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Resource efficiency audits: methodology development and application to pilots

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Abstract

The study highlights the essential role of resource audits in connecting energy, water, and material efficiency strategies. Thus, by establishing a comprehensive evaluation framework, the proposed methodology facilitates the implementation of effective resource management measures, enhancing industrial competitiveness, sustainability, and alignment with environmental and economic objectives. The methodology was also applied through on-site pilot resource audits, validating its effectiveness, and confirmed the importance of accurate measurements to quantify key performance indicators (KPIs). A total of thirteen enterprises were audited, comprising four non-SMEs (Small and Medium Sized Enterprises) and nine SMEs in four Countries. The pilot audits allowed to fully assess the associated savings' potential, the willingness of companies to implement the proposed efficiency measures, as well as the identification of key improvement points and recommendations.

1. INTRODUCTION

The potential for energy efficiency improvements in organisations is substantial, with the International Energy Agency (IEA, 2015) estimating that up to 25% could be achieved simply by encouraging behavioural changes and motivating investment in efficiency projects. A thorough understanding of organisational behaviour and decision-making is crucial, as decision-makers consider a broad spectrum of factors - ranging from financial imperatives and policy obligations to environmental commitments and internal recognition of savings opportunities. Furthermore, management commitment is essential in fostering an energy culture, which not only drives enduring behavioural change but also supports greater profitability, waste reduction, and compliance with regulations. However, investments in energy efficiency are often subject to the 'energy efficiency paradox' (Banks et al., 2012), where they demand unusually high returns due to perceived risks and a lack of strategic focus, making the visibility of resource consumption and strategic value critical in influencing investment decisions. Also, strategic considerations and non-energy benefits play a pivotal role in energy efficiency investment decisions (Cooremans & Schönenberger, 2019). Larger, energy-intensive organisations are more likely to act on efficiency opportunities, while those in public-facing sectors respond to reputational (Banks et al., 2012). Thus, decision-making models highlight that external, organisational, individual, and investment-specific factors all influence the investment process, gradually moving firms towards routine efficiency improvements. Moreover, non-energy benefits, as improved public image, regulatory compliance, and operational efficiencies, are increasingly recognised as vital for elevating the strategic importance of energy efficiency, especially in sectors where cost savings alone are insufficient (Banks et al., 2012).

On the other hand, resource efficiency audits have the capacity to boost the implementation of energy, water and materials efficiency measures, therefore increasing the companies' competitiveness and diminishing the uncertainties of externalities. Commonly, as audits are only 'energy driven', the potential to address other benefits and combine strategies between energy, water and materials efficiency is mainly neglected. This limits the opportunities for continuous improvement, not only in energy management but also in areas such as water availability, waste and wastewater reduction, CO_2

emissions reduction, maintenance cost optimization, and enhancement of working conditions, among others. Therefore, well-established key performance indicators (KPIs) and thorough resource audits can effectively quantify these benefits, offering reliable, data-driven justification for strategic investments and the adoption of recommended initiatives (Cooremans, 2012; Rasmussen, 2017).

The work presented introduced a novel resource audit methodology designed to align companies' operations with circular economy principles while promoting more efficient production processes and delivering environmental benefits. Also, by testing the model into pilot resource audits it was possible to: (1) understand which were the points that need to be improved, (2) verify the methodology viability, and (3) better understand the decision-making behaviour factors in enterprises, through direct interviews/surveys to top management and resource management technical staff.

Additionally, this methodology can be effectively integrated within the Energy Efficiency Directive (EC, 2023). Specifically, the article 11 is focused on energy management systems and energy audits and encourage the implementation of mechanism to measure the multiple benefits of energy efficiency, including resources efficiency. The mechanism of energy audits is mature in the EU Member States, hence the proposed methodology can be adapted to the national legislative frameworks.

2. LITERATURE REVIEW

2.1. Resource efficiency

According to the United Nations Environment Programme (UNEP & UNIDO, 2010), resource efficiency concerns the managing of raw materials, energy, and water along the value chain to minimize waste and detrimental impacts on the ecosystems throughout the entire lifecycle of production. Therefore, this will mean a careful selection of raw materials and energy resources; minimization of waste, emissions, hazards, and risks; responsible management of material and energy flows during the production process; accomplishment of a function, task, process or result with the minimal possible amount of water; and attention to the use, recycling, and disposal phases of the product life cycle (Cardoso, Fernandes, et al., 2022). This becomes even more significant given the consistent global trend of increasing resource use (UNEP & IRP, 2024).

Resource efficiency has been on the European Union's (EU) agenda for more than a decade. In 2015, the Commission issued its first Circular Economy Action Plan (EC, 2015), comprising measures to establish the supporting regulatory framework and policy orientation, allocate EU funding and monitor the EU's transition to a circular economy. In 2020, in response to the European Green Deal, the Commission issued a new action plan (EC, 2020), building on the previous one and setting an aspirational target of doubling the EU's share of material recycled and fed back into the economy by 2030. Lately, in February 2023, the Commission published its Green Deal Industrial Plan, which refers to the Circular Economy Action Plan in connection with their shared aim of setting the framework for the transformation of the EU's industry for the net-zero age. Moreover, since at least 2010 the Commission has been adopting a

broad range of strategies, directives and roadmaps focusing on the promoting of resource efficiency and circular-economy principles, as the 2011 ‘Resource Efficient Europe’ flagship initiative, a roadmap to make economic growth sustainable by decoupling it from the use of resources (European Court of Auditors, 2023).

Moreover, as in the OECD (Organisation for Economic Co-operation and Development) report on Resource-Efficient and Circular Economy (OECD, 2024), resource monitoring is essential to design effective sustainability policies, as reliable information and consistent data are crucial. Considering this, resource audits may facilitate a smooth transition to a circular economy by providing information on progress in public policies and sustainability programmes, and by promoting more efficient production processes, higher quality products, and maximised gains at the enterprise level.

In practical terms, resource audits can contribute to cost reduction by identifying efficiency measures that lower operational expenses; enhance competitiveness through the optimisation of production processes; provide strategic support for defining new processes and fostering innovation; facilitate the transition to a circular economy by quantifying resource flows; and enable concrete actions to reduce resources surpluses, by implementing the efficiency measures highlighted during the audit. Nonetheless, achieving this requires the establishment of adequate resource KPIs that provide a reliable foundation for informed decision-making and the implementation of efficiency measures, all supported by robust data (OECD, 2024).

However, the integration of resource efficiency within the common energy audit procedures implies the need to adequately define KPIs, capable of creating a basis for decision making and efficiency measures implementation, supported by solid data. In this sense, despite the numerous examples of KPIs linked to resource efficiency collected during the literature review performed (Cardoso, Fernandes, et al., 2022), it was not possible to find adequate literature, that collected indicators related to the multiple dimensions of resource efficiency (namely water, materials, and water-energy nexus) in an integrated way. Thus, previously a set of KPIs was proposed, using data collectable during an audit procedure, or that is already systematized within the companies’ legal or voluntary requirements (e.g., ISO standards, environmental licensing, etc.), that served as the basis for the assessment framework developed (Cardoso, Faia, et al., 2022).

The present work aims to address the resource audit for the companies with an approach that can be easily integrated in the current internal procedures and aligned with the European regulatory framework. Hence, the methodology is inspired in the decennial experience on the development of methodologies, standards and policies based on energy audits. Energy audits are demonstrated to be effective to trigger investments in energy efficiency in different countries such as United States (Anderson & Newell, 2004), China (Bai et al., 2015; Kostka et al., 2013), Australia (Redmond & Walker, 2016), Germany (Fleiter et al., 2012) or Sweden (Backlund & Thollander, 2015). The obligation of energy audits for large companies was introduced in 2012 in EU the Energy Efficiency Directive (Bruni et al., 2021) but it has been also successfully extended to the SMEs as an effective tool to enhance EE (Kalantzis & Revoltella, 2019).

Despite of the importance of the energy audits and the maturity of the policy mechanisms (Bertoldi, 2001), there are still important challenges in the harmonization and homogenization approaches between countries (Andersson et al., 2017; Claus et al., 2025; Johnsson et al., 2025; Martini et al., 2025), the limited integration with energy management systems (Dickemann, 2025) and the still reduced digitalization of the audits (Qing et al., 2026). Several efforts have been carried out in order to enhance the energy audits including other aspects such as process flexibility (Tristán et al., 2020), water consumption (Mamade et al., 2014) and gaseous emissions (Chen et al., 2023a).

Obviously, resource audit presents points in common with the environmental audits (Hillary, 1998), with the EMAS certification (Eco-Management and Audit Scheme) (Castelluccio et al., 2025), and with the Life-Cycle Analyses (Yun Zhang et al., 2016) that require information on energy efficiency, emissions, water consumption, waste management, etc. These voluntary schemes aim to enhance environmental and operational performance and obtain specific certifications required by the market (Iraldo et al., 2009). Additionally, resource efficiency is directly linked to material efficiency and circular economy concepts (Allwood et al., 2011; Lieder & Rashid, 2016). However, the resource audit must be intended as a report with a systematic procedure to analyze the use of the different natural resources in a production site, identifying and quantifying opportunities for cost-effective savings. This procedure should be aligned with the energy efficiency audit standards (i.e. ISO 16247), that provide specific details in the auditing analysis, economic analysis (i.e. EN 17463). Additionally, every country presents specific requirements to the energy auditor. A resource audit can serve as an internal decision-support document, while also being used for compliance purposes.

The link between energy and resource efficiency is usually analyzed under the ‘multiple benefits of energy efficiency’ umbrella (IEA, 2015). The more established taxonomy of multiple benefits (or non-energy benefits or co-benefits) include five categories: production, operation and maintenance, waste, emissions, working environment, and others (Killip et al., 2019; Nehler et al., 2014; Trianni et al., 2014; Worrell et al., 2003). The water-energy nexus has been also extensively studied and specific auditing schemes have been proposed at industrial level for water (Walsh et al., 2017) and steam (Niemeyer et al., 2023) consumption, at urban system level (Lenzi et al., 2013), and the energy management of integrated water systems (da Silveira & Mata-Lima, 2020).

The constant evolution of the energy efficiency policies encourage the development of a holistic approach to energy efficiency, adapting the regulation to internal and external situations and encouraging to link energy efficiency with the resource, water and other environmental topics (von Malmborg, 2024). The implementation of multiple and mixed policies is required to achieve the climate and energy targets in the European Union (Wiese et al., 2018), being necessary to tailor the policies at national level to the sectors and agents involved in the decarbonization process (Cocker, 2025). Two countries present specific resource efficiency programmes in industry: China and Germany.

In China, the System of Accountability Audit of Natural Resource (AANR) and the Cleaner Production Audits (CPAs) on Chinese manufacturing firms' total factor energy efficiency (TFEE) are two

mechanisms to increase the natural resource efficiency. On the one hand, the AANR is focused on treating pollution and improving air quality, monitoring the emissions at regional level (Yalian Zhang et al., 2023). On the other hand, the CPAs aim to increase the efficiency of the enterprises supporting the reduction of air pollution (Chen et al., 2023a) and the implementation of green technologies (Chen et al., 2023b).

The 'Federal Funding Scheme for Energy and Resource Efficiency in the Economy' (EEE) is a flagship programme that supports German enterprises in the green transition. In the past five years, more than 55,000 projects have been funded with 2.9 bEUR to improve energy and resource efficiency in six modules. Since 2021, the Module 4 of EEE programme specifically target resource efficiency, applying a life cycle assessment (LCA) approach. The greenhouse gases (GHG) savings due to reduction and/or substitution of materials are evaluated by using material-specific CO_2 conversion factors (Neusel & Hirzel, 2025). The cement, metal (stainless steel, iron, aluminium and copper), paper and plastics industries presents a high GHG reduction potential due to material and water efficiency (Weinert et al., 2024). Despite of the exemplar German EEE programme, the development of resource efficiency policies is still in an embryonic phase in most of the EU countries (Wilts & O'Brien, 2019), and usually uncoupled from energy efficiency (Bahn-Walkowiak & Wilts, 2017).

Previously to the present proposal of comprehensive resource efficiency, two similar resource audit pilot experiences have been identified. On the one hand, (Cutaia et al., 2020) presented a operational methodology, for the audit of resources at the company level, with the aim to boost resource efficiency, improving economic and environmental performance. This methodology operates both internally, by means of an efficiency increase and processes optimization, and externally, proposing industrial symbiosis collaborations at local level with local enterprises.

On the other hand, a CEN Workshop Agreement (CWA) was developed in European-funded project was developed a methodology to measure and improve the resource efficiency of resource intensive processes (CWA 17185, 2017). The procedure is focused on the use of optimization tools with five different indicators by specific 'operation unit' (OU – i.e. kg, m^3, etc.): Unit material cost [kg/OU], Direct Primary Energy Consumption [kJ/OU], Gross Water Use [m^3/OU], Net Water Use [m^3/OU], and, Resource Exergy Indicator [kJ/OU]. This methodology requires important modelling and optimization efforts to be implemented, and it was successful tested in three demo sites in fertilizer, petrochemical and in refining industries (Radatz et al., 2019).

2.2. Decision-making behaviour factors in enterprises

As the International Energy Agency (IEA) stated in its Workshop Report Influencing Business Behaviour and Decision Making to Improve Energy Efficiency (IEA, 2015) a better understanding of behaviour and decision making in organisations could contribute to the development of more effective policies and programmes and help accelerate the implementation of energy efficiency improvements. Moreover, decision-makers weigh a wide range of factors in deciding among efficiency alternatives, and not all involve economic benefit and costs. These factors may be: (i) financial imperatives; (ii) policy obligations

(namely, to achieve environmental compliance); (iii) acknowledgement of savings opportunities within the company; (iv) commitment to environment protection and energy efficiency. However, there are key aspects that should be considered. The information shared should be both aligned with the decision-makers expectations (describing the costs and benefits of the efficiency opportunities), as well as provided within an adequate timing, to maximise the likelihood of receiving positive investment decision. Also, the top management commitment is vital since early stages, engaging company executives and decision makers and providing explicit endorsement to the goal of improving energy (and other resources) efficiency (Blass et al., 2014). The establishment of an 'energy culture' (or efficiency culture) will drive long-lasting behaviour changes within the company and needs to be guided from the top-down.

This is also addressed by (Oksman et al., 2021) that consider essential the energy culture within the industrial sector, that has the potential to result in profitability increase, waste reduction, energy consumption reduction, cost savings, reduced paybacks, better public image, and support in complying with various regulations. The pillars of this energy culture are described as: (i) awareness of technologies; (ii) cultural aspects; (iii) current energy practices; (iv) external factors (e.g. community thinking, EU and national regulatory framework in place); and (v) effect and perception of barriers (that should be identified and mapped).

The support of all the energy efficiency value chain is crucial to support decision, particularly in SMEs: technological partners (manufacturers, technology suppliers, installers and ESCOs), financial bodies and public entities. Under this perspective, the energy audits that involve non-energy benefits are a crucial tool to support the decision making process (Trianni et al., 2016).

However, there are other factors apart from an energy culture of an enterprise that can influence their investments in efficiency. The 'energy efficiency paradox' shows that investments in energy efficiency appear to require remarkably high rates of return, sometimes much higher than other investments with comparable risks (Banks et al., 2012). The reasons for this include, among others: risk perception; unwillingness to replace equipment before end-of-life; and energy efficiency not being a strategic issue. In fact, the strategic value of energy efficiency (conferring competitive advantage) may be the key influence on whether investment in efficiency will take place rather than profitability, but energy (and other resources) consumption is often found to be invisible to the top management. Therefore, making energy (and other resources) use visible is an important first step. This is also stated by (Cooremans & Schönenberger, 2019) that considers that empirically, energy efficiency investments are considered as non-strategic or only moderately strategic. At the same time, profitability has a significant role in the decision-making process, although not a decisive one, and the most strategic investments are selected.

Nonetheless, the judgement of what constitutes a 'strategic' investment involve qualitative assessment, subjectivity and a view on the organisation's purpose. According to (Banks et al., 2012), the strategic value of energy efficiency is linked to the size of the organisation, its energy intensity and sector. The motivations to adopt a strategy vary, and different motivations can lead to different types of strategy being adopted. In terms of size, larger organisations are more bureaucratic and hierarchical which can

lead to principal-agent problems, as facilities staff tend to be distant in the hierarchy from the senior managers setting the strategic direction of the organisation. Conversely, larger companies tend to have more strategy, time and capacity to act on energy issues and are more responsive to issues affecting their public image – including their performance on energy and environmental issues. Furthermore, the more energy intensive the sector is the more energy efficiency opportunities are noticed and acted upon (e.g., the extent to which energy audits are used is linked to the energy intensity of the sector). Also, energy consumption is more salient in sectors which trade directly with the public such as retailers, driven by the need to maintain brand and reputation.

So, the strategic character of an investment should be considered during the decision-making investment process, as it is presented by (Cooremans, 2012). The proposed investment decision-making model shows the investment process in five steps: (1) initial idea; (2) diagnosis; (3) build up solutions; (4) evaluation & choice; and (5) implementation. It is also stressed that external factors (organisations' environment), organisational factors/internal context (structure, strategy and culture), individual factors (actors) and investment characteristics (type, scope and strategic character) are all affecting the decision-making process. The idea behind these life cycle decision-making models is that firms over time will move from a state where no energy-efficiency decisions are made towards a steady state where the firms are said to routinely seek for new energy-efficiency investments to invest in.

Finally, it is noteworthy to mention that the non-energy benefits of energy efficiency are deemed critical to raise the strategic value of energy efficiency. This is particularly relevant in non-energy intensive sectors, such as commercial offices, where cost savings from improved efficiency will not make a significant difference to the organisation's cost base (Banks et al., 2012). Also, by defining and categorising non-energy benefits according to their level of quantifiability and time frame, they can be included in the decision-making process at several stages and altogether increase the probability for adopting energy efficiency investments. Hence, the concepts of non-energy benefits and investment behaviour can be integrated and thereby contribute to improved energy efficiency (Rasmussen, 2017). Moreover, energy efficiency investments are likely to become strategic if they contribute to operational and safety issues (Cagno et al., 2026) or core business, which implies considering non-energy benefits of energy efficiency investment projects (Cooremans, 2012).

This concept is easily applied to the development of a resource audit methodology, as non-energy benefits will be taken into consideration when evaluating the company's performance. In fact, the KPIs defined will assist the quantification of non-energy benefits, namely, contributing to the comparison of resource consumption levels, and creating a basis supported by data, that will help efficiency investment choices and recommended measures implementation.

3. METHODOLOGY

3.1. Resource audits assessment framework

The first step of a resource audit is to set up an initial meeting to clearly define the audit's boundaries, engaging from the beginning all relevant staff, including top management. During this meeting, the overall methodology of the resource efficiency audit and its process should be presented, the person responsible for supporting the auditors nominated, and a pre-audit questionnaire requesting specific information from the organization shared. This first contact with the audited company is also a valuable opportunity to start to assess the barriers and drivers to resource audits implementation, as well as factors influencing companies' willingness to implement efficiency measures. Afterwards, site visits will be performed during which the auditing team will collect information required for calculating the resource efficiency KPIs.

The set of defined KPIs will be applied across different evaluation levels (D to A), acknowledging that they may not be equally applicable to all companies and sectors. With this configuration, enterprises may advance as the KPIs match to their own specific case and/or as they have data available or a specific interest. These KPIs enable the accurate quantification of potential energy, water and materials savings per year, while also supporting the proposal of tailored efficiency measures for each enterprise. Moreover, KPIs leverage existing data, using information collectable during an audit procedure, or that is already available and systematized within the companies' legal or voluntary requirements. The scenario that corresponds to the level D evaluation can be applied to most of the economic sectors and this evaluation level could be sufficient for some economic sectors or companies, even if higher evaluation levels are technically applicable.

Following the fieldwork, a report summarizing the collected data and treated information (namely, efficiency measures identified and potential resource savings) is elaborated. Finally, a closing meeting with the technical staff involved, as well as the top management, is scheduled to convey all the key points of the audit performed. Additionally, during the closing meeting (or immediately before) a survey is administered to the top management and resource management technical staff involved, to evaluate their decision-making factors and in what measure the resource audit performed influenced them.

Table 1 presents the set of KPIs according to the evaluation level where they can be applied, where P.U corresponds to 'production units'.

Table 1
Evaluation levels and KPIs

Evaluation level	KPI
Level D	Energy intensity [kWh/€]
	Carbon intensity [t CO_{2e}/kWh]
	Energy specific consumption [kWh/P.U.]
	Renewable energy production [%]
	Total water consumption [m^3]
	Water consumption per GVA [m^3/€]
	Water productivity [€/m^3]
	Water costs in the total costs incurred [%]
	Waste valorization rate [%]
Level C	Water consumption/employee [m^3/employee]
	Materials productivity [€/P.U.]
Level B	Byproducts in production process [%]
	Materials specific consumption [kg/P.U.]
	Water specific consumption [m^3/P.U.]
	Water specific cost [€/P.U.]
	Energy specific cost resulting from the use of water [€/m^3]
	Specific cost of water delivered [€/m^3]
	Energy specific consumption from the water use [kWh/m^3]
Level A	Alternative water sources used [%]
	Wastewater treated and reused [%]

3.2. Pilot resource audits relevance and selection

The implementation of pilot cases to apply the developed resource audit methodology was fundamental to understand which elements required adjustment, refinement or adaptation, and for verifying the overall feasibility of the methodology. A pilot case validates the assumptions made, collecting feedback from a real operational context, and identifying technical or operational issues. It is an important step to refine and strengthen the proposed methodology, demonstrating its value and benefits and making it

more robust for future applications. This pilot resource audits were performed by four energy agencies: EIHP (Energetski Institut Hrvoje Požar) from Croatia, CRES (Center for Renewable Energy Sources) from Greece, EWA (Energy and Water Agency) from Malta, and ADENE (Portuguese Energy Agency) from Portugal.

Firstly, it was necessary to proceed with the selection of pilot companies to be studied. This comprised two main points: (1) selection of the economic sectors to be covered and (2) identification of suitable companies within these sectors. Concerning the selection of the economic sectors, this was undertaken by each pilot partner, considering at national level: (1) the resource intensity of the sector; (2) its economic relevance; and (3) the possibility of collecting reliable data. Additionally, it was determined that at least one activity sector would be common across all countries (the food sector), and that each country would cover a maximum of three economic sectors and a minimum of three pilot companies.

After this, the pilot partners composed a short-list of suitable companies within each activity sector, ensuring the inclusion of both small and medium enterprises (SMEs) and non-SMEs. Moreover, to determine whether the pre-selected companies were suitable to be pilot cases within the framework of the project, a short survey consisting of simple yes/no questions was set up to assess if the data available from each of the pre-selected companies was adequate to proceed with the application of the resource audit methodology. This pre-screening activity was intended to assist in selecting the most adequate case studies, while simultaneously engaging the companies from the outset of the process. Furthermore, the companies' readiness and commitment to provide the required data and collaborate fully with auditors throughout the entire audit process were considered. The selected case studies were divided into the following economic sectors per country, as presented in Table 2.

Table 2
Economic sectors covered per country

Country	Food sector	Textile	Ceramics & Glass	Hospitality	Paper
Croatia	x	x	x		
Greece	x				x
Malta	x			X	
Portugal	x	x	x		

EIHP (Croatia) conducted three resource audits (one non-SME and two SMEs), focusing on the ceramics, textile, and food sectors; CRES (Greece) conducted three resource audits (all SMEs), focusing on the paper and food sectors; EWA (Malta) conducted three resource audits (all SMEs), focusing on the hospitality and food sectors; and ADENE (Portugal) conducted four resource audits (three non-SMEs and one SME), focusing on the ceramics, glass, textile, and food sectors. A total of 13 enterprises were audited, comprising 4 non-SMEs and 9 SMEs.

4. RESULTS

4.1. Decision-making behaviour factors in enterprises

A significant portion of the pilot resource audits was dedicated to gaining a better understanding of the types of factors, that could directly or indirectly influence companies in implementing resource efficiency audits. Therefore, during the resource audit initial meeting a set of three brief questions was posed:

1. Which barriers do you consider most relevant to resource audits implementation?
2. Which drivers do you consider most relevant to resource audits implementation?
3. Which are the factors that may boost the companies' willingness to implement efficiency measures?

Regarding the first two questions, Table 3 shows that the drivers and barriers identified by the audited companies can be categorised as either economic or organisational. This is consistent with the factors influencing companies' behaviour and decision-making identified in the International Energy Agency Workshop Report 2025 (IEA, 2015), namely: (i) financial imperatives; (ii) policy obligations; (iii) recognition of savings opportunities within the company; and (iv) commitment to environmental protection and energy efficiency, as well as the strategic need for top management support.

Table 3
Barriers and drivers to resource audits implementation

Economical	**Barriers**	**Drivers**
	High investment	**Financing programmes**
	Efficiency measures cost	**Fiscal incentives**
	Payback time	**Audit added value**
	Uncertainty of savings	**Cost savings**
	Lack of financial support and incentives	**Client request**
Organizational	Lack of human resources	Strategic investment
	Integration with other obligations (namely, legal)	Alignment with sustainability goals
		Top management support

Additionally, the analysis of the responses regarding the implementation of efficiency measures, as presented in Table 4 below, indicates alignment with the previously identified drivers.

Table 4
Factors to boost efficiency measures implementation

Factors	Description
Process optimisation / operation time reduction	Streamlining processes and reducing the time required for operations, leading to increased productivity and efficiency.
Resource savings	Minimising the use of energy, water, and raw materials, which can result in cost savings and support sustainability objectives.
Environmental awareness / green image benefits	Enhancing the organisation's reputation by demonstrating commitment to environmental responsibility and sustainable practices.
Improved competitiveness	Gaining a competitive edge by adopting efficient practices, which can lead to reduced costs and a stronger market position.
Legal requirements	Ensuring compliance with relevant regulations and standards related to resource efficiency and environmental protection.
Cost reduction	Lowering operational expenses through efficiency measures and optimised resource use.

After the resource audit report was completed, a final survey was shared with the audited companies. This survey was divided into three main sections: (1) sustainability and efficiency goals; (2) the project; and (3) pilot resource audits. The main objectives of this final survey were to understand the companies' sustainability policies and targets, as well as the actual impact of the project and pilot resource audits carried out.

Regarding the responses related to the companies' sustainability policy, nine of the audited companies reported having an established policy, while one indicated a policy was in development. All respondents had defined targets for energy, water, and environmental dimensions, with half also outlining objectives for materials use or waste reduction. Additionally, all but two companies intended to increase their sustainability goals; one company did not anticipate any changes, and another remained undecided.

Concerning the support required to optimise the achievement of established goals, the primary areas of focus and their descriptions are outlined in Table 5, and essentially comprise a set of advisory, capacity building and financial support measures.

Table 5
Types of necessary support identified by the companies

Type of support	Description
Subsidies/Grants	Financial support to help cover the costs of implementing sustainability measures and resource efficiency improvements.
Collaborative projects	Participation in joint initiatives with other companies, research institutions, or public bodies. This collaboration can facilitate knowledge sharing, access to best practices, and collective problem-solving.
Tax reduction	Fiscal incentives such as reduced taxes or tax credits for companies that invest in sustainability and efficiency. These incentives can improve the financial viability of resource efficiency projects.
Training	Capacity building for staff and management on sustainability practices, resource efficiency methodologies, and behavioural change. Training can include workshops, seminars, or tailored courses to address specific needs.
Tailored advisory services	Personalised consultancy to help companies identify opportunities, design strategies, and implement efficiency measures. Advisory services may include audits, technical support, and guidance on regulatory compliance.

On the other hand, addressing the answers regarding the project and pilot resource audits, among the audited pilot companies, five have previously considered conducting a resource audit, which indicates a growing interest in comprehensive approaches to resource efficiency. These companies identified several factors that discouraged them from undertaking these audits, namely: the resistance to change within the organization; lack of support or regulatory requirements; financial constraints limiting investment capacity; lack of awareness about the benefits and processes; limited technological options available; and perceived complexity of the audit process.

However, after the pilot resource audit was conducted, the companies did not perceive the audit process as time-consuming, as only one found the data requirements extensive. The audits generally met expectations, although two companies considered them too complex. Regarding the implementation of the identified efficiency measures, the audited companies expressed their willingness to implement at least one of the efficiency measures identified during the audit. However, one company indicated it was too early to decide on implementation.

In conclusion, while there is a positive attitude towards efficiency improvements, overcoming barriers such as resistance to change, financial limitations, and perceived complexity remains essential for broader adoption of resource efficiency practices.

In addition, the survey incorporated a series of quantitative questions that required companies to assess the impact of the pilot resource audits using a scale from 1 to 5, where 1 corresponds to ‘not increase at all’ and 5 corresponds to ‘highly increased’. It should be emphasised that, of the 13 audited companies, not all provided a quantitative response to the questions posed, stating that it was still ‘too early’ to assess the full impact of the pilot resource audits in these areas.

Figure 1 summarises companies perceived impacts of the pilot resource audits, indicating an overall positive influence across several strategic dimensions, despite the early stage of implementation for some companies. Respondents reported increased efforts towards sustainability objectives and a stronger willingness to adopt integrated approaches to resource efficiency.

The audits were perceived as especially effective in enhancing knowledge and awareness of energy and water efficiency practices, while impacts related to materials efficiency were more limited. A similar pattern emerged in terms of willingness to act, with companies showing a higher inclination to implement energy efficiency measures compared to water and materials-related actions. In addition, the pilot audits improved companies' understanding of the integrated resource audit concept and increased their interest in pursuing further support through the project or similar initiatives.

5. DISCUSSION

5.1. Main constraints encountered during the pilot resource audits

During the application of the developed methodology, some barriers and difficulties were encountered. However, these were not perceived in the same way by all pilot partners. Overall, issues relating to data confidentiality and availability were consistently reported. Additionally, constraints in quantifying savings due to process complexity and limited sector-specific expertise - particularly regarding the water and materials components - within the audit team were also noted. While resource audits were generally perceived as valuable, they were also regarded as resource-intensive in terms of skills and experience requirements.

A significant hurdle identified by the pilot partners was the low level of engagement from some of the selected companies, despite the efforts to adequately identify the pilot companies. This was exacerbated by the fragmented organisational responsibilities observed in companies, where energy, water, maintenance, and finance were managed by separate departments, without a centralized system for data collection and storage. Additionally, some audits were conducted during the summer period, which further contributed to the challenge. These primary constraints and challenges are outlined in Table 6 below.

Table 6
Main constraints identified during the pilot resource audits

Constraint/Challenge	Description
Data confidentiality	Restrictions on sharing certain type of information, as detailed cost data or the company's gross value added.
Process complexity	Processes demand deep sector-specific knowledge to interpret and assess system interactions. Lack of harmonised cross-sector referential to facilitate benchmarking activities.
Limited sector specific expertise	
Low engagement level	Available human resources directed toward core business operations (particularly in small companies).
Strategic prioritization	
Fragmented responsibilities	Data dispersed across departments. Lack of a centralised system for data collection and storage.
Data availability	

5.2. Improvement points and recommendations

In general, the pilot resource audits validated the resource audit methodology developed. The development of pilot cases was crucial to evaluate which points needed to be adjusted, refined, or adapted, as well as to verify the methodology viability. The pilot resource audits performed validated the assumptions made, collecting feedback from a real context, and identifying technical and/or operational issues. This was an important step to perfect and improve the methodology proposed, demonstrating its values and benefits, and making it more robust to face future challenges.

Hence, it was confirmed that pre-audit questionnaires and early audit preparation – namely, regarding data requests – as well as structured planning and preparation, are fundamental to a successful audit. This should be complemented by an adequate definition of the audit scope during the initial meeting with the audited company.

Regarding the audited dimensions, as previously expected, it was more challenging to obtain reliable and robust information on water and materials flows, as in some cases, no data was available. Consequently, without information on consumption, efficiency measures and savings are general estimates. Therefore, the implementation of a metering and monitoring system should be considered the first step to promote efficiency in these areas.

Thus, considering the constraints encountered during the implementation of the pilot resource audits, as well as the factors previously identified, some improvement points and recommendations have been identified and summarized in Table 7.

Table 7
Improvement points and recommendations

Improvement point	Recommendations
Data confidentiality	Sign non-disclosure and/or confidentiality agreements early in the process to reassure companies and formalise data protection. Implement anonymisation or aggregation techniques so companies can provide data without disclosing sensitive details. Communicate clearly how data will be used, emphasising compliance with GDPR and project guidelines.
Process complexity	Create sector specific resource audit methodologies, including a summary of the processes, typical consumption patterns, and benchmark KPIs.
Limited sector specific expertise	Strengthen sector specific auditor training, particularly for water and materials flows, where knowledge is more limited. Consider implementing a centralised repository of audit examples, typical measures, and KPI references by sector.
Low engagement level	Plan audit steps around production schedules to avoid high-activity periods (e.g., summer for certain sectors). Highlight quick wins early on to build motivation and demonstrate immediate value. Ensure top-management involvement from the start.
Strategic prioritization	Frame audit benefits in strategic terms, emphasising cost reduction, compliance, competitiveness, and risk mitigation. Identify (if available) supporting mechanisms (technical or financial) to implement the identified efficiency measures. Connect efficiency measures to corporate sustainability goals. Use payback-based prioritisation, presenting both low-cost and strategic long-term actions. Organize awareness campaigns, workshops, and training sessions to increase understanding of the benefits and processes of integrated resource audits.
Fragmented responsibilities	Identify a single focal point at the initial meeting to coordinate internally, clearly assign responsibilities and encourage cross-department meetings Recommend companies to develop a centralised digital data repository.
Data availability	Promote the installation of basic metering as a first step. Train companies on maintaining better records and recommend digitalisation of monitoring data. Establish mechanisms for monitoring the implementation of efficiency measures.

Improvement point	Recommendations
Financial supporting mechanisms	Develop and promote targeted financial instruments such as grants, subsidies, or low-interest loans specifically for resource efficiency projects.

6. CONCLUSIONS AND FUTURE WORK

Resource efficiency audits have the capacity to boost the implementation of energy, water and materials efficiency measures, reducing the use of energy, water, and raw materials, and therefore increasing the companies' competitiveness and diminishing the uncertainties of externalities. The quantification of these audits' potential savings is fundamental, and its starting point should be the definition of suitable KPIs, capable of creating a basis for decision making and efficiency measures implementation, supported by solid data. Consequently, a resource audit methodology and framework were developed, to correctly assist with the quantification of the set KPIs.

In this context, the development of pilot resource audits was crucial for refining and validating this methodology, namely by identifying areas for improvement and confirming its feasibility in real-world settings. The first step involved selecting both the economic sectors and companies for study, with each country choosing sectors based on resource intensity, economic importance, and data reliability. Each country audited at least three companies across up to three sectors, ensuring that the food sector was included in all countries for comparability. Also, companies were shortlisted to ensure a mix of SMEs and non-SMEs, as well as assessed their ability and willingness to provide necessary data. In total, 13 enterprises were audited across Croatia, Greece, Malta, and Portugal, covering sectors such as food, textiles, ceramics, glass, hospitality, and paper, ensuring broad representation and robust methodology testing.

Concerning the decision-making factors influencing enterprises in implementing resource efficiency audits and the identified efficiency measures, these were evaluated through an initial short questionnaire presented to the enterprises during the audit's initial meeting, as well as a through a final survey, shared with the enterprise's personnel involved, after the resource audit report was completed. Initially, enterprises identified two sets of main barriers to the implementation of resource audits: (i) economic (e.g., investment cost, payback time, financial support) and (ii) organisational (e.g., limited human resources, legal obligations). Furthermore, key factors for companies to implement efficiency measures included process optimisation, resource savings, environmental reputation, competitiveness, legal compliance, and cost reduction. On the other hand, the final survey results showed that most enterprises had already established sustainability policies and targets, particularly for energy, water, and environmental dimensions. Also, companies expressed a need for support in the form of subsidies, collaborative projects, tax incentives, training, and tailored advisory services to help achieve their sustainability goals and implement the identified efficiency measures. Prior to the pilot resource audits, some companies hesitated to conduct resource audits due to resistance to change, financial and regulatory limitations, lack of awareness, and perceived process complexity. Post-audit feedback was

more positive, with most companies expressing willingness to implement at least one recommended efficiency measure, though some still cited early stage of decision-making. Quantitative survey responses suggested that the pilot resource audits increased companies' efforts toward sustainability, awareness of resource efficiency concepts, and willingness to pursue further resource efficiency actions.

It should be noted that, during the implementation of resource audits, some barriers and difficulties were encountered, although not all partners perceived these in the same manner. Common challenges included concerns regarding data confidentiality and availability, difficulties in quantifying potential savings due to complex processes, and a lack of sector-specific expertise - especially for water and materials. Overall, resource audits were seen as valuable but required considerable skills and experience. Additionally, some obstacles arose from the audited companies themselves, such as low engagement, fragmented responsibilities across departments that hindered data collection, and audits coinciding with challenging periods such as summer.

In conclusion, the pilot resource audits conducted confirmed the effectiveness of the developed resource audit methodology, highlighting the importance of thorough preparation. Obtaining reliable data - especially for water and materials dimensions - proved challenging, underlining the need for metering and monitoring systems as a foundation for efficiency improvements. Several key improvement points and recommendations were identified, including: (i) ensuring data confidentiality through agreements and anonymisation; (ii) developing sector-specific methodologies and auditor training; (iii) scheduling audits to maximise engagement; (iv) framing audit benefits strategically, highlighting non-energy benefits to raise the perceived value of efficiency measures; (v) assigning clear responsibilities; (vi) promoting digital data management; and (vii) expanding access to targeted financial support mechanisms such as grants and low-interest loans. Collectively, these actions can enhance the scalability, effectiveness and long-term impact of integrated resource efficiency audits. Lastly, the present methodology can be easily integrated in the national transposition of the EED in the different European countries.

Declarations

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Author Contribution

A.C, V.F, I.P, C.H, C.T, C.M wrote the main manuscript textA.B.V, G.G, I.G, V.K, M.A provided information and data to write the main manuscript textA.C, P.C, J.F, E.B reviewed the manuscript

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Figures

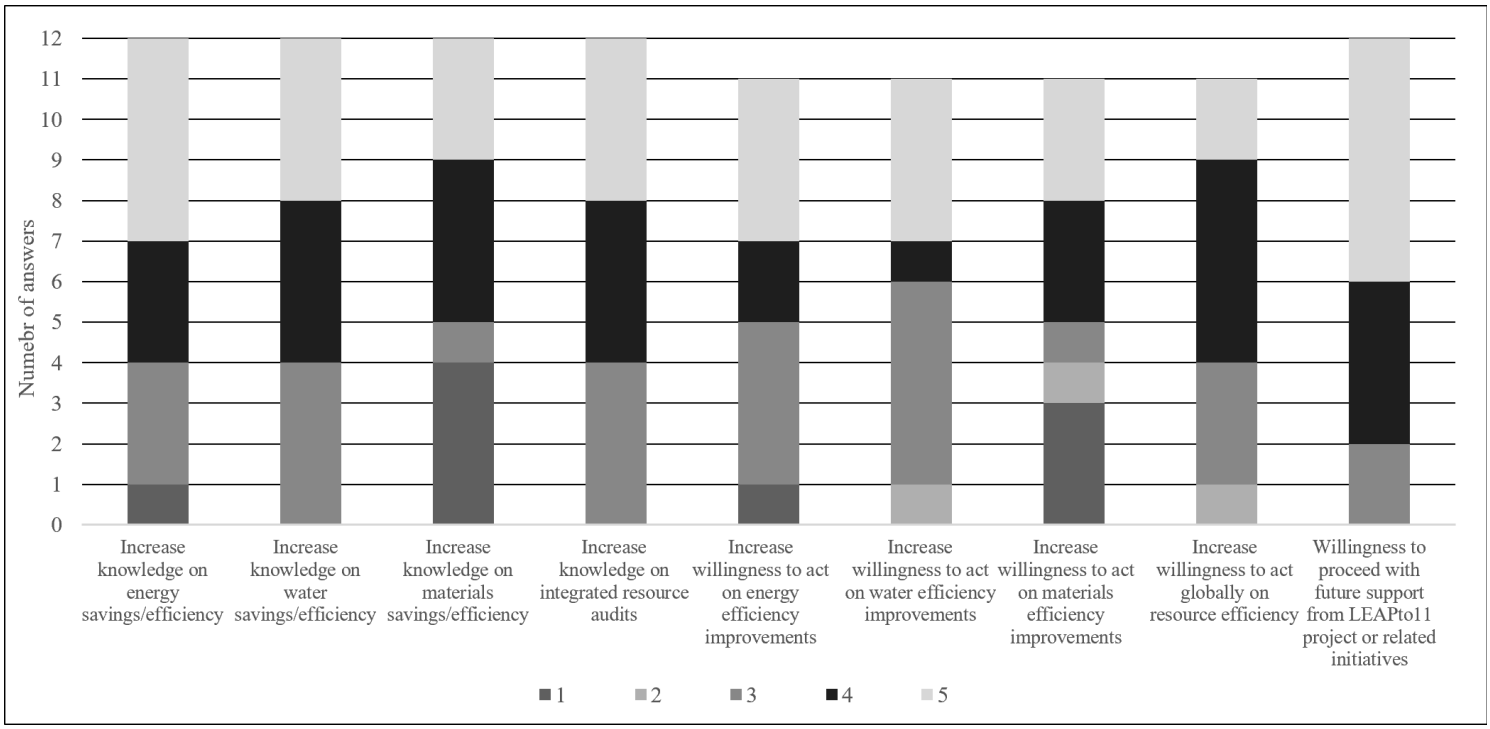


Figure 1

Perceived impact of pilot resource audits on companies' awareness, willingness to act, and strategic orientation towards integrated resource efficiency. The figure summarises companies' self-assessed perceptions, measured on a five-point scale (1 = not increased at all; 5 = highly increased).