Derivation and Use of the Pump Energy Intensity Equation for Water System Energy Analysis

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Abstract

Energy intensity—an expression normalizing pump energy use by water volume, also called specific energy—is becoming a more commonly used key performance indicator as water utilities seek to analyze and optimize their energy use. Its theoretical basis, however, has not been well documented. Beginning with Newton's second law, we derive the pump power equation and the pump energy intensity equation, provide specific values for engineering reference, and discuss applications. In a perfectly efficient system pumping water, the minimum energy intensity is 0.00272 kWh/m^3 per meter of head or 3.14 kWh/Mgal per foot of head. Considering typical pump efficiencies, these references may be scaled and used for analyzing pump performance or estimating future energy uses. As a key performance indicator, energy intensity is a convenient input-output quotient where both parts can be observed directly, enabling tracking over time and comparison among individual facilities. As a planning tool, energy intensity can estimate expected energy use without having to know details of the pumping system. Such are the high-level applications water systems may find as a prelude to deeper energy analyses in pursuit of sustainable infrastructure.

Keywords

Water supply; pump; energy; key performance indicator; sustainability; engineering

Introduction

Energy management is a rising priority for water utilities, motivated by a shifting energy market, aging water infrastructure, growing populations, and an overarching drive for sustainability (Patel et al. 2022). Pumps are a natural focus of attention, and energy intensity—an expression which normalizes pump energy use by water volume—is becoming a more commonly used key performance indicator (KPI) as water systems seek to analyze and optimize their energy use.

Energy intensity (also called specific energy, but not to be confused with the thermodynamic and open-channel meanings) has been used for years to profile both entire water systems (Wilkinson 2000; Twomey and Webber 2011; Sowby and Burian 2017, 2018; Sowby 2018; Chini and Stillwell 2018; Cabrera et al. 2021) and individual pumps, processes, and facilities (Sárbu and Borza 1998; Pelli and Hitz 2000; Jones and Sowby 2014; Steger and Pierce 2018a; Cojanu and Helerea 2021; del Teso et al. 2023). However, we have not found a primary source describing its derivation from fundamental principles. This article documents the theoretical basis for pump energy intensity, provides specific values that can be used as a reference going forward, and describes practical applications for water system energy analysis.

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General Pump Energy Intensity

The following narrative assumes water but the equations may apply to other fluids without loss of generality. We begin with Newton's second law of motion, which states that force (F) equals mass (m) times acceleration (a):

$$F = ma \tag{1}$$

When working with water on Earth, the acceleration of interest is that of gravity (g):

$$F = mg \tag{2}$$

Energy (E) is force times distance (d):

$$E = Fd \tag{3}$$

The distance in question is the pump's total head (h), including head loss. With this in mind we substitute Equation 2 into Equation 3:

$$E = mgh \tag{4}$$

The expression is that for potential energy. One may imagine a mass of water being lifted to some height and gravity acting against it. Of course, the expression is inadequate for pumping because it does not consider any mechanical inefficiency as an implication of the laws of thermodynamics, so we must include an efficiency variable, η, between 0 and 1:

$$E = \frac{mgh}{\eta} \tag{5}$$

In fluids, it is more convenient to work in terms of volume (V) and density (ρ) instead of mass, so we substitute $m = V\rho$:

$$E = \frac{(V\rho)gh}{\eta} \tag{6}$$

Recalling that the product of density and gravitational acceleration is specific weight ($\rho g = \gamma$), the expression becomes:

$$E = \frac{V(\rho g)h}{\eta} = \frac{V\gamma h}{\eta} \tag{7}$$

We then divide both sides by time t:

$$\frac{E}{t} = \frac{V\gamma h}{t\eta} = \frac{\left(\frac{V}{t}\right)\gamma h}{\eta} \tag{8}$$

Because energy divided by time is power (P) and volume divided by time is flow rate (Q), we now have the familiar pump power equation:

$$P = \frac{Q\gamma h}{\eta} \tag{9}$$

Returning to Equation (7), it is useful to normalize the energy use by the water volume. The following form of the equation, expressed as energy per unit volume of water, is known as energy intensity, which we call I:

$$\frac{E}{V} = \frac{\gamma h}{\eta} = I \tag{10}$$

Unit Pump Energy Intensity for Water

Working from Equation (10), we apply unit conversions and properties of water at 4 °C (39 °F) to arrive at specific values for pump energy intensity assuming a unit volume of 1 m^3 and a unit head of 1 m at perfect efficiency ($\eta = 1.0$), recalling that $1\ \mathrm{kN \cdot m} = 1\ \mathrm{kJ}$ and $1\ \mathrm{kJ/s} = 1\ \mathrm{kW}$:

$$I = \frac{E}{V} = \frac{\gamma h}{\eta} = \frac{\left(9.807\ \frac{\mathrm{kN}}{\mathrm{m}^3}\right)(1.0\ \mathrm{m})}{1.0} = 9.81\ \frac{\mathrm{kN \cdot m}}{\mathrm{m}^3} = 9.81\ \frac{\mathrm{kJ}}{\mathrm{m}^3}$$
$$= \left(9.807\ \frac{\mathrm{kJ}}{\mathrm{m}^3}\right)\left(\frac{1\ \mathrm{kW}}{1\ \frac{\mathrm{kJ}}{\mathrm{s}}}\right)\left(\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\right) = 0.00272\ \frac{\mathrm{kWh}}{\mathrm{m}^3} \tag{11}$$

In the US customary system (USCS), with a unit volume of 1 million gallons (Mgal) and a unit head of 1 ft, the calculation requires additional conversions:

$$I = \frac{E}{V} = \frac{\gamma h}{\eta} = \frac{\left(62.4 \frac{\mathrm{lb}}{\mathrm{ft}^3}\right)(1\ \mathrm{ft})}{1.0} = \left(62.4\ \frac{\mathrm{ft \cdot lb}}{\mathrm{ft}^3}\right)\left(\frac{1\ \mathrm{ft}^3}{7.48\ \mathrm{gal}}\right)\left(\frac{10^6\ \mathrm{gal}}{1\ \mathrm{Mgal}}\right)\left(3.766 \times 10^{-7} \frac{\mathrm{kWh}}{\mathrm{ft \cdot lb}}\right)$$
$$= 3.14\ \frac{\mathrm{kWh}}{\mathrm{Mgal}} \tag{12}$$

This means that in a perfectly efficient pumping system, lifting 1 m^3 of water to a height of 1 m takes 0.00272 kWh; lifting 1 Mgal of water to a height of 1 ft takes 3.14 kWh. (We note that the latter value is not π—the digits are a mere coincidence due to unit conversions and water properties, but they do make the value memorable, as Steger and Pierce [2018a] pointed out.) While other sources have reported the same values (van der Zwan and Blokland 1988; Delft Hydraulics 1991; Pelli and Hitz 2000; Pegios 2018; Steger and Pierce 2018a; Sowby and Burian 2020; Almulla et al. 2020), they did not provide transparent calculations as we have.

Applications

Energy intensity, as expressed in Equation 10, has two useful features. First, one may determine the left-hand numerator and denominator directly from measurements of energy use and water volume. Second, it is an input-output quotient suited to performance tracking of individual pumps or facilities, where energy is the resource being expended and pumped water is the product. Both features make observed energy intensity a potent tool.

Longitudinally, a trend of increasing energy intensity may suggest worn equipment, head loss, or capacity problems, as described by Steger and Pierce (2018b). Cross-sectionally, energy intensity may be used to compare several pumps or water sources in the same service area for the purpose of prioritizing the least-energy-intensive ones, as described by Sowby et al. (2017). It can also help characterize minimum energy requirements for pipeline pumping, as del Teso et al. (2023) propose.

The analysis might then extend a step further to expected energy use. With the reference values for unit pump energy intensity given in Equations 11 or 12, one may readily estimate energy intensity for any head and efficiency combination and compare the expected result to the observations. If the water volume is included, a kilowatt-hour estimate may be obtained and compared to a power bill. Similarly, one may calculate pump efficiency if the other variables are known and compare the result to the expected design value. Unit pump energy intensity also lends itself well to planning scenarios where details of a future pumping system are unknown but where volume, head, and efficiency may be approximated to estimate operational energy use.

Water systems are already using energy intensity in this way; we have presented the theoretical basis to justify it. These are practical, high-level applications that water systems may perform on their own with data they are likely already collecting. The practice may identify problems early, prompt deeper investigations, and lead to better long-term energy performance of water infrastructure.

References

Almulla, Y., C. Ramierez, C. Pegios, A. Korkovelos, L. de Strassler, A. Lipponen, and M. Howells. 2020. "A GIS-based approach to inform agriculture-water-energy nexus planning in the North Western Sahara Aquifer System (NWSAS)." *Sustainability* 12 (17): 7043. https://doi.org/10.3390/su12177043.

Cabrera, E., R. del Teso, E. Gómez, E. Cabrera Jr., and E. Estruch-Juan. 2021. "Deterministic model to estimate the energy requirements of pressurized water transport systems." *Water* 13 (3): 345. https://doi.org/10.3390/w13030345.

Chini, C. M., and A. S. Stillwell. 2018. "The state of U.S. urban water: Data and the energy-water nexus." *Water Resour. Res.* 54 (3): 1796–1811. https://doi.org/10.1002/2017WR022265.

Cojanu, V., and E. Helerea. 2021. "Considerations on the efficient functioning of the urban water pumping stations." *IOP Conf. Ser. Mater. Sci. Eng.* 1138: 012017. https://doi.org/10.1088/1757-899X/1138/1/012017.

del Teso, R., E. Gomez, E. Estruch-Juan, and E. Cabrera. 2023. "Minimum energy requirements of pipeline pumping." *J. Water Resour. Plann. Manage.* 149 (4): 06023001. https://doi.org/10.1061/JWRMD5.WRENG-5656.

Delft Hydraulics. 1991. "Impact of sea level rise on society: A case study for the Netherlands." GWAO 90–016. Utrecht, Netherlands: Rijkswaterstaat.

Jones, S. C., and R. B. Sowby. 2014. "Quantifying energy use in the U.S. public water industry—a summary." *EWRI Currents* 16 (4): 6–9.

Patel, S., R. B. Sowby, T. Elliott, J. Ferro, and T. M. Walski. 2022. "Preparing water utilities for the future of energy management." *J. AWWA* 114 (6): 30–37. https://doi.org/10.1002/awwa.1939.

Pegios, K. F. 2018. "A GIS-based approach for productive uses of electricity: The case study of water and electricity demand for agriculture in Tanzania." Thesis, Univ. of Thessaly.

Pelli, T., and H. U. Hitz. 2000. "Energy indicators and savings in water supply." *J. AWWA* 92 (6): 55–62. https://doi.org/10.1002/j.1551-8833.2000.tb08959.x.

Sárbu, I., and I. Borza. 1998. "Energetic optimization of water pumping in distribution systems." *Periodica Polytechnica Mech. Eng.* 42 (2): 141–152.

Sowby, R. B. 2018. "New techniques to analyze energy use and inform sustainable planning, design, and operation of public water systems." Dissertation, Univ. of Utah.

Sowby, R. B., S. C. Jones, A. E. Packard, and T. R. Schultz. 2017. "Jordan Valley Water redefines sustainable water supply through energy management." *J. AWWA* 109 (10): 38–45. https://doi.org/10.5942/jawwa.2017.109.0134.

Sowby, R. B., and S. J. Burian. 2017. "Survey of energy requirements for public water supply in the United States." *J. AWWA* 109 (7): E320–E330. https://dx.doi.org/10.5942/jawwa.2017.109.0080.

Sowby, R. B., and S. J. Burian. 2018. "Statistical model and benchmarking procedure for energy use by US public water systems." *J. Sustainable Water Built Environ.* 4 (4): 04018010.

https://doi.org/10.1061/JSWBAY.0000864.
Sowby, R. B., and S. J. Burian. 2020. "High-resolution energy intensity modeling to improve water distribution system performance." *J. Sustainable Water Built Environ*. 6 (1): 04019009. https://doi.org/10.1061/JSWBAY.0000896.
Steger, P., and D. Pierce 2018a. "Specific energy: A comprehensive measure of pump station performance." *Opflow* 44 (10): 10–13. https://doi.org/10.1002/opfl.1078.
Steger, P., and D. Pierce 2018b. "Centrifugal pumps and variable-frequency drives: A match made in heaven?" *Opflow* 44 (12): 10–14. https://doi.org/10.1002/opfl.1111.
Twomey, K. M., and M. E. Webber. 2011. "Evaluating the energy intensity of the U.S. public water supply." In *Proc., ASME 2011 5th International Conference on Energy Sustainability*. New York: ASME. https://doi.org/10.1115/ES2011-54165.
van der Zwan, J. T., and M. W. Blokland. 1988. "Water transport and distribution: Planning and design of network systems." Rijswijk, Netherlands: Keuringsinstituut voor Waterleidingartikelen.
Wilkinson, R. 2000. *Methodology for analysis of the energy intensity of California's water systems, and an assessment of multiple potential benefits through integrated water–energy efficiency measures*. Berkeley, CA: Lawrence Berkeley Laboratory and California Institute for Energy Efficiency.