which is far higher than the variation from wind turbines, for instance (compare Fig.3)

3.1.10 Other

Oil-fired boilers made a very small contribution until 2014, and appear to have been shut since then. Open-cycle gas turbines likewise made a very small contribution, although on occasions they were called upon to supply over 500MW, so they constituted a form of spinning reserve.

3.1.11 Interconnections

The French and Dutch contribution to the UK grid grew steadily from about 1000MW in 2012 to over 2500MW in 2016. In 2017, the arrival of some 400MW of solar power and a much reduced demand from Ireland appears to have reduced the need for continental supply by some 800MW.

In 2012 there was a single line to Ireland, which delivered some 200MW. In 2013, a private interconnection, the EW ict, was established, which took about 80MW from the Irish ict. Over the next few years, Irish own generation, largely from wind, grew, so that by 2017 the two lines to Ireland were contributing about 100MW to the UK grid.

3.2 Grid dynamics

One of the concerns about introducing significant quantities of non-dispatchable energy into the grid supply is ensuring sufficient spinning reserve to permit load following. It was therefore of interest to study the rate of change that was achieved with the various technologies. Gridwatch gave the load every 5 minutes; for the demand and the various supply technologies it was therefore a matter of studying the rate of change achievable, the effective ramp rate.

3.2.1 Demand

The frequency of changes in demand is shown in Fig. 7. The distribution is close to normal, and there are no trends with time, which might have been expected with a growing proportion of the supply being non-dispatchable.

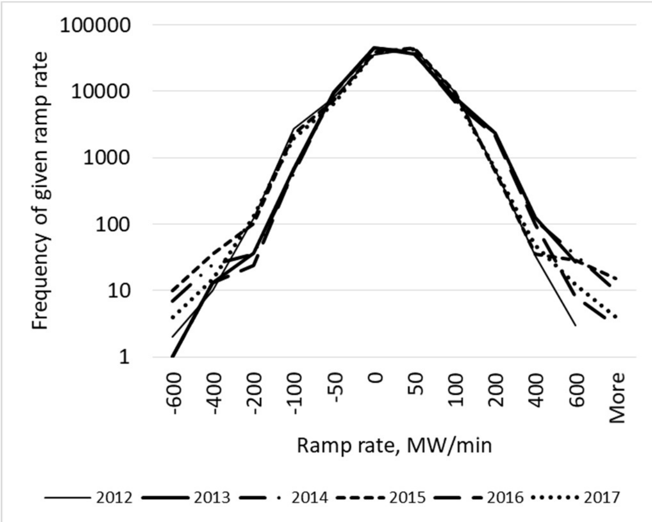

Fig.7. Variation in demand over 5 minutes for 2012 to 2017

Comparison with Fig.3 indicates that this may be a general pattern for ramp rates, and indeed data analysis shows that all technologies have a close-to-normal distribution and can be quite well characterised by their standard deviation and maximum and minimum values.

3.2.2 Dynamics of all technologies

Table 3. Average dynamic characteristics of all technologies

	Std.Dev	Max	Min
Demand	44	650	-943
Coal	17	339	-409
Nuclear	3	288	-281
CCGT	30	476	-545
Wind	7	220	-282
Pumped	14	163	-156
Hydro	4	103	-83
Biomass	2	130	-128
Oil	0	35	-30
Solar	34	900	-878
OCGT	1	48	-47
French_ict	16	389	-424
Dutch_ict	11	295	-335
Irish_ict	3	55	-62
EW_ict	4	72	-72

The 44MW/min standard deviation of the demand ramp rate can be matched by the OCGT and pumped storage, backed by the European interconnectors. Coal used to play a significant part, but has largely been replaced by OCGT in the provision of a reserve.

An unknown at this stage is the impact of solar power on the grid dynamics. There is only some six months of data, and it shows not only a large standard deviation, but also maximum and minimum ramp rates of the same order as the whole of the grid

4 Discussion and Conclusions

Britain has successfully achieved its aim of weaning itself from coal-fired power. To be sure, some of its coal-fired stations were due for replacement or closure, but the desire to achieve European emission standards was ultimately the driving force behind the change.

To a large extent, much of the base load has been taken over by combined-cycle gas turbine stations. These are significantly more efficient than even the most modern coal-fired stations, and are smaller and less capital intensive. They have one slight disadvantage, which is that, for a cold start, they must operate essentially as open-cycle gas turbines until the steam circuit gets up to pressure.

South Africa could potentially follow a similar route. However, the Gas Utilization Master Plan [7] [GUMP] has been delayed because the Integrated Resource Plan [IRP] has not been finalized:

"It is important to ensure that there is alignment between the procurement programme and the IRP and therefore, the Department has taken the decision to postpone the release of the RFQ for the LNG-to-Power IPP procurement programme."

Thus it is unclear when adequate gas to support a combined-cycle gas turbine programme in South Africa might become available. It is known that there are significant resources in northern Mozambique, but a recent assessment has suggested that gas is unlikely to become available commercially from that source before the mid 2020's. Imported LNG is certainly a possibility, but that will require regasification facilities, probably onshore. GUMP has suggested that these should be at Richard's Bay and Coega, but there is no decision to construct anything yet. Another potential source is shale gas, but the preliminary work on the Karoo is not encouraging. So until such time as gas availability becomes a reality, the promise of gas-turbine technology in South Africa must remain no more than a promise.

Nuclear is the other side of the base load equation in Britain. It has proved itself reliable, safe and cost effective. Because Britain has voluntarily surrendered its own coal resource, and its natural gas resource is shrinking, so it finds itself in a position where energy security depends on its relationships with Europe and America. The European supply is known to be vulnerable, as was seen when Russia cut supplies to the Ukraine. America is shipping increasing quantities of LNG and, of course, is the primary source of biomass on which Britain is further dependent.

Britain appears perfectly aware of its growing lack of energy security. It plans to build about 19GW of new nuclear capacity to be operational by the mid-2020s. About 8GW of existing nuclear capacity will be removed from service about then, so it will have over 20GW in service and be far less dependent on imported energy.

An important feature of the British Grid is the interconnections to France and the Netherlands. These can supply or take off as much as 2500MW in total. Having such a facility available is almost lie having an immense battery on call. Moreover, the ability to ramp at up to 800MW per minute adds to the grid's resilience. Of course, there must be a question over the continued ability of France and the Netherlands to make this facility available at this level. France is having to renew its nuclear fleet over the coming decade, so there must be questions about its continuing ability to support the British grid in this was. The Netherlands acts as a gathering point for energy generated elsewhere in Europe, such as hydropower from Norway and excess windpower generated from Denmark and northern Germany. As such, its long-term sustainability to support Britain must be called into question.

When we consider the situation in South Africa, we have to take account of several forces at work:

- A desire to reduce our reliance on coal-fired power. Guilt about carbon emissions may be misplaced, but Government's desire to be seen to be living up to its Paris commitments is very real. The fact that we are one of the only nations of the world to have achieved our current commitment seems to be adding to our ambition to pursue a peak-plateau-decline trajectory at all costs.
- An uncritical acceptance of renewable energy as a major source of our power. It is true that our solar resource is very good indeed, and that our wind resource has few equals. However, it is often forgotten that these are still developing technologies. One of the major suppliers of wind turbines, for instance, is having to replace all the blades on 108 large turbines after only three years in service. Moreover, while the contractual costs of generating renewable power have fallen gratifyingly fast, there is emerging evidence worldwide that the introduction of non-dispatchable power creates additional costs in the system that are not carried by the generators of non-dispatchable power. For instance, some thermal plant may have to be shut down for a few hours because the renewable supply is so plentiful. Thermal plant is not designed to be shut down regularly, if only because there are considerable costs in heating it up to operational temperatures after being allowed to cool. In extreme cases, overproduction of non-dispatchable energy may lead to curtailment of the non-dispatchable production and consequent loss of revenue.
- South Africa does not possess much interconnection to its neighbours. There is a 1000MW import line from Cahora Bassa, and small export lines to Botswana, Zimbabwe and Namibia that total about 1000MW. We are approximately in an import/export balance, and there is no such luxury as a 2500MW set of interconnections to assist in stabilizing our grid.

It must be concluded that there are features of the British grid which have allowed a relatively rapid move away from coal-fired power. South Africa may have ambitions to similarly move away from coal-fired power, but we lack many of the features which have enabled Britain to do so without stress.

5 References

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Author

Philip Lloyd graduated in Chemical Engineering from UCT and Nuclear Physics from MIT. He worked for the Atomic Energy Board for two years, then joined the Chamber of Mines Research Organization where he became Director. After 15 years he moved to Murray and Roberts from whom he was stolen by Ed L.Bateman, where he helped manage the Mossgas project. He then ran a Bateman subsidiary, Industrial & Petrochemical Consultants, which he bought when he finally retired. In 1994 he became professor of environmental chemical engineering at Wits; in 1999 he became senior research fellow in the Energy Research Centre at UCT; and 10 years later professor in the Energy Institute at CPUT.

The paper will be presented by Philip Lloyd