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Mathematical modelling and simulation of the water – energy nexus

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INTRODUCTION & OBJECTIVES

The intricate interdependence between water and energy referred to as the water – energy nexus is becoming increasingly important as demand for both resources rises (Fig 1).

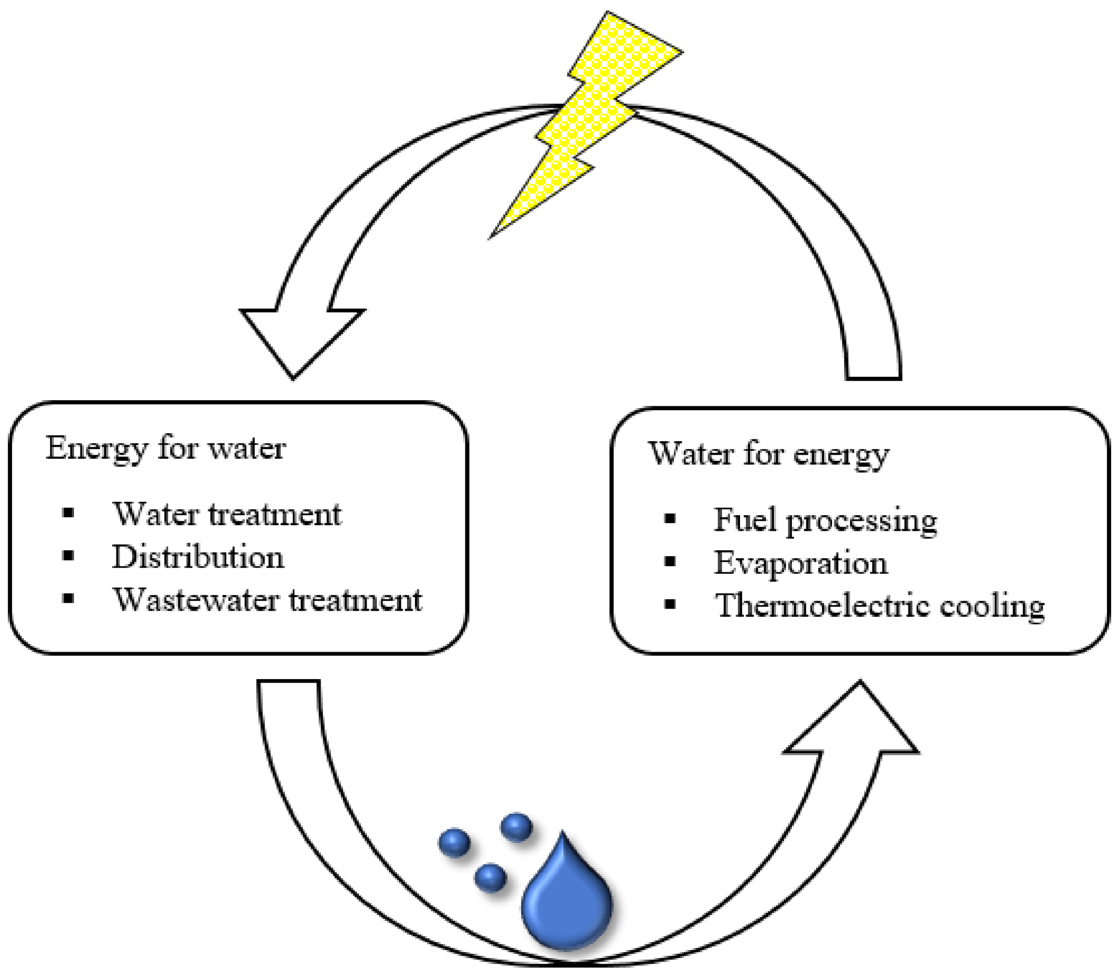

Figure 1. Water-energy nexus interdependence

It is important to understand both the water footprint of renewable energy technologies as well as energy consumption of advanced water treatment methods and water distribution systems. There's no simple and universal model for assessing the water footprint and energy consumption of power and water treatment plants respectively with most plants relying on operator data which is often incomplete and unreliable.

OBJECTIVES:

- Mathematically model the water – energy nexus to analyze the water footprint of power plants and energy consumption of water systems.
- Use process simulation in Java to visualize the effects of various variables in the water – energy nexus.

METHODS

The following mathematical models for the water footprint of hydropower and geothermal energy; energy consumption of advanced oxidation processes (AOPs), membrane separation processes and water distribution systems were formulated:

$$WF(Hydropower) = \frac{Q}{E}$$

$$Q = 10A\sum_{i=1}^{365} E_o$$

$$E_o = \frac{1}{\lambda}\left(\frac{\Delta_w(R_n - G) + \gamma(e_w - e_a)f(u)}{\Delta_w + \gamma}\right)$$

$$WF\ (Geothermal) = \frac{(1-\eta_{net}-k_{ls})}{\eta_{net}C_{p,w}\Delta T} + WF_{proc} = \frac{(1-\eta_{net}-k_{ls})(1-k_{sens})}{\eta_{net}h_{fg}}\left(1+\frac{1}{n_{cc}-1}\right) + WF_{proc}$$

$$P_{elec}(AOPs) = \frac{\eta_{overall}Nhc}{4\pi d^2\lambda t}$$

$$E(Membrane\ sep.) = \frac{q\Delta P}{\eta} = \frac{6\mu A v^2}{\eta a} = \frac{8\mu A v^2}{\eta d}$$

$$P(H_2O\ distribution) = \frac{\gamma\pi R^4(-\Delta P)}{8\mu l\eta}\left(\Delta z + \frac{\Delta P}{\rho g} + 4f\left(\frac{\sum L_{eT}}{d_i}\right)\frac{u^2}{2g} + \frac{a}{g}V_o\right)$$

RESULTS & DISCUSSION

Table 1. Water footprint of major renewable energy technologies – hydropower and geothermal energy.

Renewable energy	Variables	Discussion	Water footprint
Hydropower	▪ Air temperature ▪ Water temperature ▪ Wind speed ▪ Size of the reservoir	The water footprint varies proportional to the wind speed, 10m above the reservoir and air – water temperature difference.	22 m^3/GJ averagely
Geothermal energy	▪ Number of cycles of concentration	The water footprint varies inversely to the number of cycles of concentration with most geothermal power plants operating between 3 – 7 cycles.	0.5m^3/GJ for cooling tower systems

Table 2. Energy consumption of advanced water treatment technologies and water distribution systems.

Water systems	Variables	Discussion	Energy demand
AOPs	▪ Distance from the source ▪ Radiation intensity	The intensity of radiation diminishes proportionally to the square of distance from the source.	23.75 kWh/ H_2O treated for UV lamps
Membrane separation	▪ Cross flow velocity	For hollow fiber reverse osmosis membrane, the energy increases with the crossflow velocity.	2.7 kWh/ H_2O
Water distribution	▪ Flow velocity ▪ Pressure difference	Energy consumption was investigated by varying both flow velocity and pressure difference	Varies with distance and channel geometry

CONCLUSION

The findings of this study demonstrate mathematical modeling and simulation as viable tools in navigating the complexities of the water – energy nexus, being indispensable for improving efficiency, sustainability and ensuring optimum resource utilization

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