Methodology report on the enhancement of ETSAP ETechDS database with cooling technology parameters for thermal power plants

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Foreword

This report contains a succinct explanation on the methodology used to include in the ETSAP ETechDS database information on cooling technology parameters for power plants. The report is divided into four chapters. Chapter 1 presents the background and motivation for the enhancement of the ETechDS. Chapter 2 gives an overview of the current literature and main data sources used for expanding the ETechDS, while Chapter 3 highlights the methodological approach used. Finally, Chapter 4 briefly discusses the limitations and possible future improvements. This report is complemented by a repository of cooling systems and water saving measures for power plants, and enhanced ETechDS data sheets for power plants. The authors wish to thank Patrícia Veloso from EDP, Portugal; Anna Krook Riekkola from Luleö Technical University, Sweden; Fredrik Engstrom from Vattenfall, Sweden; Marion Labatut from Eurelectric; Jean-François Lehougre from VGB, Germany and Dominique Lafond, Mounir Mecheri and Wim van Ackooij from EDF, France for their technical input on water use for electricity generation.

Contents

1

Background and motivation

This report summarises work done on expanding and enhancing the ETSAP ETechDS database with cooling technology parameters for thermal power plants, which took place between June 2016 and March 2017, and was funded by the IEA-ETSAP. This report complements the other deliverables of the project, namely:

- A repository of cooling systems and water saving measures for power plants; and
- ETechDS technology briefs extended by characteristics of cooling technologies for thermal power plants.

There is an increased demand for water, food, and energy due to factors such as population growth and mobility, economic development, technological advancement, dietary shifts, and climate change (Hoff, 2011). Of the three nexus elements, water availability and quality seems to be the central issue (Logan, 2015). Water issues such as water redistribution over vast distances (e.g. by diverting water from one watershed to another) and, particularly in highly arid regions, extensive water production through seawater desalination, are often addressed with energy requirements taken into consideration. Most of this energy is currently derived from fossil fuels, which contribute to increased carbon dioxide emissions and climate change. Thus, energy and water resource systems are fundamentally interrelated and the two resources cannot be managed separately (Hamiche, Stambouli, & Flazi, 2016; Hoff, 2011; Mekonnen, Gerbens-Leenes, & Hoekstra, 2015; OCDE/IEA, 2016). In fact, the availability of each affects the availability of the other and thus, the declining availability of water will have an increasing impact on the energy sector (Davies, Kyle, & Edmonds, 2013; van Vliet et al., 2016).

According to the IEA’s 2016 World Energy Outlook, the energy sector (including power generation and primary energy production) accounted for 10% of total worldwide water withdrawals and around 3% of total water consumption in 2014 (OECD/IEA, 2016). The rate of demand growth for water has been double the rate of population growth over the last few decades. Over the next 25 years, water withdrawals are expected to increase by almost 10% from 2014 levels, while consumption rises by over 20% over the same period (OECD/IEA, 2016). The water footprint of different energy technologies can therefore be expected to become an increasingly competitive issue (Siddiqi & Anadon, 2011; van Vliet et al., 2016). The energy sector cites water as 1 of 6 key themes that will define its future, and it is becoming an increasingly important factor for assessing the physical, economic and environmental feasibility of energy projects (OCDE/IEA, 2016). For analysing future energy technology deployment and energy policies, the water-energy nexus represents an essential topic to be dealt with, and modelling tools need to consider this (Bazilian et al., 2011; Howells et al., 2013). The ETSAP energy technology repository (ETechDS) provides information and data on a large portfolio of energy technologies including techno-economic parameters. However, information on the water consumption and withdrawal of these technologies is missing thus far. It is a fact that, while water and energy are highly interconnected, models to estimate the future development of water and energy systems are usually uncorrelated and consider each resource separately. This report details the work undertaken to enhance the ETechsDS to include different cooling technologies and their main characteristics for thermal electricity generation technologies.

The data set which accompanies this report provides a basis for new features to be integrated into different TIMES models (national/regional/global), and is available to be used by TIMES modelling teams for enhanced energy and water systems analysis.

2

Literature review and information sources

The literature review focused not only on scientific publications, but also on technical reports, and sustainability reports for several electricity companies, as detailed in Table 1. Data collection prioritised European based companies and sources, since most existing published studies refer to data from the USA, which is regularly collected from power companies in the U.S. Geological Survey.

The review found that many published sources cross-reference each other and that most refer back to the work done in the USA by the NETL – National Energy Technologies Laboratory starting in 2006 (NETL/DOE, 2006) or follow-up work by the Argonne National Laboratory in 2011 (Wu & Peng, 2011) and in particular by the NREL – National Renewable Energy Laboratory (Macknick, Newmark, Heath, & Hallett, 2011, 2012). The work of Macknick *et al.* was expanded and updated with a life-cycle approach by (Meldrum, Nettles-Anderson, Heath, & Macknick, 2013).

Some European work on water use of power plants has been published for the UK (Byers, Hall, & Amezaga, 2014; Murrant, Quinn, & Chapman, 2015) and for Spain (Rio Carrillo & Frei, 2009), but in the former the authors refer to (Macknick et al., 2012) and in the latter to NETL publications. More recently some studies have been published for China (Qin, Curmi, Kopec, Allwood, & Richards, 2015), which seem to combine some specific national information for coal power plants, while relying on (Macknick et al., 2012) for other power plants.

An initiative that has compiled more recent data is the pilot project led by ECOFYS for the DG Environment of the European Commission (ECOFYS, TNO, & DELTARES, 2014) which has used some data from (Macknick et al., 2012), but collected new data from EU-wide power plants via a survey. Further publications by ECN demonstrate how these data can be used to perform regional and country specific analyses (for example in the MENA region and in Kenya) that examine water stress issues depending upon different climate mitigation scenarios (van der Zwaan et al., 2015; M. Halstead et al., 2014).

Table 1: Overview of main identified literature data sources

#	Type of source/ Title	Scope	Water consumption / withdrawal data source
	Scientific Publications		
S1	Li, Q., Wei, Y.-N., & Chen, Z.-A. (2016). Water-CCUS nexus: challenges and opportunities of China's coal chemical industry. Clean Technologies and Environmental Policy, 18(3), 775–786. Available at: [https://doi.org/10.1007/s10098-015-1049-z]	China	Unknown
S2	Murrant, D., Quinn, A., & Chapman, L. (2015). The water-energy nexus: future water resource availability and its implications on UK thermal power generation. Water and Environment Journal, 29(3), 307–319. Available at: [https://doi.org/10.1111/wej.12126]	UK	Based on (Macknick et al., 2011) and on (Tzimas, 2011)
S3	Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. Environ. Sci.: Water Res. Technol., 1(3), 285–297. https://doi.org/10.1039/C5EW00026B	Global	Based on (Meldrum et al., 2013)
S4	Qin, Y., Curmi, E., Kopec, G. M., Allwood, J. M., & Richards, K. S. (2015). China's energy-water nexus – assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy. Energy Policy, 82, 131–143. https://doi.org/10.1016/j.enpol.2015.03.013	China	Own data for coal, adjusted with (Macknick et al., 2011). (Meldrum et al., 2013) for other plants.
S5	Byers, E. A., Hall, J. W., & Amezaga, J. M. (2014). Electricity generation and cooling water use: UK pathways to 2050. Global Environmental Change, 25, 16–30. Available at: 8https://doi.org/10.1016/j.gloenvcha.2014.01.005 9]	UK	Based on (Macknick et al., 2011) and on (Tzimas, 2011)
S6	Davies, E. G. R., Kyle, P., & Edmonds, J. A. (2013). An integrated assessment of global and regional water demands for electricity generation to 2095. Advances in Water Resources, 52, 296–313. Available at: [https://doi.org/10.1016/j.advwatres.2012.11.020]	Global	Based on (Macknick et al., 2011)
S7	Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J. (2013) Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ. Res. Lett. 8 (2013) 015031. 18pp	USA	Updated and expanded data from extensive review - including (Macknick et al., 2011).
S8	Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters, 7(45802). Available at: [https://doi.org/10.1088/1748-9326/7/4/045802]	USA	Based on (Macknick et al., 2011)
S9	Zhai, H., Rubin, E.S., Versteeg, P. (2011). Water Use at Pulverized Coal Power Plants with Postcombustion Carbon Capture and Storage. Environmental Science & Technology, 45 (6), pp. 2479-2485. DOI: 10.1021/es1034443	USA	Own estimates based on detailed assumptions on plant characteristics.
S10	Zhai, H., & Rubin, E. S. (2011). Carbon capture effects on water use at pulverized coal power plants. Energy Procedia, 4, 2238–2244. Available at: [https://doi.org/10.1016/j.egypro.2011.02.112]	USA	Own data used in USDOE/NETL model.
S11	Rio Carrillo, A. M., & Frei, C. (2009). Water: A key resource in energy production. Energy Policy, 37(11), 4303–4312. Available at: [https://doi.org/10.1016/j.enpol.2009.05.074]	Spain	NTEL 2007 data (NETL/DOE, 2006)
	Technical reports and presentations – not electricity industry		
T1	IPTS - Joint Research Centre (2016). Best Available Techniques (BAT) Reference Document for Large Combustion Plants. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). JOINT RESEARCH CENTRE - Institute for	EU	No quantitative systematic data on water consumption per type of large combustion plant,

#	Type of source/ Title	Scope	Water consumption / withdrawal data source
	Prospective Technological Studies Sustainable Production and Consumption Unit. European IPPC Bureau. Final Draft (June 2016). Available at: [http://eippcb.jrc.ec.europa.eu/reference/BREF/LCP_FinalDraft_06_2016.pdf]		only indication on consumption for pollution abatement technologies (e.g. scrubbers)
T2	WBCSD (2015). Global Water Tool for Power Utilities. World Business Council for Sustainable Development. Available at: http://old.wbcsd.org/work-program/sector-projects/water/global-water-tool.aspx	Global	Very aggregated information for generic types of plants.
T3	ECOFYS, TNO, DELTARES (2014). Pilot project on availability, use and sustainability of water production of nuclear and fossil energy –Geo-localized inventory of water use in cooling processes, assessment of vulnerability and of water use management measures – End-Report. Funded by DG Environment. Available at: [http://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf]	EU	(Macknick et al., 2012) combined with direct data gathering to acquire specific information on cooling water intake from EU power companies and complemented with "RWE Npower review 2013"[1], presented in Table 8 of the document.
T4	JRC-IET. (2014). ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. JRC Science and Policy Report. JRC92496. 108pp. Available at: [https://setis.ec.europa.eu/system/files/ETRI_2014.pdf]	EU	Not entirely clear what were the sources. For nuclear power plants was (Duval & Samie, 2011).
T5	UK Environment Agency. (2013). Water use and electricity generation. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/489409/LIT_8990.pdf]	UK	Information from study "Water demand for Carbon Capture and Storage (CCS), Parsons Brinkerhoff, November 2012"[2]
T6	Macknick, J., Newmark, R., Heath, G., Hallett, KC. (2011). A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies. 23pp. NREL Technical Report NREL/TP-6A20-50900. March 2011. Golden, Colorado-USA.	USA	Own elaboration based on original data collected from USA companies by the USGS - U.S. Geological Survey and the U.S. Department of Energy's Energy Information Administration (EIA).
T7	Wu, M., Peng, M. J. (2011). Developing a tool to estimate water use in electric power generation in the United States. Argonne National Laboratory. ANL/ESD/11-2 Update	USA	Own elaboration based on original data collected from USA companies by the USGS and the U.S. Department of Energy's Energy Information Administration (EIA).
T8	Argonne National Laboratory and DOE. (2011). Water use in the development and operation of Geothermal power plants.	USA	Several references in its Table 3-2[3]

[1] Not available to the authors of this report.

[2] There are several sources for this document.

[3] Asanuma, H., Y. Kumano, T. Izumi, N. Soma, H. Kaieda, K. Tezuka, D. Wyborn, and H. Niitsuma, 2004, "Passive Seismic Monitoring of a Stimulation of HDR Geothermal Reservoir at Cooper Basin, Australia," Technical Program Expanded Abstracts 23:556-559, Society of Exploration Geophysists.;

Tester, J.W., et al. (2006), "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century," Massachusetts Institute of Technology, available at http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf;

Michelet, S., and M.N. Toksöz, 2006, "Fracture Mapping in the Soultz-sous-Forêts Geothermal Field from Microearthquake Relocation," Earth Resources Laboratory Consortium Report, available at http://www-eaps.mit.edu/erl/research/report1/pdf2006/Michelet06.pdf;

#	Type of source/ Title	Scope	Water consumption / withdrawal data source
	Available at: [https://www1.eere.energy.gov/geothermal/pdfs/geothermal_water_use.pdf]		
T9	Tzimas, E. (2011). Sustainable or Not? Impacts and Uncertainties of Low-Carbon Energy Technologies on Water. Proceedings of AAAS Annual Meeting, Washington DC. Available at: http://ec.europa.eu/dgs/jrc/downloads/jrc_aaas2011_energy_water_tzimas.pdf	EU	Not entirely clear "Data from literature sources and JRC analysis"
T10	EPRI – Electric Power Research Institute. (2011). Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005-2030). pp 94. Available at: [http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023676]	USA	Own elaboration based on original data collected from USA companies by the USGS and the U.S. Department of Energy's Energy Information Administration (EIA).
T11	Duval, P., Samie, R. (2011). Water for electricity. Panorama 2011. IFP Energies nouvelles. Available at: [http://www.ifpenergiesnouvelles.com/content/download/70602/1513828/version/2/file/Panorama2011_12-VA_Eau-Electricite.pdf]	France	Not entirely clear, presumably data supplied by EDF.
T12	IEAGHG (2010). Evaluation and Analysis of Water Usage of Power Plant with CO2 Capture. International Energy Agency Greenhouse Gas R&D Programme. Available at: [http://www.ieaghg.org/docs/General_Docs/Reports/2010-05.pdf]	Global	Detailed modelling based on previous IEAGHG studies.
T13	NETL (2009). Water Requirements for Existing and Emerging Thermoelectric Plant Technologies. U.S. Department of Energy, National Energy Technology Laboratory.	USA	Own surveys made to USA power plants
T15	NETL (2008). Estimating Freshwater Needs to Meet Future Thermoelectric Generation. U.S. Department of Energy, National Energy Technology Laboratory. Requirements, DOE/NETL-400/2007/1304, issued Sept. 2007, revised May.	USA	Own surveys made to USA power plants
T16	NEL, (2007). "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements, 2007 Update," DOE/NETL-400/2007/1304, available at: [http://www.fypower.org/pdf/DOE_WaterNeedsAnalysis_2007.pdf, September 24]	USA	Own surveys made to USA power plants
T17	NETL (2006). Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements. U.S. Department of Energy, National Energy Technology Laboratory. DOE/NETL-2006/1235, Aug.	USA	Own surveys made to USA power plants
T18	Schoonbaert B., The water-energy nexus in the UK: assessing the impact of UK energy policy on future water use in thermoelectric power generation, King's College London (dissertation of MSc degree in Water), August 2012, available at: https://www.kcl.ac.uk/sspp/departments/geography/study/masters/dissertations/Dissertation-2012-Schoonbaert.pdf	UK	Own surveys made to power plants, public released water data from some plants and based on NREL and Macknick; 2011 when missing data
	Electricity Industry reports and presentations		
E1	EPIA (2013). SUSTAINABILITY OF PHOTOVOLTAIC SYSTEMS - The Water Footprint. EPIA / Solar Power Factsheet. Available at: [http://www.solarpowereurope.org/home/]	EU	Based in (Macknick et al., 2011)
E2	EWEA. (2014). Saving water with wind energy. Brussels. Retrieved from	EU	Not entirely clear but most probably (Macknick et

Zimmermann, G., I. Moeck, and G. Blocher, 2009, Cyclic Waterfrac Stimulation to Develop an Enhanced Geothermal System (EGS) — Conceptual Design and Experimental Results, Geothermics 39(1):59-69, March.

#	Type of source/ Title	Scope	Water consumption / withdrawal data source
	http://www.ewea.org/fileadmin/files/library/publications/reports/Saving_water_with_wind_energy.pdf		al., 2011)
E3	ENEL (2015). Seeding Energy – ENEL Sustainability Report 2015	Italy/Global	Detailed information per type of power plant not available.
E4	ENDESA (2015). Annual Report 2015 - Sustainability Report - ENDESA	Spain/ Global	Detailed information per type of power plant not available.
E5	EDF Sustainability Report 2015- EDF	France /Global	Detailed information per type of power plant not available.

Other relevant initiatives / data sources are:

1) The EURELECTRIC Initiative - Blueprint for Europe's Waters: The Role of the Power Sector, that took place in 2012 bringing together experts from the power sector and the water policy fields. This resulted in some presentations[4] but not on a systematisation of water consumption and withdrawal;
2) Report of the UK Environment Agency from 2013 and updated in 2015 on "Water use and electricity generation". The 2015 report was withdrawn from the website on 5th January 2017. However, it made use of several UK-specific sources and studies. Nonetheless, these studies are not available to the general public.

Because of the difficulties accessing non-USA data sources, we contacted directly several electricity companies and other organisations as detailed in Table 2.[5]

Table 2: Contacted experts and organizations requesting information on water use for electricity generation

Organisation	Contact Person	Outcome
EDF power company, France	Mounir Mecheri, Charles Bourdil, Arnaud Pitard, Mathieu Gennevieve	No data was made available Information on water factors
EDP power company, Portugal	Patrícia Veloso	Data for Portuguese thermal power plants
EON power company, Germany	Volker Tuerk	No data was made available
VGB, Germany	Jean-François Lehougre	No data was made available
ENDESA power company, Spain	Nuno Ribeiro da Silva	No data was made available
ENEL power company, Italy	Generic e-mail	No data was made available
Vattenfall power company, Sweden	Frederik Engstrom	Highly detailed data for hydro power plants only
UK Environment Agency	Stuart Taylor	Supplied some of the support studies made by consultancy firm.
Institute for Energy and Transport of the Joint Research Centre of the European Commission, EU	Johan Carlsson	No more updated information than the one available on-line (JRC-IET, 2014)
EURELECTRIC	Marion Labatut	No data available Contact to VGB in Germany
NREL, USA	Jordan Macknik	No more updated information than the one available on-line (Meldrum et al., 2013)
IFP Energies Nouvelles, France	Patrick Duval	No reply
Fondazione Eni Enrico Mattei, Italy	Michela Bevione	Using (Macknick et al., 2012)

4 http://www.eurelectric.org/events/blueprint-for-europes-waters-the-role-of-the-power-sector/proceedings/

5 As can be seen in the column 'Outcome' we had limited success in getting responses from the power companies in particular.

Considering the limitations encountered, the data gathered originated mainly from the following sources:

- Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters, 7(45802). Available at: [https://doi.org/10.1088/1748-9326/7/4/045802];
- Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J. (2013) Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ. Res. Lett. 8 (2013) 015031. 18pp;
- NETL (2009). Water Requirements for Existing and Emerging Thermoelectric Plant Technologies. U.S. Department of Energy, National Energy Technology Laboratory.
- Zhai, H., Rubin, E.S., Versteeg, P. (2011). Water Use at Pulverized Coal Power Plants with Postcombustion Carbon Capture and Storage. Environmental Science & Technology, 45 (6), pp. 2479-2485. DOI: 10.1021/es1034443
- Argonne National Laboratory and DOE. (2011). Water use in the development and operation of Geothermal power plants. Available at: [https://www1.eere.energy.gov/geothermal/pdfs/geothermal_water_use.pdf]
- EPRI – Eletric Power Research Institute. (2011). Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005-2030). pp 94. Available at: [http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023676]
- ECOFYS, TNO, DELTARES (2014). Pilot project on availability, use and sustainability of water production of nuclear and fossil energy –Geo-localized inventory of water use in cooling processes, assessment of vulnerability and of water use management measures – End-Report. Funded by DG Environment. Available at: [http://ec.europa.eu/environment/archives/water/adaptation/pdf/InventoryCoolingWaterUse.pdf]

3

Approach

According to the definition adopted by the USGS (Kenny et al., 2009), "water withdrawal" is defined as "the amount of water removed from the ground or diverted from a water source for use", while "water consumption" refers to "the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment". Although several authors have focused on the whole life-cycle of electricity generation (Davies et al., 2013; Meldrum et al., 2013), this report only focuses on the power plants' operational phase only, which includes "cleaning, cooling, and other process-related needs that occur during electricity generation" as in (Macknick et al., 2012).

The literature review focused on obtaining techno-economic parameters of the main cooling systems for power plants based on the thermodynamic Rankine cycle (steam-cycle-process). This primarily applies to power plants based on nuclear energy, coal, gas, oil, biomass, and concentrated solar power (CSP) systems.

Cooling systems are classified here according to the following types: (i) Once-through cooling[6] (O); (ii) Cooling-pond (P); (iii) Wet-cooling towers[7] (T), and (iv) Dry cooling systems[8] (D). Each type is characterised by quantities of water consumption and water withdrawal per unit of energy produced, as shown in Table 3 and Table 4.

6 This cooling method withdraws large quantities of water, but almost all water is returned to water bodies once passed through the heat exchanger. Only a small amount of water is lost via evaporation.

7 For both cooling towers and ponds, water is cooled by exchanging heat from water to the air. Some water is lost through evaporation and the rest of the water is reused in the steam condenser of the power plant. These systems withdraw much less water than once-through systems, but approximately 85% of the water is consumed (EPRI, 2011).

8 Uses air instead of water to cool the steam. Using dry cooling can reduce water consumption by up to 90%. It has much less environmental impact, but because air is not as efficient as water at cooling, it requires more surface area to release waste heat to the environment. Also, plant efficiency is diminished with dry cooling; therefore the system is generally used in areas where water scarcity is an issue (EPRI, 2011).

Table 3: Water consumption factors for the electricity generation technologies

Technology	Cooling	Gallons/MWh		Litres/MWh		Source
		Min	Max	Min	Max	
Coal (O)	**Once-trough**	64	317	242		Macknick et al. (2012);
Coal (P)	**Pond**	4	804	15		Macknick et al. (2012);
Coal (T)	**Tower**	318	1,100	1,204		Macknick et al. (2012);
Natural gas (O)	**Once-trough**	20	291	76		Macknick et al. (2012);
Natural gas (P)	**Pond**	240	270	908		Macknick et al. (2012);
Natural gas (T)	**Tower**	130	1,170	492		Macknick et al. (2012); Argonne (2011)
Natural gas (D)	**Dry**	0	4	1		Macknick et al. (2012);
Nuclear (O)	**Once-trough**	100	400	379		Macknick et al. (2012);
Nuclear (P)	**Pond**	560	720	2,120		Macknick et al. (2012);
Nuclear (T)	**Tower**	581	845	2,199		Macknick et al. (2012);
Biopower (O)	**Once-trough**	300	300	1,136		Argonne (2011)
Biopower (P)	**Pond**	300	480	1,136		Macknick et al. (2012);
Biopower (T)	**Tower**	235	965	890		Macknick et al. (2012);
Biopower (D)	**Dry**	35	35	132		Macknick et al. (2012);
CSP (T)	**Tower**	725	1,057	2,744		Macknick et al. (2012);
CSP (D)	**Dry**	26	79	98		Macknick et al. (2012);
CSP (N)	**None**	4	6	15		Macknick et al. (2012);
PV (N)	**None**	1	94	4		Macknick et al. (2012); EPIA (2013); Meldrum et al. (2013)
Wind (N)	**None**	0	11	1		Macknick et al. (2012); Meldrum et al. (2013)

Table 4: Water withdrawal factors for the electricity generation technologies

Technology	Cooling	Gallons/MWh		Litres/MWh		Source
		Min	Max	Min	Max	
Coal (O)	Once-trough	20,000	50,000	75,708	189,270	Macknick et al. (2012);
Coal (P)	Pond	300	24,000	1,136	90,850	Macknick et al. (2012);
Coal (T)	Tower	358	1,329	1,355	5,031	Macknick et al. (2012);
Natural gas (O)	Once-trough	7,500	60,000	28,391	227,124	Macknick et al. (2012);
Natural gas (P)	Pond	270	6,000	1,022	22,712	Macknick et al. (2012);
Natural gas (T)	Tower	150	1,460	568	5,527	Macknick et al. (2012); Argonne (2011)
Natural gas (D)	Dry	0	4	1	15	Macknick et al. (2012);
Nuclear (O)	Once-trough	25,000	60,000	94,635	227,124	Macknick et al. (2012);
Nuclear (P)	Pond	500	13,000	1,893	49,210	Macknick et al. (2012);
Nuclear (T)	Tower	800	2,600	3,028	9,842	Macknick et al. (2012);
Biopower (O)	Once-trough	20,000	50,000	75,708	189,270	Argonne (2011)
Biopower (P)	Pond	300	600	1,136	2,271	Macknick et al. (2012);
Biopower (T)	Tower	500	1,460	1,893	5,527	Macknick et al. (2012);
Biopower (D)	Dry	35	35	132	132	Macknick et al. (2012);
CSP (T)	Tower	725	1,057	2,744	4,001	Macknick et al. (2012);
CSP (D)	Dry	26	79	98	299	Macknick et al. (2012);
CSP (N)	None	4	6	15	23	Macknick et al. (2012);
PV (N)	None	1	94	4	356	Macknick et al. (2012); EPIA (2013); Meldrum et al. (2013)
Wind (N)	None	14	84	53	318	Macknick et al. (2012); Meldrum et al. (2013)

Based on the data sources previously mentioned, the following ETSAP ETechs have been enhanced to include data on water consumption and withdrawal:

- E01 - Coal Fired Power Plants
- E02 - Gas Fired Power Plants
- E03 - Nuclear Power
- E05 - Biomass for Heat & Power
- E10 - Concentrated Solar Power.

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Limitations

There are large gaps in data for full lifecycle water withdrawal and consumption factors for different energy technologies with different cooling systems. Moreover, most of the literature reviewed refers to a single data source (Macknick et al. (2012)). Further work needs to be carried out in this area in order to develop accurate data from a range of sources, and it would in any case be beneficial for both the research and policy-making communities to attempt to fill these gaps to enhance our understanding of the energy-water nexus.

For example, and not exhaustively, different factors can influence water consumption, apart from the type of cooling technology:

- The local weather conditions (as the temperature of water, air, humidity in the air);
- The imposed environmental constraints (as the capped water temperature rise);
- The seasonal constraints (as the capped water extraction flow);
- The network constraints (as the need to vary the load of the power plants).

Thus, the water consumption quantification is difficult because it depends on all these factors mentioned above. Moreover, companies can be hesitant to release data that they might deem as sensitive. For further development, some generalizations make it possible to have estimations of water consumption levels that are different by orders of magnitude. Notably, Martin & Wauters (2009) estimate that (depending on the imposed constraints), the cooling water flow rate is 50 to 100 times higher than that of the steam in the closed circuit. Another way of calculating the required cooling water flow rate is to consider that the thermal (energy) losses to the condenser are about 60% of the thermal energy supplied by the boiler when the production cycle is considered with a 35% of electrical efficiency (it is assumed that the boiler loses about 5%)[9].

This study did not investigate the costs of different cooling system technologies. The divergent costs between various distinct systems can have far-reaching implications in terms of the water saving potential of power plants in all regions of the world, as well as in terms of the opportunities that may exist for less water-intensive cooling technologies deployable in water-stressed regions. Further work on assessing these

[9] Estimate from EDF, France.

costs is needed, and data resulting from this could be integrated into the ETSAP ETechs briefs.

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