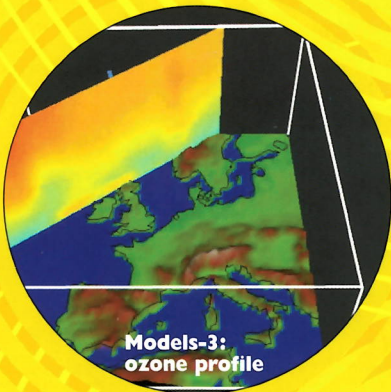




## *Water Use at Thermal Power Plant*



by  
**M-J Booth (Uniper)**  
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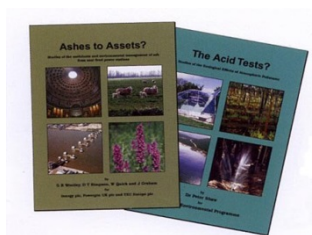
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**Flying Chemistry** Studies of the long range atmospheric transport of pollutants

**Generating Emissions?** Studies of the local impact of gaseous power station emissions

**Using Water Well?** Studies of Power Stations and the aquatic environment

**Borne on the Wind?** Understanding the dispersion of power station emissions



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**JEP18WTB03:  
WATER USE AT THERMAL POWER PLANT**

**By  
M-J Booth (Uniper) &  
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# Executive Summary

There is increasing societal interest in water use by the thermal power sector. Reliable data can inform assessment of potential future sector requirements and how these compare with other societal water demands competing for scarce available future water resource.

This report forms part of the Joint Environmental Programme package of information on use of water in power plant. It provides a compilation of recent actual UK power plant water use data. It discusses the many factors applying at sector and individual installation level which lead to the range of water use occurring. In particular it takes into account how the changes in regulating electricity markets may influence the way thermal plant are used in future with implications for the water-energy nexus.

The main conclusions of this report are as follows:

1. Thermal power plant<sup>1</sup> use water for several different purposes. The amount of water used can differ significantly between plant of different types and playing different roles within the market. It can vary significantly over time for a given plant.
2. The data provided in this report provide the best available indication of the range of water use in existing UK plant in current market conditions.
3. Future plant will be required to become “flexible operators” as they will have a key role in balancing the grid in order to ensure a secure electricity supply. In some circumstances this will adversely affect water consumption based on a m<sup>3</sup>/MWh approach. This should not be seen as a deterioration in water use efficiency but should rather be seen as a consequence of the shift in the role of the plant from energy production towards availability provision.
4. It is important to recognise the potential to provide electricity (capacity) as a product in its own right, separate to the actual provision of electricity. Electricity Market Reform has resulted in the introduction of reward for availability through the capacity auction mechanism, along with penalties should plant be called upon to operate but be unable to do so.
5. The choice of steam-cycle cooling technique is likely to dominate the water use characteristics of a given thermal power plant. In the EU this choice is made in the context of BAT which requires consideration not only of the pros and cons of alternative techniques for the aquatic environment but also for the atmosphere, the terrestrial environment and their potentially affected receptors as well as costs of the alternatives. This choice is made during plant siting and design phases. It is not usually technically or commercially feasible to change this choice for an existing plant.
6. Use of water by thermal power plant for steam-cycle cooling leads to improved thermal efficiency compared with dry-cooling. This improved efficiency delivers many key benefits, including more electricity produced for a given fuel consumption. This has life-cycle

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<sup>1</sup> As discussed in the text the focus of the conclusions is thermal power plant designed to produce electricity. Separate considerations apply for thermal power plant delivering significant amounts of steam or heat as primary products. For a given plant the output characteristics are established at the design stage and it is not usually practicable to subsequently modify them.

advantages, as well as reduced costs, which in turn contribute to the affordability of electricity supply. Another benefit is reduced specific emissions to air (i.e. mass emitted/MWh produced) and reduced specific production of waste and by-products. It also provides increased resilience to high air temperature events.

7. The selection of appropriate metrics for water use requires care as does the interpretation of reported water use for operating plant in the form of such metrics.
8. For European water-dependent thermal power plant a key principal is to use water responsibly and optimally in line with BAT. This is not necessarily synonymous with water use minimisation (as evidenced through water use metrics). In some cases improving water use efficiency may not be consistent with BAT principles and/or other policy objectives, for example if there are other environmental benefits gained from water use arrangements.
9. Different levels of water use in different plant can still be consistent with responsible and optimal water use, taking into account such factors as indicative sector BAT, site-specific BAT and the site-specific meteorology, water temperature and receptor distribution and sensitivity in the bodies of water used by the different plant. Thus, the selection and application of specific values of water use metrics as 'benchmarks' or 'targets' for thermal power plant may be inappropriate. Reported water use for a given plant lying outside an anticipated range does not automatically imply an inefficient or inappropriate use of water. Rather, it might trigger the need for a more detailed understanding of the circumstances and reporting basis for that plant in order to determine whether or not that water use was appropriate.
10. Water efficiency, intensity or use metrics based on considerations of water used per unit electricity produced may not fully capture the societal benefit provided by the use and availability of water-cooled thermal power plant. Such metrics do not capture security of electricity supply considerations linked to reliable provision of capacity available to generate.
11. Actual use of water needs to be distinguished carefully from use of water resource rights. Plant and society may derive significant value in contribution to system resilience from the availability of a thermal power plant to generate even when it is not called upon to do so. Availability to generate requires not only the technical capability of the plant to operate but also the legal right to access the water it requires to operate.
12. New build thermal power plant are required to deliver the "Pathways to 2050" low carbon energy scenarios set out by UK Government and these plant will continue to require access to water. For investment to occur sufficient investor confidence in future reliable access to sufficient quantities of water through the envisaged commercial life of the plant will be required. Similar considerations apply to significant investment in retro-fits and upgrades to existing water-dependent thermal power plant.
13. There is considerable uncertainty in the potential future freshwater needs of the sector at national and regional level. This is intrinsically linked both to the composition of the thermal generating fleet of the future, which will evolve as a result of a wide range of individual operator choices, and the role it is called upon to deliver in ensuring the resilience of electricity supply in the pathway to a net zero carbon 2050.

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## 1 INTRODUCTION

This report should be read as part of the Joint Environmental Programme (JEP) package of information on use of water in power plant consisting of:

- Gallagher, McCann, Booth & Edwards (2014) reviews use of water in and environmental performance of power plant cooling systems.
- Gasparino (2012) – considers the uncertainty in future water use at national and River Basin District (RBD) level arising through operator choices of future plant type and siting whilst precisely meeting example DECC 2050 pathways.
- Turnpenny & Coughlan (2003) – an overview of the issues of thermal power plant and water including reference to extensive earlier work not easily obtained from the open literature.

The current report extends Gallagher *et al* (2014) by incorporating a more extensive compilation of actual UK power plant water use data using the approach adopted by Ecofys (2014) in their cooling system review for the European Commission. It also updates and extends the discussion of factors influencing water use at existing plant to take account of changes in electricity markets and their regulation which may influence the way thermal plant are used in future. The current report similarly extends, and for the UK, largely supersedes Edwards (2012) and Booth and Edwards (2015).

## 2 TERMINOLOGY

Care needs to be taken in terminology regarding use of water. In particular, various authors take the term 'consumptive use' to mean different things depending on their particular focus. In this report the following terminology will be used for text prepared by the authors. Where reference is made to other authors or inclusion of material from their papers, their original wording is retained and possible differences highlighted where apparent. The International Standards Organisation have recently developed related terms in their work on water footprinting (ISO 14046-2014) but the ISO set of defined terms presents difficulty in considering water use by installations in the context of best available technology (BAT). This is discussed in detail below.

It should be noted that some water will be imported into a thermal power plant as part of the raw materials associated with operation (e.g. water content of fuels, water content of bulk process chemicals). For resource use reporting purposes this is conventionally associated with non-water raw materials and will not be considered further here.

| Term  | Commentary  |
|---|---|
| Abstraction   | Identical to withdrawal   |
| Consumptive use (by a process or entire installation) | <p>Process occurring within an installation (or the process effected by the entire installation) for which water input exceeds water output (regardless of location and timing of output relative to input).</p> <p>For thermal power plant, processes contributing to consumptive use include wet or hybrid (wet/dry) tower cooling resulting in evaporation, evaporation from wet flue gas de-sulphurisation and water bound up in ash conditioning.</p> <p>Quantified as the sum of water sources input – sum of water output, input and</p> |

|   |  |
|---|--|
|   | <p>output being defined below</p> <p>Where quantification is via metering the difference between input and output may include a contribution from leaks and other losses some of which might be to surface waters via unmetered routes. This might lead to a small overestimate of consumptive use. However, where a discharge is unmetered, it may be appropriate to estimate it for consumptive use evaluation purposes.</p> <p>Where water is discharged at a different location from that from which it is abstracted the effect may be a 'depleted reach' within a given water body or a transfer between water bodies.</p>   |
| Discharge   | <p>Intentional release of water from an installation to a body of water, sewer or a third party recipient. Discharge to a body of water may also be described as 'point source emission'. Where the discharge of water is to the same body of water from which it was withdrawn some authors describe it as a 'return flow'.</p> <p>Inevitably, operation of a real installation will lead to some unintentional discharges (e.g. leaks, losses, spills etc) some of which may be in the form of liquid water as opposed to steam) and some of which may enter surface waters or other output streams before or after metering. Collectively, these are sometimes termed 'fugitive discharges'. Their appropriate management may be important for plant operational purposes (for example for health and safety or environmental reasons) but not from an installation water balance perspective</p> |
| Diversion   | Identical to withdrawal  |
| Gross use   | The sum of all water inputs to a process or installation. (This can be from a combination of surface water, groundwater, public water supply and the discharge from some other water user).  |
| Input (of water to a process or installation)             | An intentional exploitation within an installation or process of water from a source external to the installation or process. Not all water withdrawn by an installation is necessarily input to the installation – some may be transferred to a third party without exploitation by the installation  |
| In stream use   | Utilization of water for societal benefit which does not involve withdrawal of water from the aquatic environment (e.g. small scale run of river hydro)  |
| Net use   | Same as consumptive use.   |
| Non-consumptive use (by a process or entire installation) | <p>Utilization of water by a process (or installation) in which water input equals that output.</p> <p>Unintentional but inevitable leaks and losses occur in any water using process. Where these are vanishingly small in comparison with the intended water use characteristic these are normally ignored for water balance purposes. Thus a small leak would not render a process consumptive.</p> <p>Where water is discharged at a different location from that from which it is abstracted the effect may be a 'depleted reach' within a given water body or a transfer between water bodies.</p>   |
| Output (of water by a process or installation)            | An intentional release of water from an installation (in which case it has the same meaning as discharge) or from a process. In the case of the entire installation 'water output' means discharged to surface waters or transferred as water off site (e.g. to another water 'user'). In this definition a discharge to a sewer for off-site  |

|   |   |
|---|---|
|   | treatment (either dedicated or through the municipal system) is regarded as 'output'.   |
| Re-cycling (of water)   | The taking of water output from a process and routing it to the input of that same process (possibly after treatment)   |
| Return flow   | Discharge taking place into the same body of water from which it was withdrawn.   |
| Re-use (of water within an installation)                            | The taking of water output from a process and routing it to the input of a different process (possibly after treatment).  |
| Thermal efficiency for an electricity producing plant               | Useful electricity delivered (i.e. supplied to the grid, $MWh_e$ ) divided by heat energy in the fuel used to generate that electricity ( $MWh_{th}$ ).<br><br>[For combined heat and power plant the definition of thermal efficiency needs to include energy in heat form exported.]<br><br>[Operational power plant import electricity from external supply as well as export electricity (e.g. for start-up and to maintain installation operation when not generating electricity). From a societal perspective the most relevant measure of electricity delivered is the total electricity exported to the grid – electricity imported. This is termed within the power sector 'gross net net' (i.e. gross electricity produced – electricity produced within the installation – electricity imported from outside the installation). However, given the inherent limitations in quantifying the water balance for real thermal power plant there is likely to be limited significance for 'water efficiency' metrics in the difference between different definitions of 'electricity delivered'. |
| Water body  | Used here as a generic term rather than a specifically defined extent of surface water within a river basin management plan for Water Framework Directive purposes.   |
| Water borrowing   | A water withdrawal in which water is returned to the same body of water without significant change in quality. Considerations of delay and quality mean that 'borrowing' needs to be carefully defined and whether or not a particular combination of withdrawal and discharge constitute borrowing may vary from study to study.<br><br>If the borrowed water is 'paid back' straight away see 'ephemeral abstraction'.  |
| Water efficiency of electricity production in a thermal power plant | The water 'used' by an installation divided by electricity delivered (i.e. supplied to the grid, $MWh_e$ ).<br><br>The meaning of 'used' needs to be clarified in any particular quantitative context as referring to either 'gross use' or 'net use'   |
| Water intensity of electricity production in a thermal power plant  | Same as 'water efficiency'  |
| Water use   | Utilization of water for societal benefit including both in stream purposes and purposes for which withdrawal is necessary.   |
| Withdrawal  | Intentional removal of water from its source (e.g. a body of water), either permanent or temporary. Sometimes described as for an 'extractive use' to contrast with 'in-stream'.  |

This report is written with an installation and process focus which aligns well with the Industrial Emissions Directive (IED) BAT concept and supporting documentation (BREF) and also the approach of the water rights licensing system in use in England and Wales. Thus, if an installation or process discharges the same quantity of liquid water to surface waters as it abstracts we describe it as 'non-consumptive use' regardless of precisely where and when the water is discharged or abstracted. This allows us to draw the clear distinction using the word 'consumption' between processes or installations effecting the loss of water from the environment and those that do not. This approach facilitates interpretation of plant water use data in terms of the fundamental sub-processes of the installation alone (e.g. cooling system, steam generation make up system, ashing systems, atmospheric emission control systems etc) without regard for the site-optimised choice of intake and outfall locations. Where water is discharged to a different water body to that from which it has been abstracted we regard this as a transfer rather than consumptive use associated with the installation.

In contrast some authors or jurisdictions (e.g. BS ISO 2014) describe an installation abstracting water from water body A and discharging the same quantity to a different water body B as constituting a consumptive use of water of water body A and representing a source of supply to water body B. Whether water body A and B are regarded as different may depend on the spatial resolution of the particular study.

### **3 METRICS FOR WATER USE – PRODUCTION FUNCTIONS, SOCIETAL BENEFIT AND FUTURE WATER RIGHTS ALLOCATION**

Most authors take as the headline metric of water use a product-based ratio of the form

'volume of water used': 'product output'

relating the water use over a period to the useful product output over the same period. Typically, the period of consideration would be a year though it may be necessary to take account of circumstances in shorter periods for particular purposes and consider the year on year variation in the proposed measure to account for variations in the factors that influence both water use and installation output.

For a thermal power plant designed to produce electricity an obvious measure of sector product is quantity of electricity produced (i.e. as supplied to the grid, net of within plant electricity used, MWh)<sup>2</sup> leading to a metric of the form

$$V / P$$

where

V is a volume of water over a period (typically a year) and may relate to either gross use or consumptive use, m<sup>3</sup>.

P is the electricity supplied to the grid<sup>3</sup> by the thermal power plant in the corresponding period (MWh<sup>1</sup>).

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<sup>2</sup> Separate considerations apply to installations in which there is significant supply of steam as a product.

<sup>3</sup> Clearly, electrical energy delivered for beneficial use is a societally-relevant benefit measure. In some cases the data reported by operators may be gross energy produced by the installation, though in most cases the distinction will not significantly affect the analysis. Some authors also seek to account for losses in distribution between the generating plant and the end users.

When using such metrics it is important to make clear whether the water use is 'consumptive' or 'gross' and whether it relates to 'within installation' or 'as a result of installation operation'.<sup>4</sup>

Care needs to be taken in interpreting the significance of reported metrics of thermal power plant water use given the range of different factors influencing water use discussed in Section 4. In particular the positioning of the water use reported by a particular plant within the range of metrics reported for peer group plant does not necessarily provide an indication of the appropriateness of improvement in water use efficiency for that plant. Thus care needs to be taken when considering the potential for 'targets' or 'benchmarks'. Reported water use for a given plant lying outside an anticipated range might rather trigger the need for a more detailed understanding of the circumstances and reporting basis for that plant in order to determine whether or not that water use was appropriate.

One limitation of this 'electricity produced' approach to deriving a water-use metric is that 'electricity produced' (MWh) is not in itself an adequate or necessarily complete measure of societal benefit arising through the existence and operation of the thermal power plant. For example, the electricity produced (MWh) is not regarded as equally valuable at all times. When market conditions are such that there is a surplus of available generation capacity the 'spot market' price of a MWh produced may be low. At times when demand is high relative to available generation capacity the MWh price may be much higher.

In order to provide system security plant may be rewarded for operational availability or grid stabilisation even when not called upon to generate electrical energy. To facilitate quick response to demand continuous operation of water circulation pumps are required. In such a mode of operation, the plant will use water and provide useful societal benefit but its annual m<sup>3</sup>/MWh metric will worsen because it is using m<sup>3</sup> of water but not increasing MWh produced. These considerations may become increasingly important in years to come as the proportion of electricity provided and the proportion of capacity associated with intermittent renewable generation increases. It may therefore become useful to recognise more explicitly the capacity of a plant and its potential to provide electricity should meeting demand require it as a product in its own right separate to the provision of electricity. The provision of capacity product may usefully be linked to the holding of water rights while provision of spinning reserve and grid stabilisation services may be linked to both water rights and physical water use. The electricity market operation is complex with a great variety of contractual instruments in use which distribute risk, cost and reward through time to the actors.

Thus MWh produced is not a proxy for all societal benefit and the price associated with MWh electricity produced may not capture all relevant societal benefits.

When making use of particular approaches for metrics or benefits assessments the potential limitations of the particular choices when applied to current and future societal benefit optimisation should be considered.

The way in which future water rights are allocated between potential users and the environment has been under active consideration in England and Wales within DEFRA's Abstraction Reform initiative. This was superseded in England by the DEFRA Abstraction Plan (2017) with further consideration being expected as a consequence of the multi-sector regional planning initiatives overseen by the National Water Resource Framework in the period 2019-2022. Similar

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<sup>4</sup> The latter would include incremental evaporative losses in water bodies resulting from the thermal discharge of a power plant. If the focus of the study is a particular water body, the withdrawal of water from that water body by a thermal power plant and its discharge to a different water body could be regarded by some as a consumptive use of the first water body. However, we prefer to regard the operation as effecting a transfer of water in association with non-consumptive water use from an installation perspective.

initiatives are taking place in Wales. Abstraction rights are, as of 2019, provided through abstraction licences issued under Water Resource Act (1991, as amended). However, the sections of this Act relevant to abstraction licencing are to transition to the Environmental Permitting Regulations with implementation in England in 2021 Q2. Timescales in Wales are expected to be similar but have not been confirmed at time of writing. Details are expected to be evolved in the period to commencement of the new arrangements. These initiatives recognise that the existing resource allocation system in combination with changes in population, land use, the water industry and in environmental protection requirements has led to a current allocation which may not be economically efficient and does not necessarily always achieve appropriate environmental protection. Ongoing societal change coupled with climate change may lead to increasing water scarcity in some areas, a trend which the current allocation system is incapable of flagging to users.

Electricity generation and energy supply (including thermal energy) has long-been regarded as a multi-sector activity with Cogen/CHP (Cogeneration/Combined Heat and Power) and EfW (Energy from Waste) plant potentially combined with district heating having been developed where local opportunity is identified. For such plant, which tend to be considerably smaller than dedicated power stations, appropriate water use must be considered in the context of the combination of all its products and services including electricity, steam or lower grade energy. Energy from Waste plant must also be considered in the context of its role within integrated waste management. Such plant are not considered in this report. It is possible in the near future, given the changing role of non-nuclear thermal power plant, that water abstracted at power station locations may be used for purposes other than for electricity production. For example, Ofwat (2019) considers the possibility of water abstracted under power station licences being supplied directly or indirectly (after appropriate treatment) for Public Water Supply, in line with the multi-sector thinking being promoted by DEFRA. If this were to evolve to any extent even more care would be needed in future assessments to consider appropriate metrics and indicators for 'water use at thermal power stations' as the traditional boundary between 'power' and other sectors begins to expand.

When considering future water resource allocation for thermal power plant, the difference between historic water use and the water right that it is appropriate to allocate should be appreciated. As discussed above, a thermal power plant provides societal value both by providing electricity (which involves use of water) and providing the capacity to generate electricity (which requires reliable access to and use of water at times when that generation is called upon but not at other times). As an extreme example a future plant may provide vital societal benefit through providing capacity to generate through a period but in fact may not be called upon at all to generate electricity in that period (because of benign external factors). In such a period actual use of water may be minimal but the water use metric ( $\text{m}^3/\text{MWh}$ ) would be high. The plant may even be a net importer of energy from the grid. Nonetheless a continuing allocation of water resource would be necessary to allow the plant to continue to deliver societal benefit.

It would be rare for a thermal power plant to operate for a year at 100% load factor (i.e. all units operating at full capacity for every second of a year), indeed some time may be needed for maintenance on individual units. Although schedules and plans are developed in advance and contracts for operation may be placed covering timeframes from minutes to years ahead of 'real time', the actual variation in electricity demand, transmission constraints, thermal plant available on the grid, renewables intermittency, fuel prices and other factors and constraints, including environmental, inevitably mean that the operation sought from a given thermal power plant may differ both from plan and from recent historic operation. Because of the system uncertainty, thermal power plant operators would be expected to seek water resources allocations for their plant which would not place unwarranted operational constraint on their future operation and

ability to provide capacity. The flexibility that this provides offers societal benefit in terms of security of supply and potentially affordability of the electricity supplied. Acknowledging the need for capacity as intermittent generation from renewables increased in 2017/18 the capacity market mechanism came into force to provide reward for plant made available years ahead. The capacity market also introduces commercially significant penalties if that contracted capacity is not available when required. This therefore increases the importance for operators of existing plant and would be investors in new plant to seek confidence in their water rights holding to cover their capacity market position.

New thermal power plants have a role to play in delivering the Pathway to 2050 and will require allocation of water resource use. Sufficient investor confidence in future water rights (i.e. sufficiently reliable access to sufficient quantities of water and water rights, recognising the potential for trading of water as well as water rights in future regimes, through the proposed plant commercial life) will be required before the investor regards the risk-reward balance for the considerable investment to be acceptable. Similar considerations apply to major investment of existing water-dependent thermal power plant.

In considering societal benefit associated with security of supply, the relatively high and predictable availability of thermal power plant should be considered. Thermal plant dependent on water for cooling make a particular contribution since the diversity in plant type they provide offers resilience in conditions of high air temperature in which the performance and output of dry-cooled thermal plant, particularly CCGT, declines dramatically<sup>5</sup>.

Climate change adaptation involves the better positioning of society with respect to the envisaged climate. For thermal power plant, one climate change adaptation measure, that some might consider (e.g. Ecologic 2007 sec 8.5) is to evolve to a thermal power sector in which inland plant are dry-cooled, with water-cooled plant re-locating<sup>6</sup> to the coast where water is 'unlimited' (i.e. some aspects of the societal benefit currently delivered by water-dependent inland thermal power plant could be delivered differently). This scenario conflicts with other policy drivers and may therefore be undesirable since:

- The thermal efficiency penalty associated with the widespread adoption of dry-cooling leads to
  - Increased emissions to air including carbon dioxide, waste and by-products produced/MWh delivered in many cases in conflict with other policy drivers (e.g. greenhouse gas produced/MWh)
  - Increased costs of production which could lead to affordability considerations or lack of competitiveness of dry-cooled plant.
- There is a reduction in system resilience to episodes of high air temperature not coincident with low water availability.
- There is a potential societal penalty in
  - not extracting benefit from water-dependent thermal power plant and related infrastructure already constructed and operating inland
  - and requiring new infrastructure to support new plant.
  - possible need for grid changes depending on supply – demand locations.

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<sup>5</sup> Dry cooled plant offer resilience in times of reduced water availability provided air temperature is within plant design limits.

<sup>6</sup> Here 're-location to the coast' is used as a shorthand for a scenario in which the operation of an inland power plant reduces with ultimate plant closure. The output that was provided by the original power plant is taken up over time by power plant located at the coast which may involve the construction of a new plant. It is not commercially feasible to 'move' an existing power plant.

- Opportunities for siting thermal power plant at the coast and the operation of such plant may be limited for reasons other than water resources e.g. Marine Spatial Planning, Marine Strategy Directive/Water Framework Directive considerations. Marine receptor related (Natura 2000 or Member State protection), terrestrial and integrated coastal zone management planning policies at national/regional and local scales also need to be considered.

Continued inclusion of riverine, estuarine and coastal thermal power plant in the generating fleet of the future offers diversity contributing to the future resilience of electricity security of supply against a range of geographic, environmental and regulatory pressures.

## **4 FACTORS INFLUENCING REPORTED WATER USE AT THERMAL POWER PLANT**

In this section the factors influencing water use in operational thermal power plant are discussed. Aspects of quantification of plant water use through metrics relating water use with electricity produced over a given period are discussed in Section 6.

### **4.1 Overview**

Water is used for a wide range of purposes in existing thermal power plant. The range of water use varies markedly between different plant types and may vary for a given plant over time in line with changes in its mode of operation, changes in plant technique and installation thermal efficiency, and in response to short-term and long-term variation in the environmental conditions in which it operates. Developments in regulation can drive changes in plant characteristics and outputs. Differences in regulatory regimes can affect which water uses are controlled and reported within a particular regulatory regime.

Environmental conditions can directly influence the use of water by a plant in normal operation. For example, the changing relationships between water temperature, air temperature, humidity and wind speed through the year and within day affect the balance of evaporative and other heat transfer in water-using cooling processes. Environmental conditions can also have effects on plant output directly, for example should there be insufficient water level or flow to physically allow abstraction of water and through their effect on thermal efficiency of the fuel conversion process. Indirect environmental effects may occur through the action of regulatory constraints on plant operation (e.g. EPR permit discharge conditions, abstraction licence conditions etc). Moreover, in some circumstances a plant operator may choose to modify operation in view of aquatic environmental conditions, for example to reduce or prevent intake of high concentrations of organics which could occur in low flow eutrophic conditions, or to avoid intake of high concentrations of suspended solids in high flow conditions. This choice will be made having regard to the market reward for operation compared with the plant consequences of operation in non-preferred conditions including loss of future availability and opportunity to generate, and costs of future increased maintenance or other operator intervention.

Although the techniques available for use in thermal power plant are similar throughout the world, differences in site conditions (such as relating to the water environment, meteorology etc), the market rewards for electricity production and capacity availability and differences in the regulatory balance between environmental, social, cultural and economic considerations can result in very different practical or preferred outcomes. Operator and owner risk-reward preferences and their wider portfolio circumstances may also affect plant design and plant operation choices. Thus data on historic water use by thermal power plant in the UK and

elsewhere in the world should be used with caution when considering potential transferability to current and future water usage for UK plant.

A discussion of the range of thermal plant types and associated water uses can be found in the Large Combustion Plant BREF [EIPPCB (2017)]. Information on cooling techniques, both water-using and dry, can be found in the Industrial Cooling Horizontal BREF, [EIPPCB (2001)] which includes Annex XII on the power sector. Further supporting information, relating to the pros and cons of various cooling techniques for the power sector can be found in Turnpenny & Coughlan (2003), Environment Agency (2010) and Gallagher *et al* (2014).

MacLauchlan (2012) provides a study quantifying the thermal efficiency benefit which use of water for cooling provides compared with air cooling for plant in UK conditions. This thermal efficiency benefit underlies the attractiveness of water cooling to the operator since compared with dry cooling it offers both improved electricity produced per unit fuel used and improved emissions to air and land per unit electricity produced, provided the consequences for the aquatic environment are acceptable. Maulbetsch & DiFilippo (2006) provides a similar study with a specific focus on a comparison of water use by wet tower cooled and dry-cooled CCGT for a variety of Californian conditions.

## 4.2 Regulatory and Market Context

One of the major considerations in water use at a thermal power plant for operator and regulator alike is the choice and optimisation of its steam-cycle cooling. Turnpenny *et al* (2012) provide an overview of the environmental regulatory context for such systems in Europe which remains valid for the UK as of 2015.

Thermal power plant in the UK are operating in line with site-specific BAT which represents a site-specific interpretation of the sector indicative BAT elements (as set out in BAT Reference documents published by EIPPCB) in the light of conditions pertaining to the site in question (e.g. water availability, water quality, meteorological conditions, land availability, vulnerability of local receptors etc). The Industrial Emissions Directive and its predecessor legislation require an integrated multi-media approach to determining installation characteristics consistent with BAT. The Industrial Cooling Horizontal BREF, [EIPPCB (2001)] remains the current reference at EU-level. Although published some years ago the fundamental principles within it remain valid, though some data may not be representative of that for new plant. Review of it has been expected for some time but there appears no programme for this at time of writing. Environment Agency (EA, 2010) provides a more recent UK focused regulatory interpretation of many of the issues.

In the coming decades changes to sector indicative BAT may drive change to installations to incorporate the introduction of new techniques (such as carbon capture, usage and storage) and evolution of existing techniques (such as deNO<sub>x</sub> and deSO<sub>x</sub>). Depending on how such techniques use water and affect overall plant thermal efficiency, such developments may change water use efficiency metrics (m<sup>3</sup>/MWh), actual water use (e.g. m<sup>3</sup>y<sup>-1</sup>) and the relationship between water rights required to underpin capacity provision both directly and indirectly through the consequences for the way in which thermal plant are used.

Installations and their operation will also change as a response to market forces. In the UK the electricity generation fleet mix has changed dramatically in recent years with the increasing introduction of renewables, and the retirement of older coal and nuclear plant leading to changing roles for many existing thermal power plant. The nature of the opportunity and risk profiles for new plant has changed considerably. Existing plant tend to operate at lower load factor and in ways linked to the intermittency of renewables generation. This has led to higher

incidence of part load operation and more starts and stops, both of which have implications for the water efficiency of operation (see Section 4.3.2).

Historically, in the UK, the reward for thermal plant has mostly been through electricity generation. In recognition of the future changing role for many thermal plant, Electricity Market Reform<sup>7</sup> has resulted in the introduction of reward for availability from 2018 onwards through the capacity auction mechanism, along with penalties should plant be called upon to operate but be unable to do so. At the time of writing the operation of the capacity market has been suspended pending a more detailed review of its arrangements by the European Commission.

The changing perception of the electricity market reward and risk profile in combination with aquatic environmental risk will influence operators choices of water-using plant techniques.

### 4.3 Relevant Factors

To understand water use by a specific thermal power plant it is essential to take account of the plant, its site and environmental circumstances and the market characteristics which together influence water use. Various classifications are possible. They are reviewed below under the following headings:

- Fuel type
- Operational mode
- Thermal efficiency
- Steam-Cycle Cooling technique
- Other water using techniques/processes
- Emerging techniques
- Practical aspects of operation influencing choice & optimisation of techniques and processes
- Choice of Locations for Abstraction and Discharge – Site Configuration Optimisation and Implications for the Aquatic Environment
- Practical aspects of water balances at real power plant.

The size of a plant is also a relevant factor in that generally 'economies of scale' apply allowing improvement in plant efficiency.

The above factors are not independent. There are vital links between thermal efficiency and cooling type. Recent plant tend to be most efficient, therefore most competitive and therefore would be expected to run at higher load than a similar older plant of the same fuel type operating in the same market. A power plant using once through cooling will have higher thermal efficiency than an otherwise identical plant with wet tower or dry cooling and therefore would be expected to operate at higher load. Plant using biomass in co-combustion may be less thermally efficient than an identical plant not using co-combustion but may have a higher load factor because of environmental and commercial factors. Nuclear plant operate at high load factor.

Some authors make use of other factors such as age of plant essentially as a proxy for thermal efficiency or general competitiveness. This approach may be attractive since age of plant is readily inferred from publically available information but actual thermal efficiency may be viewed as commercially sensitive information and thus not readily established. However, age is not always a good proxy since major plant components may have been upgraded during the life of

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<sup>7</sup> < <http://www.energy-uk.org.uk/policy/electricity-market-reform.html>> accessed 2016\_01\_04

the plant giving the plant improved technical characteristics. Moreover, the units making up a given plant may have been upgraded at different times and in different ways.

In general thermal efficiency of a given plant would be expected to degrade slightly over time (leading to a gradual increase in water use in m<sup>3</sup>/MWh even if the operational duty of the plant and external conditions remained constant). Plant retrofits may address some aspects of the degrading thermal efficiency and affect the rate of change. As the plant ages it begins to compete with more modern, often more efficient plant, and intermittent renewable generation sources and its commercial operation may change. This in turn affects its thermal efficiency and also its water use efficiency by increasing the proportion of part load operation and numbers of starts and stops.

Step changes in plant configuration may occur over time (e.g. in response to changing environmental regulation) and some of these changes may impact on water use (e.g. adoption of deSO<sub>x</sub> and deNO<sub>x</sub> techniques, changes in ashing systems etc).

Thus 'age' per se is difficult to treat as an explanatory factor of water use.

#### 4.3.1 Primary Fuel Type

The common primary fuel types used in commercial-scale thermal power plant include the following:

- Coal<sup>8</sup>
- Biomass
- Oil
- Gas (Combined Cycle Gas Turbine - CCGT<sup>9</sup>)
- Nuclear.

Waste and waste derived fuel may be supplementary fuels for some plant and the primary fuels of relatively small EfW (Energy from Waste) plant.

Many existing coal plant either co-combust biomass or have converted some or all units to burn biomass as a response to market and environmental changes.

The fuel type is a major factor in determining the overall thermal efficiency of the plant and hence its water use – the fuel type determines the appropriate plant combustion/steam generation design and the appropriate steam conditions (temperature, pressure, flow rate).

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<sup>8</sup> For literature comparisons it may be necessary to distinguish between subcritical, supercritical and ultrasupercritical designs for coal-fired power stations, the classification being based on the pressure at which the boiler/steam generator is designed to operate. Higher pressures and temperatures offer improved thermal efficiency, and hence potentially improved water use efficiency. As of 2019 there are no commercial scale supercritical or ultrasupercritical coal-fired power plant operating in the UK, though commercial scale supercritical and ultrasupercritical coal-fired plant are in use elsewhere in the world. Thermal efficiency of lignite plant is considerably lower than an otherwise similar bituminous or anthracite coal-fired plant. There are no lignite plant in the UK.

<sup>9</sup> Open cycle gas turbines (OCGT), for which there is no steam cycle, would not be expected to have significant operational water use and are not discussed further here. Water uses are relatively small volume and not directly related to electricity production process being for example domestic, firewater systems... etc. OCGT are very water efficient (on a m<sup>3</sup>/MWh basis) but their low thermal efficiency gives them higher operational costs and specific atmospheric emissions than CCGT leading to their use only as peaking plant. In the future, use of some CCGT in open cycle mode is possible (ie with power generation solely from the GT rather than in combination with the HRSG (see Section 4.3.2 below)).

Most strikingly, since only approximately 1/3 of the electricity output of a CCGT is via the steam turbine, which requires a cooling cycle, the water use of a CCGT in m<sup>3</sup>/MWh terms, is typically considerably less than that of a coal, oil or nuclear plant of the same electrical capacity if the electricity output is evaluated on a 'whole plant' basis. Some authors therefore present CCGT water use information on a steam cycle only basis.

The fuel type also influences the techniques (deSO<sub>x</sub>, deNO<sub>x</sub>, fuel management, ash management) which a thermal power plant may use within its overall process (in line with LCP BAT and environmental quality considerations). Some of these techniques have direct effects on overall plant water use (i.e. water is used within that process which is not sourced completely from elsewhere within the plant processes). Some techniques have indirect effects on plant water use measures (e.g. a process which consumes energy but does not use water). In some cases different processes achieving the same end may be available, all of which could be BAT, but with different water use and water use measure consequences.

In some cases a thermal plant will consist of a number of near identical units (also known as 'blocks' by some authors) all with very similar water-use characteristics. In some cases a single thermal power plant could consist of units of several different types, ages etc with very different water-use characteristics though to date it is more common in the UK for units making up a given plant to be similar. In some cases a unit will be capable of commercial operation with several different fuel types or a mix leading to different unit characteristics at different times. Finally, the techniques associated with a unit may change over time as a result of upgrades.

#### 4.3.2 Operational Mode

The operation which a thermal power plant and the units within it is required to conduct is a major influence on water use occurring for a given plant and unit configuration. At various times the plant may be called upon to deliver any or all of the products described in Section 3, namely electricity, capacity and 'balancing services'. Its water use will reflect the range of products it provides. The number of part loaded units and the number of starts and stops required influences both the thermal efficiency of the power plant and the water quality occurring in various processes within plant both of which have implications for use of water. Various terms are used to describe operational mode e.g. see Ecofys (2014):

- high load (sometimes called baseload, e.g. >4000 hours per year)
- moderate load (sometimes called 'load following' or 'mid-merit' - frequent running with part loaded units and/or repeated start stopping of units, e.g. 1500-4000 equivalent full load hours per year)
- peak load (within day or seasonal peaking with extended periods of not delivering electricity output with many starts and stops and part loading e.g. 500-<1500 equivalent full load hours per year)
- Emergency Use<sup>10</sup> (plant which does not normally run but which may be called upon on occasions to meet demand peaks caused by highest demand or when system faults have occurred e.g. <500 equivalent full load hours per year).

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<sup>10</sup> Subsequently this terminology was not adopted in the LCP BREF review initiative as of April 2016 but is retained here for consistency with Ecofys (2014). However, we prefer to use the term 'very low load' rather than 'emergency' for the lowest load category.

Thermal and water use efficiency is greatest when a plant or unit is running baseload at 100% output for extended periods (i.e. stable high load operation over many weeks). Both thermal and water use efficiency decrease with part load operation and increased numbers of starts and stops.

Depending on market circumstances an operator may choose to run a plant or unit continuously at varying part load varying its output, thus incurring a thermal efficiency penalty, in order to avoid the occurrence of stopping and starting<sup>11</sup>. Where a plant is not operating at baseload, it is likely to be operated in a commercially optimal way subject to remaining compliant with the plant permits. This may involve choosing to start or stop units, maintaining extended running of some or all units in the plant at part load rather than shutting down some and high loading others etc.

The performance of installation processes comprising and supporting unit operation will be affected since many will have been designed primarily for baseload operation. The pattern of intermittent operation, especially starting up and shutting down of units and part loading, may have consequences for water quality within the processes, and hence for operator intervention to manage water quality including discharge of process water. This may affect recycling and re-use options available.

At low load intermittent operation an operator may choose to maintain cooling water abstraction and discharge at a level which would support higher load operation. Whilst this would incur additional electricity cost in pumping and some water use related charges it may remove commercial and technical risk (such as associated with re-starting large pumps) in moving to higher load operation, thus contributing to anticipated commercial return of the plant and its contribution to system security were the plant to be called on to again operate at higher load. For some types of plant there may be operational need for some water use even when not generating electricity, for example for ashing purposes, preparation of steam cycle make up and maintenance purposes.

Such considerations are particularly relevant to plant used for low load duty. For such plant considerably higher water use metrics linked to electricity production ( $\text{m}^3/\text{MWh}$ ) would be expected than for plant with higher and stable load operation.

In general, water efficiency linked to electricity production would be expected to decrease as operational load reduces should the proportion of time spent in transient operation, with part loading and increased starting and stopping, become greater. However, this is not necessarily the case since lower operational load on an annual basis could occur through maintaining high load operation for part of the year and not running at all for the rest. In this case water use efficiency would be maintained. Care should therefore be taken in interpreting annual load as an explanatory factor.

An exception to this occurs when a CCGT (compliant with its permit conditions) runs in 'open cycle' mode in which all electricity production is via the gas turbines and none via the heat recovery steam generator. In such a mode there is zero water use (gross and net) within the main plant generation. Therefore in such periods the water use ( $\text{m}^3\text{h}^{-1}$ , say) of the power plant would reduce dramatically and the water efficiency of electricity production ( $\text{m}^3/\text{MWh}$ ) would improve dramatically. However, the thermal efficiency of the plant in open cycle mode is much reduced compared with normal operation and use of open cycle would be expected primarily to

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<sup>11</sup> Operators would generally prefer to avoid starting and stopping and associated periods of transient operation involving part loaded units in unsteady conditions since they incur significantly greater stress and damage to plant than steady operation at full load. In market conditions which do not support stable high load operation for extended periods, optimal scheduling of unit starts, stops and part loading whilst ensuring compliance with all environmental requirements is integral to operator decision-making.

meet infrequent short-term peaking requirements. It would therefore contribute relatively little to longer-period (e.g. annual) water use metrics reporting.

#### 4.3.3 Thermal Efficiency

Thermal efficiency is the ratio of useful electricity delivered to the grid: thermal energy in fuel. Higher thermal efficiency means more electricity output per unit fuel consumed and hence reduced emissions to air including carbon dioxide, reduced waste and reduced by-products produced per unit electricity produced. It also means reduced fuel required for a given electricity output with consequent societal advantages associated with the fuel life cycle considerations. Additionally, increased process thermal efficiency means reduced thermal energy to be rejected to the environment for a given amount of fuel used and hence reduced water use for steam cycle cooling, which is the dominant water use for many thermal plant.

#### 4.3.4 Steam Cycle Cooling Technique

Where wet cooling is used to condense steam in the steam-cycle, cooling tends to be the dominant water use (in gross use terms, and in many case net use terms also). The principal steam cycle cooling techniques used in thermal power plant in UK are as follows:

- once through (sometimes termed direct cooling) in which the water withdrawn is immediately returned to surface waters, often the same body of water from which abstraction occurred<sup>12</sup>. This cooling type offers the highest overall thermal efficiency but is feasible only when sufficient water flow is available and residual impacts on the local aquatic environment regarded as acceptable. For a given heat load the key choice is to determine the through plant temperature rise to be used (which will then determine the required cooling water flow rate). This choice will often be made through consideration of local receptors in the aquatic environment. Power plant once through cooling is an important example of ephemeral abstraction.
- wet tower cooling (mechanical or natural draught evaporative cooling) and hybrid tower cooling (mechanical or natural draught tower cooling with a mixture of wet and dry cooling aimed at reducing occurrence of emissions of visible water vapour plumes) – leading to thermal efficiency intermediate between once through and dry cooling. In a hybrid tower, the heat load of the dry section of the tower is perhaps 10% of the total heat load so the water use in a typical hybrid tower is similar to that in a wet tower. Most of the heat loss in a wet cooling tower is achieved through evaporation with EIPPCB (2001) suggesting variously 70 and 80% due to evaporation. This corresponds to a mass flux of around 1.5-2% of the recirculating flow. There may be some very small additional loss as droplets. In mechanical draught systems the overall thermal efficiency is reduced by the power requirements of the fans.

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<sup>12</sup> Consumptive water use within the cooling system of once through cooled plant is normally considered to be 0 (consisting of small leaks and losses or venting at start up). Given the difficulty of measurement of flows of this scale, these could not be measured as the difference of abstraction and discharge flows. Evaporative loss induced in the receiving waters is rarely of significance since such plants operate only on large bodies of water. It cannot be measured directly but there is literature on exchange of heat at open water surfaces which allows inference by modelling. Much work in heavily loaded thermal ponds is reported. Where the water can be considered otherwise to be in equilibrium with the atmosphere the flux can be estimated through a linearised heat exchange model. However, where the receiving water body is not in equilibrium with the atmosphere this may not be valid (eg a glacially fed or snow melt dominated river in which the resulting induced evaporation would be less than that in a perturbed equilibrium model). There will be quantifiable consumptive use in processes other than cooling (eg boiler make up, ashing, FGD etc). In some cases these process may use water abstracted via the cooling water intake either before or after having been used for cooling purposes).

- dry cooling (towers or air cooled condensers using natural or mechanically forced draught which do not use any evaporative cooling). Such systems may make use of fully closed recirculating water circuits from which there is no intentional loss. They have an overall thermal efficiency less than that of either once through or wet tower-cooled systems. The reduced efficiency results from the thermodynamics of heat transfer using sensible heat only and in mechanical draught systems from the additional power requirements.

Some plant outside the UK may use cooling ponds with or without spray cooling as a source of cooling water using either once through or tower-cooled techniques, though this technique is more common in commercial scale plant in the USA. The Trawsfynydd nuclear plant used Lake Trawsfynydd in North Wales as a cooling pond in conjunction with once through cooling but closed in 1991.

Discussion of the improved thermal efficiency which use of water for cooling provides compared with air cooling can be found in EIPPCB (2001). McLauchlan (2012) and Gallagher *et al* (2014) provides a quantitative comparison of thermal efficiency changes as a result of cooling system choice for modern coal and CCGT plant types for environmental factors appropriate for UK.

Thermal efficiency is a primary but not the only consideration in choice and design of cooling technique. The acceptability of the construction and operation of the cooling water circuit on the aquatic environment, including consideration of entrainment and impingement of aquatic biota is a vital consideration. Assessment of this is through the planning, environmental impact, abstraction licencing and IED permit processes. It also requires consideration of the operational management of cooling water circuit chemistry (e.g. for management of biofouling and/or scaling risks). The plant developer will also have considered the risk of environmental restriction on plant operation (e.g. arising through water resource constraints (low flows) or restrictions on discharges (e.g. through temperature or water quality considerations)) which may differ significantly for the different cooling techniques or variants of a given technique being assessed.

#### 4.3.5 Other Water Using Techniques/Processes

Water-using processes other than steam-cycle and auxiliary cooling may occur at thermal power plant and may use quantities sufficient to affect site water balance and water metric reporting. Some of the processes may occur at any thermal plant (though there may be dry alternatives) and some are only applicable at specific types of plant. Such processes include:

- ash handling, transport & conditioning for beneficial use or disposal, ash disposal site management (coal-fired plant only)
- coal stock management (coal-fired plant, dust blow)
- deSO<sub>x</sub> including by-product conditioning (coal-fired plant only)
- deNO<sub>x</sub> (not nuclear)
- boiler/steam generator make up (including steam-sourced soot blowing for coal-fired plant if applicable)
- [steam supply<sup>13</sup>].

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<sup>13</sup> Where a thermal power plant supplies steam to a consumer, that steam may constitute a complete or partial export of water from the thermal power plant depending on whether low temperature low pressure steam is returned to the thermal power plant and the extent to which returning steam quality may preclude its recovery for subsequent use within the power plant. The steam take off will affect the steam available for generating electricity in the steam turbine. Such plant require separate consideration.

The choice of such processes will have been made during the plant detailed design activity at which time the potential for water re-cycling and re-use between processes will have been considered in developing the overall site and plant water systems.

Other uses which are important for the functioning of the thermal plant though in most cases not significantly affecting the overall water balance for a site, include:

- domestic (hygiene, canteen, health & safety purposes etc)
- laboratory
- fire control systems
- general washing (vehicles, equipment)
- site maintenance
- rain water – site drainage management systems.

However, for some specific types of power plant sites (e.g. OCGT) if water use is reported at all, these may be dominant! These uses are also important from a site resilience perspective.

#### 4.3.6 Emerging Techniques Potentially Affecting Water Use

Currently, very few plant worldwide operate carbon capture usage and storage (CCUS) techniques at commercial scale, though, as discussed below, reviews of future water usage in power plant often include estimates of water use in such techniques. Many CCUS techniques under evaluation today have significant energy requirements and would therefore, if not otherwise influencing the plant, result in an increased  $\text{m}^3/\text{MWh}$  metric for a given plant. Moreover, many of such processes have process water use or cooling demands which, if met through water cooling, would have a further direct water use influence.

Developments in several techniques which may reduce water use at power plant are under investigation. For example, Feeley, Skone, Stiegel, McNemar, Nemeth, Schimmoller, Murphy & Manfredo (2008) report a number of research activities which hold promise for some membrane techniques at some plant. The Capwa project<sup>14</sup> is assessing similar techniques using membranes to separate water vapour in gas streams. However, should such techniques become commercially available, it remains to be seen whether such techniques will affect BAT when the integrated consequences are considered.

Continuing development and more widespread commercial deployment of ultrasupercritical steam generation technology for future coal-fired power plant may increase the thermal efficiency compared with peer group supercritical or subcritical plant. Burnard & Bhattacharya (2011) suggest an indicative thermal efficiency increase from around 38% for modern subcritical plant to 45% for ultrasupercritical plant and bituminous coals, though the assumptions made about other techniques used are unclear. However, it is likely that such plant would include carbon capture and  $\text{deSO}_x/\text{deNO}_x$  techniques which together may result in overall plant thermal efficiencies similar or even less than in existing plant. Thus the overall effect in water use is unclear (see for example Zhia & Rubin, 2011).

#### 4.3.7 Practical Aspects of Operation Influencing Choice and Optimisation of Techniques and Processes

Water for a given power plant may be sourced from any and all of freshwater, saltwater, groundwater, public water supply, rainwater harvesting, internally re-cycled or re-used water

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<sup>14</sup> <http://www.watercapture.eu/index.php/capwaproject>

from within installation processes and third party 'used' water. The mix of water inputs will vary from site to site and possibly over time at a given site depending on water availability, quality and pricing. Reliable access to sufficient quantities of water for cooling may be an important factor in early decision making on the siting of the power plant. Plant processes include water treatments designed to take the site-specific source waters and produce the appropriate qualities of water required for the various plant processes. Since volumes and qualities appropriate differ between processes, different water supplies may be used to source different plant processes. Opportunities for within installation re-cycling and re-use of water would be expected to be well-known within each installation and those which were technically and commercially feasible would be expected to have been implemented. For the high quality water associated with the steam circuit, the primary drivers may well be recovery of heat and the avoidance of costs and consequences of chemical processing of externally supplied water though re-cycling of water rather than considerations of water resource use directly. In other cases, water output from a process with a chemical quality unsuitable for re-cycling within that process may be re-used in another process with less stringent quality constraints (e.g. coal stock or ash site conditioning). The needs for such streams and hence the opportunity for on-site re-use differs markedly between plant types.

Thus the very high quality water for steam cycle make up purposes may originate from public water supply or from river water but with different on-site chemical process requirements and different quality and quantity of 'used' water. The choice of source water may be influenced by the source pricing, source reliability and the processing costs.

Water quality is rarely a crucial factor in determining the source of cooling water and price and volume rules out sourcing from public water supply. Where surface water is available the choice of once through or tower-cooling is determined on BAT principles with the acceptability or otherwise of residual impacts on the local aquatic environment and the significant thermal efficiency benefit of once through cooling being the crucial factors. However, if wet or hybrid tower cooling is adopted, local water quality (and sometimes availability) will be crucial in determining the appropriate chemical control and operational configuration of the cooling water circuit. Although the evaporation occurring (i.e. consumptive use) will be determined by the operational load of the power plant and the meteorology, the non-consumptive use of the cooling circuit can be chosen by the operator from the technically and commercially feasible range in line with integrated assessment-BAT principles. Reducing the non-consumptive use may require more sophisticated management of the cooling circuit chemistry and involve additional chemical pre-treatment or conditioning with an associated chemical discharge and/or waste-products.

The range of water using processes employed at a thermal plant differs between plant types and even from plant to plant of a given type since for some processes there may be several technically and commercially feasible technique choices available each consistent with BAT and each with different water use consequences. An example for a coal plant is whether fly ash handling systems are to be 'dry' (e.g. conveyors or truck based) or 'wet' (e.g. hydraulic transport as a slurry) and whether ash not conditioned for sale, is disposed of as a mound or through lagoons. For a once through cooling system a fundamental choice is the trade-off between higher cooling water flows with lower temperature rises or lower flows with higher temperature rises. For example, the choice of +8°C through plant rise as opposed to a +12°C rise would change the gross-use water metric for the installation by 50%! Either may be preferred or both configurations may be acceptable in European conditions depending on the site-specific circumstances.

The choice of cooling technique (once through or wet/hybrid tower cooled or dry cooled) is likely to dominate the water use characteristics for the plant. In the EU this choice is made in the light

of IED permitting requirements including a formal options appraisal and informed by EIPPCB (2001). The choice involves consideration not only of consequences for the water environment but also for the atmosphere and the terrestrial environments and their potentially affected receptors as well as costs. EIPPCB (2001, Table 3.1, reproduced below as Table 1) and Turnpenny & Coughlan (2003, Table 2.4) offer tabulations of some of the relevant comparisons. Required land area could also be included as a relevant factor which may be constraining in some cases. For example where use of dry cooling might be precluded were the proposed power station site land to be insufficiently large or where the only siting option would lead to towers being sited too close to receptors sensitive to noise beyond the site boundary.

**Table 1: Range of Considerations for Different Cooling Types [EIPPCB (2001, Table 3.1)]**

Table 3.1: Environmental issues of the different industrial cooling systems  
[tm001, Bloemkolk, 1997]

| Cooling system                            | Energy Consumption (direct) | Water requirement      | Fish <sup>(2)</sup> entrainment | Emissions to surface water |                    | Air emissions (direct)        | Plume formation   | Noise   | Risk            |                                   | Residues |
|---|-----------------------------|------------------------|---------------------------------|----------------------------|--------------------|-------------------------------|-------------------|---------|-----------------|-----------------------------------|----------|
|   | (§ 3.2)                     | (§ 3.3) <sup>(1)</sup> | (§ 3.3)                         | Heat (§ 3.3)               | Additives (§ 3.4)  | (§ 3.5)                       | (§ 3.5)           | (§ 3.6) | Leakage (§ 3.7) | Micro biol. risk (health) (§ 3.7) | (§ 3.8)  |
| Once-through cooling (direct circuit)     | Low                         | ++                     | +                               | ++                         | +                  | --                            | --                | --      | ++              | --/low                            | +(6)     |
| Once-through cooling (indirect circuit)   | Low                         | ++                     | +                               | ++                         | +                  | --                            | --                | --      | Low             | --/low                            | +(6)     |
| Open wet cooling tower (direct circuit)   | +                           | +                      | --                              | Low                        | +(3)               | Low (in plume)                | +                 | +       | +               | +                                 | --/low   |
| Open wet cooling tower (indirect circuit) | +                           | +                      | --                              | Low                        | +(3)               | Low (in plume)                | +                 | +       | Low             | +                                 | +        |
| Open wet/dry cooling tower                | +                           | Low                    | --                              | Low                        | Low <sup>(3)</sup> | --                            | -- <sup>(5)</sup> | +       | Low             | ?                                 | +        |
| Closed circuit wet cooling tower          | +                           | +                      | --                              | --                         | Low                | Low <sup>(4)</sup> (in plume) | --                | +       | Low             | Low                               | --/low   |
| Closed circuit dry cooling                | ++                          | --                     | --                              | --                         | --                 | --/Low                        | --                | ++      | Low             | --                                | --       |
| Closed circuit wet/dry cooling            | +                           | Low                    | --                              | --                         | Low <sup>(3)</sup> | Low                           | --                | Low     | Low             | Low                               | --/low   |

Notes:  
-- none/not relevant  
Low relevance below average  
+ relevant  
++ highly relevant  
1: paragraph in text  
2: other species can also be entrained  
3: biocides, antiscaling, anticorrosion  
4: potentially in case of leakage  
5: if properly operated no issue  
6: waste refers to sludge from water intake and from decarbonization

It is also relevant to consider the wider societal pros and cons of the available choices which, depending on the regulatory regime, may take place alongside IED-BAT considerations. Such wider considerations could include life cycle consequences associated with fuel use and its transport. There may also be affordability considerations related to the effects of choices on costs of electricity produced. Use of water for cooling is advantageous in these regards because of the improved process thermal efficiency it provides and which leads to reduced fuel use per unit electricity produced and reduced cost of production.

#### 4.3.8 Choice of Locations for Abstraction and Discharge – Site Configuration Optimisation and Implications for the Aquatic Environment

For a given thermal power plant which includes water-using techniques and the chosen set of water sources, there may be a number of possible configurations of intake and outfall locations and types. For a given set of techniques the precise arrangements will not change the gross water use and consumptive water use of the power plant as seen from the installation perspective but may affect the residual impacts of the plant construction and operation. Part of this optimisation may include considering from which water bodies to abstract and to which to discharge if there is a feasible choice. In most cases the plant will have been sited specifically

mindful of access to water for steam cycle cooling having regard to optimising<sup>15</sup> and establishing the acceptability of the effects of construction and operation of the cooling water system. In many cases the choice may be narrow. However, as well as the principal water body(ies) there may be smaller water courses which could be used to receive sub-process effluents rather than to direct all sub-process effluents which cannot be re-cycled or re-used back to the principal water body. Such arrangements might be suitable for discharge from ash lagoons, coal stocks or site drainage and, despite the potential chemical composition, the flow reinforcement may be advantageous for the biota in the receiving water course. From a water body perspective, selection of such an arrangement leads to the installation bringing about a transfer to the receiving waters.

Similar considerations apply to assess whether or not it is appropriate that some process effluent is transferred to a prospective third party user than returned to the aquatic environment.

However, in some cases there may be more than one distinct water body suitable for use as a primary source and recipient (e.g. near where rivers coalesce, where a canal runs parallel to a nearby river or estuary, etc). In such cases the pros and cons of abstraction and return to the same water body or the installation transferring some water from one to the other would be explored in early planning assessment.

#### 4.3.9 Practical Aspects of Water Balances at Real Power Plant

In interpreting literature data on reported water use at power plant many practical aspects should be borne in mind. The way water is managed at power plant sites may differ significantly in different parts of the world and the transferability of results to UK conditions should be carefully considered.

The limitations on measuring or inferring flows apply worldwide and this may lead to an appreciable contribution to the ranges in apparent water use in some cases. Whilst some flows (e.g. from public water supply) may be metered relatively accurately, the measurement or inference accuracy in large flows (such as once through cooling) may be such that flows are known only to within  $\pm 10\%$  approx. Some flows may be monitored directly whilst others (such as evaporation) are likely to be inferred either through combinations of meter readings or from thermal balances.

There may also be differences in reporting conventions or interpretations, not least being the scope of the water use being reported. The management of water flows within thermal power plant can be complex often with multiple take-offs from a common input stream with take offs from process output streams being routed to other processes, to a central 'pond', to discharge to surface waters, to a third party water user, or to the public wastewater system. It may therefore not be straightforward to characterise a particular stream within a thermal power plant water balance if that stream serves several purposes and processes.

Power plant sites are often large and the management of water on site is an important consideration, not least in seeking to ensure suitable resilience against flood events. In some cases rainfall incident on parts of the site or on buildings may be deliberately managed for subsequent use within the plant processes (rainwater harvesting). In many cases incident rainfall and evaporation may affect open components within the plant or site water system making it difficult to complete accurate quantification of a site or installation water balance.

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<sup>15</sup> 'optimising' reflects that the choice between feasible options normally involves a range of trade-offs both within the aquatic environment, other environment compartments and wider socio-economics.

The precise terminology, spatial and temporal scales and the focus of a study may significantly affect the way the water flows are represented and the findings reported especially with regard to 'consumptive' use.

#### 4.3.10 Key Principal for Use of Water by Thermal Power Plant

It is evident from the above discussion that the site and installation specific BAT and optimisation choices in combination with varying site circumstances will lead to considerable variations in reported water use between thermal plants and at a given plant over time. This is reflected in the wide range of water use metric values reported in the literature.

The cooling technique choice is so fundamental that it is made at the initial design stage of the plant and examined comprehensively within its planning and permitting processes. For a thermal power plant the scale of change and the detailed technical coupling with the rest of the plant (e.g. through choice of steam turbine configuration), would normally render it technically and/or commercially infeasible to change subsequently the fundamental cooling technique. Thus, once initially chosen, the primary characteristics of a thermal power plant's use of water cannot readily be changed.

The overriding principle for thermal power plant use of water is to use water optimally and responsibly in line with BAT principles and consistent with acceptable residual aquatic environmental effects. Since the balance of pros and cons for all media, not just the aquatic environment, are involved in the application of BAT, this is not equivalent to 'maximising water efficiency' (in terms of minimising water use  $\text{m}^3/\text{MWh}$ ) or minimising water use (in terms of  $\text{m}^3\text{y}^{-1}$ ). For thermal power plant already operating at site-specific BAT, improving water efficiency may be contrary to BAT principles and may be contrary to other policy objectives (such as climate change mitigation measures). It would be expected that water audits, including review of opportunities for water re-cycling and re-use, would form part of operator best practice.

While water use metrics of the form  $\text{m}^3.(\text{MWh})^{-1}$  may have a role to play among a range of other metrics in describing plant performance, it is not appropriate to attempt to set targets or limits for such a metric derived from peer group comparisons. Rather apparent significant departures from a plant's previous water use metric or from its peer group range should act as a trigger to understand the reasons for that position.

## **5 THE CONSEQUENCES OF INDIVIDUAL CHOICES ON FUTURE WATER NEEDS OF THE THERMAL POWER PLANT SECTOR**

In the previous sections the factors affecting water use at a given plant have been considered. In this section considerations which affect the potential water and water rights requirements of the thermal power sector as a whole are considered.

The key assumption in assessing the future needs of the sector is what set of plant comprises the generating fleet of the time, both the thermal plant and renewables. Increasingly, renewable forms of generation, both those connected via the grid and those connected locally, affect the load which thermal plant are required to deliver. Thus assumptions need to be made on the installed renewables capacity and, given their intermittency, their electricity output at the time of interest. From estimates of the overall demand, as modified by demand management, and the competitiveness and availability of electricity from interconnectors<sup>16</sup> or storage, the remaining

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<sup>16</sup> ie underpinned by generation located outside the UK

load to be met by thermal plant can be estimated. Then, having regard to the characteristics of the thermal fleet available, the load can be assigned across the available fleet and hence the fresh water needed (both gross and net) can be estimated.

The instruction of thermal plant to be available and generate in practice occurs continuously in order to both balance supply and demand for electricity and 'manage the grid'<sup>17</sup>. However assessment of water needs may be required at timeframes relevant to the way water resource is made available (e.g. daily, possibly with regard to constraints arising from operation of HOFs, short-term allocations or catchment rules, through to annual).

It is evident that the future water needs of the sector are subject to considerable uncertainty arising from the uncertainty in the composition of the future thermal fleet and the uncertainty of the demands to be made of it. The DECC 2050 pathways<sup>18</sup> and National Grid Future Energy Scenarios (FES)<sup>19</sup> show many examples of trajectories for fleets of the future and annual distribution of load across the fleet (at national level). These give no information on the geographic location or the cooling types of the underlying plant. Even at this national level the potential variation of water use can be illustrated (e.g. through making broad assumptions on freshwater/saltwater location splits and associated cooling types) but this does not capture all the uncertainty.

The fleet composition is not prescribed by Government or National Grid but will evolve as a result of many decisions made by individual companies in response to their perception of the commercial threats and opportunities they face. Their decisions will be made in response to signals from the UK Energy and Capacity Markets. These include some locational signals such as grid connection and Transmission Network Use of System (TNUoS) changing arrangements. However, there is a preference to develop existing sites due to the lower costs associated with access to existing infrastructure, grid connection and abstractable water and in some cases a perception of reduced planning risk compared with those at site which did not formally host a power station.

The significance of individual company circumstances in decision making should not be underestimated and for companies operating internationally the relative merits (risks/benefits) of investing in new UK energy projects will be evaluated against other international energy projects, all of which are likely to be competing for scarce capital.

Other important individual company choices may include:

- Re-investing in existing plant where investment leads to improved commercial position
- Timing of closing existing plant approaching the end of their commercial life
- Development of new or existing sites for new thermal power plant compared with other potential uses for the site including consideration of splitting existing sites to obtain early benefit whilst retaining options for further development
  - If development appears attractive
    - What site on which to develop
    - What size of plant
    - What fuel type for plant
    - What cooling system type for plant.

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<sup>17</sup> The geographic distribution and dynamic nature of sources of generation and demand lead to requirements of thermal plant to operate in ways other than purely supplying energy to the grid (eg contributing to frequency control, reactive power and provision of spinning reserve see < <http://www2.nationalgrid.com/uk/services/balancing-services/>>)

<sup>18</sup> <https://www.gov.uk/guidance/2050-pathways-analysis>

<sup>19</sup> <http://fes.nationalgrid.com/>

Several authors have considered the significance of local geographic location, with implications for feasible cooling type choice.

For example, Gasparino (2012) applies a monte-carlo simulation approach taking into account the location of traditional power plant sites, the cooling system choices linked to those sites and reported variability in water use of plant of a given type in expanding to River Basin District level two contrasting DECC 2050 pathways defined at national fleet level. Gasparino shows that not only can different DECC pathways scenarios lead to rather different potential sector water needs but also that there is considerable uncertainty even for a specific DECC scenario, resulting in part from choices made at individual operator level.

Byers, Hall & Amezaga (2014) considers the influence of location on national level future water use by assuming distribution of future capacity between fresh water, tidal waters (estuaries) and coastal waters (and air-cooling) having regard for fuel type and cooling type.

Murrant, Quinn & Chapman (2016) use a regional representation of the UK within the ESME modelling system and a specific 2050 pathway to explore potential future water use by thermal generation at regional level.

The collation of water use data for existing and recent UK plant presented in the following section is intended to improve estimates of future use at individual plant in the UK and for the sector as a whole compared with the data informing studies of the UK future needs to date.

## **6 WATER USE IN UK THERMAL POWER PLANT**

### **6.1 Data Collation**

A data collation exercise was initiated in July 2015 to collect water use data at JEP thermal power stations. This dataset has recently been updated in 2019. The aim of this data collection exercise was to produce a public domain dataset which gave the most recent historic range and distribution of water use of JEP plant facilitating ready error-free interpretation and extraction of data for analysis by external parties.

In order to structure the work and reporting to facilitate periodic update in subsequent years, JEP members were requested to supply information on a site by site basis using a spreadsheet pro-forma. The data request was made up of three key worksheets:

1. Contact information - includes info on company name, plant name / location and name of person completing the questionnaire.
2. Plant details - includes information on the location of the plant, plant technology, cooling water technology and other water using processes.
3. Annual data - includes data for a given year on generation, water abstraction and discharge volumes.

Quality Assured data were requested for as many years as were available. In practice the data submitted corresponded broadly to the period following the introduction of reporting to the Resource Efficiency Physical Index (REPI) which brought in the requirement to report resource use and production, including energy use and production, water consumption and waste production.

## 6.2 Data Overview

The data collated ranges from 2008 to 2018, from nine different energy operators. In total the dataset comprises 187 individual records of water use across the power sector. Table 2 below summarises the number of data records provided between 2008 and 2018 based on principal fuel type.

**Table 2: Summary of data records provided between 2008 and 2018, based on principal fuel type (level 1 grouping)**

| Principal Fuel  | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | No of records |
|-----------------|------|------|------|------|------|------|------|------|------|------|------|---------------|
| Gas (CCGT only) | 1    | 1    | 12   | 13   | 13   | 15   | 14   | 14   | 12   | 12   | 13   | 120           |
| Hard coal       | 0    | 0    | 8    | 8    | 8    | 7    | 7    | 5    | 5    | 5    | 5    | 58            |
| Oil             | 0    | 0    | 1    | 1    | 1    | 1    | 1    | 0    | 0    | 0    | 0    | 5             |
| Biomass & waste | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 1    | 1    | 1    | 4             |

Information was also requested regarding cooling technology type. Table 3 provides a summary of the number of water use records based on principal fuel type and cooling technology spread over all years (level 2 grouping).

**Table 3: Summary of water use records based on principal fuel type and cooling technology (level 2 grouping)**

| 2008 - 2018     |  |                                  |                |
|-----------------|--|----------------------------------|----------------|
| Principal Fuel  | Cooling System Typology                | Cooling Tower Type               | No. of Records |
| Biomass & waste | Closed circuit: dry                    | No cooling tower                 | 4              |
| Gas (CCGT only) | Closed circuit: dry                    | Mechanical draught cooling tower | 7              |
|                 | Open: recirculating wet cooling system | Mechanical draught cooling tower | 4              |
|                 | Hybrid (wet/dry): open circuit         | Mechanical draught cooling tower | 4              |
|                 | Hybrid (wet/dry): recirculating        | Mechanical draught cooling tower | 59             |
|                 | Open: once-through direct              | No cooling tower                 | 46             |
| Hard coal       | Open: once-through direct              | No cooling tower                 | 9              |
|                 | Open: recirculating wet cooling system | Natural draught cooling tower    | 49             |
| Oil             | Closed circuit: dry                    | Mechanical draught cooling tower | 5              |
| Total           |  |                                  | 189            |

Table 4 classifies this data further by adding an additional grouping level (3); operational mode. For the purpose of this study, the operational modes considered were based on the draft LCP BREF (2017) terminology which was also adopted for a 2014 EC study [Ecofys, 2014]. It should be noted that in the final LCP BREF the terminology for operational mode differs to that used here. In particular the final BREF does not differentiate between “base” and “mid-merit” operation<sup>20</sup>.

**Table 4: Summary of water use records based on principal fuel type, cooling technology and operational mode (level 3 grouping)**

| 2008 - 2018     |  |                       |                |
|-----------------|--|-----------------------|----------------|
| Principal Fuel  | Cooling System Typology                | Operational mode      | No. of Records |
| Biomass & waste | Closed circuit: dry                    | base load (>4000h)    | 4              |
| Gas (CCGT only) | Closed circuit: dry                    | base load (>4000h)    | 1              |
|                 |  | low load (500-1500h)  | 3              |
|                 |  | mid-merit (1500-4000) | 3              |
|                 | Open: recirculating wet cooling system | emergency (<500h)     | 4              |
|                 | Hybrid (wet/dry): open circuit         | mid-merit (1500-4000) | 4              |
|                 | Hybrid (wet/dry): recirculating        | base load (>4000h)    | 30             |
|                 |  | emergency (<500h)     | 4              |
|                 |  | low load (500-1500h)  | 4              |
|                 |  | mid-merit (1500-4000) | 16             |
|                 |  | no comment            | 5              |
|                 | Open: once-through direct              | no comment            | 4              |
|                 |  | base load (>4000h)    | 19             |
|                 |  | emergency (<500h)     | 10             |
|                 |  | low load (500-1500h)  | 4              |
|                 |  | mid-merit (1500-4000) | 8              |
|                 | no comment                             | 1                     |                |
| Hard coal       | Open: once-through direct              | base load (>4000h)    | 7              |
|                 |  | low load (500-1500h)  | 1              |
|                 |  | mid-merit (1500-4000) | 1              |
|                 | Open: recirculating wet cooling system | base load (>4000h)    | 32             |
|                 |  | low load (500-1500h)  | 4              |
|                 |  | mid-merit (1500-4000) | 13             |
| Oil             | Closed circuit: dry                    | emergency (<500h)     | 5              |
| Total           |  |                       | 189            |

There was insufficient data to provide any further classification based on other water-using systems (FGD/deNO<sub>x</sub>/ashing/use of or supply to third parties).

<sup>20</sup> The terminology applied in the final LCP BREF is as follows (L=plant load):  
L<500hours per year  
500<L<=1500 hours per year  
L>1500hours per year

### 6.3 Statistical Analysis

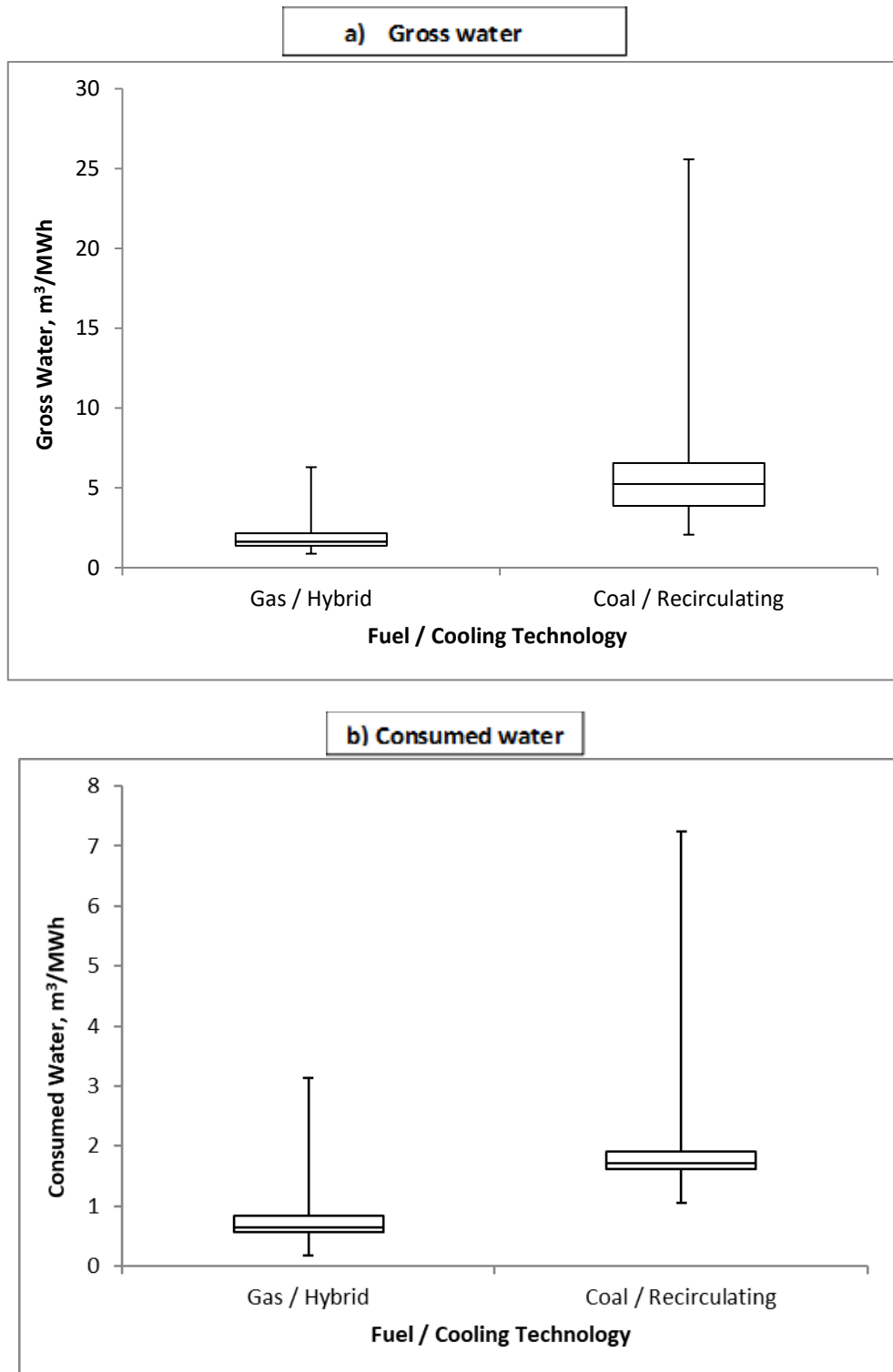
Table 5 provides the minimum, maximum and interquartile range of the dataset classed by principal fuel type and cooling system typology. Statistics are provided for gross water use and consumed water use normalised against total electrical energy exported for each station in each given year. A graphical presentation of the range of values is also provided in Figure 1 to Figure 3. For the purpose of providing representative plant statistics two outliers have been removed from this dataset:

- 1) In the category CCGT plant with a hybrid (wet/dry): recirculating operating there was one plant which operated in very low load or emergency mode for 4 years. Such low load running, continued water abstraction, together with uncertainty in flow measurement lead data unrepresentative of this plant type. This is described further in section 6.5.
- 2) In the category CCGT with open: once-through direct cooling, one plant ran for a single month during the year, with some continued abstraction and discharge. Such running lead to the maximum gross water usage of 1241.52 m<sup>3</sup>/MWh for this cooling system / fuel type.

Additionally, closed circuit: dry cooled systems have been omitted from this graphical analysis as water use is minimal.

**Table 5: Water use statistics based on plant-cooling typology category (level 2)**

| Principal Fuel Type | Cooling System Typology         | No. Records | Gross Water, m <sup>3</sup> /MWh = I/E |        |        |        |        | Consumed water, m <sup>3</sup> /MWh = (I-D)/E |      |        |      |      |
|---------------------|---------------------------------|-------------|--|--------|--------|--------|--------|---|------|--------|------|------|
|                     |                                 |             | Min                                    | 25%    | Median | 75%    | Max    | Min   | 25%  | Median | 75%  | Max  |
| Biomass             | Closed circuit dry              | 4           | 0.29                                   | 0.31   | 0.33   | 0.52   | 1.06   | 0.11  | 0.11 | 0.12   | 0.18 | 0.31 |
| Gas CCGT            | Closed circuit: dry             | 7           | 0.03                                   | 0.04   | 0.05   | 0.08   | 0.08   | 0.00  | 0.00 | 0.00   | 0.00 | 0.00 |
|                     | Hybrid (wet/dry): open circuit  | 4           | 1.98                                   | 2.06   | 2.26   | 2.50   | 2.66   | 0.79  | 0.91 | 1.00   | 1.06 | 1.09 |
|                     | Hybrid (wet/dry): recirculating | 59          | 0.88                                   | 1.37   | 1.63   | 2.16   | 6.30   | 0.17  | 0.57 | 0.64   | 0.84 | 3.13 |
|                     | Open: recirculating wet cooling | 4           | 1.22                                   | 1.75   | 2.14   | 2.60   | 3.34   | 0.00  | 0.07 | 0.10   | 0.33 | 0.98 |
|                     | Open: once-through direct       | 46          | 23.83                                  | 69.33  | 87.86  | 108.20 | 400.21 | 0.00  | 0.01 | 0.05   | 0.10 | 1.60 |
| Hard coal           | Open: once-through direct       | 9           | 120.62                                 | 125.70 | 140.15 | 189.67 | 487.50 | 0.10  | 0.15 | 0.19   | 0.22 | 1.46 |
|                     | Open: recirculating wet cooling | 49          | 2.07                                   | 3.87   | 5.23   | 6.56   | 25.58  | 1.06  | 1.61 | 1.70   | 1.91 | 7.25 |
| Oil                 | Closed circuit: dry             | 5           | 0.18                                   | 0.21   | 0.22   | 0.25   | 1.69   | 0.18  | 0.21 | 0.22   | 0.25 | 1.69 |

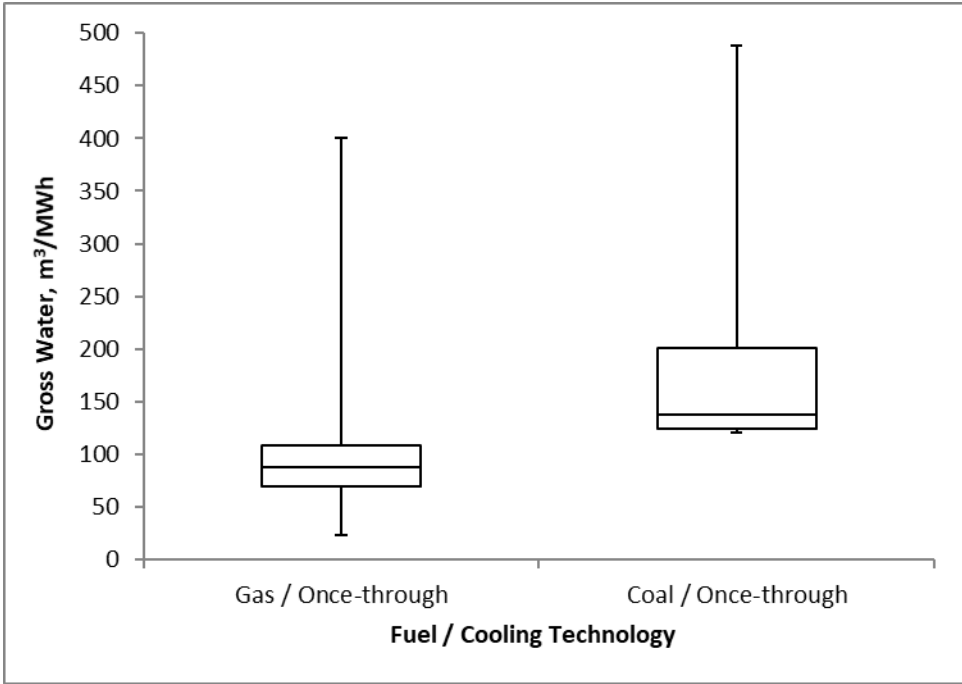


**Figure 1: Range of (a) gross and (b) consumed water usage for tower cooled gas and coal power plants across all operational modes**

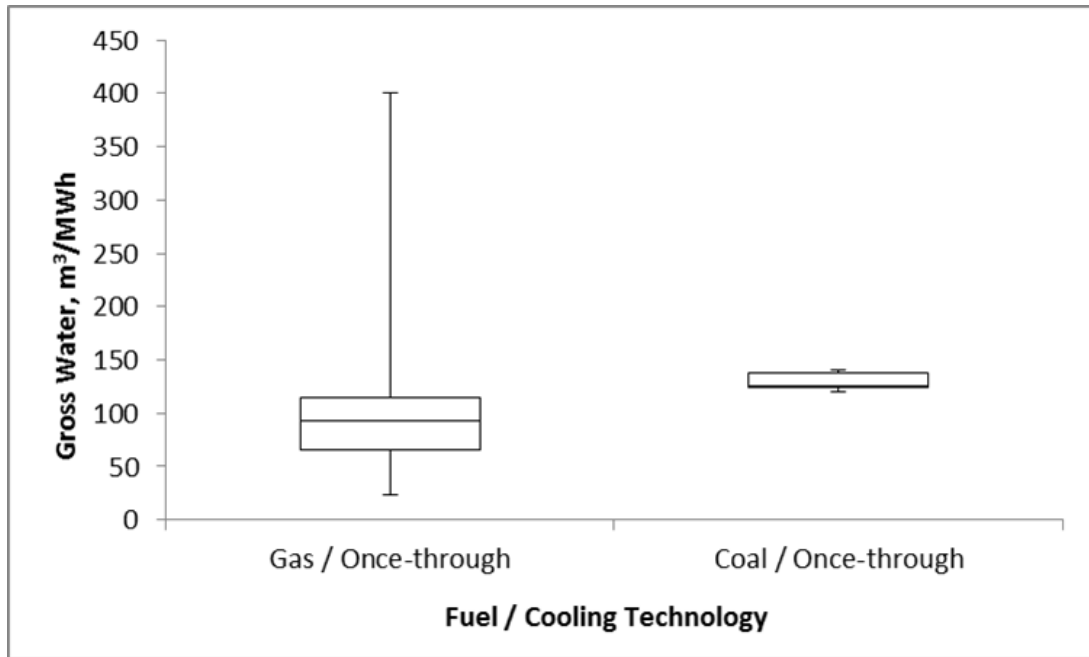
Figure 1(a) and 1(b) show that when comparing water requirements between a tower cooled CCGT versus a tower cooled coal plant it is observed that tower cooled CCGT plant typically use about 1/3 the water on a m<sup>3</sup>/MWh whole station basis, both gross and consumptive. This is in line with only about 1/3 of the electricity output from the CCGT being via the steam turbine. It

is evident that there is some scatter for both CCGT and hard coal. This is predominantly due to incidence of low and very low/emergency load factors. This scatter was not seen for coal recirculating plant in the first data collection cycle (2008 – 2014) where the majority of plant were operated under base load conditions. This illustrates the shift of hard coal plant from baseload to more variable mid-merit operation in more recent years.

Figure 2 shows of the difference in gross water use in once through direct cooled gas plant compared to coal plant. Although once through cooled CCGT tend to use lower gross amounts of water /MWh than coal plant (because only about 1/3 of the electricity output is through the steam turbine) the relative water use is influenced also by design choice of through plant temperature rise. In the current fleet coal plant tend to be older than CCGT. They date from a period in which design rise (at full load) of 10°C or more was typical. In the more modern CCGTs greater use of lower design base load temperature rise may occur. Comparison is rendered more complex by the common occurrence of intermittent operation with starting and stopping and part load operation of units. Since policies on cooling water pump running and part loading may differ significantly between plant, the relationship between flow and MWh is not so clear cut. It is interesting to compare the spread of the full dataset to that of the data collected in the first data collection exercise as plotted in Figure 3. This shows that water usage on a m<sup>3</sup>/MWhr basis has not changed significantly for once through CCGT plant. However, for once through hard coal plant the range of m<sup>3</sup>/MWhr gross water has increased. This reflects the small dataset and the influence of plant with low or mid-merit operation.



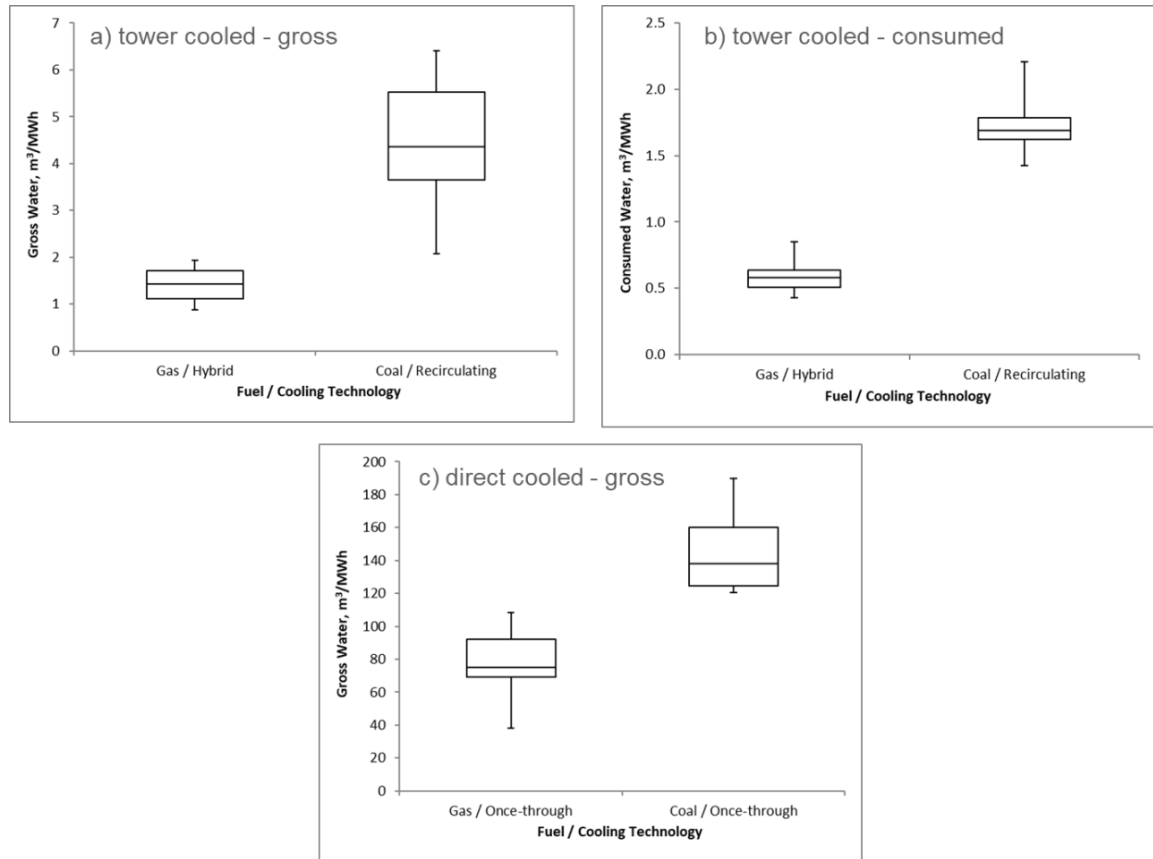
**Figure 2: Range of gross water usage for once through direct cooled gas and coal power plants across all operational modes. It should be noted that for coal-recirculating plant statistics are based on 9 data points.**



**Figure 3: Range of gross water usage for once through direct cooled gas and coal power plants across all operational modes (2008 – 2014). NB. It should be noted that for coal-recirculating plant statistics are based on 7 data points.**

Figure 1 -3 above demonstrate there can be greater variation in water use within an individual plant type-cooling system than there is between two different individual plant type-cooling systems. On manual inspection of the dataset it was observed that the extremities of the data are more likely to occur for plant with non-base load operation.

Figure 4a-c provide a summary of the statistics for plant operating in base load only. For plant operating at these operational modes the differences between the two individual plant type-cooling systems becomes more apparent.



**Figure 4: Range of water usage for gas and coal power plants across base load operation only**

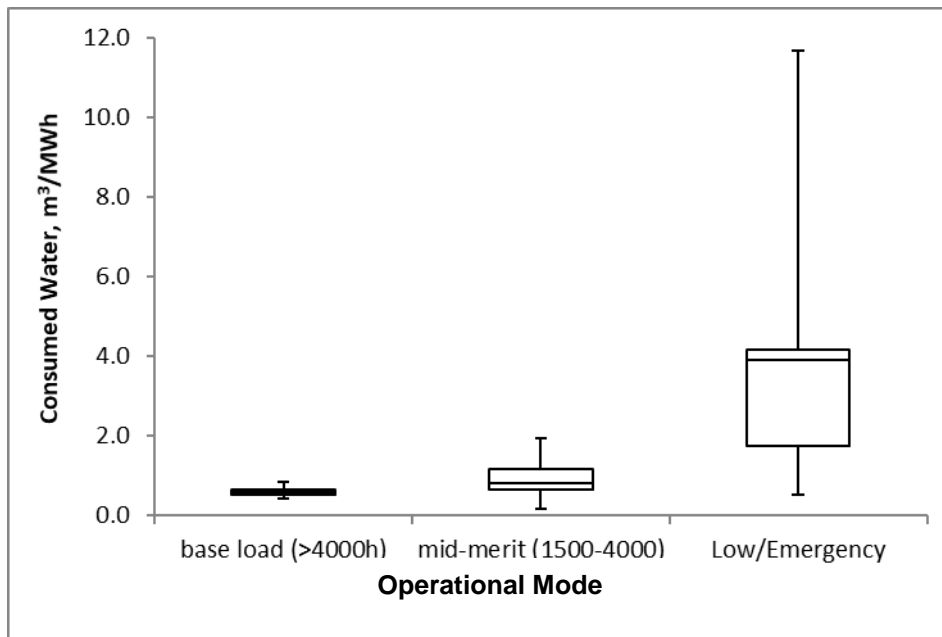
For tower cooled gross water use the concentration factor at which the cooling system is operating can lead to a variation in gross water use between similar plant. The greater the concentration factor, the less water the system abstracts and discharges. The selection of concentration factor is an important consideration in the design and operation of recirculating cooling systems and is dependent on concentration of salts present in the cooling circuit. In UK power plant, the make-up and purge systems are typically designed on the basis of allowing the concentration factor to be nominally 1.5, with some stations able to operate their cooling systems at slightly higher concentration factors of up to 2 [Gallagher, 2014]. The effect of concentration factor was apparent from the dataset for gas-hybrid, where one plant which operates at very low concentration factor (approximately 1.1) gave rise to the maximum gross water use 6.3 m<sup>3</sup>/MWh (see Figure 1a).

#### 6.4 Operational Mode Comparison - CCGT-Hybrid

Interrogation of the dataset showed that the changing operational mode leads to a variation within a plant type-cooling system type. In general, plant operating at low load give rise to higher m<sup>3</sup>/MWh. This is demonstrated by the statistics provided in Table 6 and Figure 5.

**Table 6: Water use statistics for gas-hybrid plant operating based on operational mode**

| Principal Fuel Type | Cooling System Typology            | Operational Mode      | No. Records | Gross Water, m <sup>3</sup> /MWh = I/E |      |        |       |        | Consumed water, m <sup>3</sup> /MWh = (I-D)/E |      |        |      |       |
|---------------------|------------------------------------|-----------------------|-------------|--|------|--------|-------|--------|---|------|--------|------|-------|
|                     |                                    |                       |             | Min                                    | 25%  | Median | 75%   | Max    | Min   | 25%  | Median | 75%  | Max   |
| Gas CCGT            | Hybrid (wet/dry):<br>recirculating | base load (>4000h)    | 30          | 0.88                                   | 1.12 | 1.44   | 1.71  | 1.93   | 0.43  | 0.51 | 0.58   | 0.65 | 0.85  |
|                     |                                    | mid-merit (1500-4000) | 16          | 1.05                                   | 1.66 | 2.25   | 3.48  | 6.30   | 0.17  | 0.64 | 0.82   | 1.18 | 1.94  |
|                     |                                    | low load / emergency  | 8           | 2.18                                   | 5.15 | 21.10  | 32.55 | 170.33 | 0.53  | 1.73 | 3.90   | 4.15 | 11.69 |



**Figure 5: Range of water usage for gas-hybrid plant operating based on operational mode**

There was insufficient data to justify firm conclusions to be drawn regarding low/very low load plant in the above box and whisker plot. However, inspection of data suggests a difference between these two categories. The very low plant data all fall under a single plant which gives rise to the higher consumed water values. Based on the current dataset it is not possible to determine whether this data is specific to this plant or whether it can be taken to be representative of gas-hybrid very low load plant in general. It is considered that, in general terms, plant operating in low/very low mode will give rise to higher water consumption (m<sup>3</sup>/MWh) compared to other plant operational modes. However, further data are required to characterise this category of plant/operation.

### 6.5 Effect of Flow Monitoring Uncertainty

EPR regulated sites with a flow monitoring requirement in their permit are required to comply with the MCERTS scheme in order to fulfil their environmental responsibilities. Under current practice, EPR covers only effluent flows. For effluent flow monitoring, the total daily volume of the discharge specified in the permit shall be measured with a target uncertainty of ±8% (or better) at a confidence level of 95% (EA, 2014). All JEP sites that provided data into this study are required to comply with MCERTS.

During the recent data collection exercise the effect of monitoring uncertainty on reporting water use of very low load / emergency plant became apparent. Table 7 shows the water abstraction

and discharge volumes for a single CCGT plant with hybrid (wet/dry) cooling operating as very low load / emergency plant.

**Table 7: Comparison of water abstraction and discharge for a single plant with varying operational modes**

| Year | operational mode     | Abstracted Water (m <sup>3</sup> ) | Discharge Water (m <sup>3</sup> ) | Fraction of Water consumed | m <sup>3</sup> /MWh |          |
|------|----------------------|------------------------------------|-----------------------------------|----------------------------|---------------------|----------|
|      |                      |                                    |                                   |                            | Gross               | Consumed |
| 2011 | low load (500-1500h) | 1.79E+07                           | 1.56E+07                          | 0.13                       | 32.23               | 4.04     |
| 2012 | emergency (<500h)    | 6.54E+06                           | 5.75E+06                          | 0.12                       | 27.35               | 3.31     |
| 2013 |                      | 2.49E+06                           | 2.15E+06                          | 0.14                       | 14.85               | 2.07     |
| 2014 |                      | 8.98E+06                           | 7.78E+06                          | 0.13                       | 33.49               | 4.49     |
| 2015 |                      | 7.38E+06                           | 6.87E+06                          | 0.07                       | 170.33              | 11.69    |

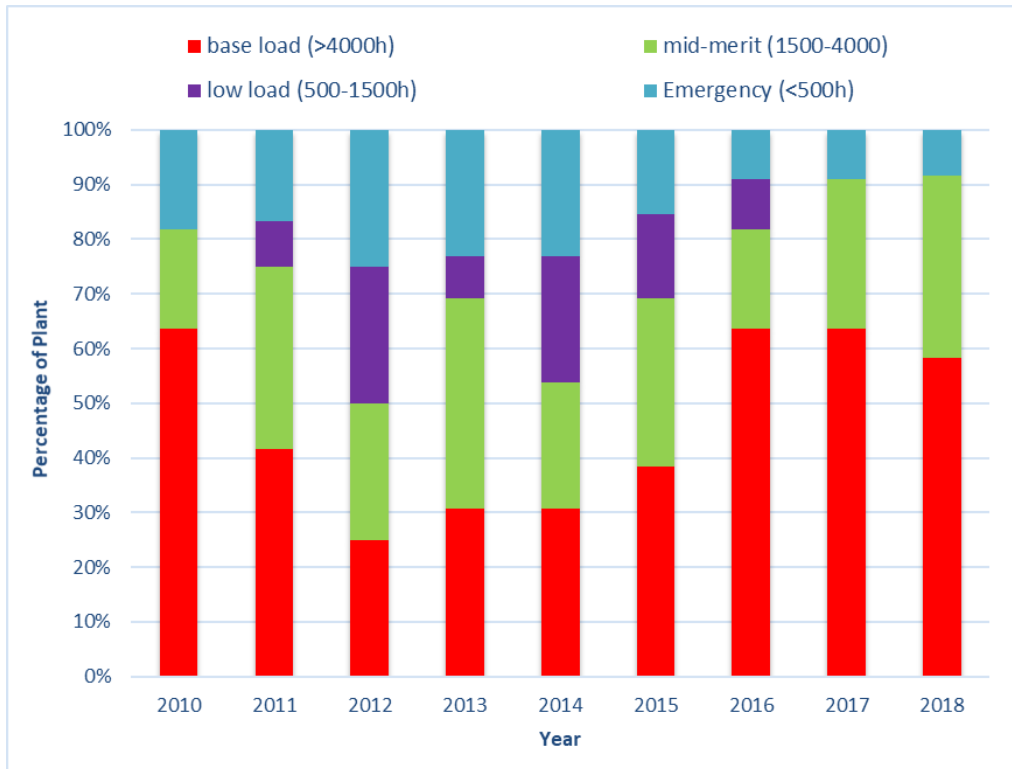
The data provided for 2015 represented a plant that ran for a total of 48hrs. Abstraction and discharge of water continued whilst the plant was not generating electricity. The data shows that water losses continued to occur. As plant was not generating these perceived losses are not attributable to evaporation in the cooling system. It is also very unlikely that losses of this scale could be real without physical effects being seen on site. It is therefore reasonable to make the assumption that the “fraction of consumed water” observed in 2015 of 0.07 could be due to measurement uncertainties, both in the metered abstracted and discharged water. These are within the MCERT range of ±8%.

The significance of these uncertainties / metering errors are reduced when larger evaporative losses, at high operational loads are occurring. However, when site has low/emergency operation, these systematic influences dominate the m<sup>3</sup>/MWh data produced, when the data covering such operation includes periods of no load CW operation, illustrating that care needs to be taken when considering such low load / emergency operation.

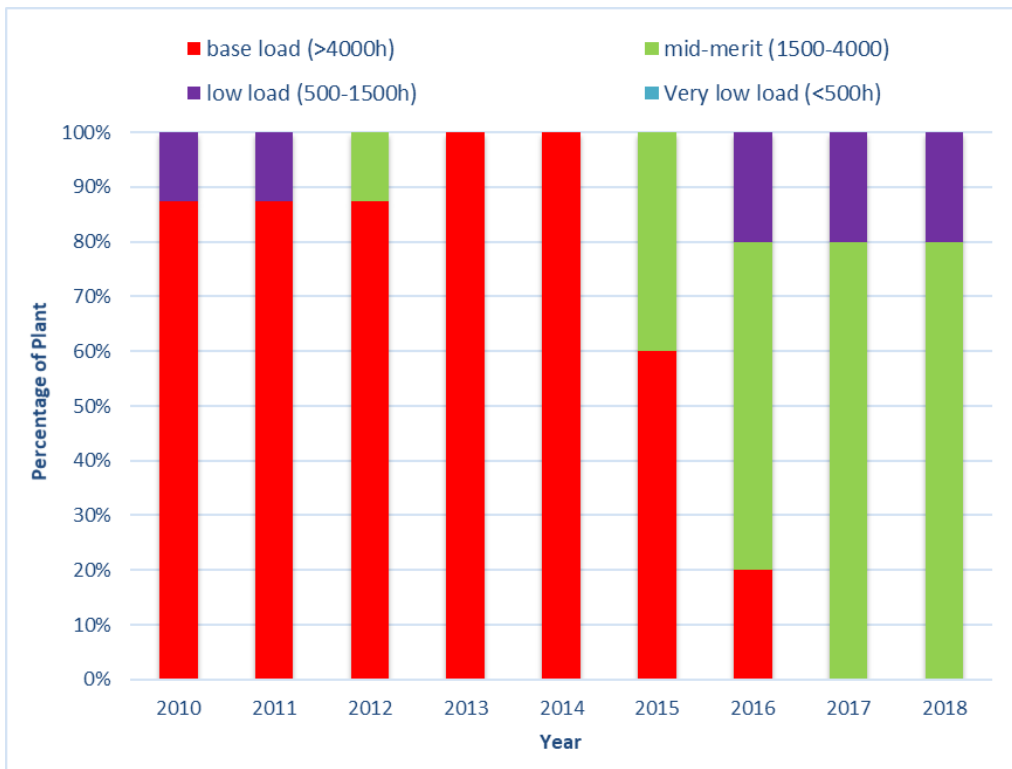
## 6.6 Changing Operation of JEP/UK Fleet

Based on the data reported between 2010<sup>21</sup> and 2018 it can be seen that there has been a change in plant operation of CCGT plant across the JEP fleet. Figure 6 shows that in 2010 over 60% of CCGT plant were operating as base load plant, with another approximately 20% operating in mid-merit mode and 15% as very low load plant. By 2014, the percentage of CCGT base load plant decreased to around 30%, compared to an observed increase in low and very low load operating plant to 45%. This was interpreted as a reflection of what has been seen across England since 2010 primarily due to high gas prices [DECC, 2014] as well as the need to meet more flexible demand due to the increase in the UK’s off-shore and on-shore wind portfolio. More recently, CCGT plant have increased in the base load provision they provide, this was due to the significant decrease in electricity generation from hard coal, which accounted for only 2.5% of the national generation in 2018 quarter 4 (BEIS, 2018), compared to 20% in 2014 quarter 4. This is reflected by the change in hard coal generation profile observed for JEP plant in Figure 7.

<sup>21</sup> There was only 1 data record for 2008 and 2009 so this was not included in the analysis.



**Figure 6: The change in operational mode of CCGT plant reported in the study between 2010 and 2018**



**Figure 7: The change in operational mode of hard coal plant reported in the study between 2010 and 2018**

The data obtained in this study indicates that as CCGT plant are required to become more flexible, resulting in lower loads, higher incidence of part load operation and more starts and stops, due to the intermittent electricity supply from renewables, then water consumption based on a m<sup>3</sup>/MWh approach will be seen to increase. This does not necessarily mean that their operation is deteriorating from a water use perspective but rather should be seen as a consequence of the changing role they are delivering being related both to the electricity produced and their availability to provide that electricity when the market conditions demand it.

## 7 CONCLUSIONS

1. Thermal power plant<sup>22</sup> use water for several different purposes. The amount of water used can differ significantly between plant of different types and playing different roles within the market. It can vary significantly over time for a given plant.
2. The data provided in this report provide the best available indication of the range of water use in existing UK plant in current market conditions.
3. Future plant will be required to become “flexible operators” as they will have a key role in balancing the grid in order to ensure a secure electricity supply. In some circumstances this will adversely affect water consumption based on a m<sup>3</sup>/MWh approach. This should not be seen as a deterioration in water use efficiency but should rather be seen as a consequence of the shift in the role of the plant from electricity production towards availability provision.
4. It is important to recognise the potential to provide electricity (capacity) as a product in its own right, separate to the actual provision of electricity. Electricity Market Reform has resulted in the introduction of reward for availability through the capacity auction mechanism, along with penalties should plant be called upon to operate but be unable to do so.
5. The choice of steam-cycle cooling technique is likely to dominate the water use characteristics of a given thermal power plant. In the EU this choice is made in the context of BAT which requires consideration not only of the pros and cons of alternative techniques for the aquatic environment but also for the atmosphere, the terrestrial environment and their potentially affected receptors as well as costs of the alternatives. This choice is made during plant siting and design phases. It is not usually technically or commercially feasible to change this choice for an existing plant.
6. Use of water by thermal power plant for steam-cycle cooling leads to improved thermal efficiency compared with dry-cooling. This improved efficiency delivers many key benefits, including more electricity produced for a given fuel consumption. This has life-cycle advantages, as well as reduced costs, which in turn contribute to the affordability of electricity supply. Another benefit is reduced specific emissions to air (i.e. mass emitted/MWh produced) and reduced specific production of waste and by-products. It also provides increased resilience to high air temperature events.

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<sup>22</sup> As discussed in the text the focus of the conclusions is thermal power plant designed to produce electricity. Separate considerations apply for thermal power plant delivering significant amounts of steam or heat as primary products. For a given plant the output characteristics are established at the design stage and it is not usually practicable to subsequently modify them.

7. The selection of appropriate metrics for water use requires care as does the interpretation of reported water use for operating plant in the form of such metrics.
8. For European water-dependent thermal power plant a key principal is to use water responsibly and optimally in line with BAT. This is not necessarily synonymous with water use minimisation (as evidenced through water use metrics). In some cases improving water use efficiency may not be consistent with BAT principles and/or other policy objectives, for example if there are other environmental benefits gained from water use arrangements.
9. Different levels of water use in different plant can still be consistent with responsible and optimal water use, taking into account such factors as indicative sector BAT, site-specific BAT and the site-specific meteorology, water temperature and receptor distribution and sensitivity in the bodies of water used by the different plant. Thus, the selection and application of specific values of water use metrics as 'benchmarks' or 'targets' for thermal power plant may be inappropriate. Reported water use for a given plant lying outside an anticipated range does not automatically imply an inefficient or inappropriate use of water. Rather, it might trigger the need for a more detailed understanding of the circumstances and reporting basis for that plant in order to determine whether or not that water use was appropriate.
10. Water efficiency, intensity or use metrics based on considerations of water used per unit electricity produced may not fully capture the societal benefit provided by the use and availability of water-cooled thermal power plant. Such metrics do not capture security of electricity supply considerations linked to reliable provision of capacity available to generate.
11. Actual use of water needs to be distinguished carefully from use of water resource rights. Plant and society may derive significant value in contribution to system resilience from the availability of a thermal power plant to generate even when it is not called upon to do so. Availability to generate requires not only the technical capability of the plant to operate but also the legal right to access the water it requires to operate.
12. New build thermal power plant are required to deliver the "Pathways to 2050" low carbon energy scenarios set out by UK Government and these plant will continue to require access to water. For investment to occur sufficient investor confidence in future reliable access to sufficient quantities of water through the envisaged commercial life of the plant will be required. Similar considerations apply to significant investment in retro-fits and upgrades to existing water-dependent thermal power plant.
13. There is considerable uncertainty in the potential future freshwater needs of the sector at national and regional level. This is intrinsically linked both to the composition of the thermal generating fleet of the future which will evolve as a result of a wide range of individual operator choices, and the role it is called upon to deliver in ensuring the resilience of electricity supply in the pathway to a net zero carbon 2050.

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