Uncertainty evaluation of EnPIs in industrial applications as a key factor in setting improvement actions

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Abstract. A methodology is proposed assuming high-level Energy Performance Indicators (EnPIs) uncertainty as quantitative indicator of the evolution of an Energy Management System (EMS). Motivations leading to the selection of the EnPIs, uncertainty evaluation techniques and criteria supporting decision-making are discussed, in order to plan and pursue reliable measures for energy performance improvement. In this paper, problems, priorities, operative possibilities and reachable improvement limits are examined, starting from the measurement uncertainty assessment.
Two different industrial cases are analysed with reference to the following aspects: absence/presence of energy management policy and action plans; responsibility level for the energy issues; employees' training and motivation in respect of the energy problems; absence/presence of adequate infrastructures for monitoring and sharing of energy information; level of standardization and integration of methods and procedures linked to the energy activities; economic and financial resources for the improvement of energy efficiency.
A critic and comparative analysis of the obtained results is realized. The methodology, experimentally validated, allows developing useful considerations for effective, realistic and economically feasible improvement plans, depending on the specific situation. Recursive application of the methodology allows getting reliable and resolved assessment of the EMS status, also in dynamic industrial contexts.
Keywords. Energy Management System (EMS), Energy Performance Indicators (EnPIs), measurement uncertainty, energy saving, targeting.

1. Introduction

Energy management requires a systematic and continuous approach, whose final goal is using energy as efficiently and effectively as possible.

Companies often make simply isolated attempts to reduce consumptions, rather than adopt a systemic approach to the problem; even when the organizations intend to face the problem in a systematic way, it is not easy for them to self-assess their possibilities for improvement [1].

The International standard ISO 50001:2011 [2] provides a framework of requirements for organizations to develop a policy for: more efficient use of energy, fix targets and objectives to meet the policy, use data to better understand and make decisions about energy use, measure the results, review how well the policy works, and continually improve energy management.

Although the process-based PDCA (Plan-Do-Check-Act) methodology still holds, the general requirements and procedures are not particularly focused on how an organization can understand and quantitatively assess its current position within this operating path to reach the targets. Being aware of the position of an organization in the operating sequence for the implementation of an Energy Management System (EMS) allows identifying and reaching strategic objectives more effectively and efficiently.

In literature, some approaches to evaluate the maturity in the energy management field exist. Carbon Trust [3] presents two tools that organizations can use to self-assess their performance across the areas of energy: the Energy management matrix [4], helping organizations assessing their strengths and weaknesses across the evaluation of six areas of energy management (policy, organizing, training, performance measurement, management); the Energy Management Assessment (EMA) tool, providing a more comprehensive and detailed self-assessment. Both consist of a simple quantitative evaluation, based on a numerical assignment to different areas examined in a range of values. Other approaches can be found, at different levels of complexity [5-8]; they are all based on qualitative evaluations of different aspects and even quantitative analysis are always based on a judgment: therefore, these assessments are inevitably characterized by elements of subjectivity.

Furthermore, even pushing the analysis at a major level of detail, the resolution of these methods is often insufficient. As a matter of fact, by means of these approaches, the ability of distinguishing little but useful improvements along the growing and progressive path of an EMS development, is strongly limited.

Usually, the energy performance is evaluated through different Energy Performance Indicators (EnPIs), which are general or depending on the specific situation examined [9]. The uncertainty evaluation of EnPIs becomes relevant to its own ability to represent correctly the aspects of interest for the scenario considered, even though just a few cases can be found in literature, where the role of the raw data uncertainty is stressed [10].

The uncertainty evaluation of the indicators is not a trivial task, especially if they are aggregate: if so, many aspects should be carefully considered. In other words, when high-level aggregate EnPIs have to be evaluated, also productive, organizational and plant aspects and features should be taken into account, and considered among the others.

The EnPIs uncertainty assume characteristic interest also for further needs and motivations, summed up as follows:

- Reliability of information:

The EnPI uncertainty is directly linked to the accuracy of the information carried out by the indicator itself. In this sense, the EnPIs uncertainty and its monitoring can be intended as a part of the data check procedure, useful to assure adequacy of data to provide reliable information.

- Tailoring the actions, since each context has its own peculiarity:

Carrying out the EnPIs uncertainty analysis and setting up actions supporting its reduction leads to a deeper understanding and knowledge of the processes under control, allowing focusing on the specific improvement action, which depends on the specific context analysed.

- Dynamic, changing and variable industrial operating contexts:

Measurement uncertainty of physical quantities of interest for the evaluation of the EnPIs strictly depends on the specific situation and it changes, if the conditions to be examined change. As a consequence, the EnPIs uncertainty involves and brings with itself also the dynamic aspects of the scenarios examined.

Only an EMS which is carried out in a complete and comprehensive manner allows a deeper knowledge able to consider all these factors, singularly and in their mutual interactions. In this sense, the EMS development path seems to support strategies for uncertainty reduction. Therefore, assuming the uncertainty as a quantitative parameter to take a picture of the current status of the inherent activities, appears interesting and promising. In fact, the EnPI uncertainty involves the information about quality and amount of actions realized to build and maintain the EMS, being the EnPI one of the possible indirect measurement of the EMS itself.

In authors' opinion, measurement methodologies and uncertainty analysis are able to return reliable information about improvement actions even if their application is referred to different situations (i.e. different industrial scenarios), at different levels of awareness, and in different stages of progress in the implementation of an energy management system. Since the actions related to an EMS are general, systematic and systemic (i.e. they are not carried out according to a spot approach focused on single machine), they require a widespread managerial ability.

In this paper, in order to endorse the systematic approach of an EMS, high-level synthetic and enough meaningful EnPIs will be considered. The possibility to evaluate their uncertainty will be studied in order to get a quantitative parameter (the EnPI uncertainty) able to return:

- the position the company achieved along the EMS life-cycle;
- a support to the designing of action plans for energy improvement depending on the definition of intervention capability;
- the reliability of the improvement actions with respect to the predicted targets.

In this way, a more resolved and accurate method could be set, aiming to overcome a mere classification into development levels.

In summary, any decision making process based on measured EnPIs could be compromised if uncertainty on EnPI is too large. The level of confidence of the decision making process depends on the weight of uncertainty on EnPI relative to the target improvement in EnPI which one aims to achieve.

Section 2 describes the methodology proposed and the industrial contexts analysed in order to test the methodology. The opportunities deriving from the test cases analysed are also discussed. Section 3 shows the obtained results with reference to the actual situations examined. Considerations of practical interest are discussed and proposed. Conclusions and future works end the paper and show also some perspectives in order to develop the concept discussed in this paper.

2. Methodology

The methodology provides for the use of the EnPI uncertainty as an indicator of:

- level of awareness of issues and opportunities linked to the development of an EMS, in the specific situation;
- ability to set the strategies referred to the energy efficiency improvement and to the evaluation of the action effectiveness;
- energy saving that can be guaranteed in advance, in relation to a pre-defined improvement target.

In particular, the proposed methodology pivots on two main conceptual steps (figure 1):

1. Step 1: EnPI identification

   The selection of the EnPI is based on its information capability and synthesis, meaningfulness and accuracy. These characteristics will assure that it will represent exhaustively the energy processes it is called to indicate. Many energy contributions should be included, in order to have a more accurate indicator providing the possibility to take into account wide ranges of actions for energy performance improvement.
2. Step 2: EnPI uncertainty evaluation in terms of standard deviation.

   The relationship in equation (1) is the simple criterion used to assess if the predicted percentage energy saving (t%, in the following) can be guaranteed on the basis of the percentage EnPI uncertainty (u(EnPI)%, in the following) which is based on the current experimental data.

$$u(EnPI)\% \leq t\% \tag{1}$$

The criterion in (1) is in accord with the common practice [11] assuming the standard deviation value, as detectability threshold.

If condition (1) is positively fulfilled, and if the action has been already defined, it is suggested that the decision-maker adopts the measure for energy savings. Else, any improvement actions to reduce measurement uncertainty should be considered. Once these latter are carried out, then the uncertainty of the selected EnPI should be evaluated again (step 2) and the flow in figure 1 repeated.

If the action has not been defined, a target according to the detectability criterion in (1) can be set. The relationship in (2), aims to provide a conceptual idea of the size of the improvement action to be carried out, in order to let the same EnPI show the target is reached (being equal the other conditions):

$$t\% = u(EnPI)\% \qquad (2)$$

The technical and economic feasibility of the action should be checked (according to the specific energy policy). If the technical and economic feasibility is confirmed, it is suggested that the decision-maker adopt the measure for energy savings. Else, any measure to reduce the EnPI uncertainty should be set, and the cycle (starting from step 2) of figure 1 begins again.

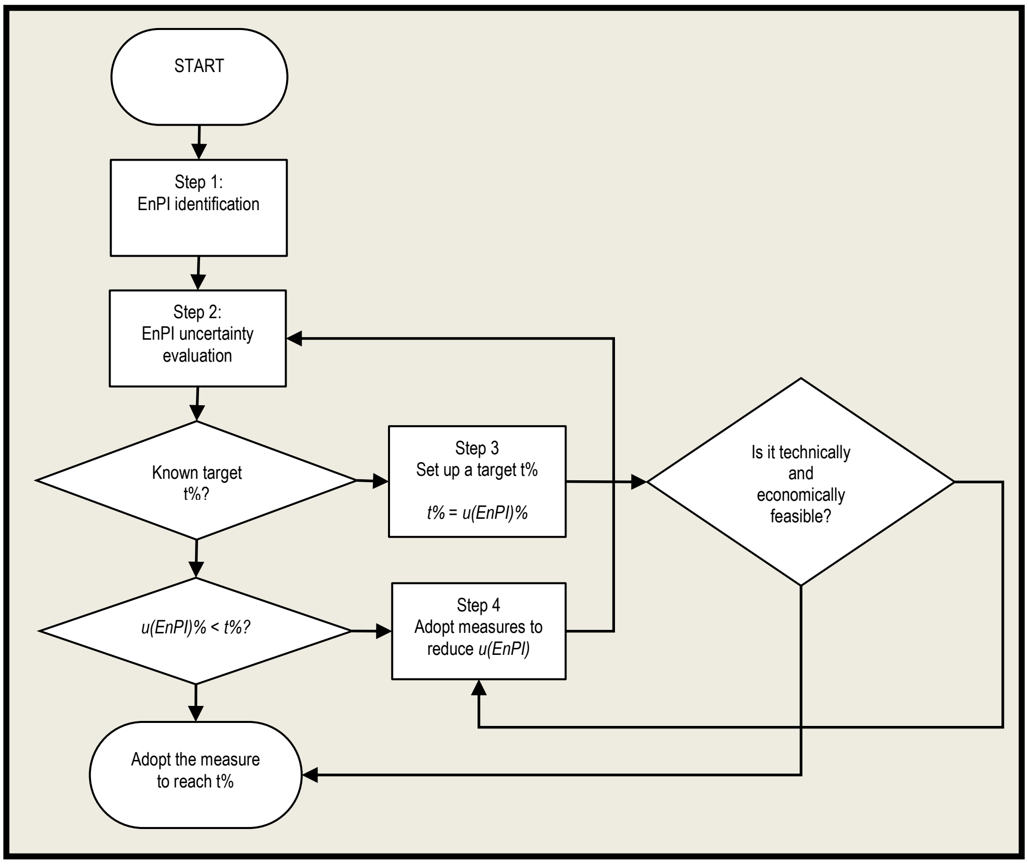

Figure 1. Methodology flow diagram

In order to verify generality and effectiveness of the methodology proposed, this latter is applied to two industrial cases, different for level of awareness in energy management and measurement issues. The differences between the two situations (named "Test case A" and "Test case B", in the following) are qualitatively highlighted using the Energy management matrix [4], able to establish a starting point for the analysis.

The test case A consists in the production of carbon fibre components for avionic industry. The main part of production process from an energetic point of view consists of certified thermal curing in autoclave.

The main utilities referred to the whole plant can be summarized as follows: autoclaves, air compressors connected to the autoclaves, industrial CNC cutting plotters, devices for mechanical treatments, refrigerating cells for Pre-preg components storage, lighting network, ventilation unit for clean room air supply.

Meters for gas, electrical power and water are available only with reference to the whole plant. There are also measuring instruments for process control with manual data recording.

A part of the recorded data is not electronically stored but it is available only on paper.

The test case B consists in the production of small plastic components through injection moulding.

The main utilities referred to the plant section involved in the analysis can be summarized as follows: injection moulding machines, chillers for mould cooling, evaporation towers and pumps for fluid handling.

Meters for electrical power are available with reference to each utility involved in the analysis, with automatic data acquisition and recording. There are also measuring instruments for process control with automatic data recording. All these data are stored in shared databases.

Further aspects to be highlighted are the following:

- formal energy management policy, but not continuously active commitment from top management;
- presence of an energy manager leading an interdepartmental team;
- diffusion of energy performance results (monthly meetings, posters, specific reports,…).

With reference to the above-mentioned situations, the Energy management matrix can be filled showing framework according to table1. For clarity is recalled that the minimum value is 0 and the maximum is 4.

Table 1. Energy management matrix for Test-case A and Test-case B

Energy management matrix		
	Test-case “A”	Test-case “B”
Energy management policy	1	3
Organizing	1	2
Staff motivation	0	2
Tracking, monitoring and reporting systems	0	3
Staff awareness/training and promotion	1	2
Investment	1	2

Table 1 underlines that the examined cases are quite different as for the current status of each company’s effort in implementing and developing an EMS. This could be useful also to test the proposed methodology with reference to different situations.

3. Results

Depending on the different level of awareness, data accuracy is a key-factor in setting the improvement actions and reaching the related targets. In fact, depending on the specific situation, paths, solutions and quality of the obtained results are different.

According to the methodology described in section 2, the EnPIs chosen for the analysis are described.

3.1. Methodology application - Step1: EnPI identification

3.1.1. Test case A

Specific Energy Consumption (SEC) is defined as follows:

$$SEC = \frac{E}{P} \tag{3}$$

where E is the total energy consumption [kWh] and P is the number of pieces produced. Both quantities refer to the same time interval. Generally this indicator is synthetic, meaningful and accurate, provided that the energy processes it is called to indicate are satisfactorily monitored. It is usually considered for energy performance evaluations [9,12].

3.1.2. Test case B

Energy per Working Hour (EWH) is defined as follows:

$$EWH = \frac{E_m}{\sum_i h_i} \qquad (4)$$

where E_m is the energy consumption of moulding plant section [kWh] and h_i are the machines working hours. Both quantities refer to the same time interval. This indicator is significant for test case B because the process is time-driven, the machines are general purpose and the produced components are similar one to each other.

3.2. Methodology application - Cycle 1

3.2.1. Test Case A

As for the Test case A, figure 2, as an example, shows the normalized SEC behaviour during one week of production, which has been selected being a full time production week. The SEC percentage uncertainty calculated as standard deviation of the SEC value, in percentage of the mean SEC value, during the examined week (5 days, 1 value for each day), is about 20%.

Target t% has not been defined. SEC uncertainty suggests to identify an improvement action so that the SEC reduction is in the order of 20%. Because of the remarkable amount of the requested improvement, the management considers this target technically and economically not feasible. Thus, some actions to improve the EnPI accuracy should be provided.

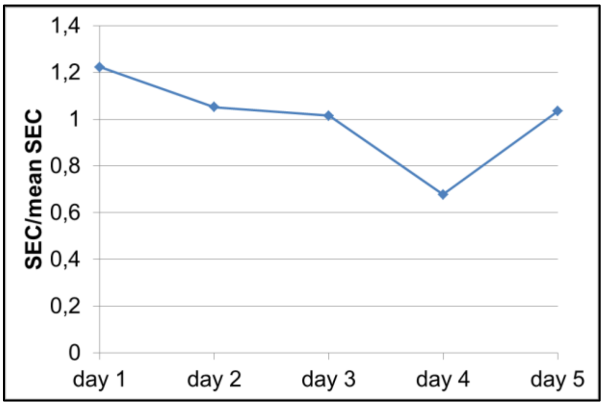

Figure 2. Trend of normalised SEC_Cc for Test-case A

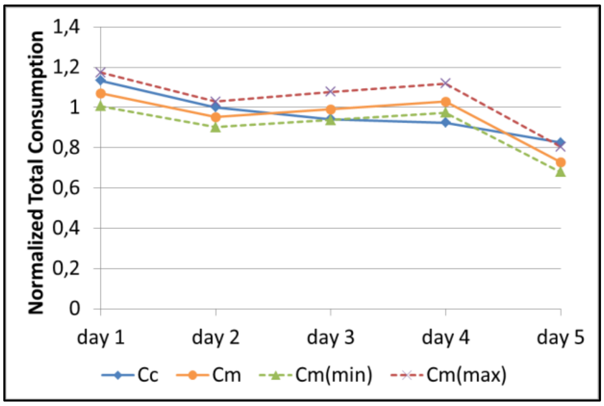

Figure 3. Normalized total consumption for Test-case A

In order to reduce the EnPI uncertainty, a consumption model considering the energy-intensive utilities based on the electric size of the utilities themselves has been set up. The model has been validated using experimental data. Figure 3 shows the obtained behaviour, together with the variability bands of the model, obtained considering the uncertainty of estimation of contributions to the whole consumption. The subscript Cc refers to the measured consumption, the subscript Cm refers to the consumption model.

3.2.2. Test Case B

As for the Test case B, figure 4, as an example, shows the normalized EWH behaviour during one year of production. The percentage uncertainty calculated as standard deviation of the EWH value, in percentage of the mean EWH value, during the examined year is about 11%.

The management could allow some actions to improve the efficiency of the injection moulding machines, extending a spot action to more machines. The extension criterion is that the specific efficiency increase should be not less than 15%, based on the payback period consideration. It should be noted that the specific efficiency increase depends on the machine technology which is different among the machines potentially interested.

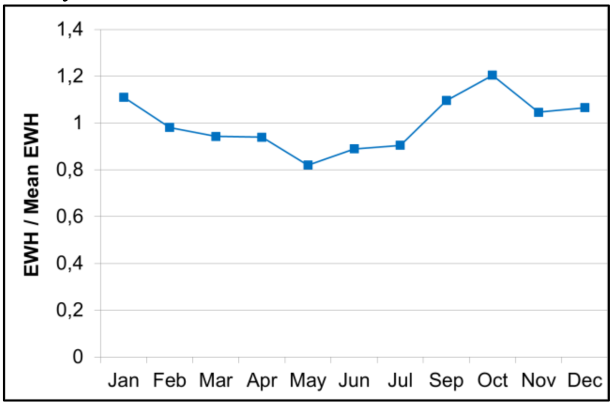

Figure 4. Trend of EWH

Table 2 shows the entity of the predictable saving corresponding to the reduction of the adopted EnPI.

Considering the EnPI uncertainty, and the target (t% = 4.2%) the criterion (1) is not satisfied, therefore the success of the action cannot be demonstrated by the EnPI itself. Thus, some action to improve the EnPI accuracy should be provided.

Table 2. Evaluation of the savings for single machine and plant section

Injection molding machine			Plant section	
Quantity	**Type**	**Single machine saving %**	**Consumption [%]**	**Saving [%]**
1	1	17	5,2%	0,9
2	2	15	2 x 5,5% = 11%	1,5
3	3	15	3 x 4% = 12%	1,8
4	4	12	4 x 3% = 12%	No upgrade
4	5	12	4 x 4% = 16%	No upgrade
12	6	9	12 x 3% = 36%	No upgrade
1	7	No possible upgrade	7,8%	No possible upgrade
		Total	100%	4,2

In order to reduce the EnPI uncertainty, some actions to improve data reliability have been identified, which are summarized as follows:

- In field check of power meters, in terms of:
    - compliance of installation connections to the electric diagrams;
    - compliance of setting parameters in respect to the current transformers (e.g. turn ratio).

- Activation of a more reliable IT architecture, specific for energy data storage and management, such as:
    - development of alarm systems in case of anomalies to avoid data loss;
    - comparison of data to assure that stored data are the same of the power meters;
    - comparison of data stored on the previous data base to the last one.

- Reallocation of consumptions after a more detailed mapping of energy flows (e.g. compressed air consumption).

3.3. Methodology application - Cycle 2

3.3.1. Test case A

Figure 5 shows the normalized SEC behaviour during the same week of production as figure 4, evaluated on the basis of the consumption model, (SEC_Cm). The percentage uncertainty calculated as standard deviation of the SEC_Cm value, in percentage of the mean SEC_Cm value, during the examined week (5 days, 1 value for each day) is about 16%.

The definition of a consumption model allowed to reduce the SEC uncertainty with respect to the previous estimation and it also supplied an indication about the relevance of contributions of different energy consuming utilities, underlining the contribution of the autoclave which is about 50% of the whole consumption. Because of the remarkable amount of the requested improvement, the management considers this target is still too hard to achieve. Thus, the EnPI accuracy has to be strongly improved by more diffused measurement of the energy flows for most relevant utilities and improved production monitoring and data registration.

3.3.2. Test case B

Figure 6 shows the normalized EWH behaviour before (11 months, 1 value for each month) and after (8 months, 1 value for each month) the interventions described in previous section. The percentage uncertainty calculated as standard deviation and in percentage of the mean EWH value, during the examined period after the interventions is about 4%.

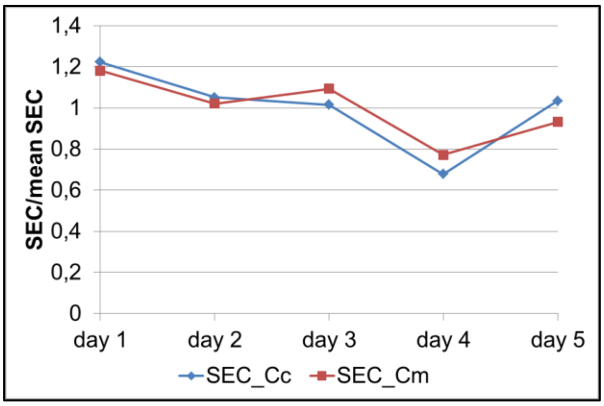

Figure 5. Trend of SEC_Cc and SEC_Cm

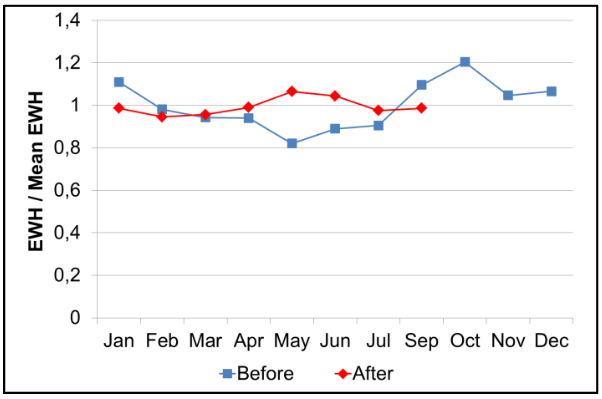

Figure 6. Trend of EWH before and after the interventions

Having reduced the EnPI uncertainty from the previous value of 11% to 4% the improvement action proposed by the management (summarized in table 2) can be done. Considering the new EnPI uncertainty, and the target (t% = 4.2%) the criterion (1) is now satisfied, therefore the success of the action can be demonstrated through the EnPI itself.

In Figure 6 the data "before" and "after" the interventions cross each other; this is linked to the reduced EnPI uncertainty. In fact a higher EnPI uncertainty corresponds to a high fluctuation of the indicator; if EnPI uncertainty is reduced the time behaviour of the indicator is much more stable.

3.4. Discussion of results

In both cases, the applied methodology allowed providing some useful indications about reachable savings and action areas to be considered to achieve the improvements targets.

About the test case A, the measurement uncertainty allows validating the consumption model, which is set up in order to compensate the lack of energy data. The possibility to set the target as the minimum of the variability band of the consumption model, allows identifying further improvement areas, even though relevant investments are required.

The actions leading to a reduction of the EnPI uncertainty allows identifying the most energy-intensive utilities, i.e. the autoclaves. Suggestions for a further reduction of the EnPI uncertainty are also given.

Ultimately, the level of the target definition results coherent with the quality of the available measurements. In this sense, the EnPI uncertainty can be seen as a support of a higher awareness and knowledge of the analysed situation.

About the test case B, a more organic strategy involving the data validation within the whole measurement chain has been set up. As a consequence, being the EnPI uncertainty decreased, the EnPI meaningfulness results increased. Therefore, the reduced EnPI uncertainty allows demonstrating the success of the proposed improvement action, and eventually the success of further improvement actions in the same plant section.

4. Conclusions and future works

In this work, the possibility of evaluating and controlling the EnPIs uncertainty has been discussed in order to demonstrate that it allows increasing the transparency level of the energy performance in terms of the aspects affecting the energy consumption. The high level EnPI uncertainty is not easy to evaluate but it offers the possibility of supporting the decision-making activities, since the measurement uncertainty involves the ability of modelling and knowing the actual energy flows and their interactions, which the indicator itself should represent.

As more the EnPI uncertainty is reduced, as more the possibility of choosing among many suitable actions is increased, maintaining a high level of confidence of obtaining the predicted improvement. The increased awareness of the actual situation is also a positive result.

In this paper a methodology has been developed and applied for validation purposes to two different cases regarding different industrial sectors and level of evolution of the EMS life-cycle. In particular, the uncertainty evaluation of high-level EnPIs has been studied.

The recursive application of the approach to the same test case allowed to demonstrate that the EnPI uncertainty is a parameter resolved and accurate enough to detect different positions along the EMS life-cycle. The same result could not be obtained by means of other qualitative methods. The same result has been achieved for both cases examined.

Furthermore, the discussion about the reached level of uncertainty supplied indications about the design of action plans for energy improvement and their reliability with respect to the predicted targets. In fact, depending on the different quality of measurements available, effective guidelines to carry on the EMS in terms of establishing, implementing, maintaining and improving coherent action plans have been suggested.

The methodology allowed also to highlight technical and economic feasibility of the improvements taking into account the possibility of guaranteeing the achievement of the predicted target with a satisfactory level of reliability.

Future works:

- testing the reproducibility of the methodology taking into account more industrial sectors and more different energy vectors typologies (compressed air, steam, renewable energies,…);
- experimentally assessing the measurement uncertainty ability to create more diffused awareness;
- evaluating the possibility of using portable plug-in measurement systems able to support the requirements of an EMS, to set demonstrator apparatuses for awareness diffusion of achievable advantages of implementing an EMS;
- examining the possibilities offered by integrating the proposed methodology in IT and informative systems business modelling, taking into account the present and future high connectivity scenario.

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