DEFINITION OF NEW TECHNICAL-ECONOMIC PERFORMANCE INDICATORS TO BETTER MONITOR THE PRODUCTION EFFICIENCY OF WINERIES

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Abstract. One of the most difficult but useful and necessary activities in an industrial context is monitoring the energy efficiency of the entire production layout, particularly of a wine-making plant. Generally, an analytical approach cannot be used because it would require knowledge of all subsystem efficiencies and energy absorptions, as well as of the interconnection schemes (series and parallels). Another possibility is carrying out a rough check on the overall output(s), disregarding the individual phases. This approach is particularly helpful for management audits and operational monitoring, as it allows calculating the most typical Energy Performance Indicator (EnPI), i.e. the "energy used to produce a unit of product" (in kWh·hL-1 of unpacked wine or kWh per 0.75-L-bottle). Nonetheless, this EnPI is not sufficient to carry out precise energy efficiency actions throughout the entire wine production process. However, if this EnPI is supplemented by other KPIs-Key Performance Indicators, it becomes possible to carry out more thorough and targeted evaluations regarding the efficiency of individual macro-phases within the process. Consequently, starting from a mathematical approach considering coefficients using all possible combinations (standard coefficients – SCs) of inputs and/or outputs (240 with both input and output factors + 226 having only input or only output factors), a set of 3 supplementary KPIs has been formulated, aiming at refining and accelerating the assessment of energy efficiency in the processes within the wine industry.

Keywords: winemaking sector, performance indicator, standard coefficient, wine production processes, productive inputs/outputs.

Introduction

A production system (PS) can be defined as an organized ensemble of resources, processes, personnel, and technologies that collaboratively work to manufacture goods or provide services [1]. These systems play a pivotal role in economic and industrial contexts as they represent the mechanism through which companies generate value. The complexity, scale, and technological deployment of PS can significantly vary depending on the type of product or service, and on the industry sector. Inputs constitute the essential resources required for the production of goods or services, which may encompass raw materials, energy, data, skills and human labour, in addition to information and technologies. The transformation process lies at the core of PS, where inputs are converted into outputs. Albino et al. [2–5] have developed specific input-output models for companies aiming to track productive activities. These models are designed to analyse and quantify the flows of energy and materials, including the consumption and use of fuels as well as the generation of pollutants throughout the entire supply chain of a final product. Within this schematization, it is therefore possible to identify material flows joining to or departing from the diagram describing the succession of steps that raw materials gradually follow to become finished products. Indeed, with reference to the type of the production process and the technological diagram that describes it, we can identify three main reference patterns [6] (Fig. 1):

- *Single-line production processes*; in these, the output of one production station enters the next station, excluding the waste; it is typical of process plants;
- *Synthetic or convergent pr. processes*; the final product is created by assembling a series of components/sub-products; it is typical of manufacturing-type production;
- *Analytical or divergent pr. processes*; in this category of production systems, a single raw material is used to obtain several products.

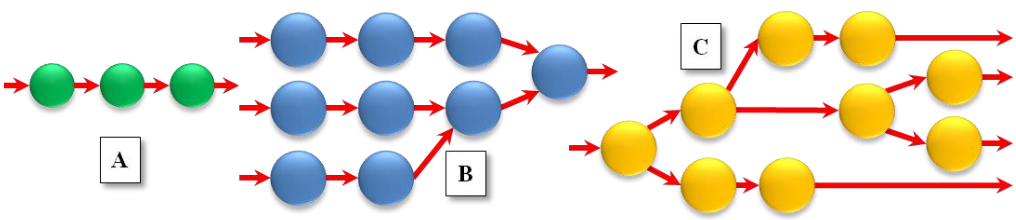

Fig. 1. **Examples of reference patterns for productive systems:**
A – single line; B – convergent or synthetic; C – divergent or analytical

Beyond the academic classification proposed here, real cases generally see a more complex and, in some ways, more nuanced situation among those proposed here, even in the case of the so-called monoline production process (i.e. a pattern normally referred to when dealing with wine production processes). In fact, a rather common situation in production involves the use of some materials, known as "*auxiliary materials*", different from the raw material (s) that, suitably transformed, will then give rise to the finished product (or the prevailing mass part thereof). These auxiliary materials enter at several points in a generic production process to perform different functions, for example: aiding the main process reactions (e.g. catalysts, chemical starters, polymerisers, cross-linkers), reacting with the work-in-progress (passivators, oxidisers), aiding the filtration of a liquid product (diatomaceous earth, flocculants), performing a chemical correction (acidifiers, basifiers, stabilisers), modifying the interface properties (encapsulators, release agents, protectors). The containers themselves can also be seen as functional input materials for the obtained finished product, which in this case consists of the container and its contents, sold together and not separately. In wine production processes, it is possible to have the following as auxiliary materials: starter yeasts, diatomaceous earth (kieselguhr), flocculants, stabilisers (sulphur dioxide), sugar, wood chips, ethyl alcohol, activated carbon, glass bottles. Similarly, other, waste materials must be removed from the main production line. The most common removed material is water (not necessarily in the liquid form), which is obtained, for example, from drying, concentration, freeze-drying processes. Waste materials in oenology, instead, include both materials remaining after the processes undergone by the raw material, and third-party materials functional to the technological cycle: stalks, grape seeds, skins (obtained from the first pressing or after maceration), fossil flours following filtration (hence, enriched by impurities), lees.

Within wine industry, PS is a coordinated set of processes, techniques, resources, and technologies used for wine production, from vine cultivation to the bottling of the finished product. This system begins with an appropriate vineyard management, where the foundation for wine quality is laid through the selection of grape varieties, the crop care and the harvesting. This is followed by wine production, i.e. chemical-physical process to transform grapes into wine, involving stages of crushing, fermentation, clarification, stabilization, and maturation. Finally, the process concludes with bottling and marketing, to prepare the wine for sale and distribution to consumers. Throughout the wine production process, there are numerous types of inputs (e.g. grapes, must, energy, etc.) and outputs (e.g. bulk wine, bottled wine, etc.). Among these, energy inputs, both electrical and thermal, play a significant role in the sector, especially when improving consumption efficiency. The understanding of where and when energy is required is a critical activity for identifying opportunities to reduce energy usage and implement more sustainable practices. In this context, the "TESLA" project [7] served as a benchmark in the analysis of energy consumption in red-wine-making companies in Italy, France, Spain, and Portugal. These audits enabled the characterization of the typical energy requirements of a winery. However, it has been noted that further in-depth analysis is necessary to characterize the energy consumption associated with white wine production. The adoption of straightforward methodologies, such as the two-factor analysis model [8] or the analysis of energy performance indicators (EnPIs), particularly the *specific energy consumption* (SEC) based on the ratio of kWh to hL of wine produced, emerge as key strategy for assessing and monitoring the energy performance of wineries over time, also allowing comparison between different production realities when appropriately classified according to their production reference models [9]. The variability in SEC data among companies of different sizes indicates the presence of non-linear scale effects on the overall energy consumption [10; 11] and underscores the importance of considering each company's specificities when assessing energy efficiency [9]. Improving energy efficiency in wineries is a complex process that requires careful analysis of energy consumption and the implementation of targeted strategies. EnPIs and SEC play a key role in assessing energy performance and benchmarking across different production realities. However, the data variability and the lack of in-depth studies on the applicability of these indicators in the wine sector highlight the need for further research.

Therefore, the aim of this study is to investigate, from a theoretical point of view, what and how many possible operational indicators might be for a company involved in various ways in wine production. The starting point is the analysis of the input or output materials (input and output) in relation to the main production process and the definition of some reference-type of wine-making companies.

Materials and methods

In general, if a part of the production process were ideally to be enclosed with a (virtual) *control surface*, isolating some process steps (and machines), it would still be possible to highlight input and output flows that would be of interest both from a technological/industrial and economic point of view. In fact, the entire transformation cycle from a raw material (e.g. of agro-food origin, as could be the grape) to a finished product (which will then be placed on the market; as could be the case for wine) may not necessarily be carried out by a single company. There are, in fact, many companies that, for technical reasons (e.g. availability of technologies, processed volumes/quantities) or economic/territorial reasons (it is more convenient to carry out the final transformations in areas where this can distinguish the product), only carry out some transformations, thus connoting themselves as *business-to-business* ("B2B") companies (Fig. 2) or *business-to-consumer* ("B2C") companies (i.e. whose output is destined to be sold to final users, instead of other companies).

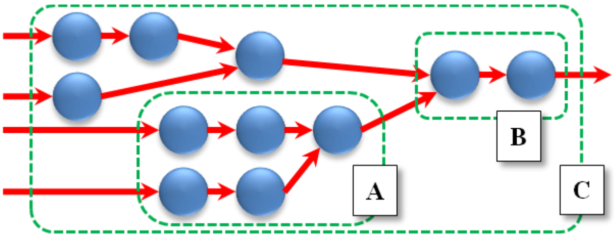

Fig. 2. **Three different companies involved in various ways in the same production cycle:** A – B2B company, selling semi-finished products to other companies; B – B2C company performing only the final phases of the whole process; C – B2C company performing the whole processing cycle)

In this logic, it is possible to characterise any company from the point of view of the transformations taking place in it by defining the generic structure of a "*standard coefficient*" (SC), which relates pairs of input and output quantities. Such a coefficient is related to the goodness of the transformations carried on by a company ("*how much output is obtained from a given input*", "*how much input is needed to obtained a set output*") and, therefore, can be regarded to as a key performance coefficient (KPI), very useful for comparisons between similar companies. Thus, it is always configured as a *ratio* between absolute quantities of incoming material/energy (I_i, at the denominator) and outgoing material/energy (O_j, at the numerator), referred to a time interval Δt of interest (this is SC_{abs}). As the choice of the input and output quantities to relate together is arbitrary, the SC_{abs} indicates a family of $n \times m \times 2$ coefficients (n: number of input quantities; m: number of output quantities; the factor 2 includes also the inverse fractions in the total number of possible combinations):

$$SC_{abs} = f\left(Input_i, Output_j\right)_{\Delta t} = \left.\frac{Output_j}{Input_i}\right|_{\Delta t} = \left.\frac{O_j}{I_i}\right|_{\Delta t} \quad \text{with} \begin{cases} 1 \le i \le n \\ 1 \le j \le m \end{cases}. \tag{1}$$

Similarly, it is possible to define other $n \times m \times 2$ performance coefficients (SC_{fl}) by carrying out a ratio between flows and thus, mathematically speaking, time-derivatives of absolute quantities (volumetric/mass flow rates, production capacities, transport capacities, powers):

$$SC_{fl} = f\left[\frac{d}{dt}\left(Input_i\right), \frac{d}{dt}\left(Output_j\right)\right] = \frac{d\left(Output_j\right)/dt}{d\left(Input_i\right)/dt} = \frac{\dot{O}_j}{\dot{I}_i} \quad \text{with} \begin{cases} 1 \le i \le n \\ 1 \le j \le m \end{cases}. \tag{2}$$

Both in SC_{abs} and in SC_{fl}, the two quantities/flows can have or not the same physical dimensions. If yes, that *SC* can be expressed as a dimensionless number or a percentage (the thermodynamic efficiency η_{th} of a system is one of these cases) and, depending on the two chosen quantities, the ratio may also not be limited to 1 (or 100%), as for η_{th}. Amongst the coefficients that relate non-homogeneous quantities in the winemaking sector, there is also the "*energy used to produce a unit of product*" (SEC, expressed in $kWh \cdot hL^{-1}$ of unpacked wine or kWh per 0.75-L-bottle). This is probably the most used EnPI in the oenological sector for B2C companies, even if it can be misleading if used for comparisons without any criticism. Indeed, as evidenced before, the extension of the boundary of the control surface (hence, the number of upstream phases of the winemaking process performed by a considered company) can be placed freely.

Results and discussion

1. Use of the inputs and outputs to individuate all possible companies in the market

With reference to the different possible inputs and outputs (or "productive factors") in the red/white winemaking cycle (Fig. 3), there are *four possible input products* (I_1 = grapes, in q; I_2 = must, in hL; I_3 = still wine, in hL; I_4 = overpressure wine, in hL) and *four possible output products* (O_1 = must, in hL; O_2 = bulk still wine, in hL, O_3 = bulk overpressure wine in hL, O_4 = bottled wine in hL). Graphically speaking, the incoming and outgoing flows of interest cross the border that encompasses the entire main production line from grape to wine.

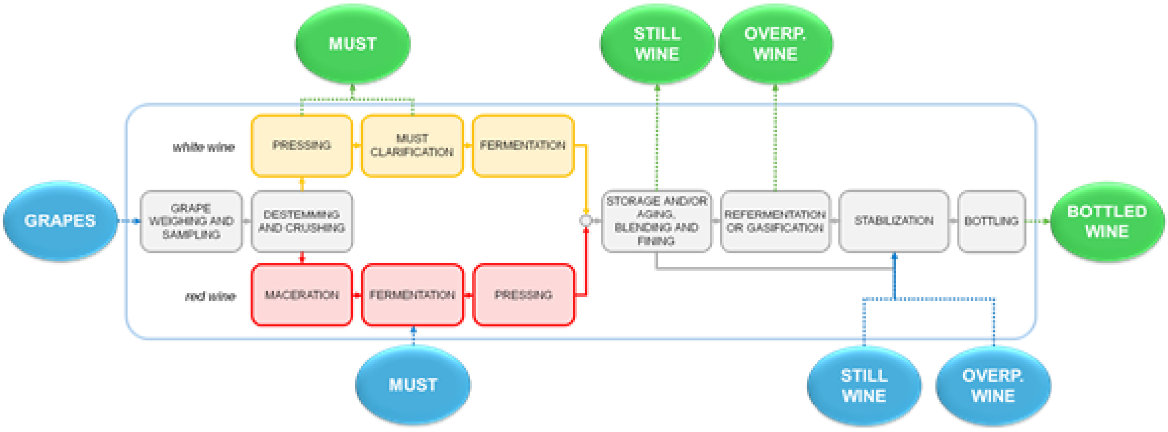

Fig. 3. **Winemaking cycle:** blue background – inputs; green background – outputs

If a generic company can have indifferently from 1 to 4 inputs and from 1 to 4 outputs, mathematically speaking, it is possible to have a total of 225 theoretical possibilities, as reported in the following Table 1. The reference formula to obtain the combinations of inputs and outputs is the formula of combinatory calculus to calculate the number of "*combinations of n objects* (here: factors) *taken k at a time without repetition*": $C_{n,k} = n!/[k!/(n-k)!]$. Notice that not all possible I/O combinations are really present on the market; in particular, only 7 of them are really present on the market. This number can be raised to 11 if considering also the two alternative processes to create a sparkling wine, i.e.: (1) refermentation (in autoclaves or bottles) or (2) gas addition (by means of dedicated equipment).

Table 1

Possible companies defined from the number of inputs and outputs crossing the control surface that includes the process steps performed by a company. The number between brackets indicates a further distinction beyond the only choice of the inputs and outputs, based on the process to create sparkling wine (refermentation or gas addition)

Number of Inputs	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Number of Outputs	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4
Input combinations	4	6	4	1	4	6	4	1	4	6	4	1	4	6	4	1
Output combinations	4	4	4	4	6	6	6	6	4	4	4	4	1	1	1	1
Theoret. I/O com.	**16**	**24**	**16**	**4**	**24**	**36**	**24**	**6**	**16**	**24**	**16**	**4**	**4**	**6**	**4**	**1**
Real I/O com.	**1(2)**	**1**	**-**	**-**	**-**	**2(3)**	**-**	**-**	**-**	**-**	**1(2)**	**1**	**-**	**-**	**-**	**1(2)**

2. Use of the standard coefficients to define all possible performance indicators

With the four above-indicated inputs (n = 4) and the four above-indicated outputs (m = 4) for a winemaking company, it is possible to define 4×4×2 = 32 "simple" SC_{abs}, i.e. relating a single input to a single output, and up to 104×2 = 208 "composite" SC_{abs}, for a total of 32 + 208 = 240 possible SC_{abs} with both input and output factors. Composite SC_{abs} have the following structure (or the inverse of it, and this explains the "×2" in the counts above):

$$SC_{abs} = f\left(Input_i, Output_j\right)_{\Delta t} = \left.\frac{\sum_j Output_j}{\sum_i Input_i}\right|_{\Delta t} = \left.\frac{\sum_j O_j}{\sum_i I_i}\right|_{\Delta t} \quad \text{with} \begin{cases} 1 \le i \le n \\ 1 \le j \le m \end{cases}. \tag{3}$$

The total number of composite SC_{abs} takes into account that the summations can include:

- one, two, three or four terms as regards the outputs, as they are all dimensionally homogeneous (indeed, they are all expressed in hL);
- one, two or three terms as regards inputs expressed in hL (I_2, I_3, I_4), or alternatively, of only one term if the input considered is grapes (I_1), expressed in q.

Table 2

Count of possible composite SC_{abs} starting from the indicated number of inputs and outputs included in the summations. This single input indicated with the asterisk is I_1, i.e. the grapes; as it is in q, it cannot be summed to other inputs

	I_2, I_3, I_4 in the sums											I_1 alone		
No. of Inputs in the sum	2	3	1	2	3	1	2	3	1	2	3	1*	1*	1*
No. of Outputs in the sum	1	1	2	2	2	3	3	3	4	4	4	2	3	4
Input combinations	3	1	3	3	1	3	3	1	3	3	1	1	1	1
Output combinations	4	4	6	6	6	4	4	4	1	1	1	6	4	1
Theoret. I/O com.	12	4	18	18	6	12	12	4	3	3	1	6	4	1

It is also possible to define some SC_{abs} using inputs only or outputs only, thus obtaining other 42 + 14 + 210 = 266 possible SC_{abs}. To arrive to this final number:

- for SC_{abs} using only terms from the input set, it is necessary to distinguish between SC_{abs} using only I_2, I_3, I_4 (a total of 42 SC_{abs}, with sums up to 3 terms at the numerator or at the denominator) and SC_{abs} having only I_1 at the numerator or at the denominator, and having respectively sums of up to 3 terms (with only I_2, I_3, I_4) at the denominator or at the numerator, respectively (other 14 SC_{abs});
- for SC_{abs} using only terms from the output set, there could be up to four terms at the numerator or at the denominator (for a total of other 210 SC_{abs}, excluding the 4 + 6 + 4 combinations with 1/1, 2/2 and 3/3 terms that are equal).

Table 3

Count of possible composite SC_{abs} using only inputs in the summations at the numerator and denominator, excluding the combination with the same terms at the numerator and at the denominator (corrected number outside the brackets). The ones with asterisks indicate the input I_1 (not to be summed to other inputs)

	I_2, I_3, I_4 in the sums								I_2, I_3, I_4 in a sum, I_1 alone					
No. of Inputs in sum-num	1	2	3	1	2	3	1	2	1	2	3	1*	1*	1*
No. of Inputs in sum-den	1	1	1	2	2	2	3	3	1*	1*	1*	1	2	3
Input combinations-num	3	3	1	3	3	1	3	3	3	3	1	1	1	1
Input combinations-den	3	3	3	3	3	3	1	1	1	1	1	3	3	1
Theoretical com.	(9)6	9	3	9	(9)6	3	3	3	3	3	1	3	3	1

Table 4

Count of possible composite SC_{abs} using only outputs in the summations at the numerator and denominator, excluding the combination with the same terms at the numerator and at the denominator (corrected number outside the brackets)

No. of Outputs in sum-num	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
No. of Outputs in sum-den	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4
Output combinations-num	4	6	4	1	4	6	4	1	4	6	4	1	4	6	4
Output combinations-den	4	4	4	4	6	6	6	6	4	4	4	4	1	1	1
Theoretical com.	(16) 12	24	16	4	24	(36) 30	24	6	16	24	(16) 12	4	4	6	4

Taking into account the existence of only 11 possible winemaking companies and, thus, the significance of SC_{abs} definable for them [9], the following three coefficients, all defined with reference to a time period of one year, are hence proposed: $SC_{abs,1}$ from the first set of 240 SC_{abs} having both input and output factors, $SC_{abs,2}$ and $SC_{abs,3}$ from the second set of 266 SC_{abs} having only input or only output factors.

$$SC_{abs,1} = f\left(I_2, I_3, I_4, O_1, O_2, O_3, O_4\right) = \sum_{i=2}^{4} I_i \Big/ \sum_{j=1}^{4} O_j \ , \tag{4}$$

$$SC_{abs,2} = f\left(I_3, I_4\right) = I_3 \Big/ \sum_{i=3}^{4} I_i = I_4 / \left(I_3 + I_4\right), \tag{5}$$

$$SC_{abs,3} = f\left(O_1, O_2, O_3, O_4\right) = O_4 \Big/ \sum_{j=2}^{4} O_j \ . \tag{6}$$

$SC_{abs,1}$ (or "*winery outsourcing index*" – WOI) allows calculating the ratio of semi-finished input products (i.e. must, still wine, and wine with overpressure) purchased from external companies (requiring only partial processing and for which it is correct to impute partial energy consumption) over the total production of the company in exam. It is related to the energy consumption required for the processing. The complement to one of $SC_{abs,1}$ is the product entirely processed by the winery.

$SC_{abs,2}$ (or "*overpressure wine share index*" – OWSI) allows calculating the ratio of overpressure wine purchased by a winery on the sum of wine purchased from external companies (still and overpressure). For some companies processing only wine, $SC_{abs,2}$ is related to the incidence of sparkling winemaking on the total winery activity.

$SC_{abs,3}$ (or "*wine bottling index*" – WBI) allows calculating the amount of bottled wine on the total production output (bottled wine and bulk wine ready for sale) of the company in exam. $SC_{abs,3}$ is related to the packaging department activity.

Just to illustrate a calculation example for the above-defined coefficients, a winery in Northern Italy was selected as case-study. The company does not own any vineyards; instead, it purchases both grapes (average value per year: 113,229 $q = I_1$) and wine (average value per year: 33,519 hL = I_3) from external sources. Internally, the company is structured to handle all the processing phases, starting from grape reception to bottling, including fermentation and secondary fermentation. This winery primarily produces sparkling wine, but it has also a significant production of still wine. The average yearly outputs are divided as follows: 87,651 hL (75%) of bottled sparkling wine, 4,149 hL (3%) of bottled semi-sparkling wine (these two outputs together, equal to 91,800 hL, constitute O_4), 25,200 hL (22%) of bulk still wine (O_2). Over the three-year period from 2020 to 2022, the company produced about 117,000 hL of wine (all the above-listed types), with a total consumption of electricity of about 3,350 MWh. Therefore, with the declared data, it is possible to calculate for this company the following indexes:

- $SC_{abs,1}$ (WOI) = (33,519 hL/117,000 hL) = 28.6%,
- $SC_{abs,2}$ (OWSI) = (0 hL/33,519 hL) = 0%,
- $SC_{abs,3}$ (WBI) = (91,800 hL/117,000 hL) = 78.5%,
- SEC = (3,350,000 kWh/117,000 hL) = 28.6 kWh·hL^{-1}.

Conclusions

1. By observing the input and output flows for a company's production cycle, it is possible to define a series of standard performance coefficients that take the form of ratios between absolute quantities (SC_{abs}) or flows of them (SC_{fl}), taken individually or as a sum.
2. After having identified 4 possible inputs and 4 outputs from the wine production cycle (not always present all together), it is possible to define up to 225 theoretical I/O combinations, which can define as many types of companies involved in various ways in the overall production cycle leading from grapes to wine (i.e. with different degrees of internalisation of the production phases). Of these, it has actually been found that there are only 11 types.
3. Similarly, it is possible to define 240 SC_{abs} having both input and output factors, and other 266 SC_{abs} having only input or only output factors. Of all the possible coefficients, 3 in particular are proposed (namely: the "*winery outsourcing index*", the "*overpressure wine share index*", the "*wine packaging index*"). These are very useful to compare different companies on the technological level, energy

consumption, energy efficiency (global and of specific phases) and related costs. In the authors' intentions, these three coefficients should be used from now on, in particular beside the usual index "*energy used to produce a unit of product*" (SEC).

Author contributions

Conceptualization: MB, GC, AZ; Data curation: MB, GC, AZ; Formal analysis: MB, GC, AZ; Funding acquisition: RG, RZ; Investigation: MB, GC, AZ; Methodology: MB, GC, AZ; Project administration: RG, RZ; Resources: MB, GC, AZ, RG, RZ; Software: MB, GC, AZ; Supervision: RG, RZ; Validation: AZ; Visualization: MB, GC; Writing – original draft: MB, GC; Writing – review & editing: AZ.

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