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Comparative water scarcity footprint study of two nuclear power plants

Key words: water scarcity footprint, nuclear power plant, LCA, comparative study, ISO 14046

Introduction

The energy sector is very thirsty. In 2014, this sector was responsible for 55% of surface water abstractions in the Czech Republic (MoA, 2015). In relation to the diminishing of coal resources in the Czech Republic, it is necessary to create scenarios of future long-term development of the Czech energy industry. Current "conceptual variant" of Czech power system development is typical mainly by the construction of nuclear blocks in two present locations Dukovany and Temelín (OTE, 2016). Development of new nuclear blocks is determined by a very detailed environmental impact assessment. The water footprint that measures the volume of fresh water used to produce a product over the full supply chain (Mekonnen, Gerbens-Leenes & Hoekstra, 2015) is a generally accepted indicator of water use. There are two different approaches to water footprint assessment described in the literature. The first approach is represented by Water Footprint Assessment Manual (Hoekstra, Chapagain, Aldaya & Mekonnen, 2011). This "volumetric" water footprint is focused on the inventory (accounting) of the total amount of water use in the full supply chain. Volumetric water footprint can be studied from different perspectives: environmental sustainability, social equity, resource efficiency or water risk (Hoekstra, 2017). This approach quantifies the amount of water consumed and polluted (degraded) for a product/company/region/nation and maps green, blue and grey water use, assesses the sustainability, and formulates response strategies.

The second approach is represented by ISO 14046:2014. This life cycle assessment (LCA) water footprint is metrics that quantifies the potential environmental impacts related to water. This assesment is calculated as amount of water use in whole life cycle of a product/process/organization multiplied by a characterization factor which reflects their relative contribution to the environmental impact. We choose LCA water footprint approach due to the main aim of the study: the environmental impact comparison of nuclear power generation on two current locations. The life cycle assessment water footprint can be calculated by a lot of characterisation models due to different impact pathways (Kounina et al., 2012; Boulay et al., 2014). In our study, we do not cover all impacts related to water, but we focus on water resource depletion only. Impacts related to ecosystems quality or human health are not covered by our study.

Current characterisation models are commonly based on the ratio between water availability and water use in the catchment. This approach was criticised for problematic interpretation and a potential duplicity of water use in calculation of characterization factor (Hoekstra, 2016). Available values of characterization factors are very often prepared at the country level or at the catchment level. These values are very often modelled by global hydrological models. Each model is a simplification of reality. And global models are validated for the main hydrologic stations in the catchments. Observations for validation of model are rarely situated in the upper parts of catchments and the modelled results for upper parts of catchments can not be so precise as for lower parts. Therefore we try to find characterisation model which is not dependent on the water use and the site-specific values of the characterization factor (based on observed/measured data) can be easily implemented in.

Material and methods

For the study, we choose the model based on renewability of water sources only, not resulting from the ratio of water use to renewability rate (Yano, Hanasaki, Itsubo & Oki, 2015). The selected characterisation model assumes that the potential impacts of a unit amount of water used are proportional to the land area or time required to obtain a unit of water from each water source. This model uses runoff or precipitation for computation of characterisation factor. It means that the local hydrological data can be very easily used for computation of site-specific characterization factor.

The goal of the study is to compare impacts of the two nuclear power plants in the Czech Republic on the water availability (water scarcity footprint). The two Czech nuclear power plants are situated in the upper part of the large international watershed. The locations of both NPP is shown in Figure 1. The Temelín NPP is situated in the central part of Bohemia in the Elbe river basin. Dukovany NPP is situated in the south part of Moravia in the Jihlava river basin, which is a part of Danube international river basin.

The scope of analysis is defined as cradle-to-gate. The functional unit represents 1 MWh of produced total energy (power energy and heat energy). Temporal coverage of analysis is a period 2005–2015. From the study, upstream and downstream processes were excluded, because these processes are the same or very similar. The water footprint of construction stage and decommissioning phase of both power plants cannot be calculated, due to missing data about mate-

FIGURE 1. Locations of NPPs in the Czech Republic

rial consumption. On the other hand, the estimation of indirect water use related to the material used in energy production ranged from 0.0005 to 0.001 $m^3 \cdot MWh^{-1}$ only (Inhaber, 2004). Scheme of water, energy and material flows for the core process in the two nuclear power plants is shown in Figure 2. The main characteristics of the both nuclear power plants are shown in Table 1, hydrological characteristics are shown in Table 2.

For the analysis, we used:

– measured production of energy and heat data from the Czech Energy regulatory office;
– measured withdrawals and wastewater discharges data from the water withdrawals and wastewater discharges evidence according to Water Act 254 from 2001, as amended;
– the approved rules of operation of the reservoirs, that create water supply systems of the nuclear power plants;
– hydrological data from the Czech Hydrometeorological Institute.

Additional information were collected from the environmental impact assessment (EIA) information system (www.cenia.cz/EIA) or from the web pages of the nuclear power plants operator (www.cez.cz)

The water footprint inventory for each power plant includes:

– power and heat production of the nuclear power plant – power production represents approximately 99% of the both nuclear power plants energy production;
– energy production of the hydropower plants, that are part of water reservoirs creating water supply systems of the nuclear power plants – energy production in the hydropower plants represents only approximately 0.3% in the case of Temelín NPP and 1.2–2.2% in the case of Dukovany NPP;
– drinking water use – we do not have data on drinking water consumption, but we suppose that amount of wastewater discharges originating from

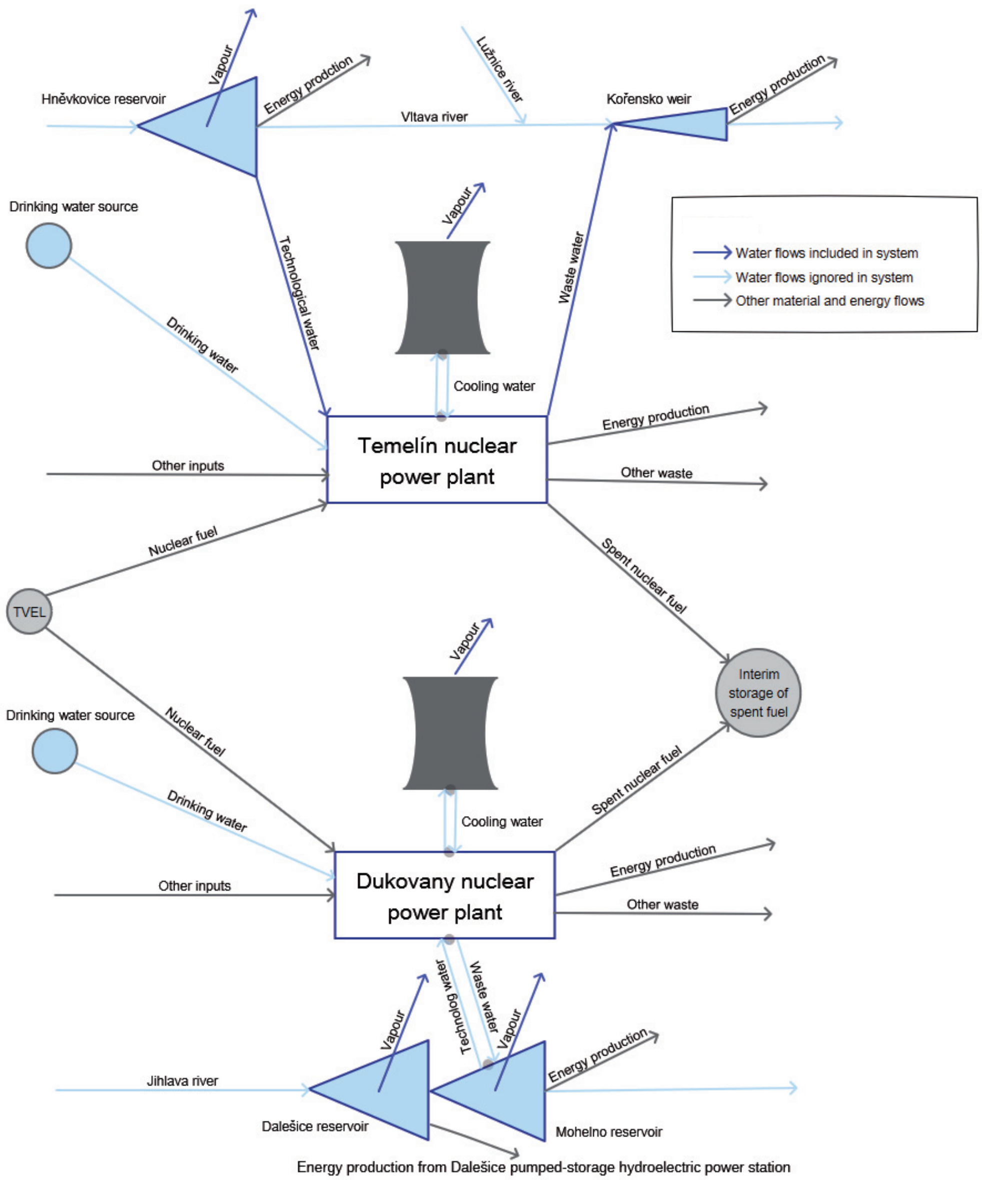

FIGURE 2. Water, energy and material flow scheme

drinking water is equal or almost the same to drinking water withdrawals and that this consumption is close to zero; the drinking water consumption was neglected due to the ratio between the amount of wastewater discharges originating from drinking water and total amount of wastewater discharges, which is approximately 1.5% in the case of Temelín NPP and approximately 0.4% in the case of Dukovany NPP;

TABLE 1. The main characteristics of compared nucelar power plants in period 2005–2015

Operational characteristics	Unit	Temelín NPP	Dukovany NPP
Total electricity production	MWh	147 916 896	157 304 074
Total heat production	GJ	5 837 514	5 029 023
Total surface water withdrawals	10^3 m^3	374 556	538 825
Total wastewater discharges	10^3 m^3	84 771	208 485

TABLE 2. Hydrological characteristics

Hydrological characteristics	Unit	Hněvkovice	Kořensko	Dalešice-Mohelno
Hydrological catchment number	–	1-06-03-076	1-07-05-001	4-16-01-1050
Watershed area	km^2	3 540.29	7 828.85	1 155.26
Average precipitations	mm	769	716	646
Average annual runoff	$m^3 \cdot s^{-1}$	30.6	54.9	5.35
Water surface area	ha	276.7	–	463.7 + 117.0
Average annual vapour	mm	659	–	725

- technological water withdrawals – technological water used for cooling systems represents 86–98% of withdrawn technological water in the case of Temelín NPP and about 99% in the case of Dukovany NPP;
- use of other water (groundwater and other water) – the groundwater has been withdrawn and discharged into the surface water in both locations, and it should be calculated as consumption; but the groundwater consumption was neglected due to the ratio between the amount of groundwater withdrawals and the total amount of surface water withdrawals, which is less than 0.2% in the case of Temelín NPP and less than 0.05% in the case of Dukovany NPP;
- wastewater discharges – waste water originating from cooling systems represents about 97% of the total amount of wastewater discharges in the case of Temelín NPP and 96–99% in the case of Dukovany NPP;
- hydrological characteristics of the profiles of water withdrawals and wastewater discharges contain long-term annual water flow rate (Q_A) [$m^3 \cdot s^{-1}$]; area of the catchment (A) [km^2]; characteristics of vapour from surface water [$mm \cdot month^{-1}$] in monthly steps and the average area of water level in reservoirs [km^2] in monthly steps.

The total water consumption (*TWC*) and water scarcity footprint (*WSF*) per functional unit were calculated according to following equations:

$$TWC_l = \sum_{i=1}^{N} \frac{Withdrawals_{i,l} - Wastewater\_discharges_{i,l} + Vapour_{i,l}}{Power\_production_l + Heat\_production_l} \quad (1)$$

$$WSF_l = \left(\sum_{i=1}^{N} \frac{Withdrawals_{i,l} - Wastewater\_discharges_{i,l} + Vapour_{i,l}}{Power\_production_l + Heat\_production_l} \times CF_{i,l} \right) \quad (2)$$

where:
i – a profile of water source (withdrawal or wastewater discharge);
l – the location of nuclear power plant (Dukovany or Temelín);

$CF_{i,l}$ – a characterization factor of profile i calculated by:

$$CF_{i,l} = \frac{Q_{ref}}{\frac{Q_{A_i} \times 86,400 \times 365.25}{1,000,000 \times A_i}} \qquad (3)$$

where:
Q_{ref} – reference volume of water [$m^3 \cdot s^{-1}$];
Q_{A_i} – annual water flow rate [$m^3 \cdot s^{-1}$];
A_i – catchment area [km^2].

The reference volume (Q_{ref}) can have an arbitrary number (Yano et al., 2015). In this study, the global mean annual precipitation over 1.0 m^2 of the landscape (1.0 $m^3 \cdot year^{-1}$) was adopted as the reference condition. It is the same value which is used by authors of characterisation model in their study. Because all freshwater resources originate from precipitation, the global mean value of precipitation is adequate for weighting uneven, global-scale renewable water resources by location (Yano et al., 2015).

Results and discussion

The results of the water footprint inventory analysis indicate that the real *TWC* of the core process ongoing in both nuclear power plants is approximately 2.0 m^3 H_2O per 1 MWh. This value corresponds with or is little lower to water consumption in other nuclear power plants in the USA (Dziegielewski & Bik, 2006; IPCC, 2011). Although *TWC* is very similar in both nuclear power plants, respectively *TWC* of core process in the Temelín NPP is of 0.09–0.54 $m^3 \cdot MWh^{-1}$ lower than *TWC* of core process in the Dukovany NPP, the *WSF* of core processes in both nuclear power plants is significantly different due to different values of *CF*. The value of *CF* is based on hydrological conditions in both locations (Table 2). The value of *CF* for the Mohelno reservoir calculated by Eq. 3 is 6.846, for the Kořensko weir is 2.045 and for the Hněvkovice reservoir is 3.669. Value of *WSF* of core process in the Temelín NPP is 8.08–9.97 m^3 H_2O_{eq} per 1 MWh lower than *WSF* of core processes in the Dukovany NPP (Table 3 and Fig. 3). Equivalent of H_2O can be interpreted as the amount of average global precipitation due to a reference condition.

The sensitivity analysis contains impact of vapour losses, heat production and drinking water usage on the total value of *WSF*. The sensitivity analysis showed the significance of loss from the nuclear power plant cooling system and vapour losses from water level in the reservoir. Vapour from reservoir represents 5.77–7.09% of *WSF* value in the case of Temelín NPP and 9.92–12.06% in the case of Dukovany NPP. Since the vapour from reservoirs was calculated from averaged data, we tested the sensitivity of *WSF* to the change of vapour value. If the value of vapour changes by 10%, then the value of *WSF* will change by 1%. Groundwater pumping was neglected as the amount of groundwater use is lower then 0.05% of surface water use. The sensitivity analyses showed the low significance of heat production in the nuclear power plants for *WSF* value. If the heat production was neglected, then *WSF* would change about 1%. Also the drinking water use has very low impact on *WSF*. Neglecting of drinking water

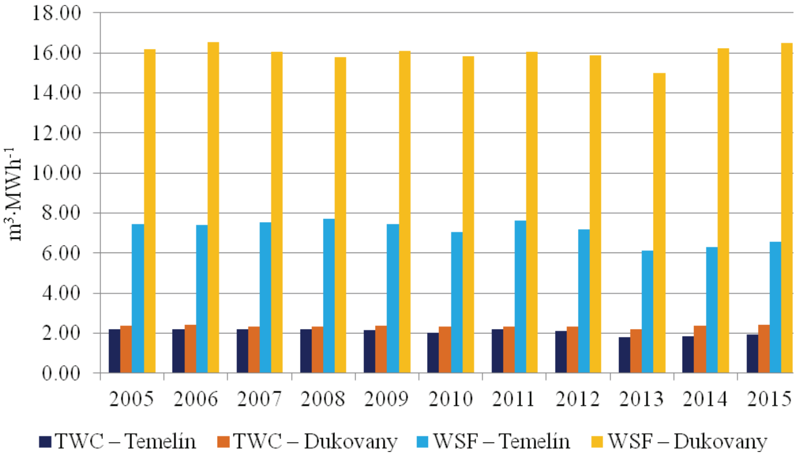

FIGURE 3. The graphic comparison of total water consumption (*TWC*) values and water scarcity footprint (*WSF*) values of the core processes of energy production in the nuclear power plants in the Czech Republic

TABLE 3. The values of total water consumption (*TWC*) and water scarcity footprint (*WSF*) of the core processes of energy production in the nuclear power plants in the Czech Republic

Year	*TWC* – Temelín	*TWC* – Dukovany	*WSF* – Temelín	*WSF* – Dukovany
	$m^3 \cdot MWh^{-1}$		m^3 H_2O_{eq} per 1 MWh	
2005	2.19	2.37	7.45	16.20
2006	2.17	2.42	7.41	16.52
2007	2.20	2.34	7.52	16.03
2008	2.21	2.31	7.69	15.77
2009	2.14	2.35	7.44	16.08
2010	2.04	2.31	7.03	15.82
2011	2.19	2.34	7.60	16.04
2012	2.09	2.32	7.17	15.86
2013	1.81	2.19	6.12	15.01
2014	1.84	2.37	6.27	16.24
2015	1.93	2.41	6.57	16.49

use in calculation results to change of *WSF* about 0.2%.

As we expected, the *TWC* is similar in both nuclear power plants, due to the similar construction of both power plants. We also expected higher impact of water use in Dukovany NPP due to the lower catchment area, lower precipitation and worse relation between the average run-off and the catchment area in both locations. The life cycle assessment water footprint allows exact quantification of the difference of this impact according to the selected charactarization model.

Conclusions

The water scarcity footprint and the total water consumption of the energy production core processes in the two nuclear power plants were calculated. The total water consumptions are similar in both nuclear power plants. The water scarcity footprint of the energy production core processes expressed as average global precipitation consumption is more than twice higher in Dukovany nuclear power plant than in Temelín nuclear power plant. Water losses from the cooling systems of the nuclear power plants represent the major part of the water scarcity footprint value. Vapour from the reservoirs, which are part of water supply system of the nuclear power plants, plays an important part of the water scarcity footprint value. This presents approximately 6.5% in the case of Temelín nuclear power plant and approximately 11% in the case of Dukovany nuclear power plant. Other water uses such as groundwater withdrawals and drinking water use can be neglected.

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Summary

Comparative water scarcity footprint study of two nuclear power plants. This study compares the life cycle assessment (LCA) based water scarcity footprint of produced energy unit in two nuclear power plants in the Czech Republic between 2005 and 2015. Primary data has been used to allocate impacts to the core processing stage. Although the real total amount of water consumption in both power plants is similar, the water scarcity footprint in Temelín nuclear power plant is of approximately 8.9 m^3 H_2O_{eq} per 1 MWh lower than in Dukovany power plant. The cooling water has the most significant contribution to the freshwater availability impact category. Evaporation from reservoirs which are a part of water management of the individual power plants has lower, but not inconsiderable, contribution to the water consumption. In the case of Temelín nuclear power plant, the loss caused by evaporation from Hněvkovice reservoir is of approximately 6.5% of the difference between withdrawal and discharge of the power plant. In the case of Dukovany nuclear power plant, evaporation from Dalešice-Mohelno reservoir is of even around 11%.

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