Flexible future for combined cycle

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Answers for energy.

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Flexible future for combined cycle

To maintain grid stability with the increased share of renewables envisaged in the generation mix of Germany (and elsewhere in Europe) will require greatly increased flexibility from the "conventional" power plants (nuclear, coal and gas-fired combined cycle). This article compares the relative merits of these technologies in terms of operational characteristics and demonstrates the benefits of combined cycle units. A second article, reviewing recent CCGT projects in Europe, to be published in next month's issue, will show just how far combined cycle technology has come in terms of flexibility, cycling and fast start performance.

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As a result of the changing structure of power generation in Germany, notably the expansion of renewables (which are given priority under the law), "conventional" power plants will increasingly be required to take on additional tasks (Figure 1), particularly in the absence of large-scale energy storage systems, which are still far away from commercialisation. What are these tasks and what are the strengths and weaknesses of the various conventional power generation technologies, principally nuclear, coal and combined cycle, in terms of performance dynamics, provision of control reserves, part-load behaviour and start-up times? It turns out that combined cycle plants complement renewables very well and can be a great help in accommodating more of them on the grid.

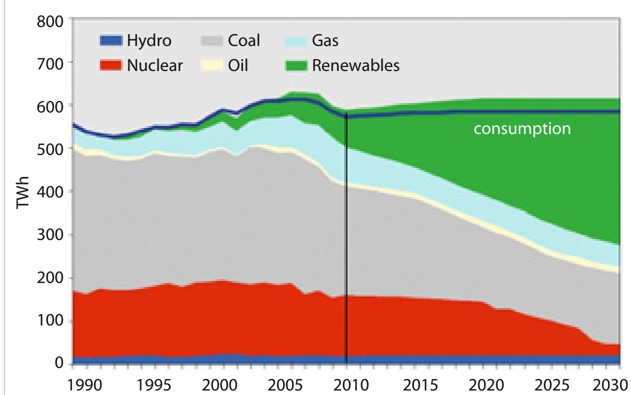
Increased unit installed capacity and high efficiency used to be the key preoccupations of the conventional power sources, but that is no longer the whole picture. The past 30 years have seen significant changes in the requirements imposed on conventional power plants. During the decade from 1980 to 1990, the key requirements for fossil-fired power plants in particular were minimum investment costs and construction times, baseload operation, and flexibility in terms of fuel (oil/natural gas/synthetic gas/blast furnace gas/coal and lignite). In the subsequent decade (1990-2000), the focus was on greater efficiency, driven by increasing fuel prices and more stringent environmental requirements. In the last ten years, from around 2000 onwards, the key area of focus – influenced by the deregulation of electricity markets – has been the switch from baseload to intermediate load operation, and thus the need for fast load ramps, shorter low-load and start-up times, and grid stabilisation. In addition, the demand for ancillary services such as provision of control reserves and frequency support, as well as tertiary control reserves and load-follow operation, has increased significantly. As a result, new operating requirements have emerged, such as two-shift operation, load-follow operation, island operation, black start capability, frequency support and very high start-up and operating reliability, in order to stabilise power grid dynamics and hence ensure secure and economic electricity supply.

Figure 2 shows how the requirements for load cycling change when not only demand but also power production become increasingly cyclical and, as is frequently the case, impossible to predict with adequate reliability. The fact that these requirements are set to expand further in the immediate future in Germany (and elsewhere), is confirmed in a recent study by the Fraunhofer Institute. This shows that by as early as 2020, assuming that the expansion of renewables such as wind and solar energy takes place as planned, we will be faced, in rapid succession, with periods in which there is an over- or under-capacity of several gigawatts, which the system will have to accommodate. Since no suitable large-scale storage capability will be available by then (apart from existing – and possibly new – pumped storage plants), this can only be achieved using advanced power plant technologies (Figure 3).

Depending on the country and power grid concerned, various dynamic capabilities are required to ensure security of supply, such as primary control, secondary control, capability for island operation, load rejection, black start capability, grid restoration following blackout, etc. Table 1 shows a comparison of nuclear and fossil-fired power plants in terms of the following characteristics:

- typical rates of load change during load-follow operation as well as for system services such as frequency control or load rejection to unit auxiliary power level;
- minimum loads;

Figure 1. Sources of German electricity, present and future, showing the planned significant expansion of renewables



- efficiency and hence specific emissions of carbon dioxide and other pollutants.

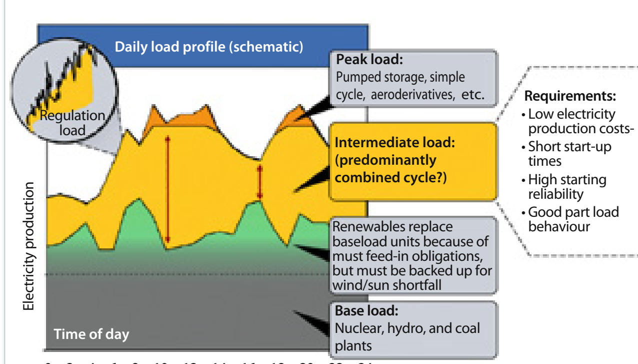
The following observations can be made on the basis of Table 1:

- All of these power plant types, including nuclear power units, are suitable for load-follow operation, and are in fact already used in this way today. Combined cycle plants allow somewhat faster load changes (depending on manufacturer and configuration) within a wider load range.
- All power plant types are also suitable for grid/frequency stabilisation.

However, combined cycle plants offer a significantly higher rate of load change thanks to innovative and specifically developed systems.

- The achievable minimum load is between 15 and 30% for all power plant types, and is therefore similar for all plant types, even if actual operating regimes differ.
- Load rejection to the unit auxiliary power level or to the island mode of operation is required in the event of partial or complete shutdown of the grid as a result of disturbances. State-of-the-art combined cycle

Figure 2. How the requirements for load cycling change when not only demand but also power production becomes increasingly cyclical



gas turbine at the auxiliary power level, with the steam turbine out of operation. This also allows auxiliary systems and equipment to be kept in operation so that they are immediately available for grid restoration. Nuclear power plants and coal-fired plants are likewise able to supply auxiliary power using their steam turbine generators following a load rejection.

- For the purposes of this analysis efficiencies are only really meaningful for the fossil-fired plants, characterising fuel consumption and specific CO_2 emissions. An important issue is plant efficiency during flexible operation, with part-load and variations in load. Combined cycle plants, especially in multi-unit configurations, have considerable advantages over coal-fired plants in this respect. Carbon capture and storage (CCS) installations, provided that they are developed on a large scale and provided that the associated waste management issues are resolved, could reduce CO_2 emissions to <100 g/kWh for both coal-fired plants and combined cycle plants, but would cause the latter to lose a significant proportion of their flexibility advantage.
- Nuclear power plants do not produce any significant carbon dioxide emissions during operation. Coal-fired power plants have significantly higher such emissions than gas-fired plants due to the higher carbon content of their fuel. If the higher efficiency of combined cycle plants is in addition factored in, the total emissions from a 1000 MW coal-fired unit are more than twice those from a state-of-the-art combined cycle plant (eg, of the SCC5-8000H type) per kWh generated.
- Neither do nuclear power plants produce any SO_2 and NO_x emissions, of course. But for coal-fired power plants, despite the use of flue gas desulphurisation and selective catalytic NO_x reduction, these emissions are several times higher than for gas-fired plants.

Overall, it can be concluded that, although nuclear power plants and coal-fired plants can, in principle, be used for load-follow operation and frequency support, combined cycle plants have significant advantages, particularly over coal-fired plants, when it comes to rates of load change and emissions.

From 0 to 100% in 30 minutes, several times a day

If, in future, the renewable capacity that is currently planned in a country such as Germany becomes operational (see Figure 3) and is given the same priority in power grids as it is now, previously base-loaded power plants will – during peak wind and sun periods – not merely have to be run down to part load, but will have to be completely shut down in many cases in order to avoid significant overcapacities, which could cause negative power prices and instabilities in the grid. These plants will then need to be started up from the shut-down condition as rapidly as possible to cover demand in the event of short-term loss of wind and solar power.

The fact that such a scenario is realistic is illustrated by the prospect that wind and solar power are expected to provide 50-60 GW of capacity in Germany by 2020, when total electricity demand will stand at approximately 70 GW.

Even if all nuclear and fossil-fired power plants (currently representing approximately 55-60 GW of capacity) were operated at minimum load, this would still leave significant overcapacity in the grid at certain periods, leading to negative residual load and negative prices, and possibly to grid instability if the situation is not resolved otherwise. Figure 4 shows a projection of the difference between renewable in-feed and total load for Germany in 2020.

Table 1. Comparison of operating characteristics of nuclear and fossil-fired power plants

Operating requirement	Nuclear power plant[a]	New coal-fired plant[b]	Combined cycle plant Siemens F-class	Siemens H-class
Average rate of load change in load-follow mode	10%/min at 80 to 100% load, 5%/min at 50-100% load, 2%/min at 20-100% load	3-6%/min at 40-100% load	4-8%/min at 40-100% load[c]	4-9%/min at 40-100% load[c]
Grid frequency control (primary/ secondary)	60%/min at 60-100% load	>60%/min at 40-100% load	180%/min at 50-100% load	180%/min at 50-100% load
Minimum load (% of rated power)	20-30%	20-25% in recirculation mode, 35-40% in once-through mode	30-50% for single-unit plant[c,d] 15-25% for multiple-unit plant (2GTs+ST)[c,d]	
Load rejection to auxiliary power/ island operation (ie capability for sudden large load reduction without trip)	Yes, to turbine bypass mode	Yes, to turbine bypass mode	Yes, to gas turbine operation	Yes, to gas turbine operation
Plant efficiency (100% load)	36-38% (EPR)	45-47%	58-59%	>60-61%
Plant efficiency (50% load)	33-35% (EPR)	42-44%	52-55% for single-unit plant <60% for multiple-unit plant	54-57% for single-unit plant >60% for multiple-unit plant
Specific CO_2 emissions (g/kWh)	None	740	345	330
SO_2 emissions (mg/Nm^3)	None	100-200	approx. 0	approx. 0
NO_x emissions (mg/Nm^3)	None	75-100	30-50	30-50

Notes and sources:

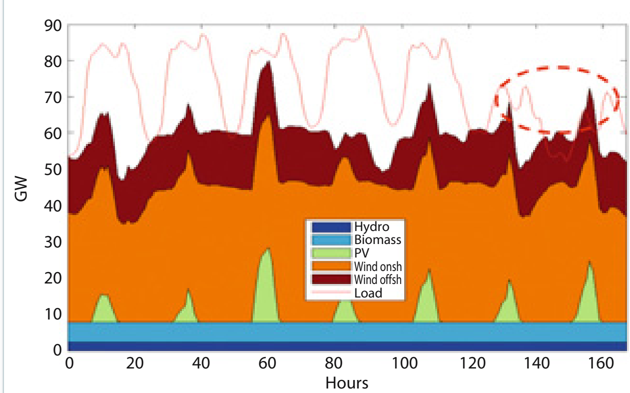
a. AREVA corporate communication 2010.

b. Experience feedback from start-up of coal fired power plants (Paiton, Kogan Creek).

c. With preheating of GT intake air.

d. Technically feasible depending on emission limits.

Figure 3. How renewable power production and electricity demand in Germany might look in 2020. Upper plot, typical winter week (January); lower plot, typical summer week (June)



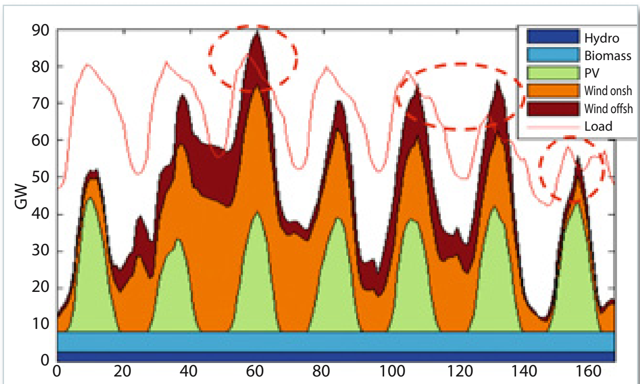
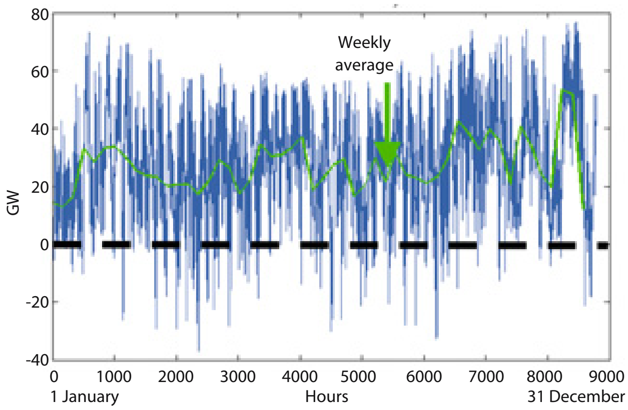


Figure 4. Difference between German load and renewable power in-feed ("residual load"), 2020 projection



The only solution, in the absence of adequate storage systems, is increased use of conventional (defined as nuclear, coal and gas) plants in so-called "two-shift operation", ie, start-up and shut-down on a daily basis (and sometimes several times per day). A comparison of the relative capabilities of nuclear, coal and combined cycle plants in this regard is shown in Table 2.

The following observations can be made:

- Under the grid conditions forecast for 2020 in a country such as Germany, conventional power plants will have to be started up and shut down several times weekly, or even daily, in order to compensate for fluctuations in load. Under these operating conditions, it is essential that hot start-ups are able to take place very rapidly and reliably, which is possible with combined cycle plants, due to the relative simplicity of their fuel and combustion systems, and the possibility of using a once-through boiler (Benson design). Hot start-ups in 30 minutes are already being achieved today in actual plants. The aim is to reduce this time by means of further innovations and optimisation.
- Warm start-ups are generally required if a plant is required to be off-line for up to around two days, and then has to start up rapidly again to cover demand in the event of a short-term loss of wind or solar power combined with a high demand for electricity, and it is uneconomic to maintain the plant in the hot condition.
- If plants are off-line for a period significantly longer than a weekend, either due to low demand or equipment-induced failure, or due to maintenance or refuelling outage, cold start-ups are generally required, since it would be uneconomic to maintain the plant in the hot condition.

After a cold shutdown, start-up times for nuclear plants may amount to several days, due to the necessary start-up testing regime. Among fossil-fired power plants, combined cycle units again have significant advantages as they can be back on-line at full capacity within just a few hours.

- Start-up reliability is becoming an increasingly important issue and, once again, combined cycle plants exhibit significant advantages over other conventional technologies in this respect, due to the fact that they have the lowest degree of complexity. Thanks to specially designed modules, fully-automated plant design, special redundant configurations and fully integrated I&C, start-up reliabilities of close to 100% are possible, even when the start-ups are frequent.

The thrust of this is that state-of-the-art combined cycle plants offer the following capabilities:

- Significantly shorter start-up times in the cold, warm and hot conditions than nuclear power plants and coal-fired power plants.
- Highly reliable start-ups and hence reliable provision of adequate capacity to meet short-term requirements.
- The lowest start-up/shut-down costs (in terms of fuel consumption) compared with other conventional power plants.
- The lowest CO_2 emissions during start-up and at full power compared with other fossil-fired power plants.
- The highest start-up reliability, making start-up of combined cycle units more economic and environmentally-friendly than minimum-load operation of other power plants.
- Lower risk of damage due to extreme load cycling and fatigue, thanks to reduced use of thick-walled components.

These features of modern combined cycle plants have already been proven at a number of facilities in Europe – to be described in a second article, in next month's issue of *MPS* – and demand for them in new projects is increasing.

Politics *vs* technical realities

Summarising, European power grids will require significantly increased flexibility over the next few years as a result of the rapid expansion of renewables. Country-specific analyses of these requirements are needed, and special investments may be called for to maintain the stability of grids.

Compared with previously built nuclear stations and other conventional power plant types, such as coal-fired units, combined cycle power plants offer advantages in terms of start-up times and start-up reliability in cases where considerable capacity has to be rapidly brought on- or off-line.

Replacement of older, inflexible fossil-fired power plants, for example coal-fired plants, with highly flexible state-of-the-art combined cycle units can provide an effective solution to the problem of grid stability, while at the same time delivering a significant reduction in CO_2 emissions as well as SO_2/NO_x. For example, replacing older coal-fired power plants having a specific CO_2 emissions level of 850-900 g/kWh with combined cycle units having specific CO_2 emissions of 330-340 g/kWh avoids over 3 million metric tons of CO_2 emissions per year (assuming 6000 h of operation annually) per 1000 MW of capacity. If such a plant is also used to supply heat or process steam, fuel efficiencies of over 80-85% can be achieved, thereby delivering a further 20-25% reduction in CO_2 in relation to the utilised heat of the fuel.

The deployment of state-of-the-art combined cycle plants to provide additional capacity and/or to replace existing power plants can help ensure the reliable and economic integration of renewables in Germany, and elsewhere in Europe.

In addition, gas supplies are assured at stable prices in the long term, thanks to planned pipelines from new sources (Nord Stream, Nabucco, etc), as well as supplies from existing and planned liquefied natural gas terminals (eg, Rotterdam) and unconventional natural gas reserves (shale gas).

The current energy mix of Germany, and for that matter Europe, features the full spectrum of power generating technologies (nuclear, coal, combined cycle, hydro, wind and solar power), each of which has to be used optimally according to its capabilities, taking into account security of supply, cost effectiveness and environmental performance. This also means, however, that any energy concept must be based on the realities of what the technologies are capable of, and not on the political stratagems of the day. MPS

Table 2. Start-up characteristics of nuclear and fossil-fired power plants

	Nuclear power plant[a]	New coal-fired plant[b]	Combined cycle plant (Siemens F-class / Siemens H-class)
Hot start-up (time taken to start-up following shut-down lasting <8 h)	60-120 min[c]	80-150 min	30-60 min (potential for <30 min depending on customer)
Warm start-up (time taken to start-up following shut-down lasting <48 h)	2-3 h[c]	3-5 h	1-1.5 h (potential for <50 min depending on customer requirements/ configuration)
Cold start-up (time taken to start-up following shut-down lasting <120 h)	15-20 h	5-10 h	2-3 h depending on customer requirements/configuration
Start-up reliability (%)	Not relevant[d]	87-93% depending on supplier/configuration	95-99% depending on supplier/configuration

Notes and sources:

a. AREVA corporate communication 2010.

b. Experience feedback from start-up of coal fired power plants (Paiton, Kogan Creek).

c. In the event of planned shutdown and subsequent restart from the hot subcritical condition, otherwise restrictions due to need to adjust reactivity control to account for xenon concentration

d. Not relevant since usually only a few start-ups per year.

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