Water Policy 22 (2020) 1126–1141

Energy audit in water supply systems: a proposal of integrated approach towards energy efficiency

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Abstract

An integrated procedure has been designed to identify and rank the opportunity for energy efficiency in water supply systems (WSS). The main objective is to help WSS managers to identify key issues to be treated as non-conformity and develop a program for continual improvement of energy efficiency. The procedure was built in collaboration with practitioners and implemented in a company. One of the concerns during the development of the procedure was to provide companies with a fast and user-friendly tool. Complementarily, it also complies with International Organization for Standardization (ISO) and European Committee for Standardization (CEN) standards, and is of great relevance for any company of the sector of water utility. Recommendations for enhancing the energy management in WSS are also addressed in the audit procedure. The findings derived from the evaluation of the state-of-the-art and applications have led to the identification of key issues for energy saving. The success of energy management programs will be based on energy audit and on the top managements' engagement, workers' attitude and qualification, and the financial resources available.

Keywords: Energy audit; Energy efficiency; Water supply systems

Highlights

- Audit is a crucial element for energy management in water utilities.
- Energy lost is related to operation conditions, system configuration, and others exogenous factors.
- Energy audit relies on both human knowledge and historical data records.
- An integrated procedure to guide water utilities towards energy efficiency is a contribution for flexible regulation.

doi: 10.2166/wp.2020.203

1. Background and introduction

1.1. Rationale for energy audit

Audit is recognized as a vital element for process control and continuous improvement (Kalantzis & Revoltella, 2019) and is essential for determining the cost-effective measures that trigger energy efficiency (von Knorring, 2019). Kalantzis & Revoltella (2019: 229) also argued that energy audit (sometimes called energy assessment or energy survey) 'besides being the first step in realizing energy-efficiency opportunities, most likely lead to the adoption of their recommendations …' and '… is a useful tool in overcoming the information barriers and facilitating investments in energy-efficiency measures'. Kluczek & Olszewski (2017) stressed that a well-defined energy efficiency program can reduce industrial energy consumption by 70%. Energy audit can lead to a water supply system (WSS) management that provides services with high energy efficiency and the least cost since previous research (Cabrera *et al*., 2010; Hashemi *et al*., 2018) proved that the energy requirements per unit of output (kWh/m^3 of water delivered) can be substantially reduced with strategic management. Efficiency is a component of the performance measure related to the use of resources in the production of goods or in the provision of services. The term refers to the best use of resources (e.g., energy, water, raw materials), usually expressed by the relationship between a desired useful effect or product (output) and the amount of resources needed for production (input) (for more information on performance measurement and efficiency, see Nudurupati *et al*. (2011), Vilanova *et al*. (2015), and Ibrahim *et al*. (2019)). Therefore, both energy costs (misuse) and environmental impact can be minimized through energy management strategy (von Knorring, 2019). Hence, energy efficiency is among the internationally agreed development goals (United Nations, 2012).

Energy audit of water supply system (WSS) must be performed to balance the total energy inputs with its use and identify and document all the energy streams: (i) energy entering the system, (ii) energy generated in the system (e.g., when microturbine or reversible pump-turbine for energy recovery is installed), (iii) energy distributed in the system, (iv) energy consumed in the system, and (v) energy leaving the system. A standard/conventional WSS usually has only energy entering and energy consumed (Cabrera *et al*., 2010; Hashemi *et al*., 2018). When properly conducted, energy audit can provide relevant guidelines to the WSS manager and insight into energy efficiency. Pelli & Hitz (2000) pointed out that energy has been used for a long time to understand the performance of engineering systems. Therefore, by making practitioners (engineers and managers) aware of how much energy is being consumed in each component (e.g., pump, pipe mains) of the WSS, an audit can result in immediate savings of energy and costs.

System audit is of noteworthy importance because it may reveal energy saving opportunities that would not be detected from isolated components' audits. For instance, by system audit it was possible to detect a high volume of water pumped under high pressure from one sub-sector to another just to satisfy a desired pressure of 22 meters of water column (or 215.6 kPa) at a given region far from the water source in a distribution network. This situation can be replaced with an energy efficient alternative that considers a small booster pump at the right location (near the consumers) to guarantee the necessary pressure, thus allowing a reduction of pressure in a considerable extension of the pipeline and significant energy saving.

Recently, efforts have been made to improve energy efficiency worldwide. For example, according to Beck *et al*. (2018), the European Directive 2009/125/EC (establishes a framework for the setting of eco-design requirements for energy-related products) requires a maximum efficiency for energy-using units (e.g., electrical motors and pumps), and the European Committee for Standardization (CEN) published, in 2016, the standard EN 16480 ('Pumps – Minimum required efficiency of rotodynamic water pumps') defining a specific threshold value of minimum efficiency index (MEI), prohibiting sales of pumps with a MEI <0.40 which are both of capital importance for energy savings. Additionally, the Energy Efficiency Directive (2012) – establishing a set of binding measures to help the EU reach its 20% energy efficiency target by 2020, its amending directive (2018/2002) that set the energy efficiency target for 2030 of at least 32.5% having 2007 as base year, and the European standard EN 16247-1:2012 that specifies the requirements, common methodology, and deliverables for energy audits (European Committee for Standardization, 2012) – developed by CEN – also brought substantial contributions for energy management.

The audit provides managers with positive orientation to the energy cost reduction, preventive maintenance, and quality control programs for continuing improvement of the systems. Hence, energy efficiency can be set as a target in the audit process since it allows the identification of the main contributors for energy consumption and priorities to sustainable energy used.

1.2. Energy consumption in water supply systems

Water scarcity and energy security and efficiency are among the challenging goals of sustainable development for 2030 (United Nations, 2015). Water supply system is a very complex and energy-intensive infrastructure which represents 7% of consumption of world global energy (Coelho & Andrade-Campos, 2014). Horstmeyer *et al.* (2017) compiled the range of energy demands for water treatment (no water conveyance and distribution included) from different authors that shows that WSS can be more energy-intensive depending on the type of water source (see Table 1).

The same work indicated that the energy demand for water conveyance in the State of California is approximately 0.79 kWh/m^3. In São Paulo municipality (Brazil), the total electrical energy demand to satisfy the entire water supply system (conveyance, treatment, and distribution) is approximately 0.64 kWh/m^3 (SNIS, 2017). In German water supply systems, where ~70% of water supply originates from groundwater, the average specific energy consumption amounts to approximately 0.53 kWh/m^3 (Beck *et al.*, 2018). The higher the energy consumption of a WSS, the higher the vulnerability to the impacts of global climate change (Kothausen & Conway, 2011). Lack of understanding of energy balance in WSS leads to overuse or mismanagement of the energy so that the water-energy nexus should be considered in WSS management strategy. Therefore, the identification of all the possible system energy

Table 1. Energy demand of water treatment from different sources.

Energy demands for water treatment (kWh/m^3)	Type of water source
0.05–0.37	Conventional water supply from surface water
0.19–0.58	Water supply from groundwater
0.26–2.60	Brackish water desalination
1.15–2.00	Potable water reuse application schemes with advanced treatment process (technology practiced for more than 50 years)
3.70–4.40	Seawater water desalination

Source: Authors based in Horstmeyer *et al.* (2017).

forms is of utmost importance for strategic energy management. Previous works (Cabrera *et al.*, 2010; Lienzi *et al.*, 2013) have described the energy forms present in WSS as: natural energy supplied by external sources (e.g., reservoir), shaft energy supplied by pumps, useful energy delivered to users, leakage energy losses, friction energy losses, and compensation energy (refers to internal system tanks). Water loss is a huge problem for energy efficiency in WSS because it ranges from 15 to 60% of the total water supply (see Ndunguru & Hoko, 2016). As highlighted by Hashemi *et al.* (2018), pumps and reservoirs supply mechanical energy to the system and the other forms of energy (e.g., water demand, pipe leaks, and frictional head loss) leave the system.

1.3. Research scope, objective, and contribution

Despite the fact that energy efficiency of WSS is widely recognized as a challenge and many studies have been published covering this subject, we did not find a single study presenting/proposing a detailed procedure for energy audit in WSS. For instance, some researchers introduced the term ‘energy auditing’ in their work but they just assessed energy metrics without depicting any audit procedure (see Cabrera *et al.*, 2010; Mamade *et al.*, 2015, 2017; Loureiro *et al.*, 2016; Ribeiro *et al.*, 2016; Gasner *et al.*, 2018). The audit procedure proposed in this work fills this gap and was developed to be applied to WSS, although users can easily adapt it to comply with the peculiarities of others urban utilities.

As suggested by Ribeiro *et al.* (2016), Loureiro *et al.* (2016), and Gasner *et al.* (2018) and recalled by Beck *et al.* (2018), companies (water suppliers) are still not aware of what to do and how to achieve global efficiency in WSS. Thus, the objective of the present work is to design an integrated procedure of energy audit to perform energy balance, identify and rank the opportunities for energy efficiency in WSS, and contribute to foster flexible regulation on energy efficiency.

This work puts forward the key issues that should be tackled for successful energy audit and management. It may represent a new opportunity for relevant actions that would contribute to more detailed energy balance in WSS.

The paper is structured as follows: Section 2 provides a step-by-step description of the adopted research approach split into eight phases. Section 3 presents the detailed procedure for energy audit, including recommendations to overcome difficulties. Finally, Section 4 concludes.

2. Research approach

The integrated procedure for energy audit of water supply systems was developed bearing in mind that energy audit consists of ‘verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost-benefit analysis and an action plan to reduce energy consumption’ (Energy Conservation Act, 2001, p. 2). To do this, the following eight phases were taken into account.

Phase 1 – state-of-the-art characterization

A survey of existing audit procedure to improve energy efficiency was performed on the Web of Science (a multidisciplinary database from Clarivate Analytics) considering all subjects’ category (see Figure 1).

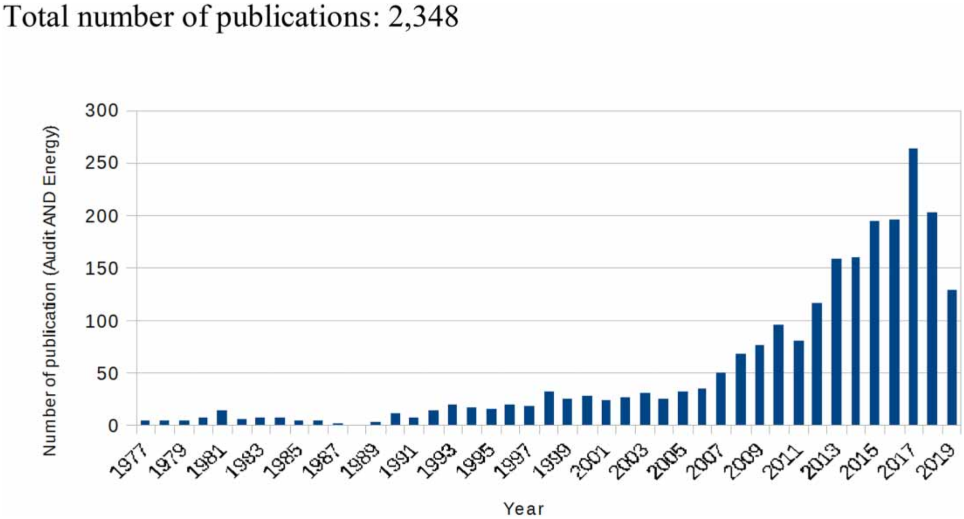

Fig. 1. Evolution of publications on energy audit from 1945 to 2019 based on Web of Science (date of search: October 26, 2019). *Source*: authors.

Figure 1 shows that among the 2,348 publications found for the search (Audit AND Energy) performed, 10%, 8%, 7%, 3%, and 2% were in respect of the categories of Civil Eng, Environmental Eng, Mechanical Eng, Chemical Eng, and Water Resources, respectively. Of 2% publications in water resources, only 14.6% (i.e., six) were about WSS, but none of them present a step-by-step procedure for energy audit. Despite that it was possible to find relevant tips in several articles from other Web of Science categories, of which, we highlight the following:

- Green energy audit (Dall'O' *et al.*, 2012).
- Energy audits in shipping companies (von Knorring, 2019).
- Energy audit of public buildings – the energy consumption of a university with modern and historical buildings (Corrado *et al.*, 2019).

Phase 2 – international standards as navigation and guidance instrument

A review of ISO documents, such as ISO 9001 (Quality management systems), ISO 19011 (Guidelines for auditing management systems), ISO 14001 (Environmental management systems), ISO 55000 (Asset management), ISO 50001 (Energy management systems), ISO 31000 (Risk management), and EN 16247-1 (Energy Audits) (from CEN) was performed to know how to develop an adequate and traceable procedure, including data collection and treatment.

Phase 3 – energy balance in water supply system (WSS)

An analysis of several WSS layouts (including sector with irregular topography) was performed to identify the elements of energy balance that have to be considered as the proposal is to develop a procedure suitable to any system. After that the concept of energy balance (see Cabrera *et al.*, 2010; Dziedzic &

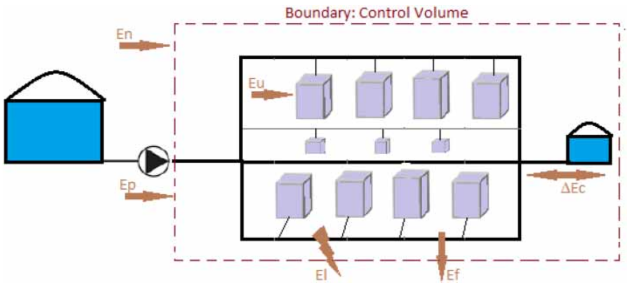

Fig. 2. Representation of energy balance in WSS. En, natural energy (supplied by external sources, e.g., reservoirs/tanks); Ep, shaft energy supplied by pumps; Eu, useful energy delivered to consumers; El, leakage energy losses; Ef, frictional energy losses; △Ec, compensation energy (associated with internal system tanks); ▨, buildings (consumers). *Source*: Authors.

Karney, 2015; Darweesh, 2017) was applied to the system's layout (see Figure 2), using the control volume concept, to identify inputs and outputs of energy that must be considered in energy audit.

Typical energy balance includes input energy (e.g., from natural/gravitational external sources and/or shaft energy which means that reservoir and/or pump supply mechanical energy to WSS), dissipated energy (e.g., friction energy losses), and output energy (e.g., energy delivered to consumers, and leakage energy). Some WSS located in areas with irregular topography were subjected to innovations that consist of using turbines (e.g., Francis, micro-hydro impulse, and Axent; see Kramer *et al*., 2018) or reversible pump-turbines (Carravetta *et al*., 2012; Meirelles *et al*., 2018) to generate electrical energy in the system. If that is the case, the energy generated in the system also must be considered in energy balance.

Phase 4 – audit planning

Brainstorming meetings (participants: researchers and practitioners of water utility) to define what should be the scope, goals, targets of energy audit as well as how to make the process user-friendly for managers, potential auditors, and other (internal) collaborators of water utilities (refer to Mata-Lima *et al*. (2016) to see how to run a brainstorming meeting).

The complexity respecting energy balance of a WSS (the concept described in Phase 3) is vital to establish the audit level since it depends, mainly, upon the size, topography of the area, number and type of accessories installed (e.g., fixed or variable speed pump, reversible pump-turbine, pressure reducing valves), and configuration of the WSS.

Phase 5 – definition of auditor profile

Based on the information gathered from the previous phases (1 to 4) it was possible to establish minimum requirements of qualification to integrate into the energy audit team so that the system benefits from professional judgment and experience. The team must be able to perform an audit that provides information on how and where major quantities of energy are being (mis)used. The experienced auditor with in-depth knowledge in the area of energy management might be able to decide where to focus attention to improve energy efficiency as much as possible. As energy audit benefits from professional judgment and experience, the audit team should be composed of experienced professional (ideally with ten or more years of experience and subjected to continuing education to keep always up to date) from different areas (e.g., civil, mechanical, and environmental engineering) to guarantee a holistic approach to the problem. Unfortunately, the sort of professional here described is not easy to find, so it is of utmost importance to provide the water utilities with sufficient information in the integrated procedure proposed in this article. The procedure proposed hereby intends to be detailed enough and user-friendly to allow utilities to use it without having to hire over-qualified auditors.

Phase 6 – water supply system characterization

This is determination of the requirements for a full characterization of the sectors of a WSS to be audited, including the description of each component (e.g., pipe, pump, pressure reducing valve). The description must provide details of the component (e.g., type of material, capacity, age, etc.).

Phase 7 – sensitivity analysis

Careful research jointly with expert knowledge of the team, as described in Phases 4 and 5, were combined to define how to perform sensitivity analysis of the energy efficiency indicators to physical properties of the system, network layout, flow characteristics, and operation scheduling (e.g., pump operation) to establish where to place priorities. Water utilities must always perform sensitivity analysis first to decide where to set priorities to obtain as much benefit as possible (e.g., energy and costs savings as well as consumer satisfaction).

Phase 8 – design the integrated procedure for energy audit

At this last phase the authors were able to develop an integrated procedure for energy audit and establish how and which data must be collected in each component of the system as well as hydraulics and energy indicators/indexes to be computed.

All of the aforementioned phases were of vital importance to develop the integrated user-friendly procedure proposed in the next section.

3. Audit procedure and recommendations

3.1. Preliminary remarks

Water utilities that have never performed an audit before should start with what the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) calls preliminary audit. This type of audit consists of identifying the WSS energy consumption and establishing improvement measures. Hence, it is a good starting point to be used with energy balance and conservation in the water supply system. To do so, the auditors must select a sector of WSS (or global system if it is small enough) where essential data are already available, and define the most likely places of potential energy saving. The review of previous research performed in this work suggests that attention should be given to pumping stations (e.g., equipment specification, operation schedule), pipe mains with high average flow, and pipe leakage. The final report must summarize relevant findings and a cost-effective analysis of the identified opportunities for improvement.

After examining the impact of the preliminary audit, water utilities will be able to conduct a more detailed audit to assess the global energy balance of the WSS to extract as much benefit (energy efficiency) as possible. This new step requires extensive data treatment, measurement of new data, several days of field visits and meeting with managers, engineers, and operators (people working at the place). It is then clear that operation data of WSS and information about specialized equipment must be maintained to guarantee the traceability of the process, as recommended in ISO 9001. Therefore, a successful audit, in terms of energy savings and reduction of the carbon footprint, depends upon integrations of the management systems (e.g., ISO 9001, 14001, 19011, 31000, and so on) and expert knowledge of auditors to namely select/propose adequate energy metrics.

3.2. The integrated procedure for energy audit of WSS

The overall process flow of an energy audit includes the following activities: preliminary contact, start-up meeting, collection of data, field work, analysis, report and final meeting. Based on the research approach adopted (Phases 1 to 8) in this work and the aforementioned remarks, it was possible to delineate the detailed energy audit procedure in seven steps, proposed in this section.

Step 1 – The beginning. The audit team might be selected among the most qualified and experienced collaborators from utilities. When utilities do not have qualified professionals to conduct an audit procedure the solution can be an ad hoc team composed partially of external professionals. It is best to avoid a full team composed of external professionals because this can be a barrier to obtaining assistance from a utility's operating management (collaborators working at the facility).

Once created, the team of auditors meets top and operating management teams to decide how in-depth the audit should be (e.g., audit scope and goals must be in accordance with a utility's budget capacity). Commitment of top management is essential to carry out a successful audit as well as assistance from the operating management. The audit scope and goals are set in this meeting. Audit scope can be defined as the entire WSS (including all components from water source/intake to distribution network) or simply water distribution network. This decision depends on willingness (top management option) to afford the costs, time, and resources available, and also on historical data records. When historical data are not available, the auditors should design a detailed procedure for data collection to make the components/processes traceable. Once the scope is defined the goals must be established. The goals of an audit to improve energy efficiency usually comprise: identify and rank where energy has been lost, set priorities concerning actions to increase energy saving, draw a recommendation plan for replacement and modernization of the equipment, identify the need for training and/or corrective and continual improvement actions with respect to operational procedures, and so on. It is important to stress that as water conservation is energy conservation, water loss should not be ignored in an energy audit. The more detailed, the more expensive and time-consuming is the audit process.

Step 2 – system description and energy balance. The energy balance of the system to be audited should be sketched out based on the available layout (map and longitudinal profile of the WSS). All forms of energy (see Figure 2) must be identified to establish how and where major quantities of energy are being (mis)used. The auditors can now establish the strategic energy management program detailing where to place priorities and which data should be collected. For instance, with respect to priorities, attention should be given to components (e.g., pumps, including coupled electric motor) where small improvements in efficiency can lead to substantial energy savings.

Step 3 – data acquisition. Step 3 is to compile and review all existing historical data that can be relevant for energy and cost assessment, analyze their relevance (preliminary analysis), and establish which additional data would be required.

Be aware that energy audit of WSS requires data concerning physical, hydraulic, mechanical, and electrical assets as described in Figure 2 (or water utilities can also include water treatment plant in the analysis). Thus, it is mandatory to have data of the system layout, tanks, pump (e.g., pumping station specification, operation schedule), pipe characteristics (e.g., material, diameter, extension, age), demand range, service pressure, leakage, electricity bill, and many others described below in Step 5.

Step 4 – field visit and stakeholder engagement. A prior field visit (walk-through of WSS) is unavoidable to know the system, gather data/information, and get involved with operating management, engineers, and operators responsible for different components of the WSS. In this step a rough draft of the plan to collect new data, including recommendation concerning measurement instrument to be used is made.

Step 5 – first attempt to the audit work plan. The decision-making process should be based on expert knowledge of all team members via, for instance, brainstorming (readers should refer to Paulus & Brown (2003) for detailed explanation), and fishbone (or Ishikawa) diagram (refer to Rothwell *et al.* (2007) and Luo *et al.* (2018)). The audit plan must detail all team members' responsibility and duties (e.g., where to go, which forms must be filled in). Auditors must be aware that for water utilities without implemented management systems (e.g., quality management system according to ISO 9001), it can be necessary to create all forms to collect data/information.

One of the most difficult tasks can be how to define which energy metrics/indicators should be considered. It is not possible to evaluate all indicators or include all components of WSS in the energy management program because the process would be expensive and time-consuming. Hence, auditors must use their expert knowledge to select the strictly necessary metrics to evaluate energy balance, identifying the places of intensive energy consumption as well as establish where to place priorities (priorities should be given to the best cost-effective opportunities for energy savings).

A room should be available for the meeting of the audit team to update the work plan and feed the audit report after a visiting day (at least the last two hours of an audit day should be devoted to writing draft documents).

The next paragraphs provide information on how to select appropriate metrics according to WSS characteristics and where to place priorities as well.

Selection of energy metrics. Energy metrics/indicators usually are intended to quantify the system energy use to deliver a certain volume of water (kWh/m^3). This work divides the indicators into two categories as shown in Table 2.

Some energy indicators require substantial financial effort, high qualification of the team, installation of advanced equipment for measurement, huge data collection, and detailed hydraulic simulation of the

Table 2. Energy metrics/indicators that can be applied to WSS.

Energy indicators	Dynamic (require hydrodynamic simulation or measurement through long period)	Modeling network efficiency and carbon emissions (see Boulos & Bros, 2010) Modeling network energy use (see Cabrera *et al.*, 2010; Gay & Sinha, 2012; Dziedzic & Karney, 2015; Mamade *et al.*, 2015; Lapprasert *et al.*, 2018). Metrics do evaluate energy performance at pipe level (Hashemi *et al.*, 2018)
	Static (do not require hydrodynamic simulation)	Based on average differences in elevation and pumping (see Pelli & Hitz, 2000; Mamade, *et al.*, 2015). Based on simplified assessment with minimum data (Mamade, *et al.*, 2015; Mamade *et al.*, 2017)

global system (e.g., a useful free software for simulation is the widely used EPANET, https://www.epa.gov/water-research/epanet). Due to that, the auditor should choose adequate indicators according to company capacity to afford inherent financial and technical requirements.

Usually, water utilities have data concerning unit head loss (UH, m/km) and average flow (Q_{av}, m^3/s) available for their pipes. When leakage is known it can be used in conjunction with UH, Q_{av}, and hydraulic proximity to support decision-making on energy efficiency, although Pinto *et al.* (2017) highlighted that a suitable assessment of water utilities' performance implies going beyond the process inputs and outputs to compute efficiency indicators. To do so, exogenous factors (e.g., customer density, topography, weather, water source (see Table 1), regulatory framework, peak factor) that create constraints ought to be taken into account to assess energy efficiency.

Relevant information to know which and how to collect audit data concerning different units of WSS:

- *Pumping station:* Check maintenance procedure and intervals, efficiency (pump and electrical motor), specification of pump (fixed speed pump (FSP) or variable speed pump (VSP)), operation schedules, opportunities to use reversible pump-turbine, electrical motor of pumps – check need for continuous operation. Pumping operations drive energy efficiency and losses in pipes close to water sources, so that hydraulic proximity (Hashemi *et al.* (2018) present a detailed description on how to compute hydraulic proximity indicator) can be an important indicator to make decisions on priorities with respect to leakage reduction or pipe replacement. Darweesh (2017) found that the replacement of FSP by VSP improved substantially the energy savings and leakage reduction by 20 and 21%, respectively. VSP has the ability to vary the rotational speed by changing supply frequency. Electrical motors of pumps also have intrinsic loss and are commonly oversized (Glover & Lukaszczyk, 2005; World Pumps, 2009; Wang *et al.*, 2017) which makes them inefficient, causing energy loss. To adjust the speed required and reduce energy consumption, a variable speed drive technology can be adopted. VSP also contributes to WSS reliability since it attenuates the effect of hydraulic transients. Although, the auditor must be aware that VSP might not be adequate for a system with high static head (such as those located in regions with irregular topography with high altitudes between water sources and consumers) compared to friction head because the operating point on the reduced speed curves exhibits an efficiency below that at the original speed (refer to Darweesh (2017) for more information). On the other hand, when high topographic energy is available in the system, reversible pump-turbine (or pump working turbines (PATs) may be installed to recover this potential energy (Cabrera *et al.*, 2015; Meirelles *et al.*, 2018).

- Dynamic pressure is a variable of utmost importance to monitor and maintain within recommended levels (21 to 70 mH_2O, according to American Water Works Association (AWWA) (see Dziedzic & Karney, 2015)) in the entire system. High pressures mean more pumping costs and leakage, and can cause system failure while low pressures can lead to the inability to meet demands, pollutant intrusion, and might facilitate cavitation. Pressure management is one of the most effective ways to reduce the amount of leakage in WSS.
- *Pipes:* Check the type of material (PVC, HDP, ductile iron, etc.), roughness, diameter, friction losses, leakages, hydraulic proximity, and age. High head losses in pipe are a result of the combination of friction loss and leakage (Hashemi *et al.*, 2018). Leaks contribute to energy lost due to ongoing energy through leaks and also friction energy losses as a result of increase in water discharges. Diurnal variation in demand also drives energy performance of pipe mains (high flow pipe) located far from the water sources, so that hydraulic proximity plays an important role in energy efficiency.
- *Pressure reducing valves (PRV):* When substantial topographic energy is available, part of this energy can be dissipated with PRV (Cabrera *et al.*, 2015). PRV reduce the excess of water pressure to decrease leakage and pipe stress as the aforementioned PATs. It is important to stress that when the topographic energy is significant PATs should be considered to recover the energy, otherwise PRV should be used to avoid overpressures. Pressure management, using PRV, is an effective way to control the amount of leakage in WSS (e.g., Samir *et al.* (2017) presented an easy and detailed procedure to assess PRV contribution to reduce leakage using model sensitivity analysis).
- *Reservoirs (balancing, break, and service reservoirs):* Volume and location of each type of reservoir must be checked, to verify need for additional reservoir (compensation reservoir to reduce pump capacity). Take into account that reservoirs drive energy efficiency and losses in pipes close to water sources (e.g., reservoir should be located near the center of consumption to reduce average flow in pipe mains and, consequently, the energy loss due to friction).

Method to perform sensitivity analysis. Sensitivity analysis ought to be considered in a detailed and advanced audit and includes dynamic hydraulic simulation of the WSS to assess the impact of different intervention measures considered among the opportunities to improve energy efficiency. Sensitivity analysis should be performed using the *ceteris paribus* concept which means that one has to keep all other system parameters constant while changing the parameter/variable of which the influence on energy savings is being assessed. Such procedure must be repeated for all likely possible interventions considered to rank the most cost-effective. This method provides important information for the decision-making process.

Nearing *et al.* (1990) presented a procedure to compute sensitivity analysis as absolute and relative sensibility and also pointed out the drawbacks of the method.

Opportunities to improve energy efficiency. The audit plan must include a form or a section where an energy management opportunity checklist is provided, and most energy intensive operations have to be identified. The information should include what ought to be improved (pump specification, pump operation schedule such as off-peak pumping, control of leakage by either pressure reduction or pipe replacement, etc.), scope of saving, most likely areas for attention as well as additional investigation that should be performed in order to obtain an appropriate assessment of energy metrics.

Rank the significant places of energy consumption (i.e., most energy-intensive process) and priorities for energy conservation. Find relationships between energy systems, correlations with demands (peak or minimum), leakage, hydrodynamic pressure as well as unusual energy consumption patterns. Bear in mind that the relative importance of the energy cost in the production is among the main drivers of the decisions of top management and that energy efficiency opportunities stand for investments that are financially sustainable and require limited capital spending compared to other core-business investments (Kalantzis & Revoltella, 2019).

Send the audit plan to the stakeholders (e.g., top management, intermediate managers of different divisions). They should return the plan with suggestions in a week or more.

Step 6 – final audit plan, execution, and report

Finalize the audit plan. Revise the audit plan considering the suggestions (if any) received from the stakeholders. The final audit plan must include a detailed timetable with all duties, date of field visit, and who should receive the auditors. The plan must be shared with all stakeholders prior to the audit date.

Audit execution. Do complementary data inventory and measurements, analyze energy balance (e.g., energy supplied, consumed, dissipated, and generated), characterize the WSS using SWOT (strengths–weaknesses–opportunities–threats) analysis to compare different possibilities of energy savings, synthesize a set of potential energy efficiency measures, and rank/prioritize the measures according to their cost-effectiveness.

Audit report. Now the energy audit report can be written. The outline of the audit report must include at least the following sections: executive summary, scope, objectives, description of the system, methodology, findings (non-conformities/misused energy, baseline/reference indicators, and opportunities for energy savings with corresponding level of cost associated as well as likelihood of the execution), and final recommendation.

The report should pay attention to cost saving (e.g., rank the opportunities for energy savings according to cost-benefits) because it is a driver for the majority of top management, therefore, explain how and to what extent to lower energy costs and reach compliance with government financial incentives (if any). It is clear that water conservation means energy conservation, as well as cost saving. In addition, non-structural actions such as operation management (e.g., off-peak pumping, pressure control) are more cost-effective than structural actions (e.g., replacements of pumps and pipes) which have long payback periods (tens of years).

After management decision on which energy efficiency measures to execute, an action plan has to be done. It is noteworthy that all tasks referred to hereby should be done following the tips provided in Step 5.

Step 7 – post-audit process. In this last phase, activities include implementing energy efficiency measures, and checking the performance of the measures. Successful measures are maintained and those that do not produce a satisfactory level of energy savings should be improved according to the well-known cycle plan–do–check–act (PDCA).

Concluding remarks

Audit is certainly a crucial element in decision-making in the context of energy management since it can identify critical points in terms of energy consumption and rank the opportunities to diminish energy expense and carbon footprint. Without energy audit, managers/engineers of WSS are unable to quantify its use as well as understand energy flows (e.g., identify where misuses are taking place) and draw a strategic management towards energy efficiency and cost savings. Audit triggers energy efficiency by relying on both human knowledge and historical data records. Thus, this work teaches how to analyze energy flows in WSS in order to reduce the energy input and consumed/dissipated without compromising the services and thus client satisfaction.

Energy is lost due to, for example, operation conditions (e.g., pump scheduling, range of dynamic pressure, leakage), system configuration (e.g., location of service reservoir, orientation of the buildings/consumers, hydraulic proximity), and complex topography (high altitude between downstream consumption nodes and upstream sources of water) of the area. Therefore, the higher the complexity of WSS (e.g., large system or that located in irregular topographic areas), the higher the complexity of the audit as well as the selection of energy metrics/indicators, particularly when benchmarking between systems is a goal. Small-sized water utilities without the capacity to perform internal energy audit (i.e., absence of trained and experienced collaborators) should ask for external auditing and/or make a contract with suppliers of specialized equipment that considers periodical energy audits to check the efficiency and recommend operation improvement or equipment replacement.

The integrated procedure proposed hereby is a guide to water utilities that are committed to energy efficiency. In addition, it is important to highlight that flexible regulation on energy efficiency can stimulate utilities' green innovation. This context, together with government incentives, may lead to progressive voluntary regulation (and certification according to ISO 50001) which refers to utilities' voluntary commitments to conduct energy management strategies.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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Received 26 October 2019; accepted in revised form 15 October 2020. Available online 13 November 2020