Development of Life Cycle Water-Demand Coefficients for Coal-Based Power Generation Technologies

Babkir Ali and Amit Kumar[1]

4-9 Mechanical Engineering Building, Department of Mechanical Engineering,

University of Alberta, Edmonton, Alberta, Canada T6G 2G8

Abstract

This paper aims to develop benchmark coefficients for water consumption and water withdrawals over the full life cycle of coal-based power generation. This study considered not only all of the unit operations involved in the full electricity generation life cycle but also compared different coal-based power generating technologies. Overall this study develops the life cycle water footprint for 36 different coal-based electricity generation pathways. Power generation pathways involving new technologies of integrated gasification combined cycle (IGCC) or ultra supercritical technology with coal transportation by conventional means and using dry cooling systems have the least complete life cycle water-demand coefficients of about 1 L/kWh. Sensitivity analysis is conducted to study the impact of power plant performance and coal transportation on the water demand coefficients. The consumption coefficient over life cycle of ultra supercritical or IGCC power plants are 0.12 L/kWh higher when conventional transportation of coal is replaced by coal-log pipeline. Similarly, if the conventional transportation of coal is replaced by its transportation in the form of a slurry

[1] Corresponding Author. Tel.: +1-780-492-7797;fax: +1-780-492-2200.
E-mail address: Amit.Kumar@ualberta.ca (A.Kumar).

through a pipeline, the consumption coefficient of a subcritical power plant increases by 0.52 L/kWh.

Keywords: Water-energy nexus, coal, water consumption, electricity generation, life cycle assessment.

1. Introduction

Coal, one of the main fossil fuels, is heavily used around the world predominantly for the generation of electricity. In the reference case (IEO, 2013) conducted by the U.S. Energy Information Administration (EIA) for the period 2010 to 2040, the generation from coal is expected to grow annually by 1.8% and it was contributed by 40% of the electricity generated globally in 2010 [1]; that is, the 1,759 GW generation capacity in 2010 is expected to rise to 2,384 GW by 2020 and this increase is largely due to the anticipated drastic increase in demand for energy in Asian countries [2].

Total electricity generation capacity from coal in 2006 was 314 GW in the U.S. and in Canada was 16 GW [3]. In the same year, Canada burned about 51 million tonnes of coal to generate electricity. The largest coal deposits are found in the Canadian provinces of British Columbia (B.C.), Alberta, and Saskatchewan, and of the 22 mines in operation, 17 of them are in B.C. and Alberta. It is estimated that Canada holds 190 billion tonnes of coal-in-place, 8.7 billion tonnes of proven resources, and 6.6 billion tonnes considered recoverable with current technologies and economic conditions. These 6.6 billion tonnes are expected to last roughly 100 years [4]. The significant market for coal is Asia and coal for electricity generation is heavily imported by China, Japan, and Korea [5]. In 2011, Alberta, B.C., and Saskatchewan produced 99% of the 67 million tonnes of coal produced in Canada. That same year Alberta exported about 7.1 million tonnes of coal, mainly to Japan, South Korea, and China [6]. Abundant coal reserves, high production rates and favourable economics make coal-based power generation more attractive than other sources of electricity.

However, coal-based power generation is associated with considerable environmental impacts, specifically the consumption of huge amounts of water. In the U.S., total water consumption from coal-based power plants is expected to increase by 21% (from about 3.32 to 4 billion cubic metres [BCM] per year) between 2005 and 2030, and some plants may be vulnerable to water supply-demand conflicts [7]. In Canada, gross water withdrawals during 2009 for thermoelectric power production were 31 BCM and net total consumption was 4.7 BCM [8]. 0.89 BCM was diverted in 2007 for commercial cooling in Alberta [9] and 0.096 BCM was consumed during 2005 [10]. As the demand for energy grows, the water requirement for coal-based power generation will increase.

The amount of water used to generate electricity from coal depends on several factors including the type of coal, the technology used to extract and process coal in its conversion to power, cooling systems, types of reclamation and ash disposal, and the mode of transportation of coal (e.g., through pipelines as slurry). There have been independent studies conducted on water demand related to energy-producing activities as part of the water-energy nexus field [11-13]. Studies have also estimated and projected water demand for power generation with different conversion technologies including coal-based power plants [14-17]. The power generation shift from coal and nuclear based fuels to natural gas will contribute significantly in decreasing the amount of water consumption in the U.S. This decrease is based on the fact that natural gas combined cycle (NGCC) using cooling towers consume 40% of the water consumption by steam cycle using the same cooling system. This expected decrease is based only on the power generation stage without consideration for the fuel extraction stage [14]. Torcellini et al. [15] has taken 1.8 L/kWh as one aggregate coefficient for consumptive water use in the thermoelectric U.S. power plants without consideration to the technology, fuel, and cooling system used. For example, coal can be converted to power through subcritical pulverized coal power plants [18, 19], supercritical coal power plants [20, 21], or ultra-supercritical coal power plants [22, 23]. Similarly, there are variations in water demand depending on the type of cooling system used by the coal power plants, the location of the power plants, and conversion efficiency of the power plant. A study conducted for eleven river basins in Texas, USA [16] showed a potential reduction in water diversion through utilizing more efficient cooling systems, such as cooling towers and dry cooling. The impact of the power plant's efficiency on the water demand is highlighted by King et al. [17] that improvement of a coal power plant's efficiency from 32% to 40% would reduce the water demand by a range of 5% – 10%. But there is a scarcity of research on the full life cycle water consumption of coal-based power generation that includes all the unit operations involved in power generation from coal. Also, there is very limited research on a comparative assessment of life cycle water consumption that takes into account the variations in unit operations involved in the production of power from coal.

This paper aims at addressing the gaps and contributes to the full life cycle assessment taking into account the variations of coal mining and transportation modes, the different power generation and cooling technologies, and impact of the conversion efficiency on the water demand for the power plant. The analysis of the impact of conversion efficiency of the power plant on water demand is another most significant contribution of this paper in the research field of water energy nexus.

The overall objective of this paper is to develop a life cycle water demand paradigm for coal-based power generation. The key objectives of this study are:

- To develop a framework to estimate the life cycle water demand for coal-based power generation including plants with advanced conversion technologies;
- To provide a comparative assessment of the water demand of 36 different pathways in the conversion of coal to power; and
- To assess the impacts on water demand from variations in power plant's performance and coal transportation methods.

2. Methodology

Water-demand coefficients for the complete life cycle are estimated through pathways developed mainly according to the unit operations for both coal extraction and power generation. Coefficients for coal upstream processes are derived from the literature, through calculations and in discussion with experts as volume of water required per unit weight of coal. An average water coefficient is developed for each pathway in cubic meters of water per tonne of coal and converted to the equivalent electricity coefficient in litres of water per kWh using the coal energy content and the conversion efficiency for each technology. Power generated from coal is structured in specific pathways (from cradle to grave), and water-demand coefficients are developed. Some of the water-demand coefficients in the U.S. for specific unit operations were reviewed and used to fill the gap for those pathways not used in coal-based power generation everywhere. Figure 1 shows the system boundary and unit operations considered for this study.

2.1 Definitions

The water-demand coefficient is defined in an earlier study conducted by Argonne National Laboratory (ANL) [24] as the ratio between the water consumed in specific process and the amount produced related to energy. Water-demand coefficients for coal-based power plants comprise the water consumed and water withdrawn during the complete life cycle (that is, the mining of coal and its processing, transportation, and conversion to electricity). Each coefficient is expressed as intensity in terms of the amount of water in litres per kWh of electricity generated.

Terms of water-demand coefficients from the U.S Geological Survey (USGS) are followed in this study. USGS defined water consumption as a portion of water withdrawals that is not returned to the source includes water consumed by evaporation, transpiration, and direct consumption by a product or any involved human or livestock and water withdrawals as the total amount of water that taken from a surface source or underground for use [25]. The difference between water withdrawals and water consumption is the amount returned to the source.

2.2 Selection of coal upstream pathways

Coal upstream pathways are disaggregated according to unit operations and their water footprints. Coal extraction pertains to mining, preparation, and transportation. Other operations are added to cover water demand coefficients for coal upstream and electricity generation.

2.2.1 Coal mining

The surface and underground mining are the two common methods of coal mining, and the geology of the coal deposit is the essential factor in determining which method to use [26]. Underground mining can be carried out by room-and-pillar or long-wall mining [27]. Surface mining recovers coal closer to the surface and is used for about 80% of coal production in Australia and about 67% in the U.S. [28]. Water demand for coal mining depends mainly on the method followed and whether revegetation is required or not. Operations and equipment used for coal mining methods differ and therefore demand different levels of water.

2.2.2 Coal preparation

Coal needs to be crushed and cleaned before being used in power plants as fuel. Coal is prepared by removing impurities, rocks, and some ash-forming materials; this is sometimes referred as coal beneficiation or coal washing [28]. The jig cleaning process, in which coal is separated from the refuse by a pulsating flow of water, is the most common washing method for coarse coal [28, 29].

2.2.3 Coal transportation

Coal can be transported by various means, and the method depends mainly on the distance travelled. Coal transportation methods include conventional and unconventional means. The conventional type in this study is meant to cover all types of moving vehicles and electric conveyors. Unconventional transportation covers different types of pipeline transport. Thermal coal used for coal-based power plants in Canada needs little transportation, but when coal is exported, it is transported long distances by rail. In Canada, more coal is transported by rail than any other commodity [30]. Pipelines are another way to transport coal, either in a slurry pipeline (SP) or a coal log pipeline (CLP).

2.2.4 Other operations

Separate water-demand coefficients are reserved for other operations resulting from upstream coal mining activities and plant operation activities. These other operations include ash handling, dust suppression, desulphurization, and plant decommissioning [31].

2.3 Selection of coal-fired generation pathways

The life cycle assessment in this study covers a number of electricity generation processes. The two main factors affecting water footprints in this stage are conversion technology which determines the level of power plant performance and cooling system used.

2.3.1 Coal-powered plant technology

Coal power plant technology is determined in this study according to the boiler operation conditions. The four most common coal power technologies are subcritical pulverized coal, supercritical pulverized coal, ultra supercritical pulverized coal, and integrated gasification combined cycle (IGCC). Improving the efficiency of coal-based power plants is critical in order to alleviate environmental impacts. Conventional subcritical coal power plants are being replaced by the more advanced and higher efficiency supercritical and ultra supercritical plants [32, 33].

2.3.2 Coal-powered plant cooling systems

Cooling system is one of the essential unit operations in a coal power plant. Steam is generated through the boiler and passed to the turbine to generate electricity. The steam expanded from the turbine then has to be condensed to water and pumped back to the boiler to start a new cycle. This condensation of steam to water is carried-out through the cooling systems which necessitates passing of cooling medium to remove the heat. This cooling medium can be water as in wet cooling systems or air as in dry cooling systems [34]. Types of cooling systems considered in this study are once-through, closed loop cooling (cooling towers and cooling pond), and dry cooling [34, 35, 36]. In the U.S., nearly half (48%) the coal-fired power plants use wet re-circulating cooling systems; 39.1% use once-through systems, 0.2% use dry cooling systems, and 12.7% use cooling pond systems [37].

Theoretically the heat rejection rate (H_R) through the steam cycle is greater than the useful output power (U_s) for all plants with cycle efficiency (η) less than 50%. This is shown in the following equation [38]:

$$H_R = U_s * ((1/\eta) - 1) \qquad (1)$$

Cycle efficiency (η) in eq. (1) is expressed in decimal fraction. Using this equation, for a coal-fired power plant with a net output of 450 MW and a cycle efficiency of 40%, the heat rejection rate is 675 MW, which is 1.5 times the amount of useful power and has to be removed through a cooling system.

2.3.2.1 Once-through cooling system

Once-through cooling in coal-based power plants is a system in which water is drawn from a natural source such as a river or a lake, passed through pipes to extract heat from the steam in the power system, and then discharged back to the water source. Heat rejection through evaporation from the mixture is a common process in all once-through cooling systems and water consumption is lower and water withdrawals is higher compared to closed loop cooling systems [38, 39, 40]. Heat rejection requires cooling water to be passed through the condenser. The water flow rate per megawatt (MW) of power output can be calculated as:

$$\mathbf{WF = 1550 * (1 - \eta) / (\Delta T * \eta)} \quad \textbf{(2)}$$

where (WF) is the amount of water in m^3/h/MW of generating capacity, (ΔT) the temperature rise of the cooling water in °F, and (η) is the thermodynamic efficiency of the power plant, expressed as decimal fraction [41].

2.3.2.2 Closed-loop cooling systems

In closed-loop systems that use cooling towers, water is circulated between the condenser and the cooling tower. A natural water source is used to feed the make-up water and receive the blow-down. The cooling devices can be wet or dry cooling towers, spray ponds, or spray canals and this type of cooling is characterized by higher water consumption and much lower water withdrawals compared to open loop systems [38, 39, 40]. Cooling ponds can be used instead of cooling towers in the closed-loop cooling systems.

In these cooling systems, theoretical make-up water requirements (WR) in m^3/h can be calculated as follows [42]:

$$\mathbf{WR = E * (1/ (1- (1/C)))} \quad \textbf{(3)}$$

where (C) is the recycling ratio and (E) the evaporative water loss in m^3/h, which for a typical mean water temperature (WT) of 80°F can be calculated as [42]:

$$E = 1.4831 * a * H_R \quad (4)$$

where ‘a’ is the fraction of heat dissipated as latent heat of evaporation (for evaporative towers a = 75% to 85%); and ‘(H_R’) the rate of heat rejection by the plant in MW, which can be calculated from equation (1) using ‘U_s’ in MW and (η) the efficiency of the plant expressed as a fraction.

2.3.2.3 Dry cooling systems

Air is used instead of water in dry cooling systems. There are two methods for dry cooling: direct and indirect [37]. Because air has a lower thermal capacity than water, the plant’s thermal efficiency is reduced and this efficiency loss is proportional to the increase in ambient temperature [43-45]. In addition, dry cooling systems have very high capital and operating costs compared to wet re-circulating cooling systems [45]. In the U.S., all new power plants do not use dry cooling due to the associated higher costs and loss in efficiency [46].

3. Input data and assumptions

3.1 Coal upstream water demand coefficients

Input data are developed through basic thermodynamic calculations, gathered from the literature and determined in consultation with the experts to estimate the water consumption coefficient over the life cycle of coal based power plants. Assumptions for heat content of coal and different conversion efficiencies as shown in Table 1 are used to convert water demand coefficients for coal upstream pathways from cubic meter of water per tonne of coal to litres of water per kWh of electricity generated. The average values of water consumptions considered in this study for coal upstream pathways are shown in Table 2 and for power generation cycle are shown in Table 3. In an earlier study, Gleick [31] published only consumption coefficients without associated withdrawals coefficients. Meldrum et al. [47] reviewed and harmonized a comprehensive data from the literature with the assumption that consumption and withdrawals coefficients are equal for coal fuel cycle. Water withdrawal coefficient for coal upstream life cycle is assumed in this study is equal to water consumption coefficient.

Based on the water consumption results obtained by King and Webber [48] for light duty vehicles (LDV) using petroleum gasoline or diesel and travelling a distance of 1600 km (1000 miles) with a load of 50 tonnes of coal, the average transportation coefficients for water consumption is 0.007 m^3/tonne. The same is considered in this study within conventional transportation coefficients.

3.2 Water-demand coefficients for power generation cycle from coal

Table 3 shows the input data for water demand coefficients gathered from the literature for the power generation stage. Data on actual annual amount of water consumption and withdrawals are collected for coal power plants in Alberta [9,10,59 - 63] and combined with power generated [60 - 66] to estimate the water demand coefficients. Capacity factor is assumed at 90% for all coal-fired power plants in Alberta.

Ultra supercritical water-demand coefficients are extrapolated from subcritical and supercritical coefficients using their associated conversion efficiencies. The average of the constants of proportionality (K2 and K3 in equations (7) and (8) of section 4.2 below) are obtained at conversion efficiencies 35% and 38% for subcritical and supercritical, respectively, then the same constants are used to estimate the ultra supercritical water demand coefficients at conversion efficiency 45%.

Water demand for dry cooling is minimal, and many studies estimate it to be one tenth of the demand of wet re-circulating systems to cover other plant operations such as boiler make-up and drinking [16, 46, 67]. The same assumption is taken for the dry cooling in this study as one tenth of cooling towers coefficients.

Table 4 shows all the average values considered in this study for water demand coefficients of power generation stage and the associated maximum and minimum ranges gathered from the literature.

4. Results and discussion

4.1 Generic water-demand coefficients

Figure 2 shows the results for water consumption coefficients of complete upstream coal processing pathways. The obtained coefficients are affected negatively by slurry pipeline transportation followed by underground mining, and slight effect is resulted from revegetation on surface mining.

Based on the boundary set for this study and data gathered from the literature, general water-demand coefficients that include consumption and withdrawals were developed for the power generation life cycle and are shown in Figure 3. Yang and Dziegielewski [76] found that cooling towers consume on average around 1 L/kWh (0.26 gallon per kWh) more water than the once-through cooling systems. From Figure 3, the corresponding difference in average water consumption for subcritical power plants is 0.77 L/kWh (0.20 gallon per kWh) and for supercritical power plants is 1.22 L/kWh (0.32 gallon per kWh). Moreover, Yang and Dziegielewski [76] concluded that on average, more than 150 L/kWh (39.6 gallon per kWh) in withdrawals could be saved if cooling towers replaced once-through cooling systems. The corresponding estimation from Figure 3 shows the same difference is 114 L/kWh (30.0 gallon per kWh) for subcritical power plants and 87 L/kWh (23.0 gallon per kWh) for supercritical power plants. The difference between two results is mainly due to the fact that Yang and Dziegielewski [76] based their work on the database of the U.S. thermoelectric power plants burning coal, petroleum, natural gas, and nuclear, while this study estimated generic coefficients for coal-based power plants with the consideration for the different generation technologies.

Coal upstream and power generation stages (Figure 2 and Figure 3) are combined to give the results shown in Table 5. These combined coefficients represent benchmarks for generic water demand coefficients associated with the type of coal mining, power generation technology, and cooling system used. Other conversion efficiencies and unconventional transportation by pipeline are studied in the sensitivity analysis to reflect the impact on water-demand coefficient for each pathway.

The lowest water consumption coefficient based on the complete life cycle is obtained through surface mining without revegetating, transporting coal by a conventional method, and using IGCC technology and a dry cooling system. New coal-firing technologies such as IGCC and ultra supercritical have higher conversion efficiencies and consequently lower water requirements during both the fuel life cycle and power generation stages. Pathways involving IGCC have lesser water-demand coefficients due to the fact that in combined cycle only about one third of the electricity generated is by Rankine-cycle and the rest two third is generated by gas turbines which need less water for cooling [9].

4.2 Sensitivity analysis

4.2.1 Impact of power plant performance

The assumed conversion efficiency of the power plants as detailed in Table 1 is changed in the range 20%[50] to 50%[33] to study the impact of the performance on the water-demand coefficients of coal upstream pathways (Figure 4). The upper part of Figure 4 is dominated by the three pathways using slurry pipeline as the means for transportation. This indicates that slurry pipeline transportation has the most negative effect on coal upstream pathways. For the pathways with the same unit operations and different only on the type of mining, underground mining have the most negative impact on water demand and affected the ranking. Within pathways using surface mining and with the same mode of transportation, revegetation is the most sensitive factor.

A factor of merit K1 in L/kWh is introduced to rank coal upstream pathways according to the water demand performance.

The profile of the curves in Figure 4 follows the relationship:

$$\mathbf{WCUP = K1 * (1/ \eta)} \tag{5}$$

where: WCUP = Water consumption coefficient in L/kWh for coal upstream pathway

$$\mathbf{K1 = 3600}\ (\text{kJ/kWh})\ \mathbf{*\ F1}\ (\text{L/tonne})\ \mathbf{/\ H}\ (\text{kJ/tonne}) \tag{6}$$

where: F1 = Water consumption coefficient in litre of water per tonne of coal for upstream pathway as detailed in Table 2

H = Heat content of coal as given in Table 1

The lower value of K1 the better performance in water-demand coefficient. K1 values are given in the legend of Figure 4 for ranking of each coal upstream pathway.

The impact of conversion efficiency on water consumption coefficient during the power generation stage is shown in Figure 5. The water consumption coefficient (WCC) is correlated to the conversion efficiency (η) according to the associated water cooling type and parameters (included in equations (2), (3), and (4)) other than conversion efficiency terms are considered constants. K2 is assumed the constant to represent the factor of merit for water consumption during power generation stage.

$$\mathbf{WCC = K2 * ((1/\eta) - 1)} \qquad \mathbf{(7)}$$

The lower value of K2 indicates the better performance of a pathway in water consumption. From Figure 5, dry cooling outperforms followed by once through cooling and cooling pond. Cooling tower systems have the least ranking with the highest value of K2=0.988.

The profile can give indication to the decision maker whether to use existed conditions of cooling system and level of performance or to change to better water use conditions. For example, a power plant (A) with 30% efficiency and using once-through cooling system has nearly the same water consumption coefficient of a power plant (B) with cooling tower system and conversion efficiency of 48%.

The water withdrawals coefficient (WWC) performance is shown in Table 6 through same procedure of correlating to conversion efficiency through constant rate (K3):

$$\mathbf{WWC = K3 * ((1/\eta) - 1)} \quad \textbf{(8)}$$

WWC can play the major role in the result of comparison between two power plants due to the fact that once-through cooling systems have different negative impact on water withdrawals. The same power plant (A) withdraws more than 100 times the water withdrawals of power plant (B), which will significantly affect the final decision regarding the water use.

To obtain the water consumption coefficient (WCOMP) or withdrawals (WWCOMP) for the complete life cycle of specific pathway, the two portions related to fuel cycle and power generation cycle can be added to conduct a better comparative assessment between different pathways:

$$\mathbf{WCOMP = K1 * (1/\eta) + K2 * ((1/\eta) - 1)} \quad \textbf{(9)}$$

$$\mathbf{WWCOMP = K1 * (1/\eta) + K3 * ((1/\eta) - 1)} \quad \textbf{(10)}$$

Equations (9) and (10) can be helpful in the decision making to save water and compare between the cooling system used and the impact of improving the power plant performance. For example a pathway using coal from underground mining transported conventionally and with cooling towers would have WCOMP 3.28 L/kWh and WWCOMP 3.79 L/kWh from equations (9) and (10) at conversion efficiency 33%. To improve the water demand coefficients of this pathway, shifting of the cooling towers to cooling pond would give the same improvement results without shifting the cooling systems but instead increasing the conversion efficiency of the power plant to 36%.

4.2.2 Impact of coal transportation mode

To study the effects of unconventional transportation of coal on the water-demand coefficients, conventional transportation is replaced by SP and CLP transportation. The effect on the total water-demand of shifting from conventional transportation to pipelines depends mainly on the power plant's conversion efficiency. To shift from conventional transportation to SP for all subcritical technologies, 0.52 more L/kWh is needed for consumption. The extra water consumption needed for supercritical, ultra supercritical, and IGCC are 0.48, 0.41, and 0.41 L/kWh, respectively. To shift from conventional transportation to CLP and using ultra supercritical or IGCC technology would increase the water consumption coefficient by 0.12 L/kWh.

Other extra values that resulted in the shift from conventional to pipeline transportation (both SP and CLP) are shown in Figure 6.

5. Conclusions

Water demand during the fuel life cycle is with significant amount and should be taken into account when estimating the water required for complete life cycle of coal-based power plants. Development of water coefficients for the complete life cycle based on unit operations and pathways can be used in management, modelling, and forecasting of water demand for coal power plants when combined with production projections. Improving the performance of coal-based power plants through new technologies, such as ultra supercritical and IGCC, would reduce water consumption during both electricity generation and the fuel life cycle due to the reduction in fuel used to generate the same amount of energy.

The key contribution of this paper is to application of life cycle assessment (LCA) concept for comprehensive development of water coefficient for the coal power generation and the impact of power plant's performance on the water demand. There have been estimation of the water consumption coefficient for only conversion of coal to power but there is very limited information on the integration of the water demand for different upstream and downstream unit operations.

Power generation pathways involving new technologies of integrated gasification combined cycle (IGCC) or ultra supercritical technology with coal transportation by conventional means and using dry cooling systems have the least complete life cycle water-demand coefficients of about 1 L/kWh. The consumption coefficient over life cycle of ultra supercritical or IGCC power plants are 0.12 L/kWh higher when conventional transportation of coal is replaced by coal-log pipeline. Similarly, if the conventional transportation of coal is replaced by its transportation in the form of a slurry through a pipeline, the consumption coefficient of a subcritical power plant increases by 0.52 L/kWh. Generally, unconventional transportation of coal increases water demand and their impact on total water use depends mainly on the conversion efficiency of the power generation. Dry cooling has the advantage of reducing water demand during power generation, although its application is accompanied with uncertain economic feasibility and technical performance.

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Nomenclature

a = The fraction of heat dissipated as latent heat of evaporation from the closed loop cooling systems

B.C. = British Colombia, a Province in Canada

BCM = Billion cubic metres, equal to 10^9 metres

Billion tonnes = 10^9 tonnes

C = The number of recycling turns of cooling water

CLP = Coal log pipeline, mode of coal transportation

E = The evaporative water loss in cubic meter per hour

F1 = Water consumption coefficient in litre of water per tonne of coal for upstream pathways

GJ = Gigajoule, equal to 10^9 Joule

GW = Gigawatt, equal to 10^9 Watt

HHV = Higher heating value

H_R = Heat rejection rate from coal power plant

IGCC = Integrated gasification combined cycle

km = Kilometre, a unit of length in the metric system, equal to 1000 metres

K1 = Factor of merit in L/kWh for ranking water demand of coal upstream pathways

K2 = Factor of merit in L/kWh for ranking water consumption during power generation stage

K3 = Factor of merit in L/kWh for ranking water withdrawals during power generation stage

LDV = Light duty vehicles

L/kWh = Litres of water per kWh of electricity generated

MW = Megawatt, equal to 10^6 Watt

m^3 = Cubic metre, a unit of volume in the metric system, equal to a volume of a cube with edges one metre

SP = Slurry pipeline, mode of coal transportation

tonne = A metric system unit of a mass, equal to 1,000 kilogram

U.S. = United States of America

U_s = Useful output power from the power plant

WCC = Water consumption coefficient in L/kWh during power generation stage

WCOMP = Water consumption coefficient in L/kWh for the complete life cycle of a pathway

WCUP = Water consumption coefficient in L/kWh for coal upstream pathways

WF = The water flow rate per one megawatt (MW) of power output

WR = The theoretical make-up water requirements in cubic meter per hour

WWC = Water withdrawals coefficient in L/kWh during power generation stage

WWCOMP = Water withdrawals coefficient in L/kWh for the complete life cycle of a pathway

ΔT = The temperature rise of the cooling water in Fahrenheit (°F)

η = Conversion efficiency of the power plant from fuel heat content up to the electricity generated

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Figure Captions

Figure 1: System boundary and unit operations for coal-based power plants

Figure 2: Water consumption coefficients for coal upstream stage

Figure 3: Water-demand coefficients for the stage of power generation from coal

Figure 4: Performance curves for coal upstream pathways

Figure 5: Performance curves for water consumption during power generation stage

Figure 6: Extra water-consumption coefficients resulting from changing conventional to pipeline transportation modes

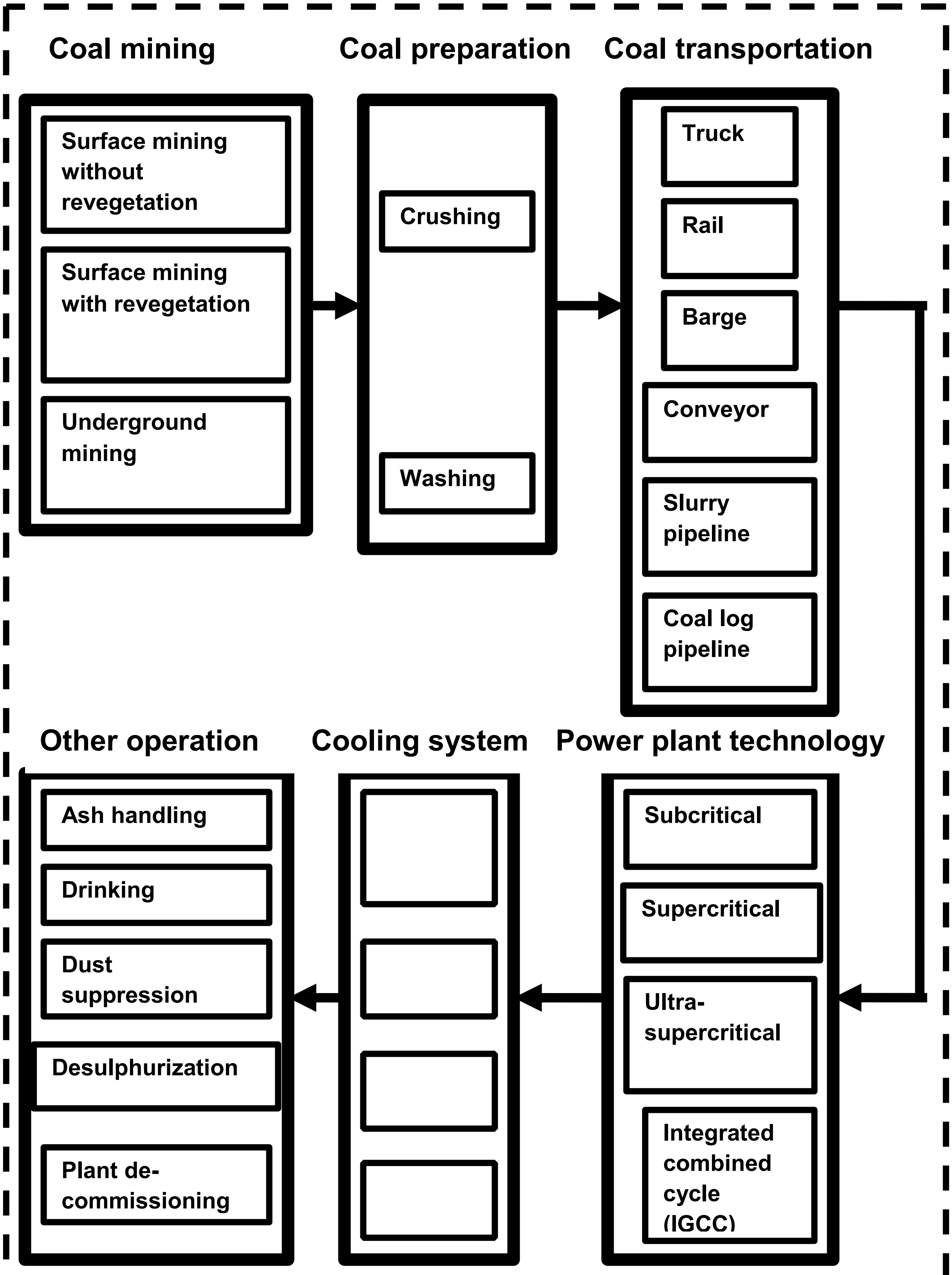

Figure 1: System boundary and unit operations for coal-based power plants

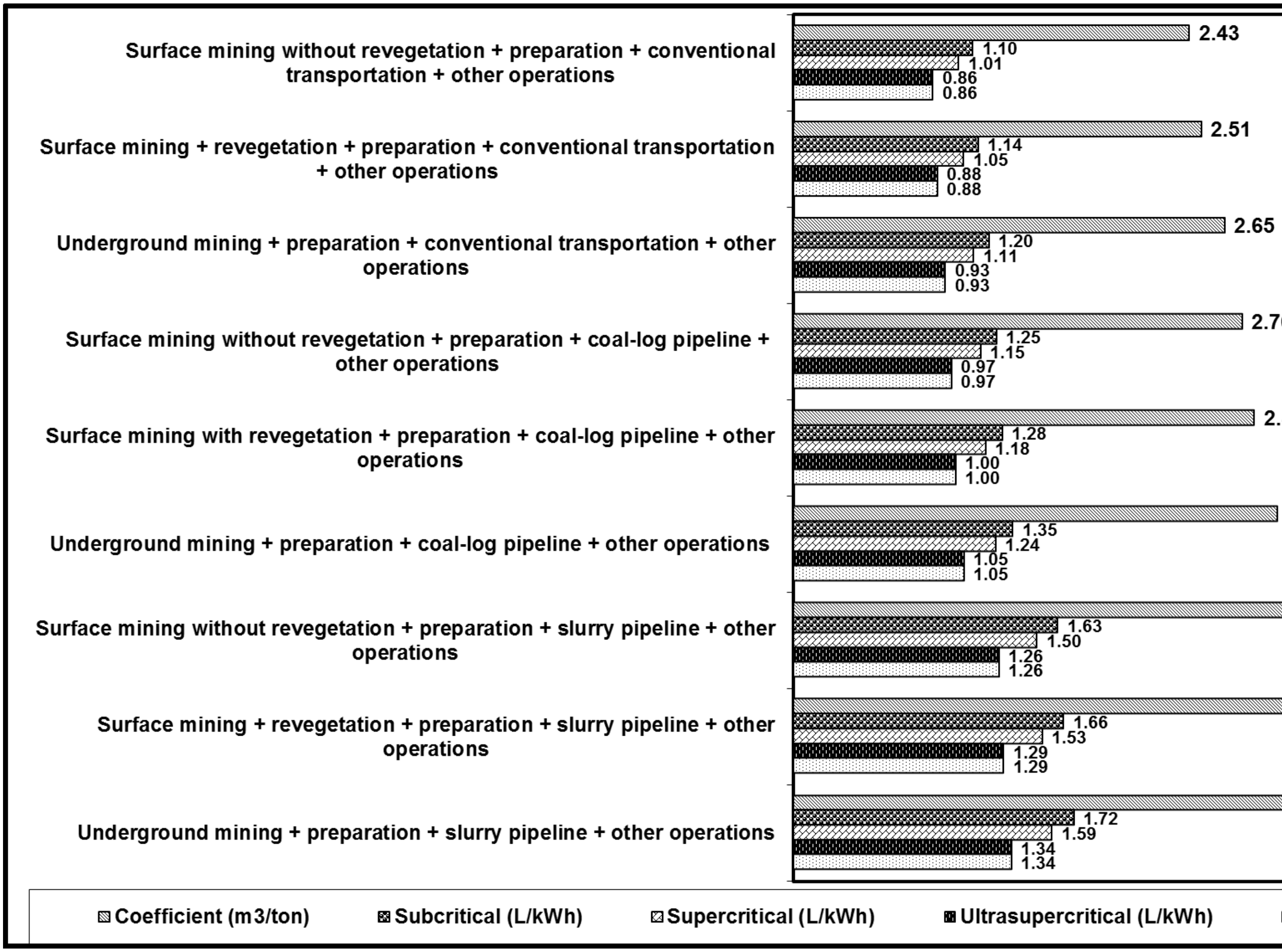

Figure 2: Water consumption coefficients for coal upstream stage

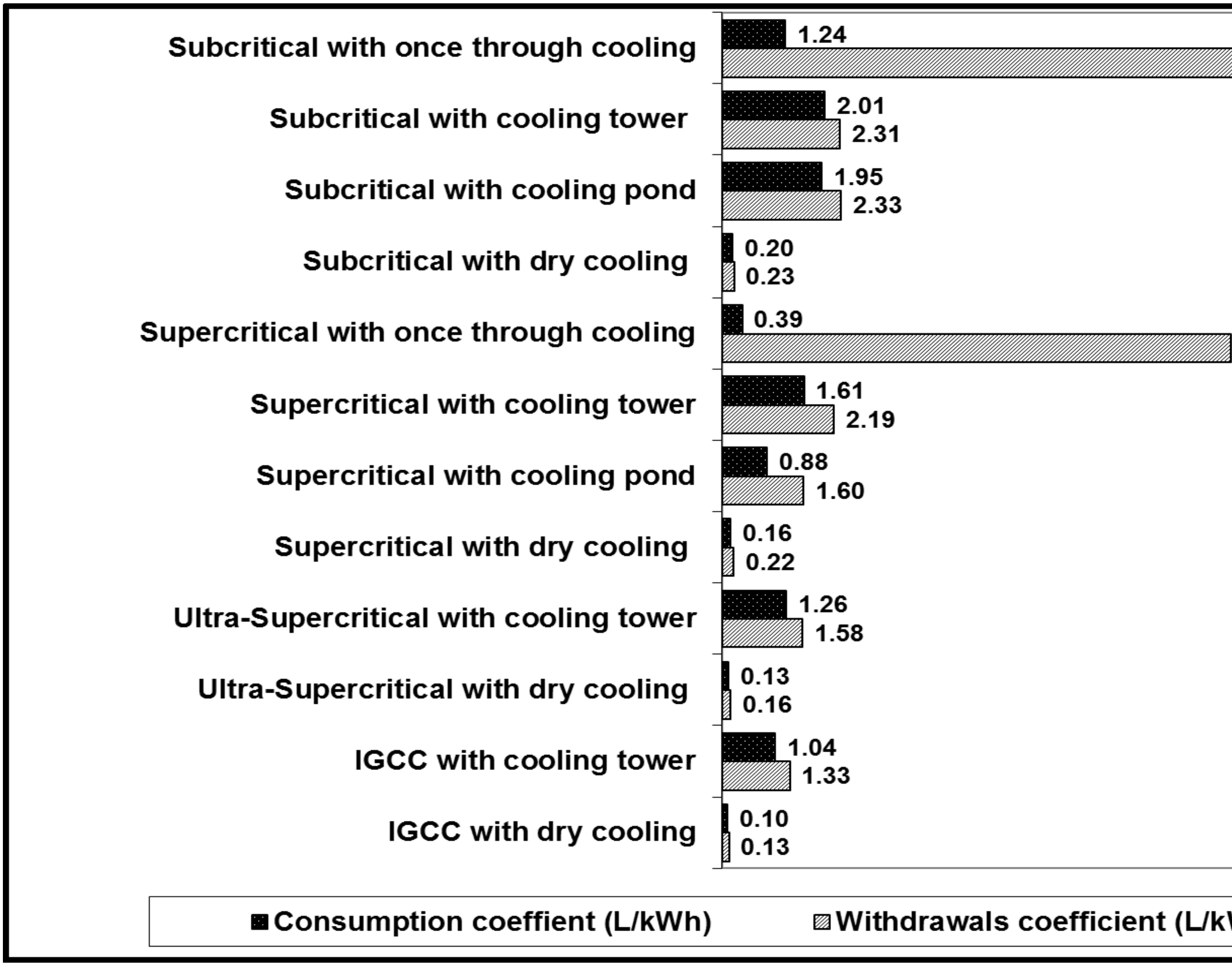

Figure 3: Water-demand coefficients for the stage of power generation from coal

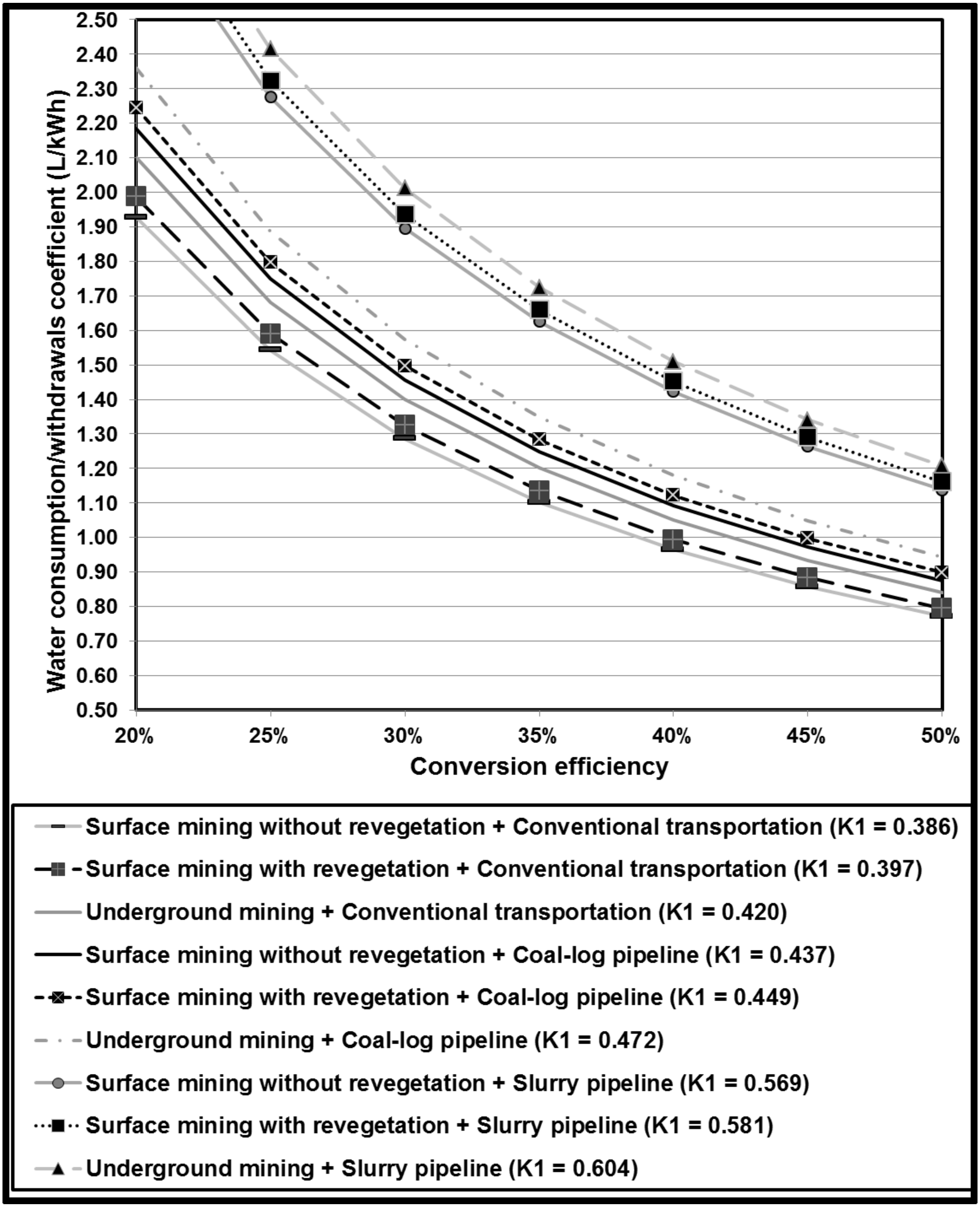

Figure 4: Performance curves for coal upstream pathways

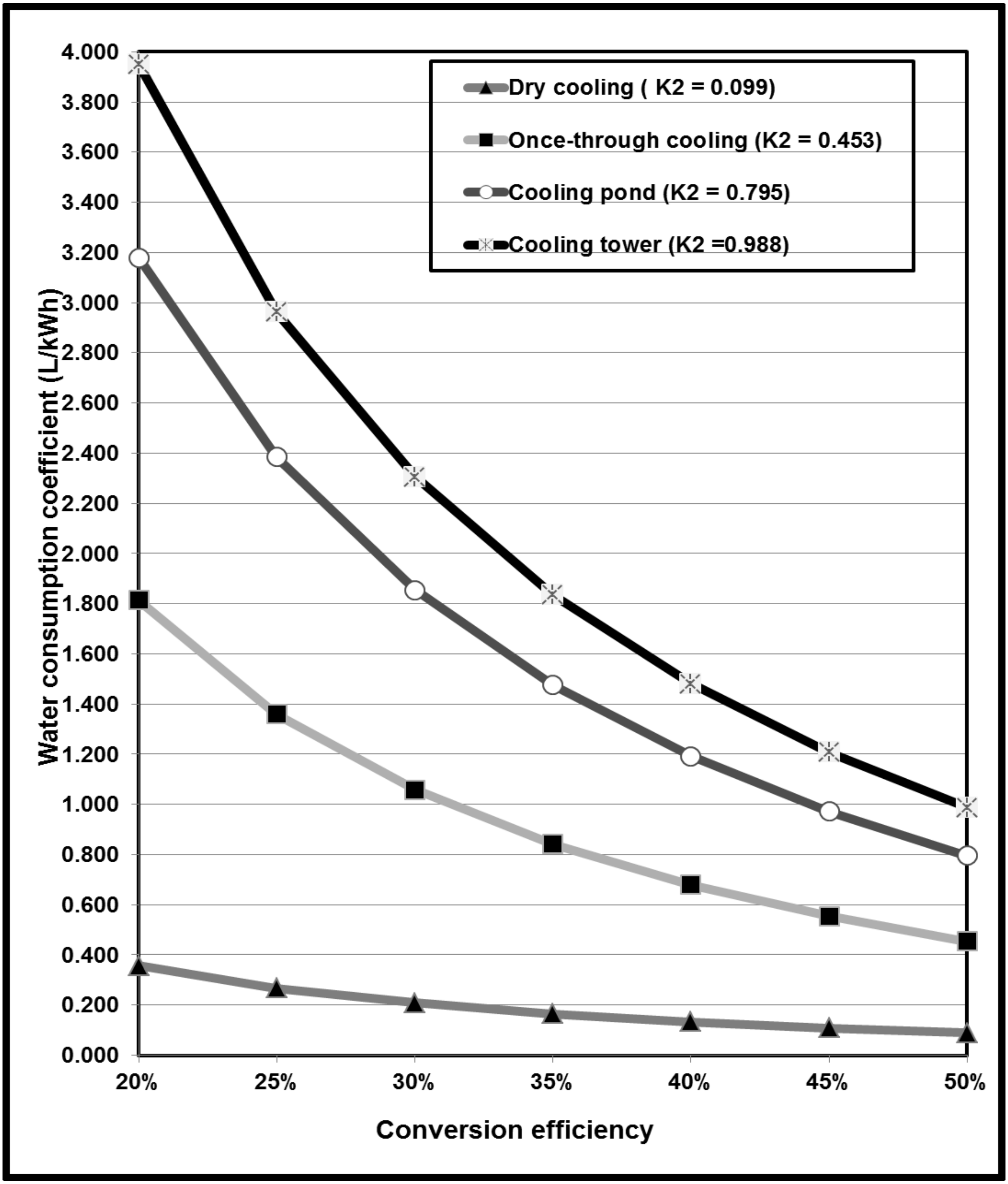

Figure 5: Performance curves for water consumption during power generation stage

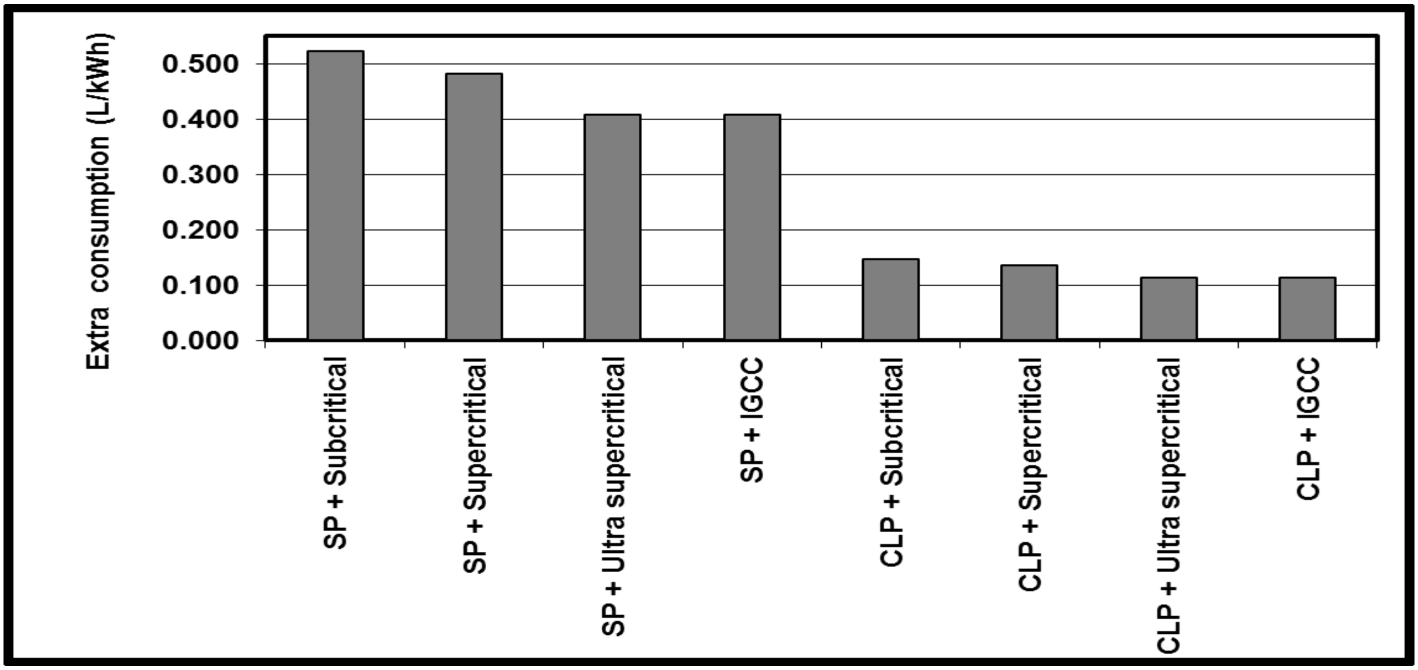

Figure 6: Extra water-consumption coefficients resulting from changing conventional to pipeline transportation modes

Table 1: Input data and assumptions for characteristics of coal and power plants

Items	Values	Comments/Sources
Heat content of coal (HHV)	22.7 GJ/tonne	Typical average heat content of coal consumed in the U.S. during 2012 [49].
Conversion efficiency (η) of subcritical power plant at (HHV) of coal	35%	Assumed based on literature [47, 50, 51, 52].
Conversion efficiency (η) of supercritical power plant at (HHV) of coal	38%	Assumed based on literature [47, 50, 51].
Conversion efficiency (η) of ultra-supercritical power plant at (HHV) of coal	45%	Assumed based on literature [46, 51, 52].
Conversion efficiency (η) of IGCC power plant at (HHV) of coal	45%	Assumed based on literature [53, 54, 55].

Table 2: Input data and assumptions for estimation of water consumption coefficients of coal upstream pathways

	Average for surface mining (m^3/tonne)	Average for underground mining (m^3/tonne)	Comments/Sources
Mining	**0.038**	**0.257**	Gleick [31] coefficient for surface mining was 0.05 m^3/tonne. extraction are also derived as 0.025 m^3/tonne for surface and underground mining from a wide range of studies conducted a Meldrum et. al [47] at an efficiency (η) of 34.3% (HHV). For unde average is taken from the range 0.075 – 0.500 m^3/tonne with t underground mining with no recycle.
Revegetation	**0.075**	**0.000**	Obtained from Gleick [31] as the difference between su revegetation and without.
Preparation	**0.140**	**0.140**	NETL[56] base case is considered here to include jig cleanin landfilling for both surface and underground mining as 0.17 m coefficient of 0.1 m^3/tonne for beneficiation is considered here both mining types. Average value of 0.15 m^3/tonne for processi mining are also considered from a wide range of studies conduct by Meldrum et. al [47] at an efficiency (η) of 34.3% (HHV).
Conventional transportation	**0.005**	**0.005**	Calculated from King and Webber [48] for transportation by LDV for both mining types. Transport by train in the range 0.001– both mining types are also included here from Meldrum et.al [47].
Slurry pipeline transportation	**1.161**	**1.161**	Assumption by Kania [57] that coal is crushed and mixed with wa about 50% by dry weight is considered here (1 m^3/tonne). Ran types from Gleick [31] as 1.0– 2.125 m^3/tonne for coal power pla also considered. The median value 0.92 m^3/tonne for both typ

			Meldrum et. al [47] is added to calculate the average.
Coal-log pipeline transportation	**0.333**	**0.333**	The assumption from Marrrero [58] that coal to water mass ratio here (0.333 m^3/tonne).
Other operations	**2.250**	**2.250**	Assumption from Gleick [31] is considered here to include pla water requirements, ash handling, and make-up water for boile desulfurization.

Table 3: Input data for power generation coefficients

Cooling system type	Consumption coefficient (L/kWh)	Withdrawals coefficient (L/kWh)	Comments and sources
Once-through		143.93	Theoretical coefficient calculated from equation (2) at η =35% and ΔT=20 °F [41].
	1.20		Derived from Gleick [31] as consumptive use at η =35%.
	1.14	75.76	For the U.S. thermal power plants based on ΔT= 30 °F [14].
	1.14	189.39	For the U.S. thermal power plants based on ΔT=12 °F[14].
	0.51	128.54	Median of subcritical pulverized coal for a wide range of studies harmonized at η =34.3% (HHV) [47].
		112.30	Calculated from actual total water withdrawals and total electricity generation from coal power plants in the U.S. during 2006 [68].
	2.31	94.70	Based on the total water withdrawals for thermoelectric power plants in the U.S. and consumption coefficient calculated as percentage from the daily withdrawals [69].
	1.8		Calculated from the total amount of water evaporated from thermoelectric power plants per

			kWh of end-use energy for all of the U.S. [15].
	0.38	98.48	Average values for all coal-fired power plants in the U.S. according to NETL [7].
	1.17	88.74	Estimated from the actual total annual water demand and electricity generated by 675 MW subcritical Battle River coal-fired power plant in Alberta, Canada with assumed capacity factor of 90% [63,70].
	1.52		Average of a range for water use by cooling systems in Missouri River Basin [71].
	1.24	**116.48**	Average value assumed for subcritical pulverized coal power plants using once through cooling systems in this study.
	0.39	88.90	Median of supercritical pulverized coal for a wide range of studies harmonized originally at η =38.4% (HHV) [47].
	0.39	**88.90**	Average value assumed for supercritical pulverized coal power plants using once through cooling systems in this study
Closed-loop using cooling towers	2.20	2.75	Theoretical coefficients calculated from equations (3-5) at a = 80%, WT=80°F, η=35%, and C =1/5 [42].
	2.20	2.45	Theoretical coefficients calculated from equations 3-5 at a = 80%, WT=80°F, η =35%, and C =10 [42].
	2.60		Derived from Gleick [31] as consumptive use at η

			=35%.
	1.82	1.89	Based on cooling water demand for the U.S. at cycle of concentration =10 [14].
	1.82	2.27	Based on cooling water demand for the U.S. at cycle of concentration = 5 [14].
	1.69		Typical evaporation from cooling systems for cold climate zone calculated theoretically for a 1000MW power plant with η =35% and ΔT=18 °F [38].
	2.09		Typical evaporation from cooling systems for hot climate zone calculated theoretically for a 1000MW power plant with η =35% and ΔT=18 °F [38].
	1.70	2.05	Average values for all coal-fired power plants in the U.S. using recirculating cooling systems according to NETL[7].
	1.95	2.43	Median of subcritical pulverized coal for a wide range of studies harmonized at η =34.3% (HHV) [47].
	2.27		Average of a range for water use by cooling systems in Missouri River Basin [71].
	1.82	2.31	Baseline established by DOE/NETL[72] for water use by subcritical pulverized coal power plants using wet recirculating cooling systems.
	2.01	2.31	Average value assumed for subcritical pulverized coal power plants using cooling tower in this study.
	1.61	2.90	Estimated from actual total water demand and electricity generated by a new 450MW supercritical

			power plant located at Keephills, Alberta, Canada with assumed capacity factor of 90% [9,65].
	1.93	2.31	Median of supercritical pulverized coal for a wide range of studies harmonized originally at η =38.4% (HHV) [47]..
	1.30	1.48	Proposed supercritical MAXIM power plant to be located near Grande Cache, Alberta, Canada [66].
	1.59	2.08	Baseline established by DOE/NETL[72] for water use by supercritical pulverized coal power plants using wet recirculating cooling systems.
	1.61	**2.19**	Average value assumed for supercritical pulverized coal power plants using cooling tower in this study.
	1.14	1.52	Baseline established by DOE/NETL [72] for water use by IGCC power plants using wet recirculating cooling systems.
	0.93	1.13	Median for a wide range of studies harmonized originally at η =38.5% (HHV) for IGCC [47]. Again re-harmonized here at η =45% (HHV).
	1.04	**1.33**	Average value assumed for IGCC power plants using cooling tower in this study.
Closed-loop using cooling ponds	1.02	1.14	Based on cooling water demand for the U.S. at C =10 [14].
	1.89	2.27	Based on cooling water demand for the U.S. at C = 5 [14].
	3.38		Calculated as stated by Gleick [31]: 30% higher than the corresponding wet cooling towers.

	2.02	3.25	Estimated from actual total water demand and electricity generated by subcritical Genesee coal power plant (G1&G2) located in Alberta, Canada [59,64].
	1.47	2.63	Based on the projected evaporation from the cooling pond from the three units (G1,G2,&G3) of Genesee coal power plant in Alberta, Canada [9].
	1.66	2.37	Estimated from actual water demand and electricity generated by two units (1 & 2) of a 766 MW subcritical Keephills coal power plant located in Alberta, Canada [60]. A capacity factor of 90% is assumed.
	1.04	1.23	Estimated from actual water demand and electricity generated by six units of a 2126 MW subcritical Sundance coal power plant located in Alberta, Canada [61]. A capacity factor of 90% is assumed.
	1.79	3.41	Estimated from actual water demand and electricity generated by two units of subcritical Sheerness coal power plant located in Alberta, Canada [62].
	2.24		Average water consumption for power plants operated by TransAlta in Alberta, Canada. Based on the total MWh generated, operated power plants include 72% from coal and the rest 28% from natural gas, hydro, and wind [73].
	3.03		Average of a range for water use by cooling systems in Missouri River Basin [71].

	1.95	**2.33**	Average value assumed for subcritical pulverized coal power plants using cooling pond in this study.
	0.88	1.60	Estimated from the expected total water demand and electricity generated by supercritical Genesee coal power plant (G3) located in Alberta, Canada [9,74,75].
	0.88	**1.60**	Average value assumed for supercritical pulverized coal power plants using cooling pond in this study.

Table 4: Ranges of consumption and withdrawals coefficients for power generation stage

Pathway	Consumption coefficient (L/kWh)			Withdrawals coefficient (L/kWh)		
	Average	Max.	Min.	Average	Max.	Min.
Subcritical with once through cooling	1.24	2.31	0.38	116.48	189.39	75.76
Subcritical with cooling tower	2.01	2.60	1.69	2.31	2.75	1.89
Subcritical with cooling pond	1.95	3.38	1.02	2.33	3.41	1.14
Subcritical with dry cooling	0.20	0.26	0.17	0.23	0.28	0.19
Supercritical with once through cooling	0.39	0.47	0.25	88.90	88.90	88.90
Supercritical with cooling tower	1.61	1.93	1.30	2.19	2.90	1.48
Supercritical with cooling pond	0.88	0.88	0.88	1.60	1.60	1.60
Supercritical with dry cooling	0.16	0.19	0.13	0.22	0.29	0.15
Ultra-Supercritical with cooling tower	1.26	1.58	1.04	1.58	1.99	1.18
Ultra-Supercritical with dry cooling	0.13	0.16	0.10	0.16	0.20	0.12
IGCC with cooling tower	1.04	1.14	0.93	1.33	1.52	1.13
IGCC with dry cooling	0.10	0.11	0.09	0.13	0.15	0.11

Table 5: Water-demand coefficients for complete life cycle of coal-based power plant pathways

Pathway	Conventional transportation		Coal log pipeline		Coal slurry pipeli	
	Consumption coefficient (L/kWh)	Withdrawals coefficient (L/kWh)	Consumption coefficient (L/kWh)	Withdrawals coefficient (L/kWh)	Consumption coefficient (L/kWh)	Withdr coeffic (L/kW
Surface mining with revegetation-Electricity-Subcritical-Once through cooling	2.376	117.616	2.523	117.763	2.899	118
Surface mining with revegetation-Electricity-Subcritical-Cooling tower	3.146	3.446	3.293	3.593	3.669	3.9
Surface mining with revegetation-Electricity-Subcritical-Cooling pond	3.086	3.466	3.233	3.613	3.609	3.9
Surface mining with revegetation-Electricity-Subcritical-Dry cooling	1.337	1.367	1.484	1.514	1.860	1.8
Surface mining without revegetation-Electricity-Subcritical-Once through cooling	2.342	117.582	2.489	117.729	2.865	118
Surface mining without revegetation-Electricity-Subcritical-Cooling tower	3.112	3.412	3.259	3.559	3.635	3.9

Surface mining without revegetation-Electricity-Subcritical-Cooling pond	3.052	3.432	3.199	3.579	3.575	3.9
Surface mining without revegetation-Electricity-Subcritical-Dry cooling	1.303	1.333	1.450	1.480	1.826	1.8
Underground mining-Electricity-Subcritical-Once through Cooling	2.441	117.681	2.588	117.828	2.965	118
Underground mining-Electricity-Subcritical-Cooling tower	3.211	3.511	3.358	3.658	3.735	4.0
Underground mining - Electricity- Subcritical-Cooling pond	3.151	3.531	3.298	3.678	3.675	4.0
Underground mining - Electricity- Subcritical-Dry cooling	1.402	1.432	1.549	1.579	1.926	1.9
Surface mining with revegetation-Electricity-Supercritical-Once through cooling	1.436	89.946	1.572	90.082	1.918	90.
Surface mining with revegetation-Electricity-Supercritical-Cooling tower	2.656	3.236	2.792	3.372	3.138	3.7
Surface mining with revegetation-Electricity-	1.927	2.648	2.063	2.784	2.409	3.1

Supercritical-Cooling pond						
Surface mining with revegetation-Electricity- Supercritical-Dry cooling	1.207	1.265	1.343	1.401	1.689	1.7
Surface mining without revegetation-Electricity- Supercritical-Once through cooling	1.405	89.915	1.540	90.050	1.887	90.
Surface mining without revegetation-Electricity- Supercritical-Cooling tower	2.625	3.205	2.760	3.340	3.107	3.6
Surface mining without vegetation-Electricity- Supercritical-Cooling pond	1.896	2.617	2.031	2.752	2.378	3.0
Surface mining without revegetation-Electricity- Supercritical-Dry cooling	1.176	1.234	1.311	1.369	1.658	1.7
Coal-Underground mining- Electricity- Supercritical-Once through cooling	1.496	90.006	1.632	90.142	1.978	90.
Coal-Underground mining- Electricity- Supercritical-Cooling tower	2.716	3.296	2.852	3.432	3.198	3.7
Underground mining - Electricity- Supercritical-Cooling pond	1.987	2.708	2.123	2.844	2.469	3.1

Underground mining -Electricity- Supercritical-Dry cooling	1.267	1.325	1.403	1.461	1.749	1.8
Surface mining with revegetation-Electricity- Ultra supercritical-Cooling tower	2.143	2.463	2.258	2.578	2.550	2.8
Surface mining with revegetation-Electricity- Ultra supercritical-Dry cooling	1.009	1.041	1.124	1.156	1.416	1.4
Surface mining without revegetation-Electricity- Ultra supercritical-Cooling tower	2.117	2.437	2.231	2.551	2.524	2.8
Surface mining without revegetation-Electricity- Ultra supercritical-Dry cooling	0.983	1.015	1.097	1.129	1.390	1.4
Underground mining-Electricity- Ultra supercritical-Cooling tower	2.194	2.514	2.309	2.629	2.601	2.9
Underground mining-Electricity- Ultra supercritical-Dry cooling	1.060	1.092	1.175	1.207	1.467	1.4
Surface mining with revegetation-Electricity- IGCC-Cooling tower	1.923	2.213	2.038	2.328	2.330	2.6
Surface mining with revegetation-Electricity- IGCC-Dry cooling	0.987	1.016	1.102	1.131	1.394	1.4
Surface mining without	1.897	2.187	2.011	2.301	2.304	2.5

revegetation-Electricity- IGCC-Cooling tower						
Surface mining without revegetation-Electricity- IGCC-Dry cooling	0.961	0.990	1.075	1.104	1.368	1.3
Underground mining-Electricity-GCC-Cooling tower	1.974	2.264	2.089	2.379	2.381	2.6
Underground mining-Electricity-GCC-Dry cooling	1.038	1.067	1.153	1.182	1.445	1.4

Table 6: Performance of cooling systems in water withdrawals during power generation stage

Conversion efficiency	WWC for once-through cooling systems* (L/kWh)	WWC for cooling tower systems** (L/kWh)	WWC for cooling pond systems* (L/kWh)	WWC for Dry cooling systems** (L/kWh)
20%	234.41	4.97	4.47	0.50
25%	175.81	3.73	3.35	0.37
30%	136.74	2.90	2.61	0.29
35%	108.84	2.31	2.08	0.23
40%	87.91	1.86	1.68	0.19
45%	71.63	1.52	1.37	0.15
50%	58.60	1.24	1.12	0.12
K3 value	**58.60**	**1.24**	**1.12**	**0.12**

* The factor of merit K3 estimated as average value from subcritical and supercritical water withdrawals coefficients at η =35% and η=38%, respectively.

**The factor of merit K3 estimated as average value from subcritical, supercritical, ultra-supercritical, and IGCC water withdrawals coefficients at η =35%, η=38%, η=45%, and η=45%, respectively.