Energy and Water Environmental Trade-Offs of Data Center Cooling Technologies

Sophia Flucker, CEng **Beth Whitehead, PhD** **Robert Tozer, PhD, CEng**
Member ASHRAE
Deborah Andrews, PhD

ABSTRACT

Historically, the rising cost of energy has been a huge driver for data center energy efficiency, and the contribution of this consumption to climate change is ever more evident. As the industry begins to look beyond energy consumption, it has become aware that environmental impact derives not just from energy consumption, but also from our use of natural resources. To ensure optimization measures do not cause a burden shift, these interdependent issues should not be considered in isolation.

Data centers consume energy to power and cool IT equipment. Current optimization efforts largely focus on the operation of cooling technologies. These can be categorized simplistically according to their use of air or water to remove the heat created by the IT equipment. Design decisions are based on the theoretical energy consumption, and resulting running costs that a certain technology has in a given location. However, water is a valuable natural resource and currently it is difficult to expand this analysis to consider its consumption alongside that of energy. It is also difficult to understand whether indirect impacts of water and energy consumption outweigh any savings of one technology over another during operation. For example, water is consumed during the production of energy, the amount of which depends on the source of generation.

To understand these impacts a life cycle approach is required. Such an approach acknowledges that water and energy are consumed from the moment raw materials are extracted and combined into process materials, to the point that it is used and then disposed of. A full life cycle impact of the different cooling technologies in a data center would consider the impacts of operation as well as those embodied in them. This, however, is a time-consuming process. Instead, the industry needs life cycle based tools and metrics that can expedite this decision process. Using life cycle assessment (LCA) to determine a single numerical value for total environmental impact, the work in this paper provides simple equations that allow designers to understand the environmental implications of their water and energy use in different parts of the world. A number of theoretical case studies are then used to demonstrate its application. Future work should look to include embodied impacts.

INTRODUCTION

The last decade has seen much research into the energy consumption of ICT (Koomey 2009) and data centers (Koomey 2011). This research has shown growing levels of consumption and facility numbers well into the future as more of the world comes online. This consumption comes typically from IT equipment and the mechanical services used to support them. The data center industry has reacted to this growth, and improvements to energy efficiency have been well documented (Tozer et al. 2015). However, whilst there are sound scientific methods for improving

Sophia Flucker is a director and **Beth Whitehead** is an associate sustainability engineer at Operational Intelligence, London, UK. **Robert Tozer** is a visiting fellow at LSBU and managing director at Operational Intelligence Ltd, London, UK. **Deborah Andrews** is an associate professor at LSBU, London, UK.

efficiency, such as air management (Tozer et al. 2015), there is still scope for further optimization.

In recent years, the concern with energy consumption has moved beyond the financial implications to its broader impact on the environment. Many metrics have been established, such as PUE, WUE and CUE (power/water/carbon usage effectiveness) to understand these impacts, but they consider different subjects in isolation. This means that in improving PUE, an operator could be shifting the environmental burden to WUE (through additional water consumption). It is difficult for non-environmental experts to understand the true impact that this shift has on the environment, because energy and water have different units of measurement. There is therefore a need for a method of assessment that allows data center designers, owners and operators to understand these trade-offs.

THE ENVIRONMENTAL IMPACT OF ENERGY AND WATER CONSUMPTION

Every human activity creates environmental impacts, which vary in intensity, severity and longevity, and may be positive or negative. Until recently the emphasis of the environmental impact assessment of energy was related to emissions from operation, because the majority of energy was from fossil fuels. The most significant emissions from fossil fuel combustion include CO_2 and other Greenhouse Gases (GHG), sulphur dioxide SO_2, nitrogen oxides NO_x, particulates and substances such as mercury. These substances are emitted to the air, soil and water and can create numerous diverse impacts; examples include human health problems (ranging from the short term/seasonal to death), and damage to and depletion of species (resulting from changes in pH levels of rain and sea water). The recent development of renewable technologies means that many operational emissions and impacts have been reduced and/or eliminated. A comparison of the operation alone is misleading, however, because the inputs, outputs and impacts of the generation technologies differ, and it is therefore necessary to assess these 'embodied' impacts. These are far more numerous and diverse and there can be more than 700 associated with any individual type of technology.

While energy is important for human activity the importance of water cannot be underestimated as it is essential for life and although it is abundant, only 2.5% is fresh and only 1% of that is accessible for direct human use; furthermore the water system is closed, i.e. there is a finite quantity in the ecosphere. Population growth and related land occupation and use, agriculture and irrigation and industrialization mean that demand is continually increasing. Water quality is affected by natural phenomena such as leaching mineral deposits and sedimentation while changes in climate and weather patterns impact on rainfall patterns and levels of surface runoff and absorption. The impacts of human activities also affect water quality and while many supplies have been polluted with pathogens from sewage, toxic chemicals and pesticides from cultivation and industrial processes, other reserves have been depleted and not replenished. These numerous inter-related factors have led to global 'water stress' and cost implications.

LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a systematic tool for assessing iteratively the impact a product, process or service has on the environment (Baumann et al. 2009). LCA is used to assess the environmental impact from raw material extraction (cradle), transportation, the manufacturing and use of the product, and its eventual disposal (grave). There are four stages to an LCA: goal and scope (including system boundaries); life cycle inventory (flows entering and leaving the system); impact assessment (inventory results are translated into environmental impacts); and interpretation (the consequences of the above environmental impacts).

Flows describe materials, energy, emissions or products entering or leaving a system. There are three common flows: elementary, product and waste flows. Elementary flows are untreated materials or energy, whilst product and waste flows are as their names suggest. At the inventory stage flows into (inputs) and out of (outputs) the system are inventoried for a given product (process). Once the inputs and outputs have been quantified, they are classified according to the environmental impacts they contribute to, i.e. CO_2 contributes to climate change. A characterization method then uses cause-effect chains to quantify the relative contribution the emission/material consumption has on environmental impact. For example the global warming potential (GWP) of GHGs can be expressed as CO_{2e}. Using damage models, the relative impact these environmental phenomena have on areas of protection (AoPs), namely human health, ecosystem quality and resources is then calculated, and a weighting applied to provide a single score.

LCAs can be completed to varying degrees of accuracy, from screening to 'full-blown' process-based (detailed) studies (Rebitzer et al. 2004; Baumann et al. 2009). In a screening LCA process-based life cycle inventory (LCI) data from previous studies is used to approximate the environmental impact. By reducing the precision of the study, users can understand the general pattern of impact in a short period of time, and identify potential areas for improvement.

THE ENVIRONMENTAL TRADE-OFF BETWEEN ENERGY AND WATER CONSUMPTION

Goal and Scope

Using a screening LCA, the goal of this study was to provide equations for assessing the environmental trade-off between different cooling technologies based on their water/energy consumption and location. The work aims to understand the general pattern of impact and provide a basis for more detailed investigations. The embodied impacts of the cooling systems are omitted and should be investigated in future work. The functional unit of the study is the provision of cooling for one year. The system boundaries include all inputs and outputs from cradle to grave for the water and electricity, but not impacts embodied in the technology itself.

The electricity data is country-specific, and includes: the electricity production in the relevant country from material extraction; the transmission network; direct SF6-emissions to air; electricity losses during LV transmission (including the HV transmission from the grid); and the transformation between voltages at switching stations (Dones 2007). The assumptions for the transmission network and emissions are based on Swiss data. A European average tap water process was used to represent the water entering a data center. The process included infrastructure and energy use for water treatment and transportation to the end user, but no emissions from water treatment. The process was compiled with estimated data for a water works in Switzerland and energy use in Germany. The data was then adapted using the Pfister et al. (2009) impact factors for regionalization to give an impact based on the water stress index found in each country. It is assumed that for every 1m^3 of water used, 50% is evaporated and 50% requires end treatment. A generic sewage water treatment has been used. Both water processes are likely to underestimate the true impact and should be the subject of future research. All datasets were secondary, based on average technologies, and from the Ecoinvent v2.2 database, with a reference year of early 2000. The Eco-indicator 99 method was used to characterize results. The OpenLCA 1.4.2 software tool was used to run the LCA.

Water Scarcity and Regionalization in LCA

The environmental impact of water consumption is dependent on its origin (country or regional level) and source (ground/surface water, rivers and lakes). Until recently, differentiation between LCA results at a regional level has been difficult because characterization methods did not include indicators and impact factors for water scarcity. There are now a number of methods that give an impact at the midpoint level (no indication of the environmental phenomena that the impact causes). These include: characterization by water stress index (Pfister et al. 2009); ReCiPe (Goedkoop et al. 2009); human health impacts (Boulay et al. 2011); and water footprinting (Hoekstra et al. 2011). However, Pfister et al. (2009) is the only method that provides an impact at the endpoint in all three AoPs (human health, ecosystem quality and resources) for the Eco-indicator and ReCiPe methods. Because these impact factors were not included in the freely available data in OpenLCA, the impact factors for freshwater consumption were applied manually to the inventory results in order to understand the impact of regionalization on the results.

LCA RESULTS AND INTERPRETATION

The results of the LCA are given in Eco-indicator points (Pt). 1,000 Pt are equivalent to the environmental load of one average European in one year. **Figure 1** shows the levels of water and energy consumption required for a given location to yield the same impact of 100,000,000 Eco-indicator points. A WUE/PUE of 6 is assumed to represent a worst-case legacy facility (see Table 2), and a line has been added to the graph. Assuming WUE and PUE values from Table 2, Table 1 below shows what size facility this WUE/PUE value relates to in each country. In Sweden a 16MW IT load, using 2 million m^3/yr of water creates the same impact as a 22kW IT load and 3000 m^3/yr of water in the US. Note, for the purpose of this example, electricity and water loads are taken for the whole facility.

Table 1. IT and Water Loads that Create a 100 Million Pt Impact (WUE=15 and PUE=2.5)

Country	Total Facility Electricity (MWh/yr)	Total Electricity (MW)	IT Electricity (MW)	Total Facility Water (m^3/year)
USA	489.4	0.0559	0.0223	2,936
UK	587.9	0.0671	0.0268	3,527
France	3928	0.448	0.179	23,570
Sweden	352,755	40.2	16.1	2,117,000

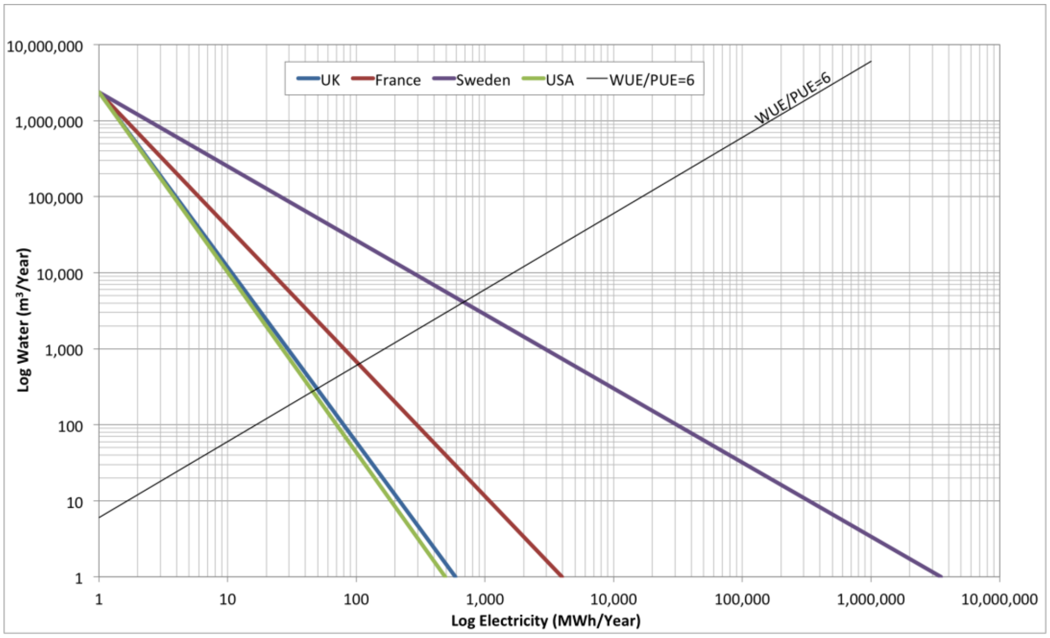

Figure 1. Water and Electricity Consumption that Yields 100,000,000 Pt of LCA Impact for Different Locations

The most important result is therefore the impact the energy mix has on the environmental impact of electricity consumption. The impact from energy consumption in Sweden is logarithmically three orders of magnitude smaller than that in the US (**Figure 1**). This is because the Swedish mix is largely reliant on hydropower and nuclear, whilst the majority of the US and UK mixes are from fossil fuels, and the French from nuclear (see table 15.1 Dones (2007)). Although the datasets were based on old grid mixes, the impact from electricity is so large, that the pattern of results is likely to remain the same until grid mixes resemble that found in Sweden.

When completing an LCA, many factors can change the results – the characterization method, emission timescales, boundaries, allocation, weighting, assumptions, and the life cycle inventory (to name but a few). Validation is therefore important. Turconi et al. (2013) reviewed 167 case studies of electricity generation LCAs with respect to GHG, NO_x and SO_x emissions. It found that the infrastructure provided the highest impact for renewables, and direct emissions for fossil fuels. Comparing life cycle CO_2-eq values, coal ranged from 660-1050 kg/MWh_{out} and hydropower from 2-20 kg/MWh_{out}. Additional studies for coal found ranges up to 1200 kg/MWh_{out}, therefore assuming a mid-range impact of 1000 kg/MWh_{out} for the coal, and a value at the lower end of the hydropower range of 5 kg/MWh_{out}, shows there is three orders of magnitude difference between the results. Although this is based only on GHG emissions, studies of the operation of a UK data center (Whitehead et al. 2015) showed that the next biggest impacts in the operation phase were from carcinogens (PAHs), respiratory inorganics (NO_x and SO_x) and fossil fuels.

These are in abundance during the operation of fossil fuel technologies, but not renewables. It can therefore be concluded that the overall life cycle impact of the fossil fuel technology is likely to be relatively even bigger than that of the renewable technology. This therefore supports the pattern of results found above. For more information on the science behind the characterization of these results, and Cultural Theory used for weighting the results see the Eco-indicator Methodology Report (Goedkoop 2001).

The second thing to note is the bearing this impact from energy mix has on the relationship between water and power impact. The less renewables, the lower the impact the water consumption has relatively. It would, therefore be easy for these countries to ignore the topic, when in reality solutions should be sought to resolve the cause, which is a need for more renewables, either on- or off-grid, whilst also limiting water consumption.

APPLICATION OF THE RESULTS

For a given country, the following equations can be used to calculate the environmental impact experienced in one year from operating a cooling system, where Pt are Eco-indicator points for the subscript location, $E_{cooling}$ is the energy used by the cooling system in MWh/year, and $W_{cooling}$ is the water used by the cooling system in m^3/year:

$$Pt_{UK} = 169,866 E_{cooling} + 42.52 W_{cooling} \quad (1)$$

$$Pt_{France} = 25,222 E_{cooling} + 42.50 W_{cooling} \quad (2)$$

$$Pt_{Sweden} = 28.66 E_{cooling} + 42.50 W_{cooling} \quad (3)$$

$$Pt_{USA} = 204,065 E_{cooling} + 42.57 W_{cooling} \quad (4)$$

CASE STUDIES – INDIRECT AIR-SIDE FREE COOLING

Values for WUE/PUE from the data centers of a single company were used to apply the equations shown above. It is assumed that the facility has 1MW of IT, with an average annualized IT loading of 75%. It is assumed that 90% of the non-IT energy is used for cooling. It is a UK site, with a WUE of 0.527 and a PUE of 1.167.

$$E_{IT} = 0.75 \times 1 MW \times 8,760\, hours = 6,570\, MWh/year$$

$$E_{DC} = 6,570 \times 10^3 \times PUE = 6,570 \times 10^3 \times 1.167 = 7,667,190\, kWh/year$$

$$WUE/PUE = 0.527/1.167 = W_{DC}/E_{DC} = 0.452$$

$$Therefore$$

$$W_{DC} = 0.452 \times 7,667,190 = 3,462,390\ liters = 3,462\ m^3$$

Assuming 100% of the onsite water use is for cooling, equation 1 is used to determine the total points:

$$PT_{UK} = 169,866 \times \left(7,667 \times \frac{90}{100} \times (1.167 - 1)\right) + 42.52 \times 3,462 = 195,750,340 + 147,208 = 195,900,000\, Pt/yr$$

The impact from electricity in the UK is 3 orders of magnitude greater than from the water consumption. Assuming the same scenario in Sweden (equation 3), however, finds the greatest impact results from the water consumption:

$$PT_{Sweden} = 28.66 \times (7,667 \times 0.9 \times (1.167 - 1)) + 42.50 \times 3,462 = 33,031 + 147,156 = 180,186\, Pt/yr$$

COMPARISON OF DIFFERENT TECHNOLOGIES

Using the above IT loads and characteristics (1MW IT etc.) PUE values were assumed for different cooling options. For options with chillers, values for COP (coefficient of performance) and η_w (efficiency of water use) have been assumed. Values for WUE and WUE/PUE have been calculated as follows and are shown in Table 2:

$$WUE = \frac{PUE \times seconds/hour}{specific\ enthalpy\ of\ water \times h_w} \times \left(1 + {}^{1}\!/_{COP}\right)\ and\ {}^{WUE}\!/_{PUE} = {}^{W_{DC}}\!/_{E_{DC}}$$

Table 2. PUE, COP, η_w, WUE and WUE/PUE for Various Cooling Technologies

Technology	PUE	Chiller COP	Efficiency of Water η_w (assumed)	WUE	WUE/ PUE	Comments
Worst case legacy	2.5	3	0.33	15	6	
Standard legacy	1.6	6	0.50	5.6	3.5	
Water cooled (100%/yr with cooling towers, no chillers)	1.1		0.50	3.3	3	
Indirect airside free cooling (average energy priority)	1.177			0.825	0.701	WUE/PUE = 0.02 - 2 (site data)
Indirect airside free cooling (average water priority)	1.187			0.47	0.394	
Direct airside free cooling	1.1			0.22	0.2	WUE/PUE = 0 - 1 (assumed)

Table 3 shows the resulting environmental impact for each option in the USA, UK, France and Sweden, and Figure 2 shows the results for Sweden and the USA (the two extreme cases).

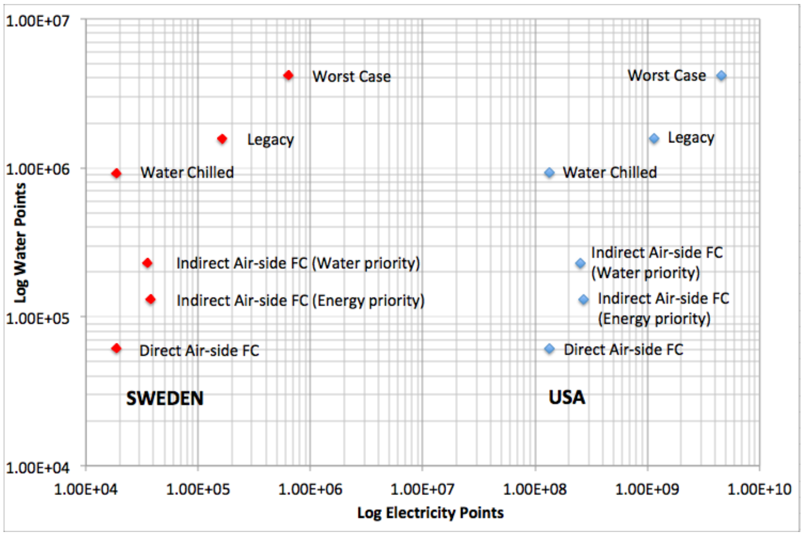

Figure 2. Electricity and Water Points for Different Cooling Technologies in Sweden and the US

For each option, the impact from electricity provides the greatest contribution to environmental impact in the UK, USA and France. In Sweden, the greatest impact comes from any water consumption, even in the case of airside free cooling where water use is limited to humidification purposes only. The over-riding burden in countries with poor access to renewables is therefore from the electricity consumption. The difference in total water impact between the two locations is small (USA is greater for each option). This is because the impact from the water treatment is far greater than the actual consumption itself (two orders of magnitude greater), and in the developed world, there is little difference in the way that water is extracted and transported. The regionalization also has little impact on the results, though this might not be the case if countries experiencing extreme water stress.

Table 3. Total Environmental Impact for Different Cooling Technologies in the USA, UK, France and Sweden

Technology	**Location**	**Electricity Impact (Pt/MWh)**	**Water Impact (Pt/m3)**	**PUE**	**WUE**	**Electricity Pt**	**Water Pt**	**TOTAL Pt**
Worst Case	USA	204065.40	42.57	2.5	15	4,524,895,179	4,195,122	4,529,090,301
	UK	169866.34	42.52	2.5	15	3,766,573,665	4,189,985	3,770,763,650
	France	25221.85	42.50	2.5	15	559,262,937	4,188,772	563,451,709
	Sweden	28.66	42.50	2.5	15	635,564	4,188,496	4,824,060
Standard Legacy	USA	204065.40	42.57	1.6	5.6	1,158,373,166	1,566,179	1,159,939,345
	UK	169866.34	42.52	1.6	5.6	964,242,858	1,564,261	965,807,119
	France	25221.85	42.50	1.6	5.6	143,171,312	1,563,808	144,735,120
	Sweden	28.66	42.50	1.6	5.6	162,704	1,563,705	1,726,410
Water Cooled	USA	204065.40	42.57	1.1	3.3	132,730,259	922,927	133,653,185
	UK	169866.34	42.52	1.1	3.3	110,486,161	921,797	111,407,958
	France	25221.85	42.50	1.1	3.3	16,405,046	921,530	17,326,576
	Sweden	28.66	42.50	1.1	3.3	18,643	921,469	940,112
Indirect Air-side FC	USA	204065.40	42.57	1.177	0.825	251,377,837	230,732	251,608,568
Energy Priority (Av)	UK	169866.34	42.52	1.177	0.825	209,249,740	230,449	209,480,189
	France	25221.85	42.50	1.177	0.825	31,069,517	230,382	31,299,899
	Sweden	28.66	42.50	1.177	0.825	35,308	230,367	265,676
Indirect Air-side FC	USA	204065.40	42.57	1.187	0.468	267,836,389	130,888	267,967,277
Water Priority (Av)	UK	169866.34	42.52	1.187	0.468	222,950,024	130,728	223,080,752
	France	25221.85	42.50	1.187	0.468	33,103,743	130,690	33,234,432
	Sweden	28.66	42.50	1.187	0.468	37,620	130,681	168,301
Direct Air-side FC	USA	204065.40	42.57	1.1	0.22	132,730,259	61,528	132,791,787
(Assumed PUE and WUE)	UK	169866.34	42.52	1.1	0.22	110,486,161	61,453	110,547,614
	France	25221.85	42.50	1.1	0.22	16,405,046	61,435	16,466,481
	Sweden	28.66	42.50	1.1	0.22	18,643	61,431	80,074

CONCLUSIONS AND FUTURE WORK

In countries with high renewables content, water usage should be limited when choosing a cooling solution. In countries with a poor renewables mix, the approach is less straightforward. Globally, governments are looking for ways to move away from fossil fuels towards more renewables. New build data centers that are optimized only for energy rather than water consumption could find themselves in future decades having (relatively) more impact from water consumption (than electricity consumption) than if they had optimized their water consumption as well.

The quality of data also needs to be improved to understand how much the relative impact changes with current grid mix data. For example, UK energy trends for the last quarter of 2015 (DECC 2016) showed that fossil fuels accounted for 81.7% of energy consumption. Production rather than consumption datasets were used because fossil fuels accounted for 74.8% and 71.9% of the mixes respectively. Although there will be seasonal variations in the actual data, it is likely that the electricity impact has still been underestimated.

In the countries assessed, water scarcity had only a small impact on the overall result. In the case of electricity, this is because the contribution of water to the overall impact is relatively minimal. In the case of the water consumption, the majority of the impact comes from the treatment of the bleed-off water. Because a generic wastewater treatment was used, this data also needs to be improved to reflect the contaminants that would be present - for example biocides, algaecides and scale/corrosion inhibitors. It should also be noted that in the case of cooling towers, no impact from drift droplets was included. Further work also needs to focus on countries with poor water availability, such as UAE and Australia, to understand the pattern of this impact in more detail. It should also be noted that if the LCA results were interrogated in more depth (beyond the single score results), based on different environmental phenomena there is likely to be more differences in location selection than suggested by this study.

The work in this paper can help clients decide between facility locations and technology types. It should also focus the industry to look into ways to reduce the volume of bleed-off and it's contents by, for example, material selection in systems. It is clear that for data centers to reduce their total environmental impact, effort should be made to include (where appropriate) on-site renewables such as suggested by Sharma et al. (2010), as well as their water consumption. A cost dimension and embodied impacts from the physical technology should also be added to the selection criteria presented here.

NOMENCLATURE

$\square_{\square\square\square\square\square\square\square}$ = Energy used by the cooling technology
$\square_{DC}$ = Energy used by the data center
$\square_{IT}$ = Energy used by the IT
η_{w} = Efficiency of water use
$\square\square_{\square ountry}$ = Eco-indicator points for the subscripted country
$\square_{\square\square\square\square\square\square\square}$ = Energy used by the cooling technology
W_{DC} = Water used by the data center

REFERENCES

Baumann, H., Tillman, A.-M. 2009. *The Hitch Hiker's Guide to LCA*. Sweden: Studentlitteratur AB.

Boulay A.-M., Bulle C., Bayart J.-B., Deschenes L., Margni M. 2011. Regional Characterization of Freshwater Use in LCA: Modeling Direct Impacts on Human Health. *Environmental Science & Technology*. 45:8948-8957

DECC 2016. *Energy Trends March 2016*. UK: National Statistics

Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenger M., Frischknecht R., Heck T., Jungbluth N., Röder A., Tuchschmid M. 2007. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. Ecoinvent Report No. 5.* http://www.ecoinvent.org/login-databases.html (09/06/2016)

Goedkoop M., Spriensma R. 2001. *The Eco-indicator 99. A Damage Oriented Method for Life Cycle Impact Assessment. Methodology Report.* Third Edition. http://www.pre-sustainability.com/download/misc/EI99_methodology_v3.pdf (17/06/2016)

Goedkoop M., Heijungs R., Huijbregts M. A. J., De Schryver A., Struijs J., van Zelma R. 2009. *ReCiPe 2008 – A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*. First edition. Report I: Characterisation. NL

Hoekstra A. Y., Chapagain A. K., Aldaya M. M., Mekonnen M. M. 2011. *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan: London, Washington.

Koomey J., Belady C., Patterson M. et al 2009. *Assessing Trends Over Time in Performance, Costs and Energy Use for Servers*. Oakland, CA: Analytics Press.

Koomey J. 2011. *Growth in Data Center Electricity Use 2005 to 2010*. Oakland, CA: Analytics Press.

Pfister, S., Koehler A., Hellweg S. 2009 Assessing the Environmental Impact of Freshwater Consumption in LCA. *Environmental Science & Technology.* 43(11):4098-4104

Rebitzer G., Ekvall T., Frischknecht R., Hunkeler D., Norris G., Rydberg T., Schmidt W.-P., Suh S., Weidema B.P., Pennington D.W. 2004. Life Cycle Assessment. Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications, *Environment International*, 30(5):701-720.

Sharma R., Christian T., Arlitt M., Bash C., Patel C. 2010. ES2010-90219 Deisgn of Farm Waste-Driven Supply Side Infrastructure for Data Centers. *Proceedings of ASME 2010 4th International Conference on Energy Sustainability*, Vol 1(2010):523-530

Tozer R, Flucker S. 2015. Data Center Energy-Efficiency Improvement Case Study. *ASHRAE Transactions* 121(1):298-304

Tozer R., Whitehead B., Flucker S. 2015. CH-15-040 Data Center Air Segregation Efficiency. *ASHRAE Transactions* 121(1):454-461

Turconi R., Boldrin A., Astrup T. 2013. Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews.* 28(2013):555-565

Whitehead B., Andrews D., Shah A. 2015. The Life Cycle Assessment of a UK Data Centre. *The International Journal of Life Cycle Assessment.* 20(3):332-349