AMERICAN JOURNAL OF ENERGY AND NATURAL RESOURCES (AJENR)

VOLUME 1 ISSUE 1 (2022)

Indexed in

doi | Crossref | Google Scholar | Directory of Research Journals Indexing (DRJI)

PUBLISHED BY: E-PALLI, DELAWARE, USA

American Journal of Energy and Natural Resources (AJENR)

Volume 1 Issue 1, Year 2022
https://journals.e-palli.com/home/index.php/ajenr

Review on Energy Audit: Benefits, Barriers, and Opportunities

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Article Information

Received: December 06, 2022

Accepted: December 20, 2022

Published: December 24, 2022

Keywords

Energy Audit, Energy Efficiency, Energy Policy

ABSTRACT

Energy audit is one lever to reduce carbon emissions of an organization (industrial site, residential building etc.;). This paper explores the energy audit savings tendance, barriers, challenges, and opportunities through an extensive review of the literature. Different variant of the methodology can be found in the literature and one aim of this research is to make a synthesis (from the most relevant variant). Energy audit can be adapted to the size and context of the organization thanks to the different levels of audits. Different cases studies are also included in this article that highlights the benefits of the energy audit. Other aspects are studied such as tools to use during audit and competencies and experience of auditors. Several barriers should be removed progressively to add more benefits to this sustainable lever. A list of opportunities has been identified and should be subject to further research.

INTRODUCTION

Energy is vital and highly present in industrial and non-industrial sectors (transport, residential etc.) as represented in figure 1. Energy is used to operate equipment and installations for movement, heating, communication, etc.

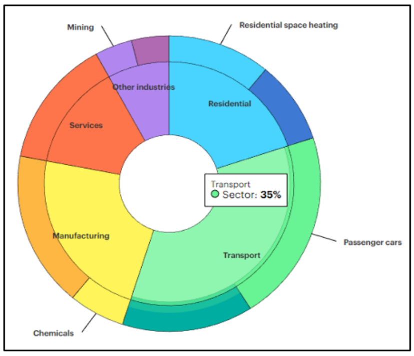

Figure 1: Largest end uses of energy by sector (IEA, 2019)

Over the past few decades, energy has allowed humanity to evolve rapidly and thus improve the living conditions of living beings. Our needs continue to increase and therefore our energy needs.

Currently, energy can be divided into 3 subparts:

- Types of energy and their availability
- Carbon emissions
- Costs

Several energy resources (gas, oil etc.) are decreasing and becoming scarce. We consume more than the earth can supply. This progressive scarcity is already having an impact on our needs, and this impact will continue to increase. Geopolitical crises also have an impact on energy. Energy resources are very disparate between countries and continents. Many countries are energy dependent on a limited number of countries as showed in figure 2 for crude oil. The slightest geopolitical tension (wars, economic sanctions etc.) can lead to major repercussions such as the ongoing Russo-Ukrainian war. Global financial crises have an impact as in 2008 and represented in figure 3.

The energy consumption increase is the cause of the

Net exporters	Mt
Saudi Arabia	352
Russian Federation	269
Iraq	195
Canada	154
United Arab Emirates	148
Kuwait	102
Nigeria	99
Kazakhstan	70
Angola	63
Mexico	59
Others	531
Total	**2 042**

Figure 2: Net importers of crude oil (IEA, 2021)

greenhouse gas emissions increase. Those gases degrade the ozone layer which protects the earth from climatic disasters (hurricanes, floods, high temperatures, etc.).

Because of the elements mentioned above, energy costs are very volatile. High costs lead to significant changes and require quick adaptation as much as possible. Some industrial companies, for example, must stop their production or slow down their production. Indeed, this has a major impact on the cost price of their finished products.

Energy efficiency is one of the levers for controlling energy consumption and its impacts (Fleiter *et al.*, 2012; Menghi *et al.*, 2019; M'Baye, 2022a). Energy efficiency includes different components such as energy management which also includes energy audit (Sala *et al.*, 2022; Dongellini *et al.*, 2014; Oyedepo & Oladele, 2013; Grinbergs & Gusta, 2013).

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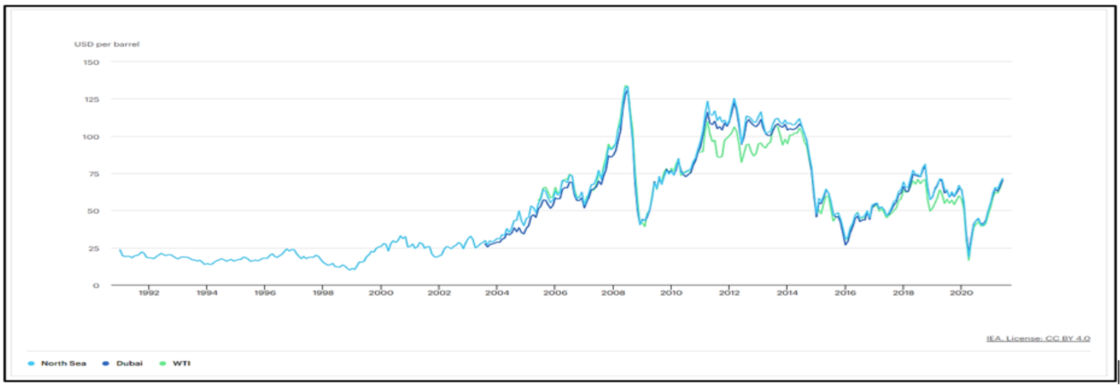


Figure 3: Average key crude oil spot prices, January 1991-June 2021 (IEA, 2021)

The purpose of this article is to carry out a literature review on the energy audit (in an industrial environment which is one of the most energy-intensive and on commercial and residential collective buildings) to highlight energy savings trend, barriers/challenges, gaps in the literature on this subject and opportunities.

Energy audit methodology

In the literature, there are different descriptions of the methodology to carry out an energy audit. Figure 4 represents the energy audit process flow of view according to Abdelaziz *et al.* (2011), Alajmi (2012), Rosenqvist *et al.* (2012), and ISO 50002 (international standard on energy

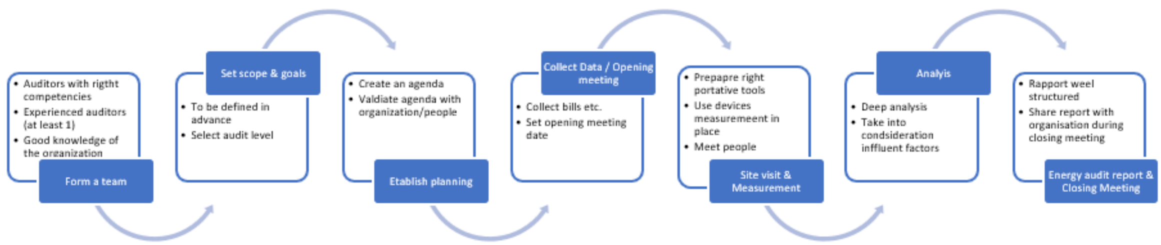


Figure 4: Energy audit process flow

auditing). Moreover, for Abdelaziz *et al.* (2011), energy audit must be a systematic approach.

Form a team

A clear and complete auditor team must be defined. The team can include internal members or/and external members (when the audit is led by an external company). If it is an audit carried out by an external company, it is imperative to include at least one member of the technical/utilities department and the users of the equipment. For the success of the audit, the team must be multidisciplinary. Auditors must have skills and experience in line with the scope and objectives.

In the case study of Alajmi (2011), as the case study has a research dimension, the group includes a project manager to coordinate and ensure that objectives are met, an electrical technician for the measurement part, a production person, and an energy consultant.

Set Scope and goals

The scope of the audit must be defined in advance. The organization (example: an industrial site or a commercial building) can be divided into several sub-parts and all or some parts can be audited. In addition, a breakdown by type of process should be done. Goals should also be as specific as possible.

The objective of the mission is to establish an overall inventory of the site's energy situation.

In the case study of Alajmi (2011), the team's first task was to define the scope of the energy audit, including the areas to be audited, the audit level to conduct, and the savings targeted.

Collect Data & Information

This step can be carried out before the intervention on site when the audit is performed by an external company. According to Rosenqvist *et al.* (2012), several step should be followed such as: Identify unit processes; Quantify energy supply etc.

Site visit and measurement

An energy audit aims to give an opinion on the energy consumption and the operation of the installations after an on-site visit:

• Visual inspection of the installations,

• Examination of existing means of measurement and analytical documents,

• Interviews with the technical members and users.

Analysis

At a minimum, the analysis consists to the following:

• Critical analysis of primary energy consumption (static approach + correlations),

• Analysis of energy bills and measurements taken on site,

- Breakdown of consumption and identification of the most significant energy uses
- Analysis of the energy management system in place

For Rosenqvist *et al.* (2012),

Several points must be taken into consideration to go further in the analysis in the energy analysis step:

- How "bad" is the utilization of the supplied energy? Where does it go wrong? How far can we reach?
- Identify both system errors and detail problems.
- Identify idling power and energy.
- Identify technologies that are far from BAT (Best Available Technology).
- Identify mismatching energy quality, where high quality energy is used for non-demanding purposes, for example, electricity for low temperature heating.
- Identifying barriers and driving forces.

Energy Audit report

The energy audit report generally includes (Oyelaran *et al.*, 2016):

- Inventory of energy consumption
- The estimation of the financial stakes, in particular energy issues related to energies and energy fluids, but also the possible implications in terms of quality and productivity induced by manufacturing,
- An inventory of the first possible improvements to be made to the installation (just do it) but also the major sources of savings (energy + financial),
- Development of an action plan to be implemented to achieve the energy savings objectives
- Evaluation of investment envelopes and returns on investment
- Ranking and prioritization of actions according to criteria of complexity and profitability.

Rosenqvist *et al.* (2012) state that the expected result of the energy audit is a number of measures that will increase the energy efficiency, switch from non-renewable to renewable sources and decrease the energy use of the company or in the energy system as a whole. The result is normally presented in a report.

Audit levels

After review of the literature, there is a consensus on the number of energy audit levels. There are 3 levels of audit as indicated below and represented in figure 5:

- Level 1 = Walk-through assessment
- Level 2 = General audit
- Level 3 = Detailed

Alajmi (2011) indicates that an energy audit can be conducted at 3 different levels depending on the time, budget constraints, the building complexity, and client requirements.

Level 1

According to Rosenqvist *et al.* (2012), this first-level assessment targets low- or no-cost measures and presents a listing of capital improvements that need to be studied further.

Level 2

Abdelaziz *et al.* (2011) precise the following on energy audit level 2:

The general audit alternatively called a mini-audit, site energy audit or complete site energy audit expands on the preliminary audit described above by collecting more detailed information about facility operation and performing a more detailed evaluation of energy conservation measures identified. Utility bills are collected for a 12–36 months period to allow the auditor to evaluate the facility's energy/demand rate structures, and energy usage profiles. Additional metering of specific energy-consuming systems is often performed to supplement utility data. In-depth interviews with facility operating personnel are conducted to provide a better understanding of major energy-consuming systems as well as insight into variations in daily and annual energy consumption and demand.

Level 3

Still according to Abdelaziz *et al.* (2011):

The detailed audit (alternatively called a comprehensive audit, Investment-grade audit, maxi audit, or technical analysis audit) expands on the general audit described above by providing a dynamic model of energy-use characteristics of both the existing facility and all energy conservation measures identified. The building model is

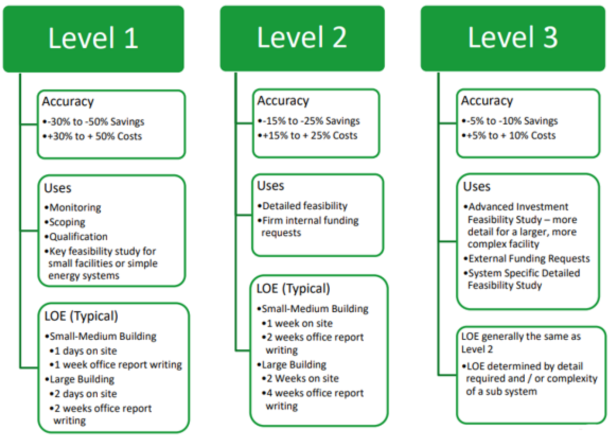


Figure 5: Energy audit levels (ELFARRA, 2019)

calibrated against actual utility data to provide a realistic baseline against which to compute operating savings for proposed measures. Extensive attention is given to understanding not only the operating characteristics of all energy-consuming systems, but also situations that cause load profile variations on short- and longer-term bases (e.g. daily, weekly, monthly, annual). Existing utility data is supplemented with submetering of major energy-consuming systems and monitoring of system operating characteristics.

Auditor's competencies & experience

A successful audit (clear and exhaustive) needs good energy auditors. That's mean energy auditors with the right competencies and experimented.

Shen *et al.* (2012) explain that several countries don't rely only on training to develop auditors but also on certification. France and Finland have already implemented mandatory training and certification requirement to carry out energy audit. By the time of the paper, US is on the way to put in place the same system. Nevertheless, some countries such as China have no official program in which individuals can be certified as energy auditors.

Shen *et al.* (2012) also add:

Without a sound certification or qualification system, the quality of an energy audit cannot be assured (difficulty in convincing enterprises to take certain energy saving measures as their creditability is often questioned)"Without a sound certification or qualification system, the quality of an energy audit cannot be assured. Without the ability to be certified, energy auditors – especially those not affiliated with a professional entity – face difficulty in convincing enterprises to take certain energy- saving measures as their creditability is often questioned. (p.356)

According to Moya *et al.* (2016), energy auditors require intensive training to provide support in the decision-making process about economic investment on energy savings opportunities. Kubule *et al.* (2016) have collected the data from the mandatory energy audit program initiated in Latvia in 2016. Figure 6 from this paper shows that:

In only 18 audits, or 16% of the analysed companies, energy auditors have suggested energy efficiency measures that exceed 10% of the company's total energy consumption. The logical analysis after manual reviewing of the audits indicates that the actual energy efficiency potential in Latvian companies could be much higher. The average technical energy efficiency potential for the companies which have reported an energy audit implementation is 6.35%. Regarding differences between various energy auditors no significant correlation was found for any specific company that would suggest biased results. However, the fact that for such a large share of companies the identified technical energy efficiency potential does not exceed 10% or even 5% of total energy consumption, points to the need to set higher requirements for energy auditors regarding the potential savings to be identified.

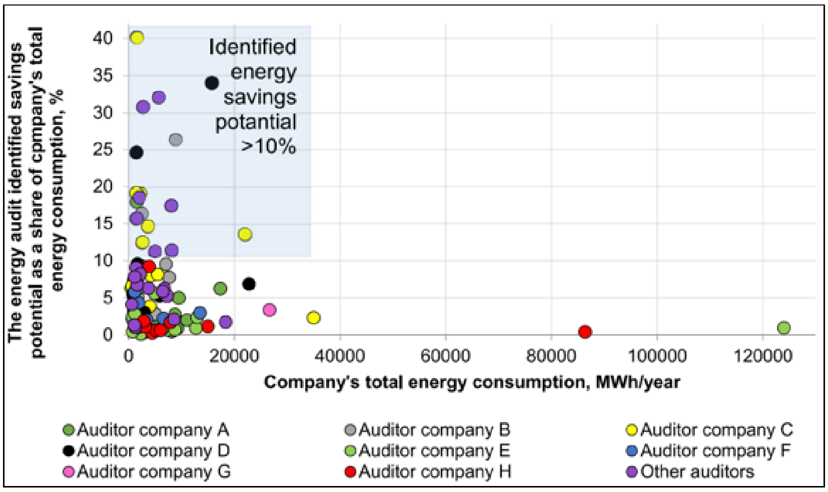


Figure 6: Energy Savings Potential of Industrial Companies Depending On Total Energy Consumption And Energy Auditor Company.

Tools

According to Kluczek & Plazswkoi (2017):

Audits vary widely in their level of detail. Depending on comprehensive audits and the plant's energy profile, various energy audit tools are used. By using a checklist that includes the major areas for energy consumption, an individual can take a baseline measurement, take notes and identify the areas where obvious improvements can be made. Table 4 categorizes auditing tools. Basic energy audits do not require advanced measurements. In most cases information provided on nameplates supplemented with basic measurements are sufficient to perform analysis. Abdelaziz *et al.* (2011) indicate some tools to use to get relevant data for motor (as motor is one of the most consuming elements in industry):

1. Fuel efficiency monitor: This measures oxygen and temperature of the flue gas. Calorific values of common fuels are fed into the microprocessor which calculates the combustion efficiency.
2. Clamp-on power meter: This type of meter helps measure power consumption, current drawn, load factor and power factor. The meter should have a clamp-on

feature to measure current and probes to gauge voltage so that measurements can be recorded without any disruption to normal operation.

3. Leak detectors: Ultrasonic instruments are available which can be used to detect leaks of compressed air and other gases which are normally not possible to detect with human abilities.

4. Portable tachometer: This meter is useful for measuring the speed of the motor. Optical type tachometer is preferable due to the ease of measurement.

5. Thermocouple sensor: Thermometer/thermocouple sensors are useful to measure the temperature of the motor so that level of temperature can be checked whether motor is overheated or not. This will prevent motor failure or damage. Moreover, temperature gain will cause a motor to consume more energy. Knowing temperature allows the auditor to determine motor efficiency. Most commonly used sensors in industry are RTDs and thermistors.

Table 4
Useful tools for energy auditing.

	Energy analysis level		
	Basic	Moderate	Advanced
Hardware	ultrasonic leak detector, pressure gauge, infrared thermometer, contact thermometer, multimeter, ammeter	power logger, pressure logger, infrared camera, ultrasonic clamp flow meter, thermoanemometer, thermohigrometer, factory measurement and data acquisition systems	
Software	–	Standard utility software provided by manufacturers, US DoE auditing software (AIRMaster+, Fan System Assesment Tool, Pumping System Assesment Tool, PHAST, etc.)	Software: Fundamentals of thermodynamics (Computer Aided), heat transfer (Interactive Heat Transfer), own design software to solve advanced, non-standard cases

Figure 7: Useful Tools for Energy Audit (Kluczek & Plazswkoi, 2017)

6. Data logger: Data loggers are used to monitor and log data such as temperatures, motor current, and power. Data loggers are normally portable and can accept different inputs from sensors.

After reviewing the literature, we can consider that it is crucial that the auditors carry out an inventory of the measures already in place, then analyze their relevance and determine the additional measures to be taken. Following these actions, the auditors choose the tools to provide and implement (considering the environment/ constraints).

Energy audit policies

There is a lack in the literature of recent energy audit policies research while this thematic evolute fast due to wars, climate crisis, new technologies etc.

This section makes a focus in the current state in the 3 major countries/areas in the world representing 55% of the world production: USA, China, and Europe. One under development country has also been include in this study to identify the gap between those high developed countries/areas and the rest of the world.

Energy audits should have an important place in the energy policy defined by government around the world (energy efficiency, energy renewable etc.).

Europe energy audit policy

According to Andrei *et al.* (2021):

The Energy Efficiency Directive promotes member states' development of energy efficiency programs to encourage industry to undergo energy audits. The Energy Efficiency Directive from 2018 amended the 2012 Directive to pursue the overall objective of at least 32.5% energy efficiency target by 2030, which is to be achieved collectively across the EU. Brief description of the general types of energy efficiency policy programs implemented in EU member states is presented in Table 1. Schubert *et al.* (2021) argue that:

Energy audits and energy management systems have been identified as helpful means of supporting companies to increase their energy efficiency (Schleich, 2004; Fleiter *et al.*, 2012; Wohlfahrt *et al.*, 2017; Schulze *et al.*, 2016; Kluczek and Olszewski, 2017). Recognizing their potential benefits, the European Commission (EC) has given political support to the implementation of energy audits since 2006 by requiring its Member States to implement "high quality energy audit schemes" under

Examples of energy efficiency programs implemented in EU member states.

Program type	Policy requirements	Reference
Voluntary agreement programs (VAPs)	Mandatory energy audits, energy management certification, sometimes combined with tax exemption/subsidies for energy-intensive companies and SMEs	Price (2005), Bröckl (2014), Johansson (2007), Farla and Blok (2002)
Mandatory energy audit	Mandatory energy audits for large companies	Mundaca and Neij (2010)
Voluntary energy audits	Subsidized energy audits for SMEs	Thollander et al. (2014) Johansson et al. (2019)

Figure 8: Examples of Energy Efficiency Programs Implemented In EU Member State (Andrei *Et Al.*, 2021)

the European Energy Services Directive (ESD, 2006/32/EC) (Art. 12 (1) ESD; EC 2006).

The EC enforced implementation by requiring all Member States to oblige large companies to regularly conduct mandatory energy audits unless they implement an energy management system (Art. 8 (4, 6) EED). Furthermore, the EC requires Member States to encourage their small and medium enterprises (SMEs) to also undergo energy audits.

US energy audit policy

There is a lack of studies in the literature regarding energy audits policy/program in USA. May be due by the fact that USA is a federal country and each state, local entity (e.g., Municipality) has its own regulation.

For Taylor *et al.* (2016), several local governments have implemented energy policies for buildings and linked to energy benchmarking and transparency, and energy audits. The New York City Mayor's Office of Sustainability indicate that:

Local Law 87 (LL87) mandates that buildings over 50,000 gross square feet undergo periodic energy audit and retro-commissioning measures, as part of the Greener, Greater Buildings Plan (GGBP). The intent of this law is to inform building owners of their energy consumption through energy audits, which are surveys and analyses of energy use, and retro-commissioning, the process of ensuring correct equipment installation and performance.

Kontokosta *et al.* (2020) specify that more than 20 cities in the United States, including Austin, Chicago and San Francisco, have adopted energy informational policies in recent years, and the pace of adoption continues to increase

Figure 9 shows the policy details for building for 3 Cities/States (Boston/ Massachusetts; Boulder/Colorado, Edina/Minnesota and Los Angeles/California) from the Institute for Market Transformation (2021).

Jurisdiction	Policy Details		Buildings Included	Requirements				Performance Exemptions	Policy Schedule	
City/State	Policy Name	Year Enacted	Types of Real Estate and Sizes (Sq. Ft.)	Energy Audit (ASHRAE Level I, II, III)	Water Audit	Tune-Up	Retrocommissioning	Description	Upcoming Compliance Date(s) + Applicable Bldgs	Length of Compliance Cycle (Years)
Boston MA	Building Energy Reporting and Disclosure Ordinance (BERDO)	2013	Comm ≥ 35,000 MF ≥ 35,000/35 units All Public/Gov't	Audit OR performance actions required. Actions are significant investment in efficiency, comprehensive energy management plan, or retrocommissioning of energy systems. Bldgs over 50,000 sq. ft. have more stringent requirements.	-	-	Owners can comply by retrocommissioning instead of an audit.	ENERGY STAR score of 75 or above LEED certification Pattern of significant improvement in energy efficiency or greenhouse gas emissions Comprehensive energy management plan	May 15, 2021: Non-residential bldgs 35,000 to 50,000 sq. ft. May 15, 2022: Residential bldgs ≥ 35 units or 35,000 sq. ft. May 15, 2024: Non-residential bldgs ≥ 50,000 sq. ft. May 15, 2025: Residential bldgs ≥ 50 units or 50,000 sq. ft.	5
Boulder CO	Boulder Building Performance Ordinance No. 8071	2015	Comm & MF ≥ 20,000 if built on or before 2014 Public/Gov't ≥ 5,000	ASHRAE Level I for bldgs < 50,000 sq. ft. ASHRAE Level II for bldgs ≥ 50,000 sq. ft.	-	Option for bldgs < 50,000 sq. ft. to participate in Xcel Energy Building Tune-Up Program or meet the RCx scope outlined by the City Manager.	Owners must implement measures with paybacks of two years or less.	ENERGY STAR-certified buildings LEED: O&M certification Demonstrated pattern of significant and consistent efficiency or emissions improvements Equivalent assessment conducted within 10 years and implemented the recommended energy conservation measures Any bldg in a large industrial campus	June 1, 2021: Buildings ≥ 50,000 sq. ft. + bldgs ≥ 10,000 sq. ft. for which the initial permit was issued on or after January 31, 2014 June 1, 2023: bldgs 30,000 to 49,999 sq. ft. June 1, 2025: bldgs 20,000 to 29,999 sq. ft.	10
Edina MN	Efficient Building Benchmarking Ordinance	2019	Comm & MF ≥ 25,000 Public/Gov't ≥ 25,000	Required'	-	-	-	-	June 1, 2022: bldgs ≥ 100,000 sq. ft. June 1, 2023: bldgs 50,000 to 99,999 sq. ft. June 1, 2024: bldgs 25,000 to 49,999 sq. ft.	5
Los Angeles CA	Existing Buildings Energy and Water Efficiency (EBEWE) Program (Ordinance No. 184674)	2017	Comm & MF ≥ 20,000 Public/Gov't ≥ 15,000	ASHRAE Level II	Required	-	Required	Residential hotels, broadcast antennas, vehicle charging stations, utility pumping stations, treatment facilities, sound stages, structures primarily used for the production and post-production of motion pictures and television and similar use. ENERGY STAR certification for the year of the building's compliance due date, or for two of the three years preceding the due date CA-licensed engineer or architect certifies that the energy performance is at least 25% better than the median energy performance of similar buildings, compared to CBECS CA-licensed engineer or architect certifies that the building has reduced its weather normalized source EUI by 15% compared to five years prior The bldg is new and has been occupied for less than five years from its first due date	June 1, 2021: Bldg IDs ending in "0" Dec 1, 2021: Bldg IDs ending in "1" June 1, 2022: Bldg IDs ending in "2" Dec 1, 2022: Bldg IDs ending in "3" June 1, 2023: Bldg IDs ending in "4" Dec 1, 2023: Bldg IDs ending in "5" June 1, 2024: Bldg IDs ending in "6" Dec 1, 2024: Bldg IDs ending in "7" June 1, 2025: Bldg IDs ending in "8" Dec 1, 2025: Bldg IDs ending in "9"	5

Figure 9: Comparison Of U.S. Building Audit, Tune-Ups, And Retrocommissioning Policies (Institute For Market Transformation, 2021)

Energy audit policy in China

According to Shen *et al.* (2012):

Over the last three decades, industrial energy audits in China have gone through different periods.3 The largest and most recent energy auditing program was undertaken during the 11th Five-Year Plan (FYP) (2006–2010). In 2005, the Chinese government announced an ambitious goal of reducing the country's energy intensity, defined as energy use per unit of gross domestic product (GDP), by 20% by 2010. One of the key initiatives for achieving this goal was the Top-1000 program, which was launched in 2006 and targeted the 10084 largest energy-consuming enterprises across nine sectors that each consumed a minimum of 180,000 t of coal equivalent (tce) (or 5268 TJ5) of energy but combined accounted for one-third of China's total energy use and almost half of industrial energy use in 2004 (NDRC, 2006a). To achieve the specific energy-saving targets, Top-1000 enterprises were required to fulfill six sets of tasks, one of which is to perform energy audits and develop energy-saving plans (NDRC, 2006a).6 The mandatory energy audits – which are only required once for each participating enterprise unless they failed to pass the government review – had several components including an analysis of energy consumption throughout the enterprise, an examination of the energy measurement and reporting system, an assessment of the efficiency of equipment operations, an evaluation of energy use indicators of products and production, and a detailed plan for implementing efficiency measures (NDRC, 2006b).

Lack of long-term and concerted policy mechanisms to promote energy auditing:

due to the absence of long-term policy mechanisms and symptomatic of the "campaign-style" approach to regulation and policy-making in China, the use of energy audits ceased when programs ended. The necessity to create a long-term policy mechanism and supporting measures to spur more energy audits in enterprises has not been truly reflected in China's legislative and regulatory efforts.

No evolution has been seen in the China's policy; The figure 10 below is a synthesis from Wang *et al.* (2021) for China and other main countries (The 13 FYP = 2016 - 2020).

Strategic Policy	Main Policy Tools	Country/Region	Literature
Energy Efficiency Directive	Energy audits, Energy efficiency funds, Combined heat and power, Emissions trading.	EU	Bertoldi [32] Malinauskaite [33]
Energy policy act of 2005	Energy efficiency standards, Fuel consumption tax, Carbon taxation.	USA	Metcalf [34] Barbose [35]
5 th Strategic Energy Plan	Emission trading, Energy Service Company, Energy efficiency standards.	Japan	Kucharski [36] Kanada [37]
2010–2019 Plan for Energy Expansion	Utility-funded, Feed-in tariffs, Direct subsidies to renewable power.	Brazil	Geller [38] Aquila [39]
The 13th Five-Year Plan	Reducing excess capacity, Coal resource tax, Emissions trading.	China	Lin [40] Pan [41]

Figure 10: Examples of International Energy Consumption Control Policies

For Voïta (2018):

The objectives of the 12th and 13th FYPs (2011-2015 and 2016-2020) confirmed the new orientation of the 11th FYP (see Table 3). Some of the projects were extended, including for instance the "TOP 1,000" that initially targeted the 1000 biggest energy-consuming companies of the country. It was extended to 10,000 companies in the 12th FYP and then to 30,000 in the 13th FYP.

Topic	12th FYP		13th FYP
	Targets	Results	Targets
Carbon intensity reduction	17%	Target overachieved with a 20% reduction	18%
Energy intensity reduction	16%	Target overachieved with an 18.2% reduction	15%
Energy consumption cap	None	None	5 Gtce/ 3.5 Gtoe
% of non-fossil fuels in primary energy consumption	11.4%	Target overachieved with 12% of non-fossil fuel in primary energy consumption	15%

Figure 11: Energy efficiency related goals of the 12th and 13th FYPs (2011-2015 and 2016-2020)

According to Abdelaziz *et al.* (2011):

In 2005, the Chinese government announced 11th Five-Year Plan and declared a targeted goal of reducing energy consumption per unit of GDP by 20% below 2005 levels by 2010. The government projects that meeting this target would reduce China's greenhouse gas emissions 10% below business as usual; researchers estimate that over 1.5 billion tons of CO2 reductions would be achieved. One of the key programs for realizing this goal is the top-1000 Energy Consuming Enterprises program which was launched in 2006 by The National Development and Reform Commission (NRDC). The energy consumption of these 1000 enterprises accounted for 33% of national and 47% of industrial energy usage in 2004. Activities to be undertaken through this program include benchmarking, energy audits, energy saving action plans, information and training workshops, and annual reporting of energy consumption [2,61,63].

Cases studies

This section includes 3 cases studies of audits carried out on a pharmaceutical industrial site (2019), an industrial food site (2016) and a residential building (2014).

Industrial food site

The industrial site manufactures dry food for dogs and cats. The site produces 72 000 tons of food per year on average and uses electricity and gas. This section contains some parts of the audit: analysis of the electrical consumption and 2 savings actions.

This audit complies with EN16247-1 and 3 energy audit – processes* and makes it possible to meet the energy audit obligation imposed on certain companies by article 8 of directive 2012/27/EC, transposed into law. French by law no. 2013-619 of July 16, 2013, and integrated into the energy code in its Articles L233-1 to L233-4.

Analysis Of Electrical Consumptions

Figure 13 represents the electricity consumption evolution (green bars) with:

•A production indicator (extruded tonnage [t/500]) _ Orange curve

•A climatic indicator (average outside temperature [°C]) _ Bleu curve

Conclusion: There is a dependence of electricity consumption on the tonnage produced. Production Figure 14 is a correlation between electricity and production.

electricity consumption and production. The production increases over the years, so the electricity consumption too.

llation trough the energy
ʒ compressed air, 2 dryers,

Figure 12: Example of Energy Audit Certification

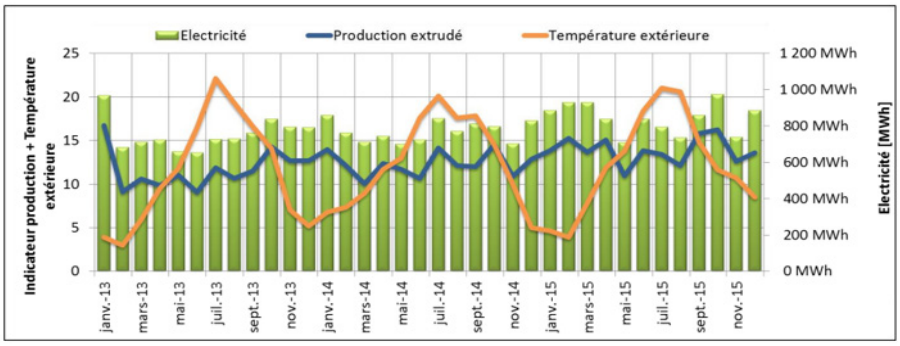


Figure 13: Analysis of Electrical Consumptions

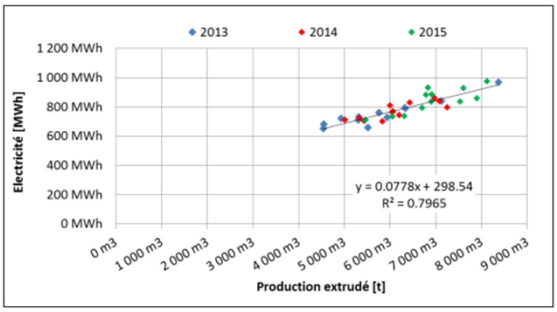


Figure 14: Correlation between electricity and production

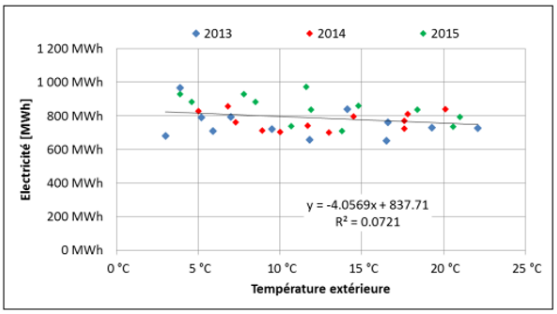


Figure 15: Correlation Between Electricity and Temperature

Temperature

Figure 15 shows the correlation between electricity and temperature. Conclusion: We can see that there is no correlation between power consumption and outside temperature.

Figure 16 contains the elements of the predictive equation for electricity consumption and their influence level (base, production and climate):

Conclusion: We can see that there is no correlation between power consumption and outside temperature.

Correlation factor	2013-2014-2015 Electricity		Influence
0,76	K1 (base)	334 MWh/month	★ ★
	K2 (production)	0.08 MWh/t.month	★ ★ ★
	K3 (climate)	-3.2 MWh/°C	★

Figure 16: Elements of The Predictive Equation For Electricity Consumption

Figure 16 contains the elements of the predictive equation for electricity consumption and their influence level (base, production and climate):

As seen in figure 17, the mathematical model follows well the actual consumption (Green light curve = electrical consumption prediction; Bleu curve = 2013; Red curve = 2014; Dark green curve = 2015).

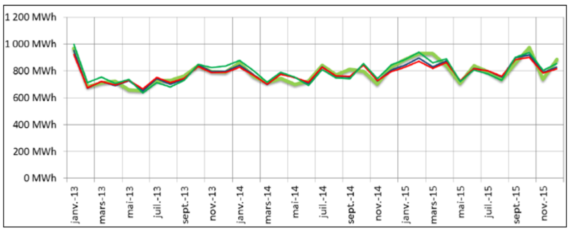


Figure 17: Electrical consumption vs electrical predictive consumption

The predictive indicator corrected for external factors will make it possible to detect real energy degradation and confirm energy improvements.

Saving action on compressed air

The site used electricity to produce compressed air for the functioning of its equipment manufacturing and packaging.

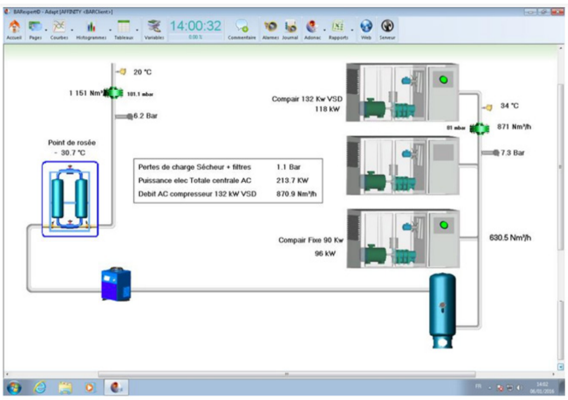


Figure 18: Compressed air installation

A compressed air flowmeter is in place at the exit of the compressed air installation. Figure 19 is a graph representing a period of functioning (for 2 weeks).

Leak rate = 465 Nm3/h (factory closed during the week-end; from 05/06 to 06/12/2015); Maximum flow in production = 1215 Nm3/h ==> 38% of compressed air production is used to fill leaks

Saving action = Carry out a campaign to detect and repair compressed air leaks using an ultrasonic detector once a year. Objective to be achieved: 20%, i.e., a leak rate of

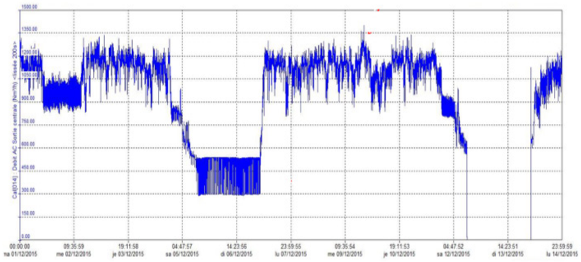


Figure 19: Compressed air consumption for 2 weeks

188 Nm3/h.

Financial saving = 21 k€/year; Environmental saving = 21 TCO2; Payback = 6 months

Saving actions on steam

The site used gas to produce steam for the functioning of its manufacturing equipment.

The site has a steam boiler, as represented in figure 20, that can produce 7000 kg/hour (boiler manufactured in 1978). A stages burner also in place.

The following energy efficiency are already in place (and some implemented after previous energy audit):

- Boiler economizer on fume as shown in figure 21 (to heat feed water by using fumes temperature and thus reduce the amount of energy required to make steam)
- Insulation of boiler and associated pipework
- Supply pumps with variable speed drive (7.5 kW)
- Automatic surface purges based on conductivity probe
- Heat recovery on surface drains for preheating softened water
- Steam traps audit at least every year

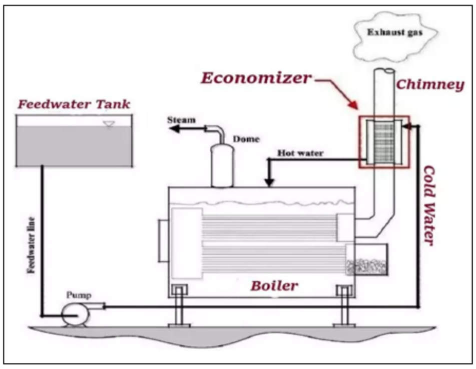


Figure 20: Steam boiler representation

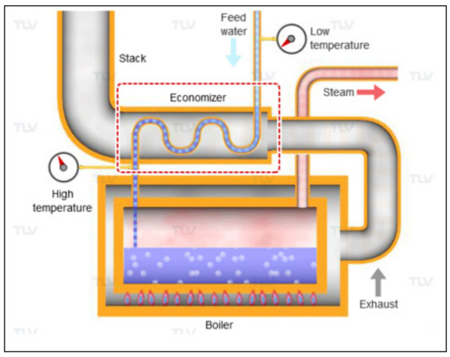


Figure 21: Steam boiler economizer (TLV, 2022)

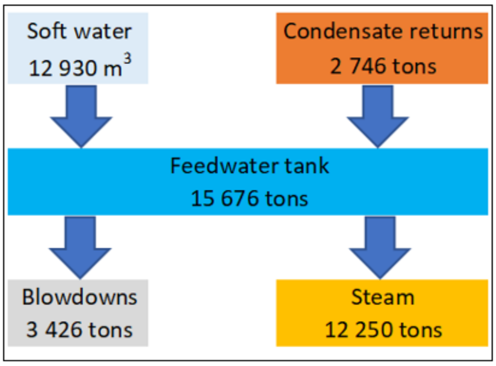


Figure 22: Boiler's mass balance

Figure 22 represents the boiler's mass balance done and estimated from water analyzes (Engin & Ari, 2005): The purge rate is high: 22%. Mainly related to continuous bottom purges of the boiler.

Action = Close the bottom purges bypass (regulation via surface drains and not via continuous leak to reduce TA). The minerals are on the surface. The bottom purges are used only to remove the sludge. Objective: achieve a purge rate of 11%.

The rate of condensate returns is low: 22%. Mainly related to direct steam injection in manufacturing equipment (extrusion and spray).

Action = However, the condensate returns must be brought back to feed water tank from the 3 lines traps on the extrusion side.

Financial saving = 12keuros/year; Environmental saving = 68 CO_2 tons; Payback = 3 months

Industrial Pharmaceutical site

The industrial site manufactures pharmaceutical products. The site uses natural gas to produce steam with 2 boilers (named A & B).

An analysis of the boiler combustion measurement tickets has been done. It shows that the average excess air is around 45.3% on boiler A and 26.1% for boiler B

Excess air λ is calculated from the following formula:

$$\lambda = 1 + O_2 / (21 - O_2) \quad (1)$$

O_2 is the oxygen level present in the fumes. The excess air therefore directly depends on the quantity of O_2 present in the fumes. Excess air can be reduced by reducing the amount of combustion oxygen. This would also improve combustion efficiency, as shown by Siegert's formula:

$$\eta combustion = 100 - f * (Tfumes - Tambiant) \%CO_2 .. (2)$$

- f is a constant (0.47 for natural gas)
- Tambiant is the ambient temperature of the boiler room (20°C)
- Tfumes is flue gas temperature at the boiler outlet (°C)

$\%CO_2$ is directly indicated on the boiler tickets, but it is also calculated as follows:

$$\%CO_2 = \%CO_2MAX * (21 - O_2) / 21 \quad (3)$$

The %CO2max is equal to 11.9% for natural gas. This equation clearly shows that by reducing the amount of oxidizing O2, and therefore the excess air, the combustion efficiency can be increased.

Action = Installation of a new micro-modulating burner on boiler A and acting on the regulation of O2. A 10% excess air is considered optimal.

Which means: A rate of O2 in the fumes equal to 1.91%; A CO2 rate in the fumes equal to 10.8%; A combustion efficiency equal to 92.74%, an increase of more than 1.3% compared to the current average (91.4%).

Financial saving = 5,1 k€; Environmental saving = 29,4 CO2 tons; Payback = 10,8 years

Residential building

The entire residence is made up of 46 apartments and a basement with cellars. These accommodations are spread over 5 levels.

One of action done during the energy audit of this residential building is the infrared thermography.

Why use infrared thermography (Lucchi, 2017; Çay, 2018)?

It is the discipline that makes it possible to measure, remotely and without contact, the temperature of an object or surface from these infrared emissions thanks to a camera. It is a very effective way to diagnose the condition of a building, the lack or fault of thermal insulation, thermal bridges. Inside a building, we therefore look for the coldest areas. Outside a building, the hottest areas.

Figures 23, 24 and 25 represent some defaults captured during the infrared thermography.

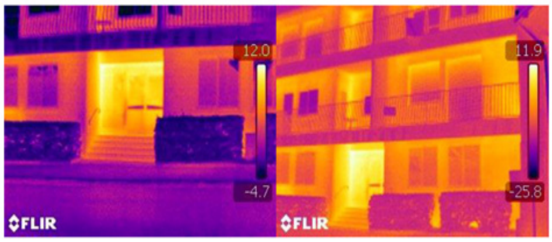


Figure 23: Heat losses in the entrance halls (heated)

Figure 24: Lack of airtightness on joinery

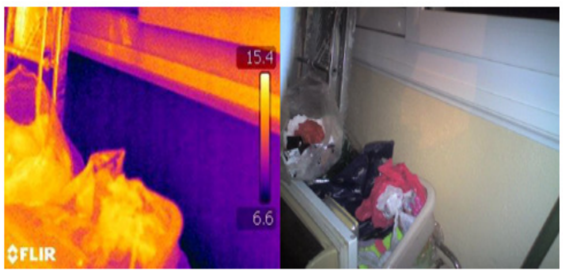


Figure 25: Heat loss from uninsulated walls

Figure 26 summarizes the savings, cost, and payback for the interior wall insulation.

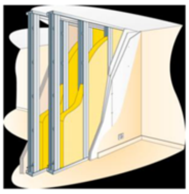
INSULATION			
Work to do	Comments		
Interior wall insulation	Insulation from inside the walls with the removal of the existing partition, the installation of a glass wool type insulation with a thickness of 12 cm. A BA13 partition is then installed. Price estimate does not take into account the movement of appliances (electrical outlets, plumbing, etc.). 		
Consumption item	Heating		
Consumption before modification (per year)	Consumption in kWh	Consumption %	
	573 531	82	
Modification cost and payback	in €	Payback	
	379 906	16	
Savings after modification (per year)	in kWh	in €	in CO2 tons
	265 491	23 868	62,12

Figure 26: Interior wall insulation

Figure 27 summarizes the savings, cost, and payback for windows and doors joinery replacement.

WINDOWS AND DOORS			
Work to do	Comments		
Replacement of single-glazed wood joinery with double-glazed PVC joinery	Joinery double glazing PVC with argon gas and a heat transfer convection coefficient of 1.3 W/m²K. Warning : Changing the joinery on a dwelling systematically requires a review of the air renewal system. 		
Consumption item	Heater		
Consumption before modification (per year)	Consumption in kWh	Consumption %	
	573 531	82	
Modification cost and payback	in €	Payback	
	189 056	23	
Savings after modification (per year)	in kWh	in €	in CO2 tons
	91 489	8 225	21,41

Figure 27: Windows and Door Joinery Replacement

Barriers and Challenges

Training

Training is one of the current barriers on energy audit. Without proper training and training policies, energy audit success is at risk.

Training is one of the current barriers on energy audit. Without proper training and training policies, energy audit success is at risk.

According to Moya *et al.* (2016):

While effective tools are necessary in the conduction of energy audit techniques, auditors also need to have proper training to use them in an efficient way. Energy Auditors require intensive training to provide support in the decision-making process about economic investment on energy savings opportunities [30]. In Ecuador, institutions offering special training in energy auditing techniques are basically universities and the Ministry of Renewable Energy. However, this training is not nationally organised and supported by energy policies.

More qualified energy auditors are required in order to increase energy auditing. Nevertheless, this is a responsibility of Government and Technical Institutions. This lack is provoked by universities when they include the energy audit techniques only as a topic of energy efficiency and, not as a deep understanding of these techniques in graduates. The recommendation is that Technical Institutions, supported by Universities and Government, create programs to encourage more qualified energy auditors.

Shen *et al.* (2012) also indicate the following on this subject: Increased capacity in energy auditing could start with the development of effective training programs at both national and provincial levels. Trainings need to be organized on a regular basis and should provide system-wide and component specific trainings to enterprise energy managers, staff of provincial energy conservation centers, and energy audit professionals.

In all training programs, trainees should be taught about technical options, economic/financial feasibility, and the use of assessment tools. In addition, improving staff skills on energy management and on the use of proper auditing devices should also be part of the training scheme.

To improve its effectiveness, energy audit training should be linked directly to the job requirements and performance evaluation of enterprise energy managers, Furthermore, to assure the quality of energy auditing, China could consider of developing a certification or qualification scheme for energy audit professionals.

Opportunities

Specific energy maintenance program and reliability

Maintenance program and reliability (also named operation and maintenance "O&M) can greatly contribute to energy efficiency.

Focus should be made on maintenance operations and management during energy audits (Alajmi, 2011).

According to Sullivan *et al.* (2010):

Effective O&M is one of the most cost-effective methods for ensuring reliability, safety, and energy efficiency. Inadequate maintenance of energy-using systems is a major cause of energy waste in both the Federal Government and the private sector. Energy losses from steam, water and air leaks, uninsulated lines, maladjusted or inoperable controls, and other losses from poor maintenance are often considerable. Good maintenance practices can generate substantial energy savings and should be considered a resource. Moreover, improvements to facility maintenance programs can often be accomplished immediately and at a relatively low cost.

Energy software: Monitoring, predictive etc.

There is also a lack in the literature on the use of energy software while it has several benefits:

- Support to perform audits
- Monitor the effectiveness of the actions that have been implemented

- Make consumption predictions
- Etc.

Zhu (2006) argues that:

In general, energy auditing has been an effective tool that can assist facility managers to develop their energy saving plans and to achieve their energy saving goals [e.g., 4,8–12]. However, many existing energy auditing approaches may overlook the intricate relationships between different factors that will affect the energy consumption of a large facility [e.g., 10,13], and the cross-effect that two or more different solutions may result in. Therefore, a more effective validation tool is needed to fine-tune the results from an energy auditing process. Computer-based simulation is accepted by many studies as a tool for evaluating building energy

Mandatory implementation of actions

It would be interesting to go further on energy audit policies. Indeed, the implementation by governments of a percentage of savings to reach following any energy audit would be a plus (Hasanbeigi & Price, 2010). Too often, organizations do not have an obligation to apply the actions identified. Obviously, this obligation will have to be propositional to the size of the organization.

Another opportunity identified: The establishment of an investment threshold on energy efficiency or renewable energy projects according to the sales of the organization. If it is this rule is not followed, a fine will be raised toward the organizations by the governments.

Renewable energy

During energy audits, there is currently a lack regarding renewable energy. Often, there is no specific section on renewable energies, or it is not detailed enough. It is imperative to focus on the organization's renewable energy potential (Jayakumar, 2022) and not just focus on energy efficiency. Example: Area available for installing solar panels? Possible wind turbine sizes in relation to regulatory constraints? Space available for the installation of a Biomass boiler?

10.6 ISO 50002

ISO 50002 specifies the basic requirements for the implementation of an energy audit. It is a norm in addition to the ISO 50001 for the implementation of an energy management system. Unfortunately, this standard is not enough widespread. ISO50002 requirement are basic but efficient and a good start. Communication should be improved on this standard trough for example energy policy. Like this it will be more taken into consideration by internal and external auditors/organizations.

Additional element to review during energy audit

The elements below should be reviewed during the energy audit:

• Site has an automated energy monitoring and targeting system in place and in use for all major energy consumers, using individual meters on electricity, steam, water & nitrogen.

• Each utility-including HVAC, compressed air, and refrigeration- and each production line has a target/forecast energy usage.

• Energy consumption is checked daily and reported to the committee direction weekly.

• All significant energy deviations are investigated.

• Ownership of consumption and investigation of deviations is evident at all levels of the organization and in all areas.

• Idle equipment and idle buildings are powered down when not in use, subject to EHS & Quality requirements.

• All capital project proposals are reviewed for energy efficiency.

• Variable speed drives are installed on all variable load compressors on compressed air, nitrogen generation and refrigeration systems.

• The electrical power factor is > 0.95.

Water audit

According to Barrington et Ho (2014), water auditing is an analytical tool which quantifies water flows and quality within a predefined boundary. The water audit is the counterpart of the energy audit. There are similarities between the 2 methodologies/approaches. Studies should be carried out on these 2 methodologies and to make a connection to enrich these 2 methodologies/approaches.

CONCLUSION

This paper highlights, through an extensive literature review and cases studies, current benefits, challenges, and opportunities on energy audit.

Energy audit when well defined, supported and deployed can be a powerful lever to reach neutral or zero carbon emission.

Cases studies of this paper show it is judicious to carry out regular energy audits because of the savings significant identified.

Regarding barriers:

A common policy around the world should be put in place progressively to remove this barrier. There are currently too many differences between countries and continents. Other barriers have been identified and discussed such as training and certification on energy audit.

A list of opportunities has been established to improve energy audit starting from training to water energy. Those opportunities should be subject to specific research.

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