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SIMPLE ENERGY LOSS ESTIMATION IN WATER DISTRIBUTION SYSTEMS

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Abstract

Water and energy are valuable and critical resources. There is a need and will to reduce its consumption due to the impact of climate changes and drought. Both resources are closed related. Water is needed to produce energy but, the water supply system is also an energy intensive process using up to 4% of worldwide energy.
Analyzing the energy balance of water distribution systems confirms the water leakage as a loss of energy. Although there are already precise methods to accurately estimate the energy losses, these are complex and need a deep knowledge of the infrastructure. This work proposes a simple method, with few and easily available global parameters, to estimate upper and lower bounds of energy losses due to leakage. The goal is to quickly access the economic potential of energy efficiency investments in water networks. The method was tested over 21 water distribution entities in Portugal, showing this approach potential for a high-level decision on energy efficiency projects.

Keywords: Water distribution systems, energy losses, water leakage, energy efficiency, water energy relationship

1 INTRODUCTION

Energy supply depends on water, water depends on energy supply [1]. It is expected that this interdependency will increase over the following years. The International Energy Agency [2] estimates that 4% of global energy is used by the water sector. The rising global temperatures have led to longer and more severe droughts making fresh water an even scarcer and energy dependent resource [3].
On the other hand, the European Union through the RepowerEU program, aims to reduce the energy consumption by 20%, and an increase in energy efficiency goals [4] to 13% by 2030.
The need to reduce water and energy consumption forces us to have a new look on the water distribution systems and efficiency measures to optimize it. According to ERSAR (Portuguese water and waste services regulation agency) in 2021 Portugal used 659GWh in the water distribution (38% in local distribution) [5]. According to ERSE (Portuguese energy regulation agency), the annual household energy use is 21.5 TWh [6]. This suggests a 3% of energy consumption for the water system, in line with IEA estimations [2].
Understanding the relationship between water leaks and energy losses opens the opportunity for energy efficiency projects in water distribution. This work is focused on water losses in local water distribution networks (LWDN). It is common for a LWDN to have around 20% of water losses due to a sum of small leakages. From [5] data, the water loss in LWDN for the whole country varied between 19% to 22% from 2011 to 2021.

2 WATER DISTRIBUTION SYSTEM

2.1 System description

The LWDN is usually comprised of pumps, reservoirs, pipes, valves, and other devices. A simplified model [7] described for energy balance assessment is shown in Figure 1.

Tanks have as main function water storage, but also as potential energy storage, depending on how high they are ($E_N = mgh$). Pumps supply external energy to the system by moving water trough pipes up to end users. Pipes transport water and are sources of leakage and energy loss through friction.

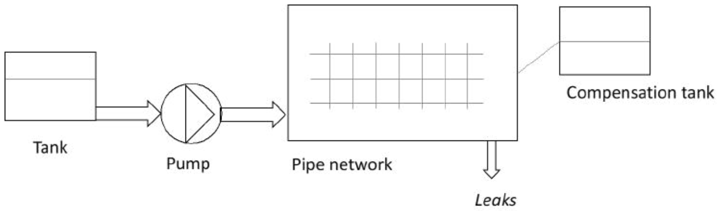

Figure 1 - Simplified LWDN model

Following Cabrera *et al* model [7] and its assumptions, the power balance equation for the system can be expressed by:

$$P_N + P_p = P_u + P_L + P_f \pm P_c$$

P_n is the natural power input to the system, P_p the pump power [9], P_u the power received by the end users, P_l losses to leakage, P_f losses to friction and P_c the power change on compensation tanks. Integrating over a long period of time (example: 1 year), the energy equation balance is simplified to:

$$E_{in} = E_N + E_p = E_u + E_l + E_f$$

2.2 Simplified model

To find an estimation on energy losses, the Lipiwattanakarn *et al.* [10] model approach will be used as described in Figure 2.

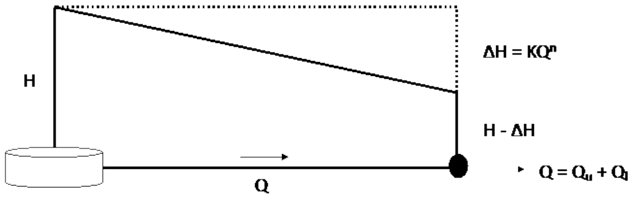

Figure 2 - Simplified model

With:

- Q – input flow
- Q_u – output flow
- Q_l – lost flow
- H – input energy head
- K – friction loss coefficient
- n – flow exponent
- γ – specific gravity

Where the following variables are defined as

1. Water loss ratio defined as $p = \frac{Q_l}{Q}$
2. Input energy: $E_{in} = \gamma Q H$
3. Energy lost in friction: $E_f = \gamma Q \Delta H = \gamma Q(KQ^n)$
4. Friction energy lost in a water loss-free system: $E_{f0} = \gamma Q_u(KQ_u^n)$
5. Energy loss by water losses: $E_l = \gamma Q_l(H - KQ^n)$
6. Energy associated with water losses: $E_{wl} = E_l + E_f - E_{f0}$

Normalizing all energy components by E_{in} ($E_x' = E_x/E_{in}$) and doing the same for ΔH ($\Delta H' = \Delta H/H$), after some algebraic manipulation detailed in [10], the following relation for E_{wl} is obtained:

$$E'_{wl} = p + p_n \Delta H'$$

Where p_n is defined as

$$p_n = (1 - p)[1 - (1 - p)^n]$$

This is a very interesting result as it directly relates energy losses with water and head losses. The first term accounts for energy lost in leaks, and the second for friction losses of leaked water.

2.3 Lost energy boundaries

Because E'_{wl}, p and $\Delta H'$ are ratios, they are in the [0,1] interval. Using $\Delta H'$ limits, E'_{wl} is bounded by:

$$p \leq E'_{wl} \leq p + p_n$$

Both limits are not real-life scenarios. The lower bound is for a perfect frictionless system, and the upper bound for full head loss, meaning no pressure would arrive to end customers rendering the system useless. Nevertheless, these boundaries allow for a simple estimation of loss energy based on water loss ratio and no other information.
Laminar flow is for n = 1, for n = 2 a case of turbulence and rough pipes [10]. In the empirical Hazen–William's formula n = 1.852, and in [8] estimated a field value of $n = 1.76$. Assuming $n = 2$ (Darcy-Weisbach equation), p_2 is a reasonable approximation, and has the advantage of algebra simplicity [10]
Expanding p_n for $n=2$:

$$p_2 = 2p - 3p^2 + p^3$$

$$p \leq E'_{wl} \leq 3p - 3p^2 + p^3$$

The spread between the two boundaries is plotted in Figure 3.

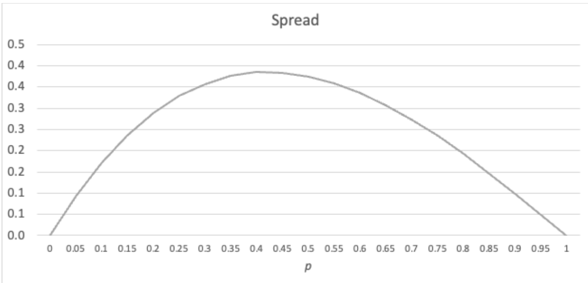

Figure 3 – Difference between upper and lower bound

In the limit cases of p, the gap between bounds is null. The spread reaches maximum of 0.38 for water losses around 40%.
The country's average leakage ratio (p) is approximately 20%. For this value, energy loss is bounded from 20% to 50%. Results from [11,12] shows experimental cases of leakage reduction projects. The energy saving varied between 20% to 40%, in line the theoretical assumptions.

3 ANALYSIS OF THE PORTUGUESE WATER DISTRIBUTION NETWORK

3.1 Characterization

Portugal water sector is mapped into two types of companies, the high-level distribution (10 companies) and LWDN [5]. In 2021, 229 different providers were registered for local water distribution. Most providers are the municipalities or clusters of municipalities. Few are private concessions or private-public companies.
Main variables reported for 2021 for all LWDN providers is shown in Table 1:

	Water in	Losses	Energy (GWh)	p (%)
2021	824 001 957 m3	174 983 661 m3	247.3 GWh	21%

Table 1 – Key figures for Portuguese LWDN in 2021 [6]

3.2 Energy loss estimation

Using high-level data provided by ERSAR [5]: energy used, water in and water loss per year it is possible to estimate the boundaries of lost energy for each provider using the proposed formula:

$$p \leq E'_{wl} \leq 3p - 3p^2 + p^3$$

This method doesn't need any knowledge on the network topology, or any physical parameters. This is not the case for a more accurate estimation with systems like the EPANET toolkit. It's a tradeoff between simplicity and accuracy.
Using the Portuguese dataset, Table 2 shows the E'_{wl} estimation for 2 example entities for the limit cases of $\Delta H'=0$ and $\Delta H'=1$. Overall values and average values were calculated using the 21 entities data set.

Provider	Water In (m3)	Losses (m3)	Energy (GWh)		*p*	$p+p_2$		E_{wl} *Min* (kWh)	E_{wl} *Max* (kWh)
2	12 128 590	1 090 558	11 766 753		9.0%	25%		1 058 022	2 897 221
6	21 446 126	3 006 161	3 257 167		14.0%	36%		456 566	1 186 674
(...)	(...)	(...)	(...)		(...)	(...)		(...)	(...)
Overall	**345 186 715**	**53 262 313**	**132 278 315**		**15.4%**	**39.5%**		**20 410 545**	**52 269 538**
Average	15 690 305	2 421 014	6 012 651		15.4%	39.5%		927 752	2 375 888

Table 2 – Energy loss boundaries calculation

On average, each entity has losses between 1GWh and 2GWh. On average case, the losses are equivalent to 280 to 720 yearly households' consumption [13] per provider.

3.3 Economic valuation

As far as water leakage there are two economic losses, the cost of water and the energy used to transport the lost water E_{wl}. And, although water is available in nature, there are costs associated with extracting, cleaning, and transporting it to the LWDN. Usually, the LWDN buys water from sourcing and high-level distribution companies.
From [5], the cost of a m^3 of water wholesale is estimated as 0.98€/m^3. This value incorporates the cost of energy, labor, and margin from the high-level supply company. The breakdown of these costs is out of the scope of this work, but it is assumed that energy is an important chunk of the overall cost.
From [14] for 2021, the average cost of kWh (without taxes) was 0.14€/kWh.

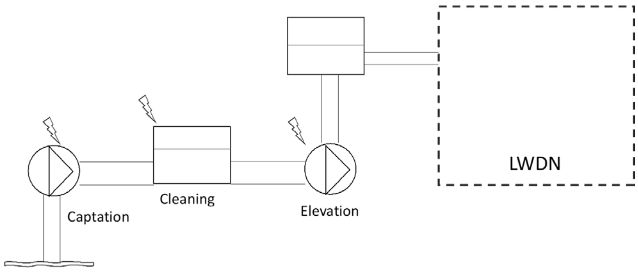

Figure 4 – High level water distribution system simplified model

Table 2 shows the economic losses estimation using water and energy costs for two examples. The overall and average were computed using 21 entities dataset.

Provider	Cost of lost water	Cost of lost energy min	Cost of lost energy max		Total (min)	Total (max)
2	1 068 746 €	148 123 €	405 611 €		1 216 869 €	1 474 357 €
6	2 946 038 €	63 919 €	166 134 €		3 009 957 €	3 112 172 €
(...)	(...)	(...)	(...)		(...)	(...)
Overall	**52 197 067 €**	**2 857 476 €**	**7 317 735 €**		**55 054 543 €**	**59 514 802 €**
Average	**2 372 594 €**	**142 496 €**	**344 142 €**		**2 515 090 €**	**2 716 736 €**

Table 3 – Economic loss boundaries calculation

These values are important for energy efficient investment analysis. By knowing the cost of losses, the payback of an investment can be easy calculated.

4 CONCLUSIONS

Using basic knowledge on water distribution parameters, it was possible to approximate the value of energy losses and economical costs due to water leakage for each LWDN provider. With a few assumptions and 3 global parameters a high-level energy and cost audit it is possible to make a first decision on an energy efficiency (or leaks reduction) investment. It also possible to compute pay-back boundaries.

This method is not intended to give an accurate view of the overall system but as a quick decision support approach. Due to the rising importance of energy and water saving projects, this tool can be helpful, and hopefully boost the number of efficiency initiatives on water distribution systems.

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