LCA Model for Water Footprint for Reciprocating Engine (Re) Power Plant

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Abstract

The key objective of this paper is to develop a LCA model for water demand coefficients of the life cycle of natural gas-fired power generation. A spread sheet-based model has been developed to characterize water use in electricity generation from Reciprocating Engine (RE) Power Plant in Bangladesh.The model is built upon a data inventory that analyzes water requirements by fuel source, generation technology, and cooling system. Water demand coefficients include water consumption for various stages of natural gas production, life-cycle of power plant as well as for power generation from it. Pathways were structured based on the unit operations of the types of natural gas sources, power plant, and power generation technologies, and cooling systems. From previous research papers it has been observed that the lowest life cycle water consumption coefficient of 0.12 L/kWh is for the pathway of conventional gas with combined cycle technology, and dry cooling. The highest life cycle consumption coefficient of 2.57 L/kWh is for a pathway of shale gas utilization through steam cycle technology and cooling tower systems. The goal of this study is to provide a baseline assessment of freshwater use in electricity generation from a Reciprocating Engine Power Plant (REPP). A spreadsheet-based model has been developed to conduct the estimates of water footprint (WF). This tool is intended to provide decision makers to make a quick comparison among various fuel, technology, and cooling system options in respect of water use for power generation. In this study it has been found that the WF for reciprocating engine power plant is 0.10 L/kWh , which is much less compared to other technology of power generation.

Keywords
Water–Energy nexus, Natural Gas, Electricity Generation, Life Cycle Assessment

1. Introduction

The water is needed for energy production and energy is needed for water supply.As there had been an acute shortage of electricity in Bangladesh a few years ago, the government took Quick Rental Power Plants Program (QRPP) and under this program, many small power plants based on reciprocating engines (around 1000 MW) were commissioned by 2012.As per statistics of Bangladesh Power Development Board (BPDB), installed generation capacity of Bangladesh is 19,428 MW in September 2019. Different types of power plants generate electricity in the country and synchronize it with the national grid. The share of different types of power plants [2] is shown in Figure 1.

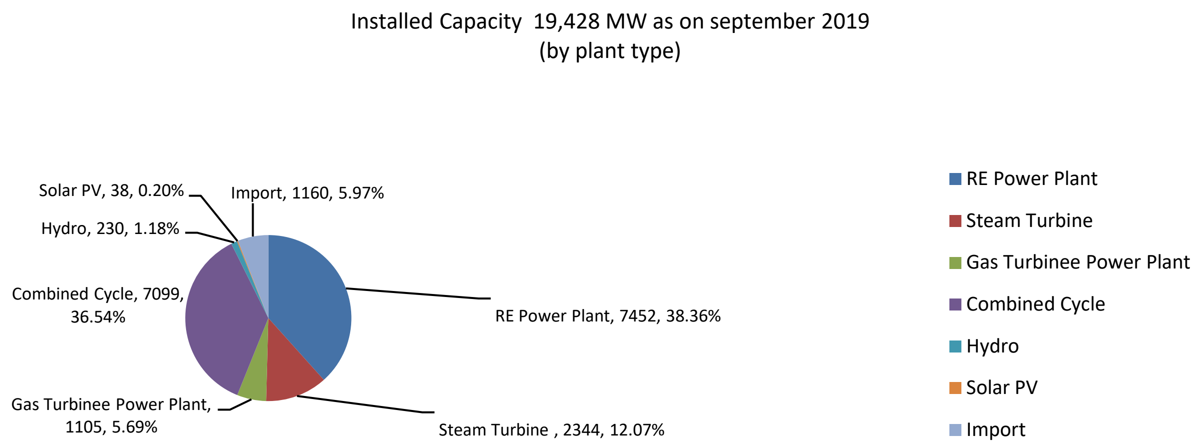


Figure 1:Installed capacity of power plants as on September 2019 (plant type) in mw

Around 36.54 % electricity generation comes from reciprocating engine power plants and rest power from steam turbine 12%, gas turbine 5.69%, combined cycle 36.54 and hydro 1.18%. Most common technologies used to generate powers from fossil fuels are single cycle, steam cycle, and NGCC. But in Bangladesh, reciprocating engine (RE) power plants also have remarkable contribution in generation of power. Many researchers studied water footprint (WF) for power generation for steam cycle, gas turbine cycle, and combined cycle globally, but very few papers are available for WF of reciprocating engine (RE) power plants. A water footprint is the volume of water needed for the production of unit quantity of goods, electricity (Hoekstra and Chapagain 2007 [5].

In this paper we studied a reciprocating engine power plant named Shun Shing Power Plant supplying electricity to 'Seven Circle Cement Factory'located at Ghorashalaround 90 km away from Dhaka, Bangladesh. The power plant, based on natural gas, uses closed loop radiator cooling and this system has been described later in methodology in details.The aim of this paper is to develop a 'LCA Model'forlife cycle water demand/consumption for power generation from reciprocating engine power plant. The key objectives of this study are:

- To develop a LCA Model and assessthe water footprint (WF) for power generation from a RE Power Plant.
- To structure pathways of water consumption to cover the life cycle of fuel, materials, equipment of RE power plant and evaluate water consumption.
- To assess the impacts on environment in respect of climate change, because ofwaterconsumption due to power generation from a RE power plants.

2. Literature Review

In 1994, Gleick published the growing water crisis and its relationship to energy supply. Especially energy–water interdependencies are recognized in the United States, [5,13]. The topic became an issue to initiate research for reducing water demandin energy production. The study focused on the volume of consumptive water use to generate electricity[5,7]. E S Spang et al [8] mentioned in their paper, water is necessary for almost all production and conversion processes in the energy sector, which include fuel extraction and processingand electricity generation (thermoelectric, hydropower, and renewable technologies) [6].To assess the water use impact of energy production, it is very common to apply the well-developed concept known as the water footprint [5,8].

A number of previous studies were carried out by Wu *et al*2009, Mittal 2010, Mekonnen and Hoekstra 2010, Barker 2007, Macknick*et al*2011, Gleick1994, and DOE 2006,for water footprint of electricity generation by estimating of water use coefficients for energy technologies. The studies were also done by Fthenakis and Kim 2010, Mulder *et al*2010, Mielke*et al*2010, Meldrum *et al*2013with emphasis on fuel production. The results of these studies revealed that the WF varies significantly by energy process and technology. Hence, the selection of technologies has important implications on energy production and generation of electricity [8]. The electricity generation from natural gas consistsof a number of pathways, which include unit operations forproduction of natural gas, its processing, transportation and utilizationof power production. Power generation pathwaysare branched according to the unit operations that affect the water footprints significantly. The minimum, maximum, and average water demand coefficientsfor the upstream stage of NG were mentioned by Babkir Ali et al [3]. Most studies carried out in the water–energy nexus consider only the power generation stage without taking into account the fuel cycle, water demand through detailed pathways are scarce [3].The type of technology and cooling system used for power generation from different fuels has essential unit operations to be considered in determining the amount of water required. However, it is important to highlight that for a power plant the amount of water required for cooling will depend on the type of cooling system being used in the power plant. In general, cold-water cooling systems allow for more efficient operation [5].Cooling systems used in power plants are - i. Once-through cooling, ii. Closed Cycle Cooling System, iii. Cooling Tower (wet cooling and cooling pond), iv. Dry Cooling

3. Methodology

In this study, we consider the life cycle into three main stages: fuel cycle, which pertains only to fuel (natural gas for this study); power plant, which represents the life cycle of the physical power plant equipment& construction; and operation**,** which include cooling for thermal technologies and all other plant operation and maintenance functions. The unit operations and system boundary considered for this study are shown in Figure 3.

3.1 Systemboundary

The unit operations and system boundary considered for this study are shown in Fig 2.

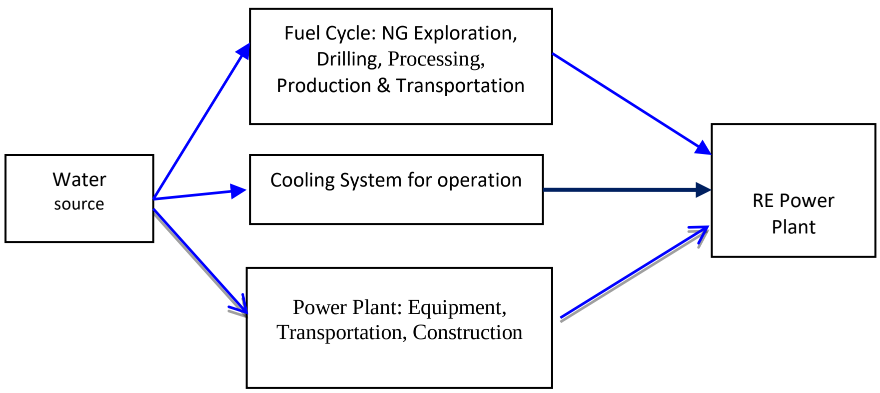


Figure 2:Thesystem boundary for WF of REPP

We define life cycle water use factors, W_{LC} is the life cycle water use per unit of generated electricity, termed as water footprint (WF) expressed as liters or gallons per kWh. We calculate factors for the life cycle water consumption for a RE power plant a particular generation technology. These factors represent water use factors for each of the three major life cycle stages defined in system boundary figure 3. Hence, life cycle water use factors, i.e. WF is as follows:

$$W_{LC}= W_{fc} +Wpp + W_{op} \quad (1)$$

Where, $\mathbf{W_{fc}}$ is amount of water used in the fuel cycle per unit of electricity generated (expressed in litre/kWh), W_{PP} is the amount of water used for component manufacturing, power plant construction, and power plant decommissioning (i.e. the power plant equipment life cycle (litre/kWh); and W_{OP} is the amount of water used in the operations of the power plant per unit of generated electricity (L/kWh).

3.2 Model Development for WF of RE Power Plant

We quantify water use in RE power plant by developing a simple generic model focusing on heat balance of the power plant. The heat rate (HR, kJ/kWh) of a power plant is the amount of energy required to produce one unit of electricity (kWh).

$$\text{Heat Rate (HR)} = \frac{\boldsymbol{Heatinputoffuel}}{\boldsymbol{NetPowerOutput}} \quad (2)$$

The power plant's heat rate depends on the fuel type and the specific power plant design. All the heat input into the power plant that is not converted into electricity (shown in Figure3). Some heat is wasted and has to be dissipated somehow to the environment. The majority of this heat is rejected to the environment through flue gasandcooling

system, which usually use water as the heat transfer medium. The water consumption, **Wcw** can be calculatedfrom the equation below:
The heat dissipated to cooling water, $Q_{cw} = W_{cw} * C_{cw}\Delta T_{cw}$;

$$\text{Hench water consumption, } W_{cw} = Q_{cw} / (C_{cw}\Delta T_{cw}), \quad (3)$$

The water foot print (WF) model for electricity generation can be shown in figure 5.

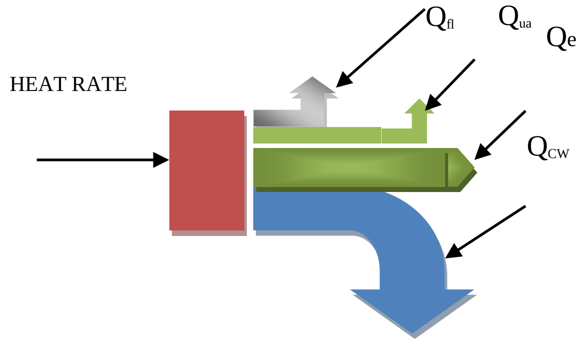


Figure 3: Simplified Visualization of Heat Balance of a Power Plant

The energy input into the plant as fuel has to be equal to the energy going out of the plant. The amount of heat that is rejected to cooling water is Q_{cw}.The total amount of water required in the power plant,Wcw depends on the amount of heat, Qcw to be dissipated through the cooling system, which depends on the efficiency andthe type of cooling systemconnected in the closed loop. Other parameters of the model, Qfl, Qun, and Qe are heat dissipated through flue gas, unaccounted heat loss, and heat used for the generation of electricity respectively.

3.3 Parameter Q_{cw}

We can evaluate the amount of energy Q_{cw} from the equation (6).

$$Q_{cw} = HR - (Q_e + Q_{fl} + Q_{ua}). \quad (4)$$

Thus, the smaller the heat rate, the smaller the waste heat that needs to be rejected; and therefore, less cooling water is required per kWh produced.The required water consumption per unit of electricity genaration can be estimated from the equation 8 is given below:

$$W_{cw} = Q_{cw} / (C_{cw}\Delta T_{cw}), \quad (5)$$

3.4 Data collection

In this study, data were collected and developed from the plant operation log sheet and the literature, then harmonized for technology of power generation and cooling system used by the power plant. In the estimation of WF of fuel cycle, the average value for the data are used to represent water demand coefficients for the various upstream and downstream unit operations involved in power generation from natural gas. These water demand coefficients for each unit operations are used to estimate the complete life cycle water demand coefficient of gas-fired power generation. Water consumption was calculated for each pathway for gas-fired RE power plant with actual load factor **66%.** The unit operations and system boundary considered for this study are shown in Figure 3**.** Water consumption coefficient ranges of power plant equipment and construction including decommissioning of the plant have taken from the paper of Babkir et al.[3]. Actual waterconsumption quantities during operation of the plant have been collected from the power plant operation log sheet. Every 2 days after, the make up water is poured in the water expansion/make up vessel.

3.5 Cooling System of the Power Plant

The closed loop radiator cooling system is used in the studied power plant for cooling of RE engines, lubricating oil and charged air. This is a dry cooling system, sometimes referred to as air cooling; use air instead of water as the heat transfer fluid. The system consumes water as make up water which is to be topped up at the makeup water tank every after 2-3 days around 200-300 liter.

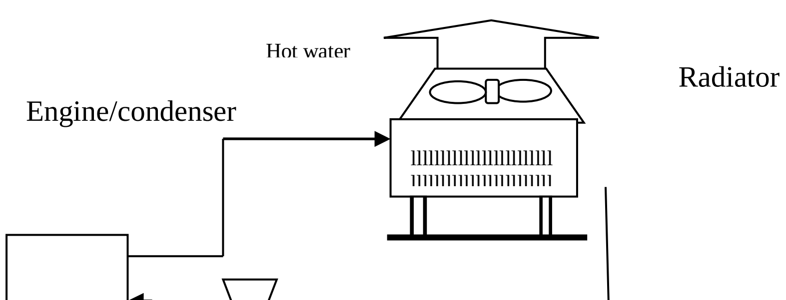


Figure 4: Closed loop radiator cooling (dry cooling)

The water, re-circulated in the system takes heat from engines, lubricating oil heat exchangers & charged air coolers and dissipates heat in the radiators where air is used to cool the hot water. The mass of circulation water between engine and radiator can be calculated from the following thermodynamic equation,

$$Qcw = m_{cir} Cp\Delta T \text{ or } \qquad m_{cir} = Qcw/(Cp\Delta T) \qquad (6)$$

The mass of water consumption can be calculated the equation below:

$$m_{con} = \alpha_{cr} * m_{cir} \qquad (7)$$

Where, Qcw is the heat to be dissipated in cooling water (kJ/kWh), ΔT is the temperature increase of the water, m_{cir} is the amount of water circulated (L/kWh) in cooling system, m_{con} is the water consumed. A small part of m_{cir} evaporates and leaks out through the radiator cap (i.e. consumed), which is captured by the coefficient α.Hence, m_{con} is much smaller than m_{cir}. α_{cr} is the percentage of the water circulated that is consumed due to evaporation & leak out through the radiator cap and depends on ambient conditions and cooling system condition. Lifetime water consumption was calculated for the pathways of the gas-fired reciprocating engine power plant with average load factor around 66% determined from power plant operation data.

3.6 Estimation of water consumption of upstream pathways of NG

Each pathway of electricity generation from natural gas fired reciprocating engine power plant consists of a number of unit operations. This includes unit operations for production, processing, transportation and direct combustion of natural gas in the power plant. Power generation pathways are shown in the figure5according to the unit operations that affect the water footprints significantly.

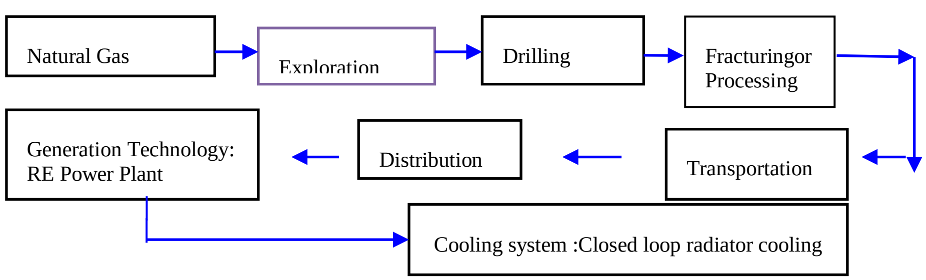


Figure 5: Upstream pathways of NG

The estimation of water footprint of natural gas upstream paths has been calculated from the formula given below:

$$WF_f = V_f * (WF_{expl} + WF_{dril} + WF_{extr} + WF_{proc} + WF_{tran}) \qquad (8)$$

Where, WFexpl, WFdril, WFextr, WFpro, WFtran, are water footprints for exploration, drilling, extraction, processing, and transportation of NG and Vf is the lifetime consumption of natural gas. The water footprint,WFf for fuel (NG) supply has been estimated using water demand co-efficients of NG upstream pathways from the research paper of Babkir et al [3].The water demand coefficients (Water Footprint, WF) for the upstream stages of natural gas are obtained from Babkir et. Water consumption co-efficient of RE Power Plant for power plant construction The water footprint for equipment and construction of power plant, WFpp is 0.32 - 1.1 m3/ TJe of electricity obtained from the paper of Mesfin et al [5] and shown in Table 1.

Table 1: Water Footprints for construction of power plant and fuel supply

	WFpp, m3/TJ$_e$	WFpp, m3/MWh
Water consumption for construction of power plant [1].	0.32-1.1	0.00396

In this study, average values of the data are used to represent water demand/consumption coefficients for the various upstream unit operations involved in power generation from RE power plant.

4. Results and Discussions

4.1 Assumptions and Input Data

The operation parameters of the RE power plant have been collected from the operation log sheet and the paper of Mafizul et al. [13] (shown in Table 2).

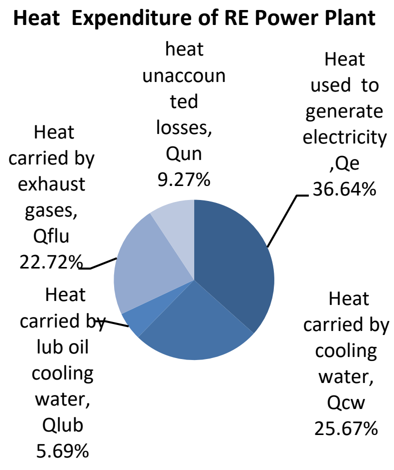
Table 2: Operating Parameters of the Power Plant

Parameters	Unit	Value
Net power output	MW	10.00
Capacity factor	%	65.87
Full power lifetime	Years	25.00
Lifetime output	GJ	4,684,565.56
Direct fuel input	GJ	12,509,493.37
Life-cycle energy input	GJ	13,692,868.87
Thermal efficiency of operation of the power plant, ɳ	%	37.45
Life-cycle efficiency	%	34.21

4.2 Heat Balance of the Power Plant

The heat balance of the studied reciprocating engine power plant is shown in the Table 6. The efficiency of the power plant is found to be 37.93 %. It means 37.93 %of the heat energy from the fuel has been used to generate electricity. The remaining heat energy has been lost by different means, which have been calculated for this power plant using data from the plant.

It has been observed that the heat carried out by the cooling water is around 25.18 %, flue gas 15.45 %, and heat loss unaccounted 21.43%. The heat balance of the power plant has been shown in Figure 6 and 7.



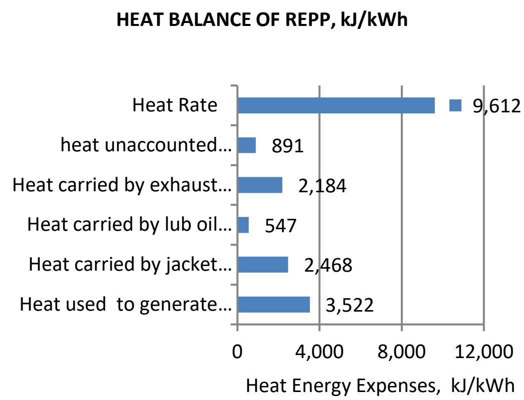


Figure 6: Heat Expenditure of RE Power Plant Figure 7: Heat Expenditure of RE Power Plant

4.3 Water Consumption for the Fuel Upstream Stages

The water footprint WF_f for fuel (NG) supply has been estimated using equation 9. The WF_f of natural gas has been calculated for this RE power plant and it is 0.0937 L/kWh shown in Table 5.

Table 3: Life time water footprint for natural gas upstream paths

pathways	WDCs[1]	life-cycle NG requirement for power generation, Vf[2]	Lifetime water requirement (col 2 x col 3)	lifetime electricity generation	WFf of fuel upstream pathways
	L/m3 of NG	m3	liters	kWh	L/kWh
exploration	0.000	342,334,444.19	0.00	1,304,319,250	0.0937
drilling	0.045		15,405,049.99		
extraction	0.003		1,027,003.33		
processing	0.194		66,412,882.17		
transportation	0.115		39,368,461.08		
Total	0.357	342,334,444.19	122,213,396.58	1,,250304,319	0.0937

Notes: 1. Average of WDCs of the paper of Babkir et al.[3] have been used.
2. Vf, taken from the paper of MafizulHuq et al.[13].
3. life-time electricity generation data taken from the paper of Mafizul Huq et al. [13].

4.4 Water Requirement for Operation of RE Power Plant

The life time water requirement for operation of the RE power plant isestimated from the gathered data from the paper of Mafizul Huq et al. [15] in respect of average water use during operation of the plant.

Table 4: life time water estimation for operation of RE power plant

Unit operations	Life time water consumption1	life-cycle electricity generation 1	Water Demand Coefficient (WDC)	Water Demand Coefficient (WDC)	Water Demand Coefficient (WDC)
	m3/life	kWh/life time	m3/kWh	m3/MWh	L/kWh
Life time water consumption for operation of the plant	5,673.03	1,304,319,250	0.00000435	0.00435	0.00435

Notes: 1. Data obtained from the study of Mafizul Huq et al. [13].

The water consumption coefficient for the operation stage of the power plant has been estimated from the actual consumption of water collected from the plant. Closed loop dry cooling systems of the power plant have very low water demand coefficients. Theconversion efficiency of the power plant is important, and it affects the two stages of the life-cycle (NG upstream stage and power generation stage).The water consumption for construction of the power plant is obtained from the study of Babkir Ali et al [3] which is in the range of 0.32-1.1 m3/TJ shown in Table 12. We take the average of it for calculation of WF for construction of power plant.

Table 5: Estimation of WF for construction of the plant [3].

	WFs of Electricity	
	$m3/TJ_{e+C28}$	L/kWh
Water consumption for construction of power plant.	0.32 -1.1	0.00256

4.5 Estimation of Life Cycle WF for Power Generation of the RE Power Plant

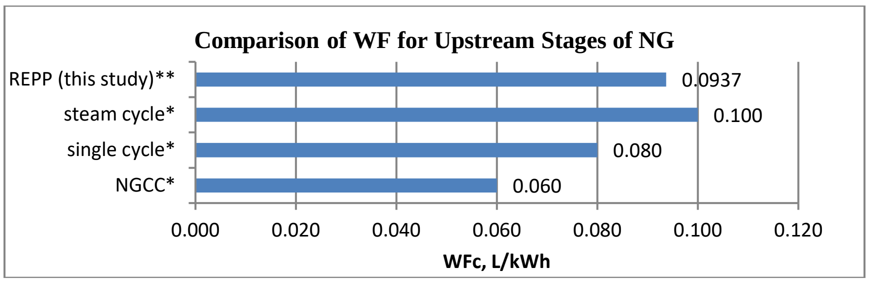
The calculation of WF of the power plant considering phases of life cycle generation of the RE power plant is shown in Table 8 :

Table 6: Life Cycle Water Footprint of Electricity Generation for RE Power Plant.

	WFs of Electricity		
	m3/TJ_e	L/kWh	%
Water consumption for construction of power plant [1].	0.32 -1.1	0.00256	2.54
Water consumption for fuel NG upstream pathways [2].		0.09370	93.14
Water consumption of operation of RE power plant [3].	data collected from power plant	0.00435	4.32
Water Footprint of electric power generation		0.10060	100

4.6 Comparison with Earlier Studies

Comparison of water consumption coefficient, that is water footprint, WF_f for upstream stages of natural gaslife cycle of RE power plant with other power plant types of research paper of babkir et al [3], which has been shown in Figure 8.



Notes: * Data obtained from the study of Babkir et al.[3], ** Data obtained from this study for RE Power Plant & Dry cooling tower

Figure 8: Comparison of Water Footprint for Upstream Stages of Fuel (Natural Gas)

The more efficient power generation technology would consume less energy to produce electricity and consequently would use less natural gas and water. NGCC is the most efficient power generation technology and hence its water consumption is much less than that of REPP and other technology. Water consumption of NG upstream stage depends on the efficiency of the power generation technology, that means NG consumption per unit electricity generation. The WF of power generation for NGCC is 0.06 L/kWh, steam cycle 0.10 and that of REPP is 0.09 L/kWh.

The water consumption coefficient for the operation stage of the power plant has been estimated from the actual consumption of water collected from the plant. In this power plant, closed loop radiator type dry cooling system is being used. Closed loop dry cooling systems have very low water demand coefficients. Theconversion efficiency of the power plant is important, and it affects the two stages of the life-cycle (NG upstream stage and power generation stage). Comparison of WF for operation stage of different power plants have been with the study of Babkir Ali et al [3].

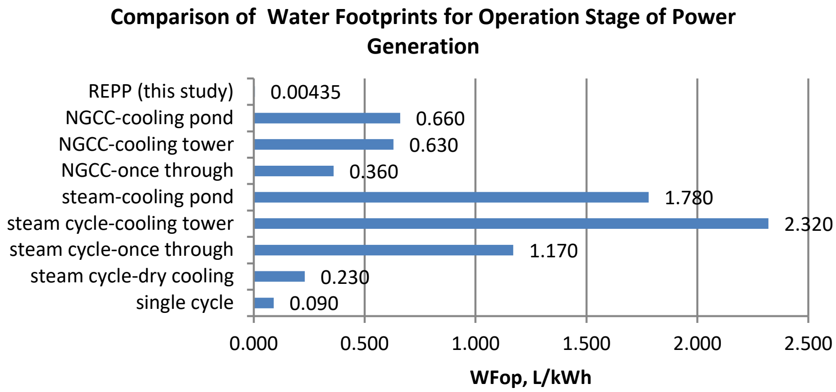


Figure 9: Comparison of WF for operation stage of different power plant types and different cooling systems.

4.7 Comparison of Life Cycle Water Footprint (WF) for Power Plant types

The WF of different power plant types is shown in Figure 11: Comparison of Life Cycle WF of Power Plant types

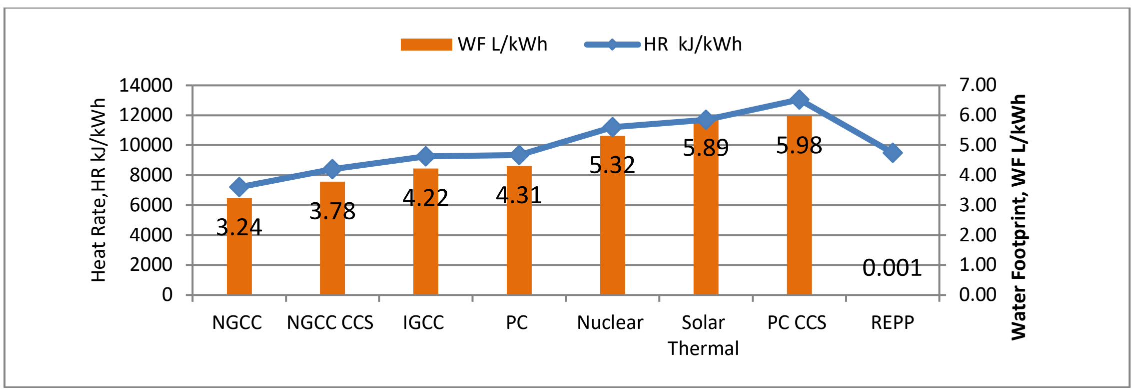


Figure 10: WF of different power plant types

The WFs of different stages of power generation is shown in Figure 11..

WFs of different stages of Power Generation L/kWh

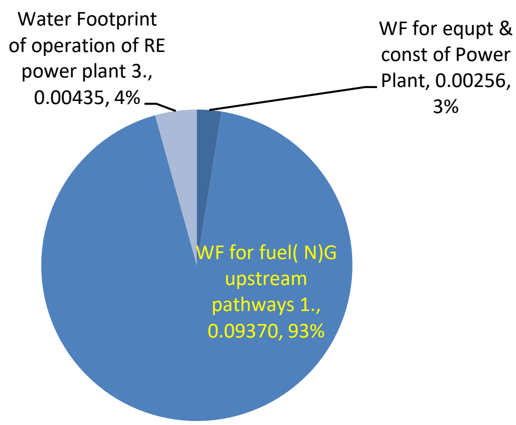


Figure 11: WFs of stages for power generation

Except REPP, the lowest water consumption coefficient of 0.12 L/kWh is achieved through the pathway that uses NG to generate electricity through NGCC technology and dry cooling. This lowest coefficient is achieved due to the low water requirement for NG and dry cooling, along with the highest conversion efficiency of NGCC technology. The highest water consumptioncoefficient (2.42 L/kWh) is observed for power generation from steam cycle with cooling tower Figure… shows that reciprocating engine power plant (REPP) has the lowest water consumption of 0.001 L/kWh, even lower than NGCC. In NGCC technology steam is condensed through dry cooling system and both latent heat and sensible heat need to be removed from the steam whereas in REPP only sensible heat need to be removed. That is why more water is required for NGCC than REPP.

REFERENCES

1. Mustfa K Mujeri and TahreenTahrimaChowdhury, "Quick Rental Power Plants in Bangladesh: An Economic Appraisal", Bangladesh Institute of Development Studies. Sher-e-
Bangla Nagar,Dhaka 1207. June 1013.
2. Bangladesh Power Development Board, http://www.bpdb.gov.bd/bpdb/
3. Babkir Ali, AmitKumar , "Development of life cycle water footprints for gas-fired power generation technologies", Energy Conversion and Management 110 (2016) 386–396, science Direct, Elsevier.
4. E S Spang[1], W R Moomaw[2], K S Gallagher[2], P H Kirshen[3] and D H Marks[4], "The water consumption of energy production: an international comparison", Published 8 October 2014 © 2014 IOP Publishing Ltd ,Environmental Research Letters, Volume 9, Number 10
5. Mesfin M. Mekonnen,* P. W. Gerbens-Leenes and Arjen Y. Hoekstra ,"The consumptive water footprint of electricity and heat: a global assessment", Environmental Science Water Research & Technology, Published on 09 March 2015. Downloaded on 17/03/2015 13:55:08.
6. R.Pate,M.Hightower, C.Cameron and W. Einfeld, Overview of energy-water terdependencies and the emerging energy demands on water resources, Report SAND 2007-349C, Sandia National Laboratories, Albuquerque, New Mexico, USA, 2007.
7. W. Wilson, T. Leipzig and B. Griffiths-Sattenspiel, Burning, our rivers: the water footprint of electricity, River Network, Portland, Oregon, USA, 2012.
8. E S Spang[1], W R Moomaw[2], K S Gallagher[2], P H Kirshen[3] and D H Marks4, "The water consumption of energy production: an international comparison", Published 8 October 2014 • © 2014 IOP Publishing Ltd., Environmental Research Letters, Volume 9, Number 10
9. Emily Grubert and SayaKitasei , "How Energy Choices Affect Fresh Water Supplies: A Comparison of U.S. Coal and Natural Gas", Published in World Watch Institute, November 2010
10. Abu Musa Md. Motaher AHMED et. al,"Utilization and Conservation of Water Resources in Bangladesh" Nihon University,Japan
11. J Meldrum[1], S Nettles-Anderson[2], G Heath[2] and J Macknick[2] , "Life cycle water use for electricity generation: a review and harmonization of literature estimates", Published 12 March 2013 • 2013 IOP Publishing Ltd.,Environmental Research Letters, Volume 8, Number 1
12. Water for energy Water for Energy World Energy Council, Published 2010 by: World Energy Council, Regency House 1-4 Warwick Street, London W1B 5LT United Kingdom ISBN: [978-0-946121-10-6]Water
13. Mafizul Huq , Md. Mustafizur Rahman, A.K.M. Sadrul Islam, Md. NurulAbsar Chowdhury.
'Life Cycle Assessment of a Reciprocating Engine Power Plant in Bangladesh' , published in AIP Proceedings of 8th BSME ICTE 2018 as Volume no. 2121, 18 July 2019. , http://aip.scitation.org/toc/apc/2121/1
14. Julion Fulton et al., "The water Footprint of California;s Energy System", 1990-2012, energy and resources group, University of Calfornia, USA
15. E. D. Williams and J. E. Simmons, Water in the energyindustry: An introduction, BP International, London, UK,
2013