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Energy Indicators for Enabling Energy Transition in Industry

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Abstract: Energy transition is a fundamental process in the move towards sustainable development, but in industry, it is complicated by the remarkable sectoral heterogeneity. Fostering the realization of energy transition in the industrial sector requires the characterization of its energy dimension, in terms of energy mixes and end-uses as the determinants of transition pathways, and energy solutions and tools as the enablers of this transition paradigm. We observe that the suitability of tools for energy analysis depend on trade-offs between comprehensiveness, ease of use, robustness, and generalization ability. In this regard, we discuss the appropriateness of energy indicators and provide an overview of indicator typologies, methodological issues, and applications for energy performance evaluation and improvement. With reference to the dairy processing industry, selected as a representative industrial branch, we outline current and desirable energy benchmarking applications and exemplify the effectiveness of energy indicators in the quantification of the potential of energy solutions. The obtained results are promising and suggest that researchers should further explore the novel applications of energy indicators for energy performance improvement. To foster the establishment of energy indicators in industrial practice and energy policies, we remark that cooperation between industrial stakeholders is essential.

Keywords: energy transition; industry; energy indicators

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1. The Energy Transition in Industry

1.1. Current Situation and Driving Forces behind Energy Transition

The positive impact of energy use on societal development and human wealth is well recognized [1]. Nonetheless, current energy use represents a major concern for the environment and for human health, as fossil fuels are acknowledged as the main source of anthropic CO_2 emissions [2] and air pollution [3]. In addition, energy security is identified as a critical issue for geopolitical and macroeconomic stability [4].

Accordingly, sustainable development requires an energy transition. Although such a concept is typically linked with fuel switches, in the recent years the introduction of energy efficiency has had a greater effect than that of carbon intensity reduction [5], with a major role being played by improvements on the demand side of the energy system [6].

1.2. The Industry Context

When considering energy demand, industry stands out as a key sector, as in 2018 it globally accounted for 37% of final energy use and for 24% of carbon emissions [7]. Other driving forces for energy transition in industry are rising energy prices [8], which threaten business continuity, and the need to contrast delocalization pushes [9], which negatively impact both local economies and global energy use [10].

The energy transition in this sector faces several challenges, mainly due to its various aspects of heterogeneity [11]. This is clear by looking at the several industrial sectors, within which various manufacturing products, production processes, and technological devices are found. Ideal transition pathways differ according to the branch and must involve both cross-cutting interventions and sector-specific solutions [12]. Sector heterogeneity also extends to the dimension of the involved realities, as industrial sectors encompass both large corporations and small and medium enterprises (SMEs). This impacts on how these firms deal with energy performance improvements. In addition, another challenge is the competitiveness within branches, which hampers the spread of effective solutions and often causes a huge difference between the energy performance of leading and outpaced realities.

1.3. Tools for the Energy Transition in Industry

The energy transition is a very complex problem that needs to be driven from above but is only realized from below. Accordingly, policymakers are called to guide industrialists in continuous energy performance improvement, helping poor-performing firms align with those following the best practices.

Understanding how and where energy is used is the first step towards this goal. In this regard, in [13], a relevant gap was found between the absence of indicators at process or plant level, and that at sector or country level. While the latter can only contribute to track energy efficiency progresses [5], the former can also contribute to identifying hotspots for energy performance improvement, enabling practical action.

Various studies have sought to fill this gap by proposing methods for developing Key Performance Indicators (KPIs) [14] and taxonomies for organizing them into aggregation levels [15] based on suitable indicator typologies [16]. Most studies on energy indicators refer to specific industrial sectors, including both energy-intensive, such as steel [17], cement [18], pulp and paper [19], aluminum [20], and food [21], and non-energy intensive, such as textile [22] and engineering [23]. Studies have been mostly concerned with the development of sets of indicators rather than portraying the role these can play in the energy transition.

1.4. Original Contribution of the Paper

This paper broadens the horizon of industry as a whole and attempts to frame energy indicators within the paradigm of energy transition.

A deeper understanding of the industrial energy dimension is essential to shaping concrete action toward the desired sustainable development. To this end, we outline the energy mixes and end-uses of industrial sectors as determinants of transition pathways, and energy solutions and tools as enablers of this process.

In light of the widening audience of stakeholders interested in energy performance improvement, we identify energy indicators as appropriate tools thanks to the trade-offs between comprehensiveness, ease of use, robustness, and generalization ability. Accordingly, we critically overview indicator typologies, methodological issues, and possible applications. With regard to the latter, we discuss established applications of energy indicators in the evaluation of energy performance and propose novel applications for the improvement of energy performance, supporting the discussion with an analysis of a specific branch of industry: the dairy processing industry.

Lastly, we conclude by discussing the intertwined role of the stakeholders in helping energy indicators to be established in industrial practice and energy policies.

The main original contribution of the paper was the holistic approach that we adopt, which allows us to portray how energy indicators can enable energy transition. This is meant to draw the attention of all the involved stakeholders on the relevance of the issue and on the role they can play to accelerate the desired energy transition through appropriate tools.

2. The Industrial Energy Dimension

Promoting the energy transition in industry requires a thorough analysis of its complex energy dimension. In this regard, industry is the most diverse sector compared to buildings and transport, as energy is required for a wide range of purposes. This leads to different portfolios of energy mixes and energy end-uses among industrial sectors, and consequently to different transition pathways.

2.1. Energy Consumption of Industrial Sectors

The energy consumption shares of industrial sectors for EU-27 in 2018 [24] are shown in Figure 1. The EU represents a good example of a developed region of the world, as it includes various national contexts and is a leader in terms of industrial energy intensity reductions [25]. The first six industrial branches (CP, NMM, PPP, FBT, IS, and M) cover more than 80% of specified industrial final energy consumption. Their predominance is also clear at a country level, where the share remains greater than 75% for the 15 most energy-consuming EU members despite different proportions, such as the abundance of CP in the Netherlands and of PPP in northern countries. This suggests the possibility of focusing on specific sectors without sacrificing the significance of the energy consumption addressed.

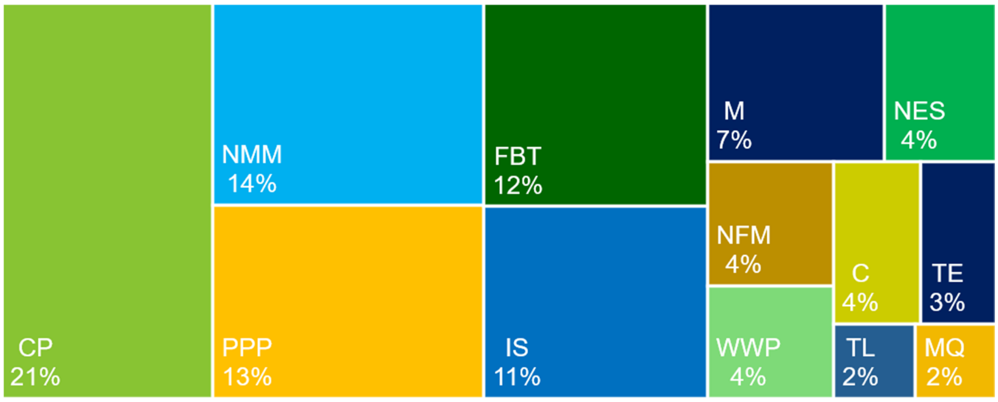


Figure 1. EU Energy consumption share of industrial sectors. Based on data from [24]. (CP, Chemical and Petrochemical; NMM, Non-Metallic Minerals; PPP, Paper, Pulp, and Printing; FBT, Food, Beverages, and Tobacco; IS, Iron and Steel; M, Machinery; NES, Not Elsewhere Specified; NFM, Non-Ferrous Metals; WWP, Wood and Wood Products; C, Construction; TE, Transport Equipment; TL, Textile and Leather; MQ, Mining and Quarrying).

To provide more detail, sectoral energy consumption can be analyzed from the supply and the demand sides. Figure 2 shows the breakdown of the energy consumption for the major branches in terms of energy vectors (categorized into fossil fuels, electricity, renewables, heat, and non-renewable waste) and energy end-uses (categorized into process heating, other, space heating, process cooling, and space cooling).

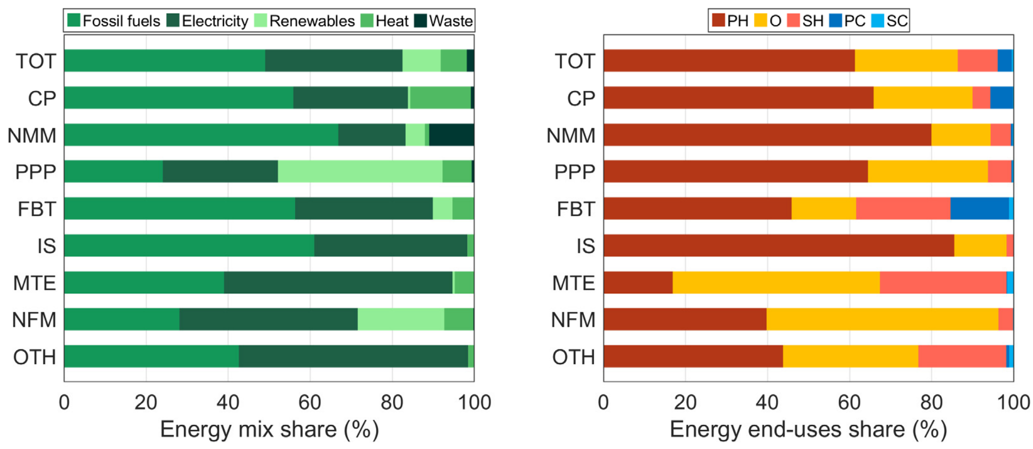
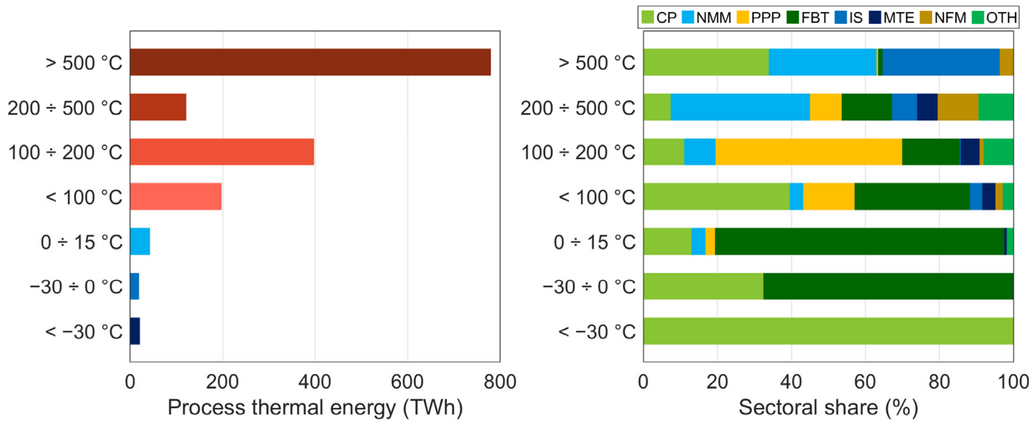


Figure 2. Breakdown of sectoral energy consumption: (**a**) supply side; (**b**) demand side. Based on data from [24,26]. (PH, Process Heating; O, Other end-uses; SH, Space Heating; PC, Process Cooling, SC, Space Cooling).

Concerning the energy mix, fossil fuels account for 49%, electricity for 34%, and renewables, heat, and non-renewable waste for 9%, 6%, and 2%, respectively. In fact, the indirect use of fossil fuels should be considered too, as about 40% of electricity generation is due to their combustion. The major role of fossil fuel is clear in all energy-relevant industries except for PPP, in which biomass is used as raw material but also for energy generation. Concerning the end-uses, thermal energy demand dominates industry, as process heating accounts for 61% and space heating, process cooling, and space cooling for 10%, 3%, and 1%, respectively. As opposed to other thermal uses, which are absent or irrelevant for some branches, process heating is the main end-use for most energy-demanding sectors. The link between fossil fuels and process heating is easy to grasp, as combustion is traditional method for achieving the high temperatures required in industry.

Process energy demand accounts for almost two thirds of final energy consumption, and therefore requires an in-depth analysis. Indeed, both process heating and process cooling can be further characterized in terms of temperature level, as this is an important index of energy quality. Figure 3 shows the temperature level distribution and the sectoral breakdown for process heating and process cooling, adapted from [26] for 2018 energy consumption. We can see that about 800 TWh of process thermal energy is required at a temperature greater than 500 °C, and that the other 600 TWh is required at a temperature lower than 200 °C. For process cooling, near-ambient thermal demand is the most common, but this only reaches around 40 TWh. Concerning the sectoral distribution, high-temperature process heating is required mainly in specific branches such as CP, NMM, and IS, while low-temperature process heating is more equally distributed. Meanwhile, near-ambient process cooling is concentrated in FBT, while low-temperature process cooling is common in CP.



(**a**) (**b**)

Figure 3. Process thermal energy: (**a**) temperature level distribution; (**b**) sectoral breakdown. Based on data from [26].

2.2. Pathways for Energy Transition

Once the sectoral energy profiles are traced, the optimal transition pathways can be identified. This refers both to the solutions that can bring the desired benefits and to the tools required for their spreading.

A recent series of reviews concerning the most energy-consuming industries analyzed these branches from the perspective of decarbonization [27–32]. The solutions that were identified were pretty much the same across the various sectors, although their importance differed according to the branch. The identified energy-related solutions can be grouped into three categories according to how they impact on industrial energy use: there are solutions for a carbon-neutral supply (renewables and biofuels), solutions for an improved energy transformation (electrification and multigeneration), and solutions for a more rational demand (heat recovery, process optimization, and energy and resource efficiency).

The applicability of these solutions depends especially on the sectoral energy mixes and end-uses, as, for example, most renewables can hardly substitute fuel combustion, and heat recovery is effective only if applied to high-temperature energy excesses. In light of the industrial heterogeneity, it is clear that there is not a single solution that can alone ensure energy transition in industry. Comprehensive portfolios need to be developed based on the specific features of a sector and must be promoted through comprehensive and well-targeted instruments [33].

As the transition is realized from below, the effective potential of each solution needs to be demonstrated for each specific case. On one side, this requires tools able to accurately depict how and where energy is used in order to identify energy performance hotspots and quantify the achievable improvements; on the other, it requires tools characterized by the relevant ability to generalize in order to enable knowledge transfer across similar contexts.

As the audience of industrial firms interested in improving their energy performance is expanding due to increases in energy prices and environmental awareness, tools that can be applied by non-experts in the field of energy are required. On the one hand, complex tools such as exergy analysis have failed to spread due to their poor convenience of use [34]; on the other, oversimplified tools performing only qualitative evaluations based on economic considerations have become useless considering the drastic changes in energy prices.

Suitable tools should represent a trade-off between comprehensiveness, ease of use, robustness, and generalization ability. As such, they should be general in scope in order to ensure their applicability in all the relevant industrial sectors; they should make use of elements within the reach of non-experts in order to ensure their use by all the industrial stakeholders; they should convey energy-relevant information in order to provide technically solid results; and they should enable knowledge transfer in order to simplify the generalization of effective solutions to other cases. In industrial contexts, this trade-off can be found in energy indicators due to the confluence of the energy and production dimensions in them.

3. An Overview of Energy Indicators

The concept of linking the energy dimension to other relevant dimensions has been long recognized as an effective practice to track changes in energy efficiency and make them more comprehensible. Indeed, the fundamental definition of energy indicator consists of the ratio of a useful output to the energy input, where the useful output is not necessarily an energy output [35]. When referring to industrial sectors, this has resulted in the development of physical and economic, or volume- and value-based, indicators [36].

However, to enable energy transition, tracking energy efficiency changes is not enough. This must be developed into identifying opportunities, setting targets, and taking action to achieve them [37]. First, this section overviews the two major types of energy indicators, identifying physical indicators as the most suitable because of their quantitative nature, which useful at low-aggregation scales to identify energy efficiency hotspots, and at high-aggregation levels to support energy policies. Then, we discuss the methodological issues that arise in the development and deployment of energy indicators and present an overview of possible applications for the evaluation and improvement of the energy performance required for enabling energy transition.

3.1. Physical Indicators and Economic Indicators

In industry, a physical indicator can be defined as the ratio of energy use to the amount of product or feedstock; instead, an economic indicator can be defined as the ratio of energy to the added value or increase in gross domestic product. As shown in Figure 4, physical and economic indicators have various scales of application, ranging from process to sector level for the former, and from product to country level for the latter.

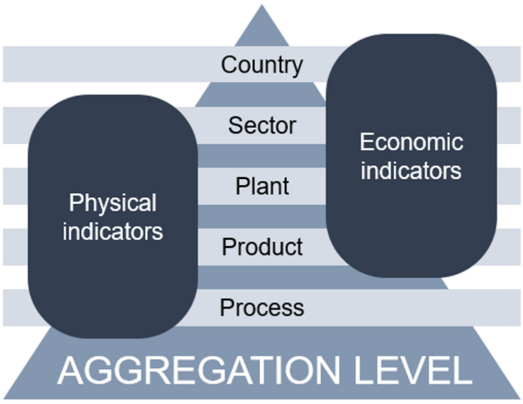


Figure 4. Physical and economic indicators according to aggregation level. Adapted from [38].

At low aggregation levels, economic indicators do not make much sense, as they do not provide the technical information required. At the same time, their application for high aggregation levels should be further questioned, as they cause a significant amount of information loss and lead to several conceptual problems when dealing with time series [39]. Their qualitative nature inhibits their ability to inform energy policies of the extent to which improvements can be achieved through the promotion of specific energy solutions [16].

Instead, physical indicators convey technically sound information as they are defined at levels where the use of energy can be effectively monitored and evaluated. Their bottom-up aggregation could provide a precise picture of the status of energy performance. Physical indicators can therefore be useful for linking low and high levels of aggregation to meet the transversal nature of energy transition, which requires guidance at large scales and is performed at small scales.

3.2. Methodological Issues and Development Methods

A deeper critical assessment of physical indicators can help to identify the major issues that characterize their development and deployment. The first element is to recognize that valuations and value judgements are an integral part of energy indicators [35], both regarding what concerns the useful output and the energy input.

Concerning the production side, the typical choice is to use the product as the basis for energy indicators. This requires some specifications, such as defining whether all of the product produced or only the product eligible to be sold is considered [40] (in the case of the use of raw material, this problem would not arise, as wastes are intrinsically included). Although commonly established, the use of product-based indicators can bring some problems, as with, for example, the allocation of energy use in the case of joint production. Feedstock-based indicators can be helpful in these situations and in cases where the product quality highly depends on the feedstock [41]. Nonetheless, such indicators can be tricky, as they can apparently be influenced by opposition energy and resource efficiency.

Meanwhile, concerning the energy side, a renowned problem is the so-called energy quality problem [42], which refers to the fact that not all forms of energy are equal, and therefore, some need to be adapted before adding them all together. Especially at low aggregation levels, this problem can be typically overcome by making use of sets of indicators, rather than resorting to equivalents. Indeed, the use of primary energy, which allows one to commensurate different vectors, is critical, as it includes inefficiencies external to the boundaries of the production site, such as the efficiency of electricity generation. Additionally, it is important to include internal energy production, as it does not contribute to reducing the energy required but only the energy purchased.

All these elements contribute to specifying the importance of the definition of the system and its boundaries and should not be overlooked when developing or deploying energy indicators. Indeed, this often leads to wrong evaluations in the latter case, due to the lack of reporting relevant information. This is more important at low aggregation levels [40], where deviations in assumptions can lead to more significant differences.

Concerning the availability of information about production and energy, a significant difference can be evidenced: as production is the basic purpose of industry, information is usually available at a satisfactory level of aggregation and temporal resolution; on the contrary, energy information is seldom available with the desired granularity. The lack of energy monitoring is recognized as a recurrent barrier for energy management [13]. Modelling efforts can help to depict energy uses down to process level [43] and fill gaps in data. These models must be based on accurate energy balances, thermo-physical properties of the various streams, and performance curves of the involved components. The coupling of solid energy models and key energy-related data can provide a sufficient description of the energy dimension of production and allow for the development of reliable energy indicators.

3.3. Applications for Energy Performance Evaluation and Improvement

Energy indicators can be helpful for the evaluation and the improvement of energy performance. While applications of energy indicators in the evaluation of energy performance are well established, their applications in the improvement of energy performance have much room for improvement.

Benchmarking is the most straightforward application for energy performance evaluation. It consists of direct comparison between the energy indicators of two or more comparable entities for the identification of opportunities for improvement. It can be performed at different aggregation levels (processes, products, plants, etc.) and categorized according to the realities with which the comparison is made. Referring to plants, for the sake of simplicity, these realities can be the plant itself, similar plants belonging to a certain company, or all the plants dedicated to similar production within the sector [44]. Figure 5 shows how the horizon broadens from historical to company-wide to sector-wide benchmarking, and how the performance of more plants is considered.

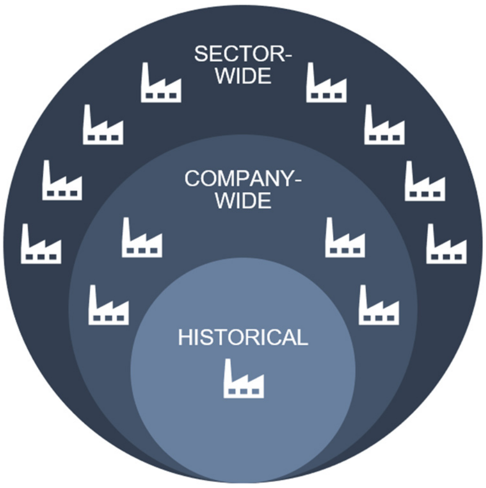


Figure 5. Different types of benchmarking with a broadening horizon.

Historical benchmarking compares current to past energy consumption of the plant itself and can be used to identify faults in production or to monitor the effects of changes in production modes, depending on the time resolution of data. This type of benchmarking is the most accessible to SMEs because it does not require external information, although it may require a large amount of data which are not often monitored. Company-wide benchmarking refers to the comparison of the energy performance of different plants belonging to the same company. In this context, information exchange is not prevented by confidentiality, and both virtuous and poorly performing plants can be easily identified. Sector-wide benchmarking has the broadest horizon and involves the comparison of all plants dedicated to the same production. Although characterized by significant informative power, it is often hindered by companies' reluctance to share energy data, as these are deemed sensitive. It is therefore the duty of authorities to enable this interesting opportunity by promoting greater cooperation between firms.

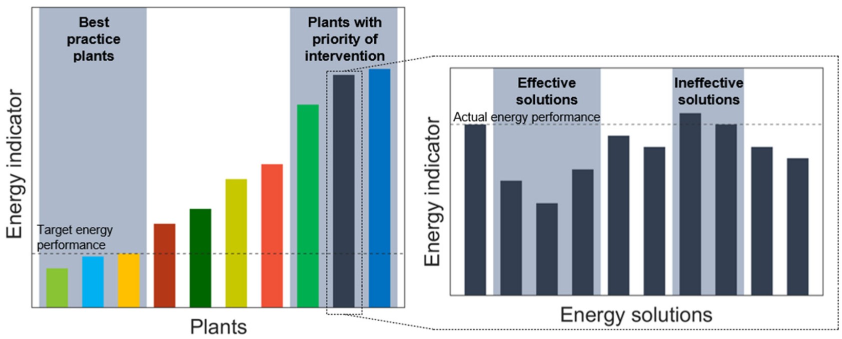
All of these types of benchmarking are characterized by their comparison with a real benchmark. Another possible solution is to make use of a theoretical benchmark, completely based on energy analysis. As opposed to real-case benchmarking, the theoretical benchmark identified by a model does not represent either an economic or a technical potential, but rather an ideal limit to be approached as closely as possible.

Although seemingly simple, when performing any kind of benchmarking it is essential to consider all of the features that can affect the validity of the comparison, as overlooking one of them could lead to faulty conclusions. The most influential parameters include plant size (the amount of production may determine economies of scale), plant location (boundary conditions may impact technology efficiency), operation modes (operational constraints may induce inefficient behaviors), and automation level (human labor may substitute energy consumption).

Applications of indicators for the improvement of energy performance are still scarce in the field but have good potential, for example, in enhancing technology transfer for effective energy solutions. The relevance of this task is recognized [45] and is also witnessed by the spreading of publicly available databases, such as the EU-MERCI project [46] which gathers energy efficiency measures from real cases. A weakness of this database, and of other similar ones, is that energy-related information is typically provided in absolute terms. This does not inform the user about the status of the energy performance precluding the evaluation of the similarity between the cases, which is crucial for knowledge transfer. This issue is very important as the potential of a solution strongly depends on the actual energy performance of the specific context. Through the inclusion of energy indicators, similarities could be more precisely pointed out, strengthening extrapolations on the effectiveness of a solution.

Besides technological transfer, energy indicators can be useful in the direct quantification of the potential of an energy solution. To this purpose, their coupling to other KPIs allows for the representation of the performance on multiple aspects in a rigorous and straightforward way, and for highlighting the relations between these aspects. Thanks to this, the effects of various energy solutions can be properly synthetized and evaluated from the perspective of all the relevant aspects on which a solution is impactful.

To summarize, energy indicators play a key role in enabling energy transitions thanks to the various applications for identifying energy performance hotspots and solutions that can guarantee the desired achievement. Figure 6 shows how applications for energy performance evaluation are linked with those for its improvement.



(**a**) (**b**)

Figure 6. Applications of energy indicators: (**a**) energy performance evaluation; (**b**) energy performance improvement.

The use of energy indicators for the evaluation of energy performance concerns the comparison between various plants, highlighted in Figure 6 with different colors. It allows to define a target energy performance that can be reached through best practices, and also to identify which plants deviate more from best practice and need prioritized interventions. Then, with regard to a generic plant, the use of energy indicators for the improvement of the energy performance can help to synthetically quantify the potential of various energy solutions in that context. This would allow for the comparison of the energy performance of the plant under various combinations of energy solutions, and approach as closely as possible the target energy performance. Such analysis would help to identify the most effective solutions, which address the bottlenecks of the specific plant, and to avoid ineffective ones, which may even cause a worsening of the energy performance.

4. Applications of Energy Indicators: The Dairy Processing Industry as an Example

Before discussing the establishment of energy indicators in industrial practice and energy policies, we here exemplify concrete applications of energy indicators in a representative industrial branch. On the one hand, this allows us to assess the maturity of established applications for energy performance evaluation, such as benchmarking at product or process level, and to point out the large variability in energy performance. On the other hand, it allows us to exemplify novel applications of energy indicators for energy performance improvement, such as the use of KPIs for the quantification of the potential of an energy solution, and to bring out the significant potential for energy performance improvement.

For this purpose, we selected the dairy processing industry because of its representativeness of FBT and the valuable opportunities provided by a more systematic use of energy indicators.

The dairy processing industry consists of the transformation of raw milk coming from dairy farms into products which are transported through a cold chain and later used by consumers.

Figure 7 shows that this branch is characterized by a large range of products deriving simultaneously from a single raw material and obtained through common processes. Raw milk is first cooled and stored, and then it is separated into cream, a stream which is rich in fat, and skimmed milk, a stream which is low in fat. At this point, the fat content is adjusted by mixing cream and skimmed milk to meet the various products' requirements. Once standardized, most products undergo thermal treatment of different magnitudes and are then cooled to or below ambient temperature depending on the thermal treatment received. Figure 7 also highlights every product demands for heating, cooling, and electricity: the various energy demands are identified with three different colors. Heating is used to inactivate bacteria and spores naturally present in the raw material through pasteurization or high-temperature treatments, while cooling is used mainly to store the raw material and the products to preserve their quality, and electricity is used for a large number of processes, including separation, homogenization, and packaging.

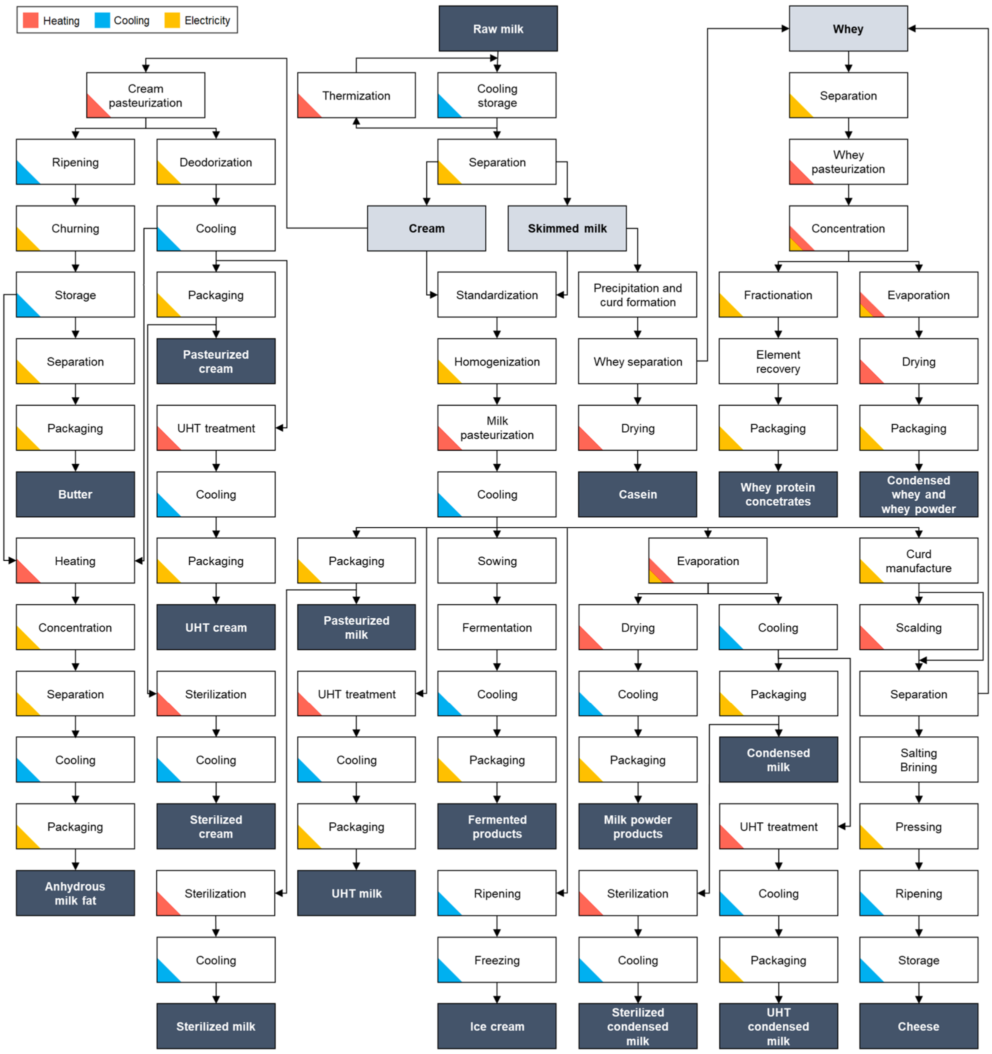


Figure 7. Map of the dairy processing industry. Adapted from [47].

4.1. Sources of Indicators and Energy Benchmarking Applications

As in any industrial sector, a first source of indicators is the BAT-REF document from the IPPC [48]. For the dairy industry, this document provides feedstock-based indicators for only some of the many dairy products, such as milk, cheese, powder, and fermented milk. However, it does not provide indicators on the process level.

Various scientific papers have presented a more detailed source of reference for product-based indicators [49,50]. A recent review on the energy consumption of food manufacturing gathered information from the literature for various food branches, including the dairy processing industry [51]. The collected data show a lack of up-to-date information and large variations across the same products. The latter can be mainly attributed to the variability of the energy performance of different production sites, but also to the low reporting detail. The variability of energy performance is due to the varying use of advanced or less advanced technologies, which significantly affects the energy performance. Clearly, increases in the availability of such indicators could help to correctly identify best practices. The encountered low reporting detail, instead, may lead to comparison of products that are similar only in appearance. For example, in the case of drinking milk, products with different thermal treatment may be compared, although this has been proven to significantly impact the energy consumption [52]. Another limitation is in the comparison of indicators provided in terms of primary and final energy.

The available product-based indicators can be transformed into feedstock-based indicators by multiplying by mass yield, and vice versa. In Table 1, we obtain product-based indicators from typical mass yields and best practice feedstock-based indicators [48]. These ranges of indicators are representative of best practice and therefore provide insights on the available potential for improvement for some exemplary dairy products. As we can see, on a feedstock basis, the values are lower than 0.6 kWh/kg and cover similar range for all the considered dairy products; on a product basis, instead, these values reach up to more than 8.3 kWh/kg and are very different because of the variable mass yield of these products. On a product basis, powder products quality as the most energy-intensive in light of the high energy consumption of evaporation and drying.

Table 1. Product-based and feedstock-based energy indicator equivalents.

	Feedstock-Based Indicator (kWh/kg) [48]	Mass Yield (kg/kg)	Product-Based Indicator (kWh/kg)
Milk	0.1 ÷ 0.6	0.88 ÷ 0.98	0.1 ÷ 0.7
Cheese	0.1 ÷ 0.22	0.06 ÷ 0.15	0.7 ÷ 3.7
Powder products	0.2 ÷ 0.5	0.06 ÷ 0.13	1.5 ÷ 8.3

The diffusion of joint production in the dairy industry implies further complications in the establishment of these indicators. This is important both for product-based indicators and for feedstock-based indicators. Concerning product-based indicators, this makes it necessary to allocate energy uses among products; to this purpose, several methods can be used with different results [52]. Concerning feedstock-based indicators, the processing of a by-product inevitably increases the energy consumption, suggesting a degradation in performance, as the feedstock quantity remains unchanged. This contradiction is, however, only apparent, as the two situations compare different modes of production. Indeed, the processing of the by-product satisfies a product demand that otherwise would have required other raw material. This not only represents an increase in resource efficiency, but also in energy efficiency, as less raw material is being processed.

Efforts are needed to obtain more reliable indicators that do not refer only to products, but to their production modes. Only upon this can a fair representation of the dairy industry be provided, as joint production of the various products is the common production mode. Providing indicators for production modes would foster benchmarking, allowing for a direct comparison between dairy plants. Examples include the simultaneous production of drinking milk and cream [53], of milk, cream, and ghee [54], and that of cheese and whey processing [52].

When delving into dairy energy performance to identify opportunities for energy performance improvement, process-level indicators need to be considered. As one can imagine, such detailed indicators are not commonly discussed in the literature, due to the amount of energy information they require. The example reported in Table 2 is that of process-level indicators for 17 Canadian fluid milk plants [55].

Table 2 highlights the importance of support processes in non-energy intensive industries, as their average reaches about 40% of total average. Focusing on specific processes, we can see how energy is mainly required for homogenization and pasteurization, and cleaning in place, as these amount to 33% and 28%, respectively. As opposed to the indicators in Table 1, the values reported here provide insights on the large variability that characterize similar industrial productions. Contrasting the median and the maximum value for any of the processes involved, we observe a large difference for each of them. This emphasizes how inefficiencies can be found at all the phases of production. Considering the maximum value, several processes are shown to account for a considerable share of total energy consumption. This emphasizes that besides common energy-consuming processes, significant opportunities may also lie in other specific processes. In addition, the difference between the maximum value of the total indicator, about 0.3 kWh/L and the sum of the maximum values of the indicators for the single processes, about 0.7 kWh/L, indicates that there is not just a single plant that features a potential for improvement but that this is spread across them. Accordingly, more detailed energy analysis should be promoted to identify the hotspots for energy performance improvement in any specific case.

Table 2. Process-level benchmarking in fluid milk plants. Based on data from [55].

[kWh/L]	Min.	Median	Max.
Total	0.11	0.18	0.30
Production processes			
Receiving	<0.01	0.01	0.06
Separating	<0.01	0.01	0.03
Homogenization and Pasteurization	0.02	0.06	0.21
Filling and Packaging	0.01	0.01	0.08
Refrigeration and Cold Storage	<0.01	0.01	0.08
Support processes			
Cleaning in Place	<0.01	0.05	0.09
Heating, Ventilation, and Air Conditioning	0.01	0.01	0.13
Other	<0.01	0.01	0.03

4.2. Quantification of the Potential of Energy Solutions

The dairy industry is of particular concern for the environment due to the harmful organic concentration of its products and wastes. The organic concentration, typically represented by Chemical Oxygen Demand (COD), is more significant in products than in WasteWaters (WW), but wastewaters show greater variations [56]. The variable organic concentration of wastewaters is directly linked with nutrient retention in products derived from Raw Milk (RM) and can be considered as a measure of the quality of production in terms of resource efficiency along with the volume of wastewaters produced.

The typical treatment of dairy wastewaters is aerobic treatment, although anaerobic treatment is an increasingly common solution [57] as it results in the production of biogas. This technique enhances waste by producing biofuels that contribute to reducing fossil fuel consumption, thus enhancing the sustainability of the dairy industry. A greater spread of this solution could be achieved by drawing the attention of industrialists to its significant potential; this may be achieved by providing them with an easy way to quantify the potential that such solution can have for their specific case. The amount of energy demand that can be covered using biogas can be expressed in terms of indicators of energy performance and resource efficiency, as shown in Equation (1):

$$EC_{biogas} = r_{CH_4} \cdot LHV_{CH_4} \cdot \frac{I_{NL} \cdot I_W}{I_E} \tag{1}$$

where EC_{biogas} is the energy coverage of biogas production, r_{CH_4} is the rate of production of methane equivalent, LHV_{CH_4} is the lower heating value of methane, I_{NL} is the indicator of nutrient losses in $\mathrm{kg_{COD}/l_{WW}}$, I_W is the indicator of water consumption in $\mathrm{l_{WW}/l_{RM}}$, and I_E is the indicator of energy consumption in $\mathrm{kWh/l_{RM}}$. For r_{CH_4} and LHV_{CH_4}, constant values equal to 0.28 $\mathrm{m^3{}_{CH_4}/kg_{COD}}$ [58] and 10.5 $\mathrm{kWh/m^3{}_{CH_4}}$ can be used. Therefore, the energy coverage of biogas production can be expressed solely in terms of the KPIs for nutrient loss, water consumption, and energy consumption.

Figure 8 shows a mapping of the energy coverage of biogas production for fluid milk processing. Concerning KPI values, we have considered an acceptable range to be equal to 0.7 ÷ 3.0 $\mathrm{g_{COD}/l_{WW}}$ for I_{NL} [56,59] with a mean value of 1.85. Since it is estimated that the dairy industry generates 0.2 ÷ 10 $\mathrm{l_{WW}/l_{RM}}$ [60] with a mean value of 2.5 [61], we have considered an acceptable range to be 1 ÷ 4 $\mathrm{l_{WW}/l_{RM}}$ for I_W;. For I_E, we have used the range of values in Table 2; that is, 0.11 ÷ 0.29 $\mathrm{kWh/l_{RM}}$.

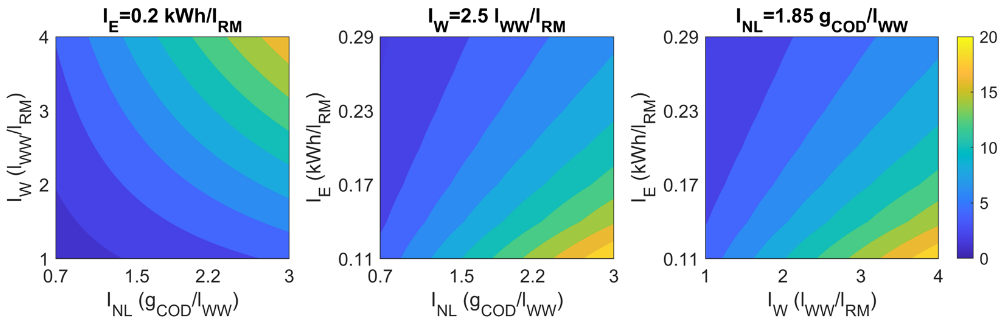


Figure 8. Maps of the energy coverage of biogas production from fluid milk wastewaters.

The maps show how the potential of biogas production significantly depends on the values of the KPIs considered. For the average value of an indicator, the other two contribute to a strong variation in the energy coverage, which ranges from about 1% to 20% in all three cases. This emphasizes the importance of a comprehensive monitoring of all the relevant KPIs, as each of them has a strong impact on the analyzed intervention. Overlooking one of them may result in missing significant improvement opportunities.

Quantitatively speaking, the results for biogas production are very promising as they show that biogas production can cover up to about 20% of the total plant energy consumption when the performance is bad, in terms of only two indicators. To consider the incidence on fossil fuel use, we should exclude electricity consumption, which ranges from 22% to 55% [55]. The relevance of this intervention increases with improvements in energy performance, testifying to the fact that solutions for the decarbonization should always be coupled to energy efficiency solutions to maximize the benefits.

The effectiveness of the results must not only be considered in terms of the promising energy potential of the solution but also in terms of the ease with which the potential can be evaluated in every different case. Thanks to this, the benefits of biogas for any dairy plant can be assessed by only considering three KPIs. This evaluation favors the implementation of this technology in the case of the identification of a significant potential, and it allows for the exclusion of this intervention and the prioritization of other energy solutions in the case of the identification of a limited potential.

In conclusion, the proposed attempt represents a straightforward early-stage energy analysis, useful for drawing stakeholders' attention to the relevance of the analyzed solution for their case. It therefore represents a starting point for more specific technical and economic evaluations aimed at the concrete implementation of the considered energy solution. This attempt represents only one example of the use of energy indicators for energy performance improvement purposes, emphasizing the promising value of these applications. Not only may it stimulate the establishment of energy indicators, but it also promotes the use of other related KPIs for comprehensive performance mapping.

5. The Establishing of Energy Indicators in Industrial Practice and Energy Policies

We have demonstrated the suitability of energy indicators for the comparison of energy performance, aimed at suggesting improvement opportunities; and the quantification of the potential of energy solutions, aimed at realizing the desired improvements.

We now provide our vision regarding the establishment of such indicators in industrial practice and energy policies, which this paper advocates. This requires widening back the horizon and dealing with the complexity of the various industrial sectors, which can be achieved only by examining the roles of the various stakeholders.

The establishment of energy indicators in industrial practice is the most straightforward. Various studies have been dedicated to this task for energy-relevant industries, with different impacts in various contexts. Sectors characterized by a small number of products and processes have seen the successful impact of energy indicators, which is because of the predominance of large corporations, which have access to more detailed and frequent energy metering and have clearly defined energy strategies [62]. Instead, sectors characterized by many products and processes are still scarce in the deployment of energy indicators, as shown in Section 4, which is because of the large presence of SMEs, for which detailed information on energy uses is rarely available [63]. The barriers preventing energy efficiency in SMEs are widely recognized [64]. Accordingly, to support the spread of energy indicators in these contexts, researchers must focus on motivating industrialists beyond these barriers [65]. A key role is played by policymakers, as they can positively contribute to triggering energy investments [66]. In this regard, policymakers could make available energy indicators for sectors in which they are still rare. This would allow industrialists to compare their energy performance with that of similar firms and to identify and set achievable energy performance targets. With the spread of process-level energy indicators, academics could direct their research efforts towards new technologies for energy-relevant processes and industrialists could direct their actions towards processes which are found to deviate from best practice in their specific case.

The establishment of energy indicators to inform energy policies is still premature, even though they require identifying, evaluating, and measuring energy performance and potential improvements [67]. Most policies refer to absolute amounts of energy consumption, despite their loss in relevance if not accompanied by indications of production [68]. Currently, energy policies focus on what is energy-consuming rather than on what is energy-intensive, i.e., on the magnitude of energy use in absolute terms rather than the magnitude of energy use relative to production. The former can help to highlight where significant amounts of energy are consumed, identifying areas of interest; it can therefore represent a guide for early-stage analyses aimed at narrowing the horizon to relevant industrial sectors, as remarked in Section 2. The latter, instead, can help to spot where an excess of energy is consumed, upon the comparison between similar productions; it can therefore represent a guide for detailed analyses aimed at identifying opportunities for energy performance improvement, as remarked in Section 3. In our vision, these two concepts are complementary and not in contrast. Accordingly, the inclusion of the concept of energy-intensive production and the consequent role of energy indicators in energy policies should be promoted. Based on the characterization of energy policies proposed in [69], the spread of energy indicators fits well with stringent and compliance-flexible policies. Stringent policies are focused on the level of compulsion and are linked to the possibility of assigning rewards and penalties to well- and poor-performing firms on a solid basis through the indicators, while compliance-flexible policies allow for a degree of discretion regarding the solution implemented and encourage the independence of energy indicators from a specific solution. The latter is essential to leave firms ample scope for improving their performance and developing innovative solutions.

To conclude, the establishment of indicator-based industrial practice and energy policies requires a step forward in the support of data as the basis for improved energy management. This entails a significant increase in energy data monitoring, but also sharing, as a key element for the evaluation of energy performance. In this regard, the intermediary role of industrial associations or consultants as third parties is crucial, as they can mediate between policymakers and industrialists. On the one hand, they can contribute to enhancing data sharing from firms to authorities, fostering the availability of best-practice indicators, which are essential for setting targets regarding energy performance. On the other, they can ensure confidentiality in this process, so as to not to discourage companies from providing reliable and detailed data.

6. Conclusions

An energy transition in industry is required due to several driving forces, including increased environmental awareness, the rising energy prices, the need to contrast delocalization pushes, and the very topical issue of energy security.

As the heterogeneity of industrial sectors represents a major barrier to this process, we have provided a detailed characterization of the industrial energy dimension, pointing out similarities among sectoral energy mixes and end-uses as determinants of transition pathways.

To enable such pathways, the availability of suitable tools is required. In order to be applicable to a large number of industrial sectors and relevant for various industrial stakeholders, solutions pose trade-offs between comprehensiveness, ease of use, robustness, and generalization ability. In this regard, we have identified energy indicators, and physical indicators, as appropriate tools because of the confluence in them of the energy and production dimensions. Accordingly, we have provided an overview of critical issues in their development and deployment, and of applications for energy performance evaluation and improvement, with examples from a representative industrial branch: the dairy processing industry.

We have remarked the prematurity of energy indicators in this branch by suggesting the extension of benchmarking applications from processes and products to also encompass production modes. We have also demonstrated the effectiveness of energy indicators in the quantification of the potential of energy solutions through the enhancement of dairy wastewaters for biogas production.

Given the promising potential of energy indicators, we have discussed what is required for their establishment in industrial practice and energy policies. Cooperation and a propositional attitude for all the industrial stakeholders emerge as strong enablers because of the intertwined role of the stakeholders. To promote a rigorous approach to energy where it is still lacking (mainly in non-energy-intensive sectors and energy policies), it is important to introduce the concept of energy performance to support the convergence between the energy and production dimensions.

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Nomenclature

I	Indicator
LHV_{CH_4}	Methane Lower Heating Value
r_{CH_4}	Rate of production of methane equivalent
Subscripts	
E	Energy consumption
NL	Nutrient Losses
W	Water consumption
Abbreviations	
C	Construction
COD	Chemical Oxygen Demand
CP	Chemical and Petrochemical
FBT	Food, Beverages, and Tobacco
IS	Iron and Steel

KPI	Key Performance Indicator
M	Machinery
MQ	Mining and Quarrying
MTE	Machinery and Transport Equipment
NES	Not Elsewhere Specified
NFM	Non-Ferrous Metals
NMM	Non-Metallic Minerals
O	Other end-uses
OTH	Other sectors
PC	Process Cooling
PH	Process Heating
PPP	Paper, Pulp, and Printing
RM	Raw Milk
SC	Space Cooling
SH	Space Heating
SME	Small and Medium Enterprises
TE	Transport Equipment
TL	Textile and Leather
TOT	Total for all the sectors
WW	WasteWaters
WWP	Wood and Wood Products

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