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RESEARCH

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Operational blue water footprint and water deficit assessment of coal-fired power plants: case study in Malaysia

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Abstract

Freshwater is an essential resource used to generate electricity at coal-fired power plants. Previous literature has shown that a few states in Malaysia will face a high risk of water stress. Hence, coal-fired power plants located at risk states are exposed to potential water risk. This study aims (i) to determine the operational blue water footprint at coal-fired power plant from 2009 until 2020; (ii) to assess the water stress index at Perak, Negeri Sembilan and Johor; and (iii) to compare the water deficit impact across three states. This study accounted the operational water footprint using Water Footprint Assessment Global Manual. The study boundary focuses on water consumption of generating electricity at operational level. The water stress index was assessed based on ratio of water demand and water availability at Perak, Negeri Sembilan and Johor watershed. Next water deficit impact was determined to compare the impact of operational blue water footprint on local water resources. Data for this study were collected from the state's water authority, published literature, national reports, and statistics. Result of this study found the average operational blue water footprint recorded by coal-fired power plant located at Perak is 0.11 m^3/MWh followed 0.09 m^3/MWh (Johor) and 0.04 m^3/MWh (Negeri Sembilan). Water stress index at Perak and Negeri Sembilan shows moderate water stress, whereas Johor indicates low water stress index. The water deficit result shows Perak has the highest total water deficit at 12,542,824 m^3H_2Oeqn from 2009 to 2020. This is due to moderate water stress condition at Perak and the total blue water footprint of coal-fired power plant at Perak is 67% and 42% more as compared to Negeri Sembilan and Johor, respectively. The result from this study is useful in enhancing understanding of water consumption pattern at coal-fired power plant and its impact on state's water resources for future electricity scenarios.

Keywords Water–energy, Blue water footprint, Coal-fired power plant, Water stress index, Water deficit

Introduction

Freshwater is renewable but has limited resources since the quantity and quality of freshwater availability are changing over time and location. There is limitation of precipitation, ground water recharge and river flow in a certain period throughout the years. Problems related to freshwater scarcity and pollution are substantial as water demand is increasing, but water availability and quality is decreasing due to population growth, unsustainable water use, water degradation and climate change [16, 28, 58]. It is forecasted that the world's primary energy demands will increase by 80%, and global water

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consumption will increase by 55% in 2050, leading to a great threat to energy and water security [18].

Malaysia is blessed with abundant freshwater resources [1]. Annual surface runoff in Malaysia is estimated to be 566 billion cubic meters per year, with an average rainfall of 990 billion cubic meters per year Malaysia Water Association [38]. However, water demand in Malaysia is increasing annually due to population and economic growth although Malaysia [8]. In addition, the sustainability of water resources in Malaysia is also threatened by water pollution [5]. Thus, the nation water supplies, especially states with large industry and agriculture productions are under pressure [6]. Malaysia's water industry outlook has reveals that several states in Malaysia, such as Perlis, Kedah, Penang, Selangor, and Melaka, have water deficits, while Perak, Kelantan and Negeri Sembilan were exposed to high water risk Malaysia Water Association [38].

Malaysia's thermal power generation plays the main role in Malaysia's electric generation mix. About 43% of Malaysia's electric generation is dependent on coal, followed by gas (40%), hydro (15%), diesel (1%) and others (2%) [35]. Thermal power plant depends much to water as resources to generate electricity. The water footprint of electricity generated at thermal power plant (1.19 m^3/GJ) plant is higher as compared to wind power plant (0.14 m^3/GJ) and nuclear power plant (0.19 m^3/GJ) [15]. Water is used at major processes in the power plant such as boiler and boiler feedwater system, cooling system, pollution control system and ash handling [10, 51]. Hence, high water consumption at the thermal power plant would have a substantial influence the local water resource.

Water footprint is an environment indicator used to determine the amount of water consumed and polluted in production system considering geographical and temporal context in which these processes take place [24, 25]. Presently, analysis of water footprint along a supply chain are significant [19] since freshwater scarcity is a threat to sustainable development [40]. Previous study on water footprint at coal-fired power plant has been conducted in China [11, 15, 32, 57, 62], United States [12], Europe [56] and India [60]. These regions are among the major coal power producers [27] Research related to water footprint and water impact of energy industry would be beneficial for future energy planning and water resources management [57, 62].

Water usage at thermoelectricity power plant showed significant impact on local water resources [29]. Regions facing high to extreme water stress are contributing to water implications for thermal power generation [60]. Previous studies addressing water impact due to electricity production from coal-fired power plant are based on mid-point life cycle impact [32], water deprivation and water scarcity footprint [57]. Results reveal that uneven spatial and temporal distributions water resources among regions also created vulnerability to thermal power [57, 62].

Currently, water footprint has been widely used in Malaysia's agriculture sector such as paddy production [21], palm oil plantation [42] and other agriculture products [23]. More attention was given to agriculture since irrigation for agriculture used a lot of water [21, 42] and about 70% of water in Malaysia is used for national food security and rural development [54]. Aside from that, studies on agriculture water footprint showed that determining water use of the products help to identify processes with high water consumption to enhance water management practice in Malaysia [21, 23].

Studies on water footprint and water resources impact due to power generation in Malaysia are still in infancy. There is a need to conduct spatial and temporal water footprint to investigate the impact of water footprint on local water resources perspective [24]. As a starting point this study focus on investigating water footprint of electricity generated at coal-fired power plant since coal-fired power plant is major electricity generator from 2017 until 2020 in Peninsular Malaysia. The total install capacity of coal-fired power plant has been increasing from 49% in 2009 to 60% in 2020 [36]. As in December 2019, the total installed capacity of coal-fired power plant in peninsular Malaysia is 12,180 MW at Perak, Negeri Sembilan, Johor and Selangor state [37]. In addition, the average water footprint of electricity and heat produce using coal is 83% higher as compare to natural gas [39]. Hence, based on the above motivation, this study aims:

a. to determine the blue water footprint and calculate the operational blue water footprint of coal-fired power plant.
b. to determine and compare the water stress index at Perak, Johor and Negeri Sembilan.
c. to calculate water deficit due to blue water footprint of coal-fired power plant and compare the water deficit among the three states.

This study shows the overview of blue water footprint of at coal-fired power plants located in in high-risk state in Malaysia. This study also helps addressing status of local water resources using water stress index parameter where the value varies from country to country based on the local water supply and the demand for water from various sectors. The water deficit impact on local watershed would benefit the water authorities and power plant owner for future water management plan.

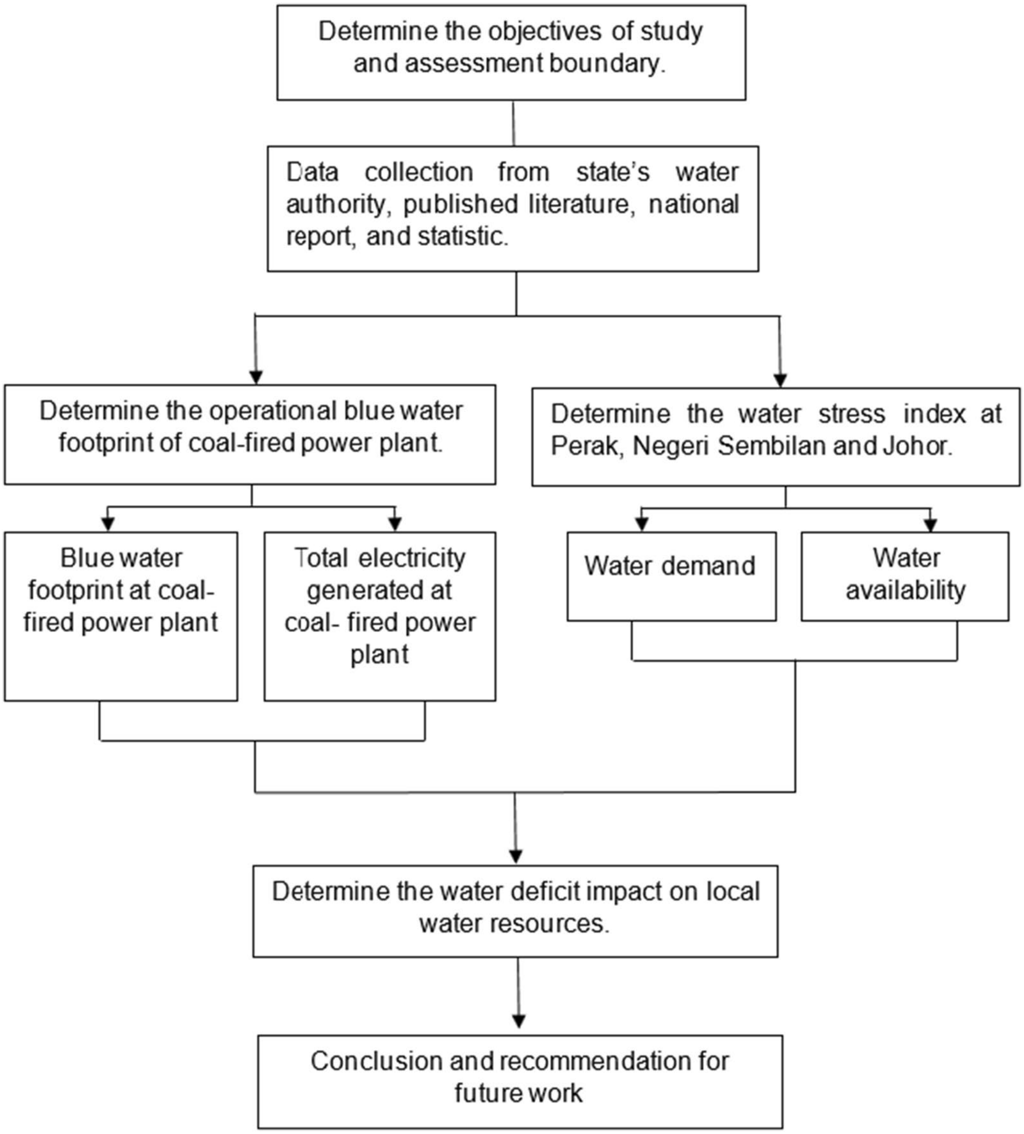

Fig. 1 Flowchart of assessing the operational water footprint and water deficit at coal-fired power plant

Methodology

Figure 1 shows the flowchart of assessing the operational water footprint and water deficit at coal-fired power plant. The coal-fired power plant in Peninsular Malaysia was located at three states which are Perak, Negeri Sembilan and Johor, as shown in Table 1. Perak was the major coal electricity producer (4080 MW) followed by Negeri Sembilan (3400 MW) and Johor (3100 MW) [37].

Table 1 List of coal power plants in Peninsular Malaysia

No.	Power plant	Location	Install capacity (MW)
1	Janamanjung Power Plant (JMPP)	Perak	4080
2	Jimah East Power Plant (JEPP)	Negeri Sembilan	2000
3	Jimah Power Plant (JPP)	Negeri Sembilan	1400
4	Tanjung Bin Power Plant (TBPP)	Johor	2100
5	Tanjung Bin Energy Power Plant (TBEPP)	Johor	1000

Operational blue water footprint of coal-fired power plant

This study uses Water Footprint Assessment Manual [24] to determine the operational blue water footprint of coal-fired power plant. It measures the blue water footprint per unit of electricity generated at the power plant as shown in Eq. (1); whereas he blue water footprint is defined as the amount of freshwater consumed and not returned to the same catchment area in certain period as shown in Eq. (2):

$$\mathrm{WF}_{\text{blue, operational}} = \frac{\mathrm{WF}_{\text{Blue}}\left[\mathrm{m}^3/\mathrm{year}\right]}{\text{Amount of electricity generated}[\mathrm{MWh/year}]}, \tag{1}$$

$$\begin{aligned}\mathrm{WF}_{\text{Blue}} &= \text{blue water evaporation} \\ &\quad + \text{blue water incorporate} \\ &\quad + \text{lost return flow.}\end{aligned} \tag{2}$$

The main blue water resources at coal-fired power plant located in Perak, Negeri Sembilan and Johor is freshwater and the effluents from coal-fired power plant were not discharged to the same catchment area. Consequently, the effluent is considered as lost return flow in the blue water footprint. Therefore, this analysis assumed that the blue water footprint of coal-fired power plants is equal to the amount of freshwater supplied to the power plant per unit of electricity generated at the power plant. Table 2 shows freshwater data coverage at coal-fired power plant from 2009 to 2020 obtained from the local authorities, i.e., Syarikat Air Negeri Sembilan (SAINS), Lembaga Air Perak (LAP) and Syarikat Air Johor (SAJ).

The annual electricity production for each power plant using the capacity factors (CF), as shown in Eqs. (3) and (4). The CF of electricity generation measures the amount of electrical power that is generated by a coal-fired power plant in relation to the maximum amount that could potentially be produced for 24 h per day for a year [9]. The coal capacity factor of Peninsular Malaysia is data obtained was from Malaysia Energy Information Hub [36]. The coal capacity factor data plotted in Fig. 2 show the coal capacity factor varies throughout the years between 55 to 83%. After conducting calculation, the total electricity generated

Table 2 Freshwater data coverage at coal-fired power plant at Negeri Sembilan, Perak and Johor

Power plant	Freshwater data coverage (year)											
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
JMPP	/	/	/	/	/	/	/	/	/	/	/	/
JEPP	X	X	X	X	X	X	X	X	X	X	X	/
JPP	/	/	/	/	/	/	/	/	/	/	/	/
TBPP	/	/	/	/	/	/	/	/	/	/	/	/
TBEPP	X	X	X	X	X	X	X	/	/	/	/	/

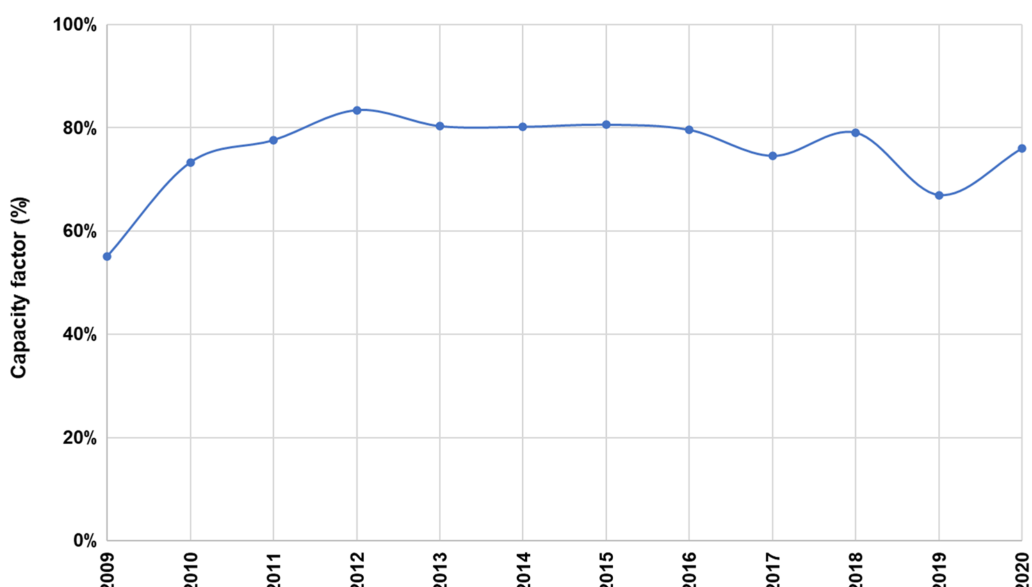

Fig. 2 Coal capacity factor in Peninsular Malaysia from 2009 until 2020

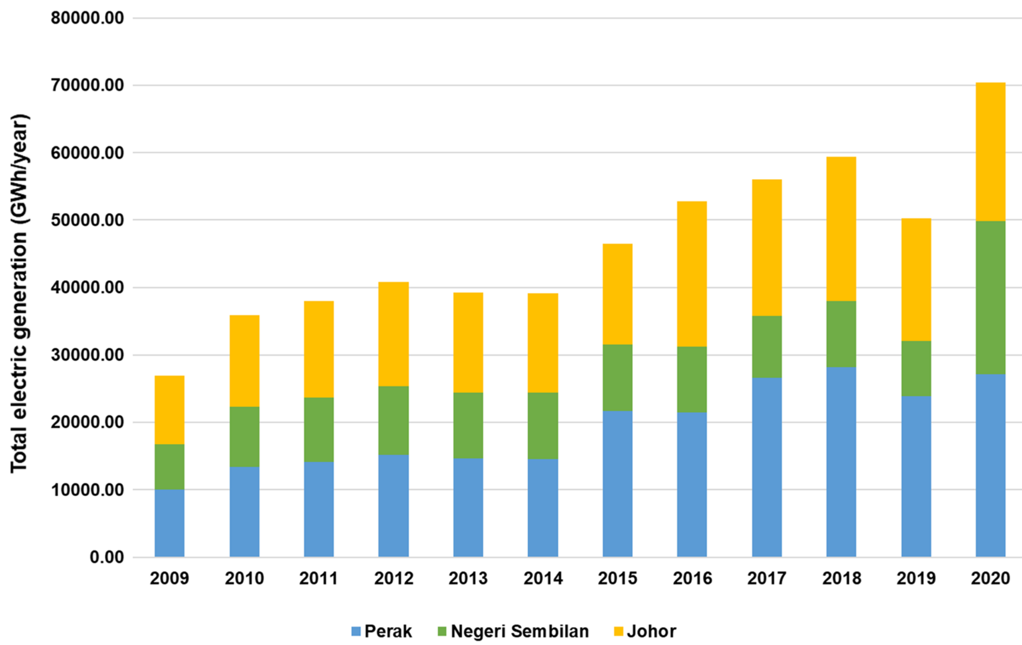

Fig. 3 Total electricity generated at coal-fired power plant located at Negeri Sembilan, Perak and Johor

at coal-fired power plant located at Negeri Sembilan, Perak and Johor is visualized in Fig. 3.

$$\text{Coal capacity factor, } \mathrm{CF}_{ij}[\%] = \frac{\text{Total generation}[\mathrm{MWh}]}{\text{Install capacity}[\mathrm{MW}] \times 24 \times 365}, \tag{3}$$

$$\text{Total generation}[\mathrm{MWh}] = \mathrm{CF}_{ij} \times \left(\text{Install capacity}[\mathrm{MW}] \times 24 \times 365\right). \tag{4}$$

Water stress index (WSI)

This study intends to determine the water stress index at Negeri Sembilan, Perak and Johor since these states are where the coal-fired power plant at Peninsular Malaysia is located. The coal-fired power plant received freshwater supply from Sg. Linggi (Negeri Sembilan), Sg. Perak (Perak) and Sg. Johor (Johor) watershed. The state's water availability data are obtained from rainfall Malaysia Water Association [38] and water demand data were obtained from National Water Resources Study 2000–2050 (Ranhill [47]).

Figure 4 shows the water availability and demand in Negeri Sembilan, Perak and Johor. Freshwater in Malaysia is utilized for social, economic, agricultural and environment consumption. About 70% water distribution in Malaysia is used for agriculture and irrigation, 28% for domestic and industrial, while remaining for environmental purposes (Malaysia Water Association [38]). Perak, agriculture and livestock contribute about 80% of total water demand and portable water for domestic and industry left only 20%. Meanwhile, in Negeri Sembilan and Johor, most of the water demand is for potable water, which includes domestic and industrial water supply, the remaining 20% to 22% of water demand is for agriculture and livestock.

This study adopted water stress index technique from Pfister et al. [45]. Water stress in Eq. (5) is defined as the ratio between water demand and water availability at a specific watershed [45]. The water stress index value varies from 0 to 1, and the index classification is shown in Table 3.

$$\text{Water stress index} = \frac{1}{1 + e^{-6.4\mathrm{WTA}*\left(\frac{1}{0.01} - 1\right)}}. \tag{5}$$

WTA in Eq. (6) is the water demand (WD) ratio by different sectors (domestic, industry, agriculture, and livestock) to water availability (WA) in specific watersheds:

$$\mathrm{WTA} = \frac{\sum \mathrm{WD}}{\sum \mathrm{WA}}. \tag{6}$$

However, WTA* in the watershed may be adjusted with the variation factor (VF) of water flows due to the monthly and annual variations of rainfall, as shown in Eqs. (8) and (9). S*month and S*year represent the standard deviations of each watershed's monthly and annual rainfall over the past ten years:

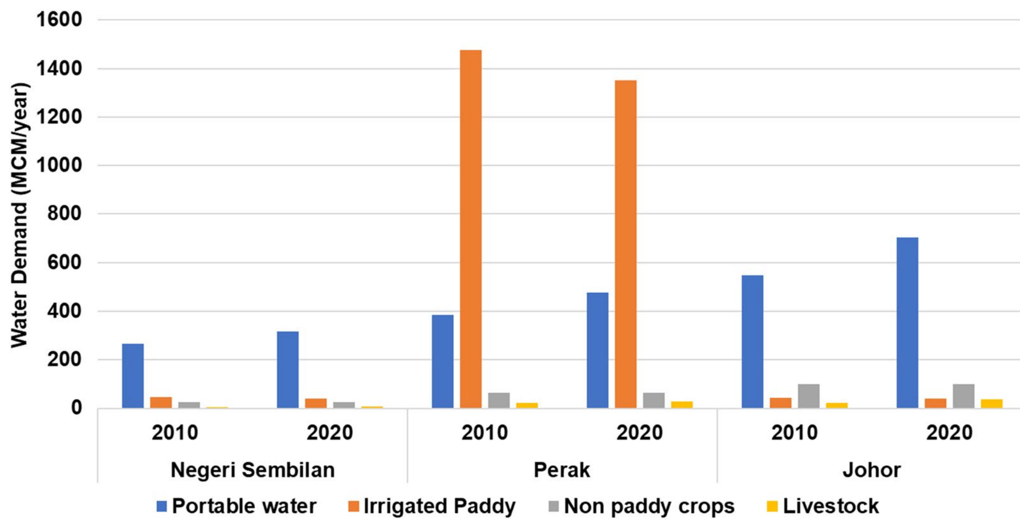

Fig. 4 Water demand at Negeri Sembilan, Perak and Johor

Table 3 Classification of water stress index [45]

Water stress index	< 0.1	0.1–0.49	0.5	0.51–0.89	> 0.9–1.0
Condition	Low	Moderate	Stress	Severe	Extreme

$$\mathrm{WTA}^* = \sqrt{\mathrm{VF}} \times \mathrm{WTA}, \tag{7}$$

$$\mathrm{WF} = e^{\sqrt{\ln\left(S^*_{\mathrm{month}}\right)^2 + \ln\left(S^*_{\mathrm{years}}\right)^2}}. \tag{8}$$

Water deficit

Impact of freshwater consumption by human activities not only depends on how much water is consumed during the activities, but it also involves water stress condition of area where the water was withdrawn [50]. The water deficit impact used to compare the impact of blue water footprint at the coal-fired power plant located at different states where the water stress index is different. Equation (9) determines the amount of water deficit to downstream users and ecosystems [44]:

$$\begin{aligned}&\text{Water deficit}_{\text{coal power plant},i}\\&= \text{Blue water footprint}_{\text{coal power plant},i} \times \mathrm{WSI}_i,\end{aligned} \tag{9}$$

where blue water footprint represents the amount of blue water footprint of coal-fired power plant in watershed, i (m^3/year); $\mathrm{WSI_i}$ represents the water stress index of watershed, i. The unit is expressed in cubic meter water equivalent (m^3H_2Oeqn).

Results and discussion

Water footprint of coal-fired power located at Perak, Negeri Sembilan and Johor

Blue water footprint of coal-fired power plant from 2009 until 2020

Figure 5 exhibits blue water footprint of coal-fired power plants located in Perak, Negeri Sembilan and Johor from 2009 until 2020. Blue water footprint of coal-fired power plants represents as the amount of freshwater consumed at coal-fired power plants per year. The blue water footprint at each state in Peninsular Malaysia varies since the power plant total install capacity is different throughout the years.

Perak recorded the highest trend of blue water footprint in 2018 as compared to Negeri Sembilan and Johor. The blue water footprint of coal-fired power plant in Perak is 53% and 65% more than blue water footprint of coal-fired power plant located in Johor and Negeri Sembilan since the installed capacity of coal-fired power plants in Perak is larger than in Johor and Negeri Sembilan. The 2020 blue water footprint at Negeri Sembilan was increased twice at 2,335,272.00 m^3/year as compared to previous year since there is additional 2000 MW install capacity of coal-fired power plant has started operating at Negeri Sembilan; whereas, in Johor the 2016 blue water footprint at Johor increased 18% due to addition of 1000 MW coal-fired power plant install capacity that started its operation in 2016.

Figure 6 shows the timeline of coal-fired power plant development in Peninsular Malaysia. Janamanjung Power

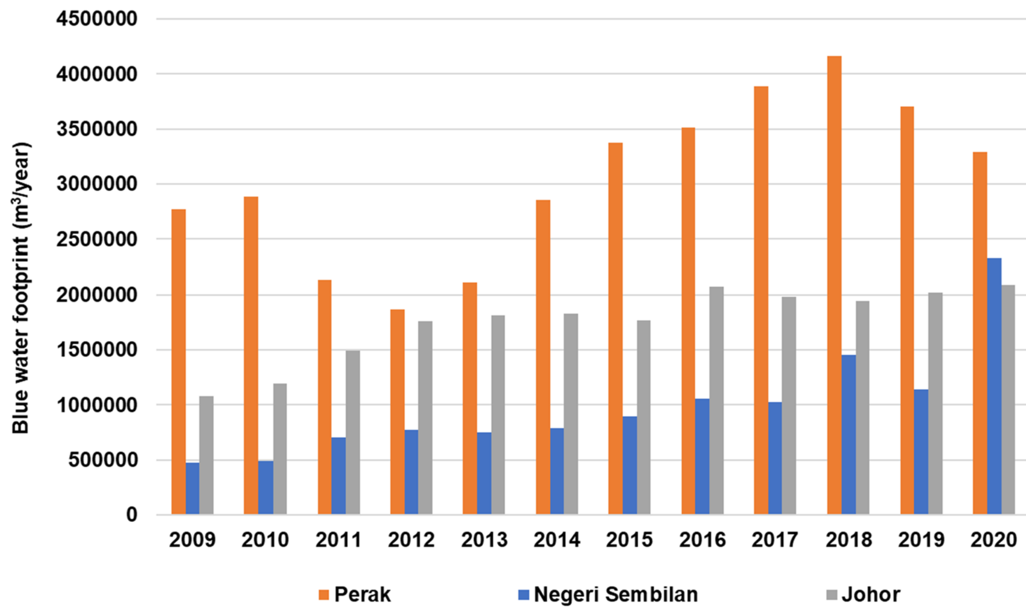

Fig. 5 Blue water footprint of coal-fired power plant from 2009 until 2020

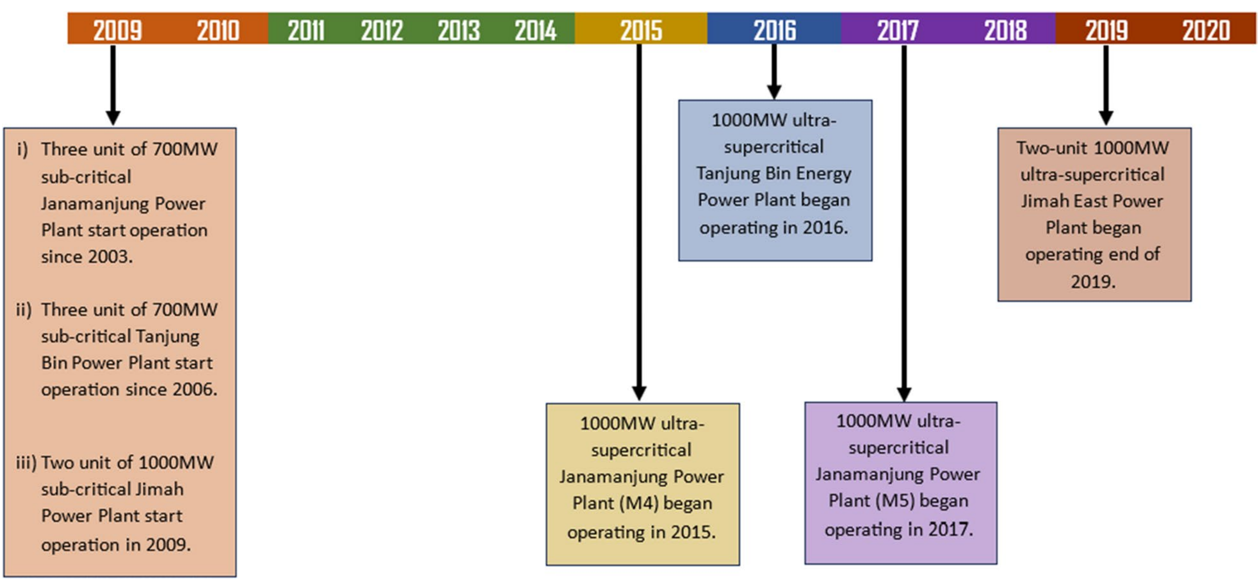

Fig. 6 Timeline of coal-fired power plant development in Peninsular Malaysia

Plant (JMPP) and Tanjung Bin Power Plant (TBPP) are among the earliest coal-fired power plant in Peninsular Malaysia. JMPP first generating facilities consist of three unit of subcritical generation technology has started operating since 2003, while TBPP in Johor has start operating since 2006 where this coal-fired power plant consists of three unit of 700 MW subcritical generating technology. Next, Jimah Power Plant (JPP) has started its operation on 2009 where this coal-fired power plant consists of two unit of 1000 MW subcritical generating technology.

The first ultra-supercritical coal-fired technology has started its operation in 2015 at Janamanjung Power Plant (M4). This generating technology has continued develop in Peninsular Malaysia, as in 2016 Tanjung Bin Energy Power Plant (TBEPP) has started the operation of 1000 MW ultra-supercritical coal-fired power plant. The third unit of ultra-supercritical technology started its operation in 2017 under Janamanjung Power Plant (M5).

Recently, Jimah East Power Plant (JEPP) which consists of two unit of 1000 MW ultra-supercritical has started its operation at the end of 2019.

The development of coal-fired technology from subcritical to ultra-supercritical technology has an effect on Malaysia's electricity generation mix. During 2009 until 2016, Malaysia's electricity generation mix was dependent on natural gas power plant [35]. However, after 2017 onwards, the dependencies have changed to coal-fired power plants. This subsequently has influence the pattern blue water footprints of coal-fired power plant before and after 2016. The average value of blue water footprint before 2016 is 5,057,667.63 m^3 per year. The amount has increased 44% after 2016 by 7,258,808.25 m^3 per year.

Operational blue water footprint of coal-fired power plant from 2009 until 2020

The operational blue water footprint measures the amount of water consumed per unit of electricity generated at the power plant. This functional unit of operational blue water footprint applied in this study is m^3/MWh. Figure 7 shows operational blue water footprint of coal-fired power plants from 2009 until 2020. The average operational blue water footprint at Perak is 0.17 m^3/MWh and it was followed by Johor (0.11 m^3/MWh) and Negeri Sembilan (0.09 m^3/MWh).

The technology of the power plants one of the factors that influences the operational blue water footprint results. Coal-fired power plants produce electricity by burning coal in boiler to produce high-temperature, high-pressure steam. Thermodynamic steam cycle distinguishes between subcritical, supercritical, and ultra-supercritical types of coal generating technologies [61]. Literature by Macknick et al. [34] and Meldrum et al. [41] exhibits that coal-fired power plant with supercritical generating technology record less water consumption and withdrawal as compared to subcritical generation technology, as shown in Fig. 8.

Similarly, Ali and Kumar [7] found that subcritical and supercritical generating technology consume 60% and 34% more water as compared to ultra-supercritical generating technology. Ultra-supercritical boilers operate at very high pressure and temperature and thus are 3–6% more efficient subcritical boilers that use subcritical technology [48]. Due to power plant net efficiency, the subcritical and ultra-supercritical generating technology use 13% more and 18% less total makeup water than supercritical generating technology [59]. Besides, the ultra-supercritical technology also promotes low environmental impact as compared to subcritical and supercritical technology since this generating unit has the low score in life cycle impact category [30].

The implementation of ultra-supercritical in Perak has started from 2015. Before 2015 the average of operational blue water footprint is 0.18 m^3/MWh. However, the value has improved by 20% to 0.15 m^3/MWh. Similar trend was shown in Johor, where the ultra-supercritical coal-fired power plant has started its operation in 2016. The average of operational blue water footprint has improved 10% from 0.11 m^3/MWh (2009–2015) to 0.10 m^3/MWh

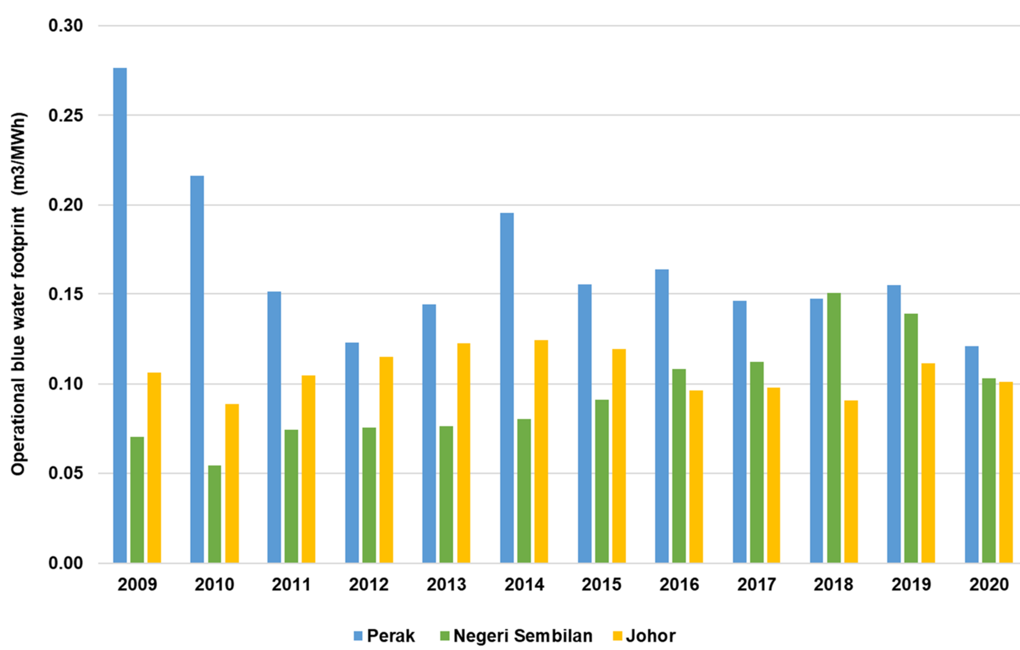

Fig. 7 Operational blue water footprint of coal-fired power plant from the year 2009 until 2020

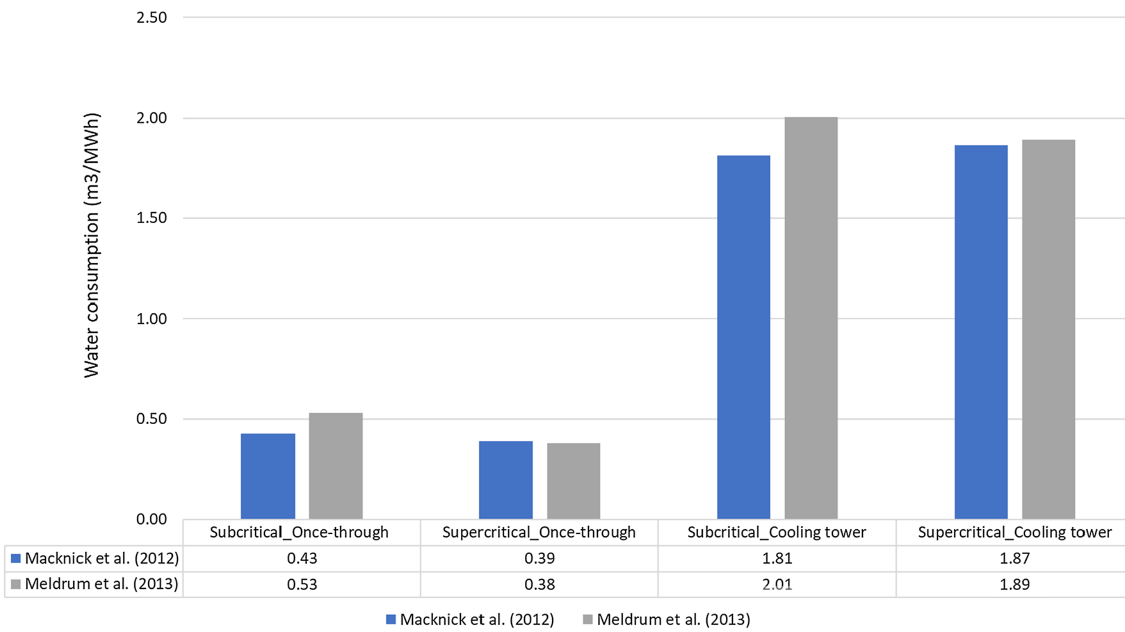

Fig. 8 Water consumption for subcritical and supercritical coal-fired power plant [33, 41]

(2016–2020). Another scenario is observable in the operational blue water footprint within Negeri Sembilan. The operational blue water footprint of Jimah Power Plant has increased from 0.07 m^3/MWh (2009) to 0.15 m^3/MWh (2018) before the adoption of ultra-supercritical technology. The operational blue water footprint has experienced a decrease to 0.10 m^3/MWh in the year 2020, after the commencement of operations of the ultra-supercritical coal-fired power plant in December of 2019. The above explanation demonstrates that technological advancements have an impact on the operational water footprint of coal-fired power plants within specific states.

Malaysia has pledged not to build new coal power plant in future and target to increase the renewable energy capacity to 31% by 2025 (Unit Perancang Ekonomi Jabatan Perdana Menteri 2021). Nevertheless, coal power generation will still in Malaysia energy mix with lower contribution (Suruhanjaya [52]). The operational blue water footprint of coal-fired power plant at Perak (0.15 m^3/MWh), Johor (0.10 m^3/MWh) and Negeri Sembilan (0.10 m^3/MWh) is expected to be sustain since there is no more coal-fired power plant development within the state. The pattern is expected to decrease in future due to the convection coal-fired power plant which are Janamanjung Power Plant, Tanjung Bin Power Plant and Jimah Power Plant are expected to retire by 2030, 2031 and 2033 [53].

Next, the operational blue water footprint results were compared with previous literature value. Table 4 exhibits blue water footprint of coal-fired power plant establishes in previous literature. The blue water footprint of coal-fired power plant varies from 0.21 to 3.89 m^3/MWh. The results are varying since some previous literature include direct and indirect water footprint assessment. The direct blue water footprint indicates the water consumption during power plant operation

Table 4 Blue water footprint of coal-fired power plant established in previous literature

Blue water footprint (m^3/MWh)	Assessment year	Water footprint boundary	References
0.21–5.08	2008	Operational consumptive water footprint	[39]
1.35	2015	Total direct and indirect blue water footprint of coal-fired power generation	[32]
2.14	2012	Direct blue water footprint of coal-fired power generation	[11]
3.89	2013	Total direct and indirect blue water footprint of thermal power	[15]
1.57	–	Operational blue water footprint	[56]
2.26	–	Direct blue water footprint of thermal power plant	[57]
1.63	2016	Total direct and indirect blue water footprint of coal-fired power generation	[62]

whereas indirect blue water footprint indicates water consumption during coal extraction, processing, and transportation. Ma et al. [32] and Ding et al. [15] indicates 64% and 62% blue water footprint contribute to direct water footprint (operational blue water footprint), respectively. It specifies that blue water footprint has significant contribution to direct water footprint at coal-fired power plant, whereas grey water footprint contributes a lot to indirect water footprint.

The operational blue water footprint calculated in this study is comparable to the direct blue water footprint from previous literature. The average operational blue water footprint of coal-fired power plant located in Perak, Negeri Sembilan and Johor is lower compared to establish study which are 2.14 m^3/MWh [11], 1.57 m^3/MWh [56] and 2.26 m^3/MWh [57]. It indicates that freshwater consumed per megawatt electricity generated in Malaysia is much better as compared to others given in literature. Low operational blue water footprint results from cooling system that has been implemented at coal-fired power plants. The coal-fired power plant in Peninsular Malaysia mostly located near the sea or river mouth, and these power plants utilized seawater as a cooling medium. Hence, the operational blue water footprint of coal-fired power plant is low as compared to coal-fired power plant that used freshwater as their cooling medium.

Type of cooling system influenced the operational blue water footprint in the generating unit of coal-fired power plant [39]. There are four main types of cooling system which are open-loop (once-through) system, close-loop system (closed-cycle or recirculating), dry system (using ambient air) and hybrid cooling system [10]. Xie et al. [57] indicates thermoelectric plant that utilized dry cooling system and once-through cooling system consume 82% and 79% less water as compared to recirculating cooling system. Smart and Aspinall [51] also found that Australia's subcritical and supercritical coal-fired power plant that utilized recirculating cooling system has 13% and 15% more water consumption as compared to 13% for once-through cooling system.

Furthermore, utilizing alternative water resources in cooling systems such as saline water would substantially reduce freshwater consumption at power plants. However, the application is limited to power plant located only at coastal area [22]. Diehl and Harris [13] indicate that coal thermoelectric plant that utilized once-through cooling system using saline water has 93% less water withdrawal as compared to once-through cooling system using freshwater.

Water stress index (WSI) at Perak, Negeri Sembilan and Johor

Water stress index determines the condition of water resources at based on water demand and water availability factor which could relate to the sustainability of water resources [26]. A region is considered under water stress if the threshold water supply drops below 1700 m^3 per capita per year, while if the threshold water supply further drops below 1000 m^3 per capita per year that means the region was under chronic water scarcity [14]. Due to increase in freshwater demand due to urbanization and economic growth, it is important to ensure our state's water demand match with water availability to avoid water stress issue.

Table 5 shows the water stress index at Negeri Sembilan, Perak and Johor. Perak and Negeri Sembilan show moderate water stress index condition with an average of 0.34 and 0.28, whereas Johor has an average of 0.04 water stress index which falls under low condition. The results indicate, Perak and Negeri Sembilan has high water risk as compared to Johor. Malaysia's water industry outlook also reported Perak and Negeri Sembilan would face water risk [38]. However, current water demand for domestic, industry, agriculture and livestock in Perak, Negeri Sembilan and Johor state's still did not exceed water availability in those states areas [21, 49].

The water stress index results were influenced by water demand and water availability factor. Even though total water demand in Johor for 2010 and 2020 is twice higher than in Negeri Sembilan at 1596 million cubic meters and 731 million cubic meters, respectively, nevertheless, water stress index indicates that Negeri Sembilan has higher water stress than Johor. This is because ratio of water demand and water availability (WTA) in Johor is lower than Negeri Sembilan. The WTA in Negeri Sembilan is 59% (2010) and 56% (2020) more than WTA in Johor. This indicates that water pressure at Johor is less compared to Negeri Sembilan.

The WSI in Malaysia would become more significant in the future due to climate change in urbanized and developed regions [26]. Malaysia is expected to experience intense rainfall in the wet period and a lack of rainfall in the dry period due to climate change [46]. It may have

Table 5 Water stress index at Negeri Sembilan, Perak and Johor for 2010 and 2020

Watershed	Water stress index		Classification
	2010	2020	
Negeri Sembilan	0.23	0.33	Moderate
Perak	0.35	0.34	Moderate
Johor	0.04	0.05	Low

negative impact on the availability of renewable freshwater resources [31]. Hence water stress index indicator can help in balancing the water demand and the water availability ensure future water security.

Water deficit impact of coal-fired power plant on local water resources

This study adopts water deficit as a parameter to determine impact of blue water footprint at coal-fired power plant on Perak, Negeri Sembilan and Johor water resources. Water deficit refer to depletion of available water resources due to water consumption of human activities. This parameter has been used in case study related to agriculture [17, 20, 50] and biofuel product [43]. The advantage of using water deficit parameter is that the policy maker is able to compare the impact of water consumed at coal-fired power plant according to state's water stress level [20]. Low impact means lesser water competition with other water users [20, 21].

Figure 9 shows the water deficit in at Negeri Sembilan, Perak and Johor from 2009 until 2020. Perak has the highest water deficit value at 1,428,446 m^3H_2Oeqn since Janamanjung Power Plant has the highest blue water footprint water at 4,163,111 m^3/year in 2018. Meanwhile the maximum water deficit at Negeri Sembilan is 62,132 m^3H_2Oeqn which occurred in 2020. The blue water footprint at Negeri Sembilan in 2020 is 2,335,272 m^3/year which is 51% more as compare to previous year since Jimah East Power Plant started its operation at the end of 2019. Similar trend can be seen in Johor, when Tanjung Bin Energy Power Plant started its operation in 2016 the blue water footprint increase was 15% as compared to previous year. This causes the water deficit at Johor to increase from 81,362 m^3H_2Oeqn (2015) to 95,597 m^3H_2Oeqn (2016). However, increment in water deficit in Negeri Sembilan is much higher as compared to Johor, since the additional install capacity in Johor is 1000 MW, whereas in Negeri Sembilan the additional install capacity is 2000 MW.

Water deficit result was not only influenced by blue water footprint of coal-fired power plant, but state's water stress index also contributes to significant impact. Water deficit at Perak and Negeri Sembilan is higher than water deficit at Johor since Perak and Negeri Sembilan has moderate water stress index. The total water deficit in Perak from 2009 until 2020 recorded 73% and 92% more than Negeri Sembilan and Johor, respectively. Apart from that, the water deficit of coal-fired power plant is considered as low as compared to the agriculture sector in Peninsular Malaysia. The water deficient of rice production in Peninsular Malaysia on 2002–2011 is between 3,880,000–4,030,000 m^3H_2Oeqn (Perak), 43,600–57,100 m^3H_2Oeqn (Negeri Sembilan) and 57,900–5800 m^3H_2Oeqn (Johor) [21]. This is because paddy irrigation in Perak contributes about 73% of water demand in Perak. Meanwhile, percentage of water demand for paddy irrigation in Negeri Sembilan and Johor are 12% and 5%, respectively.

Water footprint application in power generation industry

Power sector required ample and stable water supply to generated electricity especially at thermal power plant. With emerging water demand due to population growth, urbanization, and economic development, it drives pressure on water resources. Current practice indicates that power plants are receiving freshwater supply from nearer water treatment plants. Hence, it is important to ensure

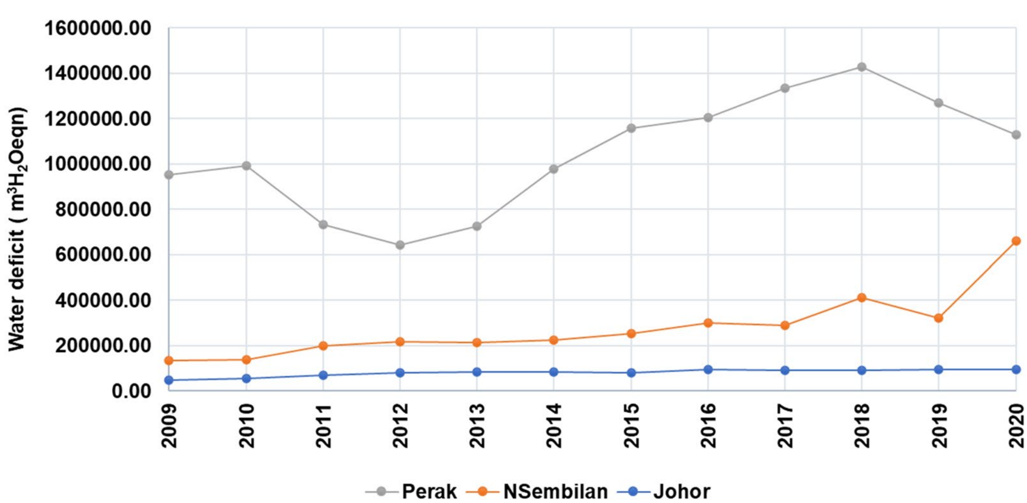

Fig. 9 Water deficit in Negeri Sembilan, Perak and Johor from 2009 until 2020

sufficient water can be supplied to power plants to avoid interruptions during operation. Even though power generation industry is not the biggest water consumption in Malaysia, this industry is among the key stakeholder, thus it would beneficial if the power generation industry contributes positively to managing freshwater resources efficiently. The implementation of water footprint approach could help in controlling the freshwater consumption at power generation industry in a few aspects such as:

(a) Water footprint provides a greater understanding on freshwater consumed and polluted through the life cycle of a product, process or activity. Through this approach, the water demand of power plant may be accurately measured through observing the facility's "operational water footprint". As a result of this study, it is possible to determine the quantity of freshwater consumed to produce electricity especially at coal-fired power plants. Additionally, the connectivity between energy and water can be strengthened.
(b) Water footprint helps to improve freshwater resources sustainability. In this study, water deficit parameter was utilized as indicator to determine the amount of freshwater depleted due to water consumption in generating the electricity at power plant. Through water deficit parameter, the water footprint is paired up with water stress index. Depending on the water stress index condition where the power plant is located, it will give variation of water deficit and also help towards future power generation planning.
(c) Water footprint helps to highlight opportunities to improve water efficiency. Upon conducting the water footprint accounting, power plant operators are also able to analyze the hot-spot water consumption in their operation and could formulate solution to reduce water footprints within the power plant. Current practice shows that the effluent from power plants is being discharged after proper treatment to comply with environmental regulation. However, by implementing water conservation strategy within the power plant, such as water recycling or adoption of water-efficient technologies, it would not only contribute to a positive water impact on power generation industry, but it also helps to reduce environment risk of discharging the effluent into the ecosystem.

Malaysia government has embarked on various plans to ensure water security for all. Recently, Malaysia has launched Water Sector Transformation 2020–2040. This plan was announced under *Rancangan Malaysia ke-12* (Unit Perancang Ekonomi Jabatan Perdana Menteri 2021), where Malaysia has vision to have precision water supply and demand practice at all levels for better efficiency and sustainability. Malaysia has strategies in place to accelerate the implementation of Integrated Water Resources Management (IWRM) [4]. Virtual water (VF) and water footprint (WF) has become one of subsector studies in the agenda to empower people focused on IWRM and to have impact on the socio-economic outcome. This sub-sector aims to measure Malaysia's VW and establish a WF inventory of economic sectors towards efficient use of water [4]. Hence, study related to water footprint of power generation should expand in line to support the above agenda.

Conclusion

Malaysia is blessed with abundance of water resources, however water pollution is a severe problem in Malaysia. Insufficient freshwater supply may create a threat of uncertainty to Malaysia's power generation industry. Hence, it is important to determine the interdependencies between water and energy for future water demand management. Besides, increment of water demand throughout the year and the decrease in water availability due to pollution and climate change may accelerate water stress index in the future.

The focus is on determining the blue water footprint of coal-fired power plant located at Perak, Negeri Sembilan and Johor, since these states are the major coal electricity generator in Malaysia other than Selangor and Sarawak. The water consumption data were collected from state's water authority from year 2009–2020. The highest blue water footprint in Perak at 4,163,111 m^3/year, whereas Negeri Sembilan (2,335,272 m^3/year) and Johor (2,088,310 m^3/year). The value is varying due to huge difference in the coal install capacity among the states.

Next, this study calculates operational blue water footprint of coal-fired power plant. The result of operational blue water footprint varies at each state which are 0.11 m^3/MWh (Perak) followed 0.09m^3/MWh (Johor) and 0.04 m^3/MWh at (Negeri Sembilan). Power plants generating technology and cooling system influence the operational blue water footprint results. The operational blue water footprint at coal-fired power plant located in Perak, Negeri Sembilan and Johor is much lower as compared to previous literatures since the freshwater was consume at generating unit and these power plant utilized seawater using once-through cooling system which substantially reduces freshwater consumption.

Through this study, it was found Perak and Negeri Sembilan record moderate water stress index while Johor has low water stress index. It is indicated that water resources at Perak and Negeri Sembilan would face much pressure due to high water demand and water availability ratio. Perak also recorded the highest water deficit impact follow by Negeri Sembilan and Johor due to high blue water footprint at coal-fired power plant and moderate water stress index condition. However, water deficit due to coal-fired power plant contributed to minor water impact at state's watershed as compared to agriculture industry.

Low water footprint could lead to positive sustainability of power plant operation. Water conservation approach can help to improve efficiency of operational blue water footprint at coal-fired power plant. Power plant operators can start implementing water reuse and recycle within power plant. Besides, utilizing alternative water resources such as seawater in cooling system could effectively reduce the operational blue water footprint. However, it is constrained by the availability of other water resources in the area.

Limitations of this study:

(a) The water footprint assessment of electricity generated at coal-fired power plant involves water footprint of supply chain and power plant operation. However, the water footprint from the supply chain is not included in this study since 90% of coal usage in Malaysia was imported from Indonesia, Australia, and South Africa [2]. Since the study focusses on local impact, the freshwater consumed during coal extraction, processing and transportation is not considered.
(b) There are two elements in operational water footprint of coal-fired power plants which are blue and grey water footprint. Grey water footprint is measured by the amount of freshwater required to minimize a pollutant to the point where it is no more harmful. In this study, the grey water footprint is not included because the effluents from the coal-fired power plant were not discharged into the same water resources as the local catchment area. As a result, the effluent pollutants did not directly affect the local water resources. However, it is important to note that the grey water footprint could potentially have an impact on the surrounding ecosystem, which is beyond the scope of this study.

Recommendations for future work:

(a) Water stress would be greatly impacted by the current climate change. As mentioned in previous literature, Malaysia may experience extreme precipitation during the wet period and a deficiency of rainfall during the dry period. Hence, it is recommended to conduct a seasonal water footprint study to help in understanding variation of water allocation especially for power generation industry.
(b) The energy industry has a strong water dependency. Thereby, approach used in this study could be potentially expanded to other types of power plants in Malaysia to help investigate the water–energy interdependencies in the country.
(c) Coal-fired power plants are known for its environment impact such as air pollution and greenhouse gas emissions. It also would contribute to social impact such as human health effect. Thus, future sustainability assessments should incorporate environmental and social impacts for a comprehensive evaluation.

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Author contributions
Data collection and methodology: NHM. Formal analysis: NHM. Writing, review, and editing: ELW, MAM, ANA and CKH.

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
The authors undertake that this article has not been published in any other journal and that no plagiarism has occurred. The authors agree to participate in the journal.

Consent for publication
The authors agree to publish in the journal.

Competing interests
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References
1. Abdul Rahman H (2021) Water issues in Malaysia. Int J Acad Res Bus Soc Sci 11:860–875. https://doi.org/10.6007/ijarbss/v11-i8/10783
2. Abdul Latif SN, Chiong MS, Rajoo S, Takada A, Chun YY, Tahara K, Ikegami Y (2021) The trend and status of energy resources and greenhouse gas emissions in the Malaysia power generation mix. Energies 14(8):2200
3. Academy of Sciences Malaysia (2022a) Water Sector Transformation 2040-Final Report (Volume I)
4. Academy of Sciences Malaysia (2022b) Virtual water and water footprint (Volume VI)

5. Afroz R, Masud MM, Akhtar R, Duasa JB (2014) Water pollution: challenges and future direction for water resource management policies in Malaysia. Environ Urban ASIA 5:63–81. https://doi.org/10.1177/0975425314521544
6. Ahmed F, Siwar C, Begum RA (2014) Water resources in Malaysia: issues and challenges. J Food Agric Environ 12:1100–1104
7. Ali B, Kumar A (2015) Development of life cycle water-demand coefficients for coal-based power generation technologies. Energy Convers Manag 90:247–260. https://doi.org/10.1016/j.enconman.2014.11.013
8. Anang Z, Padli J, Kamaludin M, Sathasivam S (2017) The effect of climate change on water resources using panel approach: the case of Malaysia. Int J Acad Res Bus Soc Sci 7:141–152. https://doi.org/10.6007/ijarbss/v7-i11/3446
9. Bolson N, Prieto P, Patzek T (2022) Capacity factors for electrical power generation from renewable and nonrenewable sources. Proc Natl Acad Sci USA 119:1–6. https://doi.org/10.1073/pnas.2205429119
10. Carpenter AM (2017) Water conservation in coal-fired power plants Water conservation in coal-fired power plants. IEA Clean Coal Cent. Available via United States Energy Association. https://usea.org/publication/water-conservation-coal-fired-power-plants-ccc-275. Accessed 24 Jan 2022
11. Chai L, Liao X, Yang L, Yan X (2018) Assessing life cycle water use and pollution of coal-fired power generation in China using input–output analysis. Appl Energy 231:951–958. https://doi.org/10.1016/j.apenergy.2018.09.178
12. Chini CM, Logan LH, Stillwell AS (2020) Grey water footprints of U.S. thermoelectric power plants from 2010–2016. Adv Water Resour 145:103733. https://doi.org/10.1016/j.advwatres.2020.103733
13. Diehl TH, Harris MA (2014) Withdrawal and consumption of water by thermoelectric power plants in the United States, 2010
14. Ding GKC, Ghosh S (2017) Sustainable water management—a strategy for maintaining future water resources. Encycl Sustain Technol 4:91–103. https://doi.org/10.1016/B978-0-12-409548-9.10171-X
15. Ding N, Liu J, Yang J, Lu B (2018) Water footprints of energy sources in China: exploring options to improve water efficiency. J Clean Prod 174:1021–1031. https://doi.org/10.1016/j.jclepro.2017.10.273
16. Ercin AE, Hoekstra AY (2014) Water footprint scenarios for 2050: a global analysis. Environ Int 64:71–82. https://doi.org/10.1016/j.envint.2013.11.019
17. Farooq N, Gheewala SH (2019) Water use and deprivation potential for sugarcane cultivation in Pakistan. J Sustain Energy Environ 10:33–39
18. Gao X, Zhao Y, Lu S et al (2019) Impact of coal power production on sustainable water resources management in the coal-fired power energy bases of Northern China. Appl Energy 250:821–833. https://doi.org/10.1016/j.apenergy.2019.05.046
19. Gerbens-Leenes W, Berger M, Allan JA (2021) Water footprint and life cycle assessment: the complementary strengths of analyzing global freshwater appropriation and resulting local impacts. Water 13(6):803
20. Gheewala SH, Silalertruksa T, Nilsalab P et al (2014) Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand. Water (Switzerland) 6:1698–1718. https://doi.org/10.3390/w6061698
21. Hanafiah MM, Ghazali NF, Harun SN et al (2019) Assessing water scarcity in Malaysia: a case study of rice production. Desalin Water Treat 149:274–287. https://doi.org/10.5004/dwt.2019.23841
22. Harto CB, Finster M, Schroeder J, Clark C (2014) Saline Water for power plant cooling: challenges and opportunities. Available via Argonne National Laboratory website. https://www.anl.gov/argonne-scientific-publications/pub/109681. Accessed 17 Feb 2023
23. Harun SN, Hanafiah MM (2018) Estimating the country-level water consumption footprint of selected crop production. Appl Ecol Environ Res 16:5381–5403. https://doi.org/10.15666/aeer/1605_53815403
24. Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual. Setting the Global Standard. Available via Water Footprint Network. https://www.waterfootprint.org/resources/TheWaterFootprintAssessmentManual_English.pdf. Accessed 24 May 2021
25. Hogeboom RJ (2020) The water footprint concept and water's grand environmental challenges. One Earth 2:218–222. https://doi.org/10.1016/j.oneear.2020.02.010
26. Ideris MM, Cai GY, Zainol Z, Amin MZM (2020) Development of water stress index for water resources under changing. Malaysia Water Res J 10:1–11
27. International Energy Agency (2021) Coal-fired power. In: Int. Energy Agency. https://www.iea.org/reports/coal-fired-power. Accessed 20 Dec 2022
28. Lee K, Shahabudin S, Mokhtar M et al (2018) Sustainable water resources management and potential development of multi-purpose dam: the case of Malaysia. Appl Ecol Environ Res 16:2323–2347. https://doi.org/10.15666/aeer/1603_23232347
29. Lee U, Chou J, Xu H et al (2020) Regional and seasonal water stress analysis of United States thermoelectricity. J Clean Prod 270:122234. https://doi.org/10.1016/j.jclepro.2020.122234
30. Liang X, Wang Z, Zhou Z et al (2013) Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. J Clean Prod 39:24–31. https://doi.org/10.1016/j.jclepro.2012.08.003
31. Liu X, Liu W, Tang Q et al (2022) Global agricultural water scarcity assessment incorporating blue and green water availability under future climate change. Earth's Futur 10(4):1–16. https://doi.org/10.1029/2021EF002567
32. Ma X, Yang D, Shen X et al (2018) How much water is required for coal power generation: an analysis of gray and blue water footprints. Sci Total Environ 636:547–557. https://doi.org/10.1016/j.scitotenv.2018.04.309
33. Macknick J, Newmark R, Heath G, Hallett KC (2012a) Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 7(4):045802. https://doi.org/10.1088/1748-9326/7/4/045802
34. Macknick J, Sattler S, Averyt K et al (2012b) The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. Environ Res Lett 7(4):045803. https://doi.org/10.1088/1748-9326/7/4/045803
35. Malaysia Energy Commission (2020a) Malaysia Energy Statistics Handbook 2020. Suruhanjaya Tenaga (Energy Commission)
36. Malaysia Energy Commission (2020b) Malaysia Energy Hub-Statistics. http://meih.st.gov.my/statistics. Accessed 9 Dec 2022
37. Malaysia Energy Commission (2022) National Energy Balance 2019. Suruhanjaya Tenaga (Energy Commission)
38. Malaysia Water Association (MWA) (2020) The Malaysian Water Industry Status & Outlook Report 2020/21. The Malaysian Water Association
39. Mekonnen MM, Gerbens-Leenes PW, Hoekstra AY (2015) The consumptive water footprint of electricity and heat: a global assessment. Environ Sci Water Res Technol 1:285–297. https://doi.org/10.1039/c5ew00026b
40. Mekonnen MM, Hoekstra AY (2016) Sustainability: four billion people facing severe water scarcity. Sci Adv 2:1–7. https://doi.org/10.1126/sciadv.1500323
41. Meldrum J, Nettles-Anderson S, Heath G, Macknick J (2013) Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett 8(1):015031. https://doi.org/10.1088/1748-9326/8/1/015031
42. Muhammad-Muaz A, Marlia MH (2014) Water footprint assessment of oil palm in Malaysia: a preliminary study. AIP Conference Proceeding 1614(1):1803–1807. https://doi.org/10.1063/1.4895305
43. Nilsalab P, Gheewala SH, Mungkung R et al (2017) Water demand and stress from oil palm-based biodiesel production in Thailand. Int J Life Cycle Assess 22:1666–1677. https://doi.org/10.1007/s11367-016-1213-7
44. Pfister S, Bayer P, Koehler A, Hellweg S (2011) Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ Sci Technol 45:5761–5768. https://doi.org/10.1021/es1041755
45. Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43:4098–4104. https://doi.org/10.1021/es802423e
46. Rahman HA (2018) Climate change scenarios in Malaysia: engaging the public. Int J Malay Nusantara Stud 1:55–77
47. Ranhill Consulting (2011) Review of the national water resources study (2000–2050) and formulation of national water resources policy
48. Rocha DHD, Silva RJ (2019) Exergoenvironmental analysis of a ultra-supercritical coal-fired power plant. J Clean Prod 231:671–682. https://doi.org/10.1016/j.jclepro.2019.05.214

49. Samsudin MF, Mohd Amin MF, Syed Omar SA et al (2020) Analysis of Water Stress Index (WSI) for district surrounding Ulu Sat Forest Reserve, Kelantan, Malaysia. IOP Conf Ser Earth Environ Sci 549(1):012015. https://doi.org/10.1088/1755-1315/549/1/012015
50. Silalertruksa T, Gheewala SH, Mungkung R et al (2017) Implications of water use and water scarcity footprint for sustainable rice cultivation. Sustain 9:1–13. https://doi.org/10.3390/su9122283
51. Smart A, Aspinall A (2009) Water and the electricity generation industry. Waterlines Series report number 18. National Water Commission, Canberra, pp 1–83
52. Suruhanjaya Tenaga (2019) Peninsular Malaysia Electricity Supply Outlook 2019. Suruhanjaya Tenaga (Energy Commission)
53. Suruhanjaya Tenaga (2021) Report on Peninsular Generation Development Plan 2020
54. Ti LH, Facon T (2001) The FAO-ESCAP Pilot Project on National Water Visions—From Vision to Action—A Synthesis of Experiences in Southeast Asia
55. Unit Perancang Ekonomi Jabatan Perdana Menteri (2021) Ucapan YAB. PM RMKe-12 Ismail Sabri. Percetakan Nas Malaysia Berhad 1–532
56. Vanham D, Medarac H, Schyns JF et al (2019) The consumptive water footprint of the European union energy sector. Environ Res Lett 14(1):104016. https://doi.org/10.1088/1748-9326/ab374a
57. Xie X, Jiang X, Zhang T, Huang Z (2020) Study on impact of electricity production on regional water resource in China by water footprint. Renew Energy 152:165–178. https://doi.org/10.1016/j.renene.2020.01.025
58. Zeinali M, Bozorg-Haddad O, Azamathulla HM (2021) 7-Water policy and governance. Econ Polit Soc Issues in Water Resour 129–153. https://doi.org/10.1016/B978-0-323-90567-1.00005-X
59. Zhai H, Rubin ES (2011) Carbon capture effects on water use at pulverized coal power plants. Energy Procedia 4:2238–2244. https://doi.org/10.1016/j.egypro.2011.02.112
60. Zhang C, Yang J, Urpelainen J et al (2021) Thermoelectric power generation and water stress in India: a spatial and temporal analysis. Environ Sci Technol 55:4314–4323. https://doi.org/10.1021/acs.est.0c08724
61. Dongke Z (2013) Introduction to advance and ultra-supercritical fossil fuel power plant. Woodhead Publishing Limited, pp 1–19
62. Zhu Y, Jiang S, Zhao Y et al (2020) Life-cycle-based water footprint assessment of coal-fired power generation in China. J Clean Prod 254:120098. https://doi.org/10.1016/j.jclepro.2020.120098

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