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Energy Assessment of Pastoral Dairy Goat Husbandry from an Agroecological Economics Perspective. A Case Study in Andalusia (Spain)

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Abstract: This paper presents a methodological proposal of new energy sustainability indicators according to a novel accounting that follows agroecological and ecological economics criteria. Energy output is reformulated to include manure and thus consider the contribution to fertilization made by pastoral livestock farming to agroecosystems. Energy inputs calculations include the grazing resources. These new definitions and calculations allow for new formulations of the energy return on investment (EROI) as measures of the energy efficiency of livestock farming systems (final EROI and food/feed EROI). The environmental benefit of manure is estimated from the avoided energy cost of using this alternative to inorganic fertilizers (AEC_M). The environmental benefit of grazing is measured through the energy cost of avoiding cultivated animal feed (AEC_P) and its impact in terms of non-utilized agricultural area (ALC_P). The comparative analysis of different livestock breeding systems in three pastoral dairy goat farms in the Sierra de Cádiz in Andalusia, southern Spain, reveals the analytical potential of the new energy sustainability indicators proposed, as well as the potential environmental benefits derived from territorial-based stockbreeding and, more specifically, grazing activities. Those benefits include gains in energy efficiency, a reduction of the dependence on non-renewable energy, and environmental costs avoided in terms of energy in extensive pastoral systems.

Keywords: sustainability; EROI; avoided costs; food/feed competition; pastoral farming; ecological economics

1. Introduction

The increasing demand of livestock products and the search for an increase of livestock productivity have induced the rapid transition of livestock breeding systems from pastoralism into intensive systems. This search for livestock productivity has been based on the genetic selection of improved breeds to the detriment of indigenous ones adapted to the various agroecosystems and on the change in animal feeding associated to the growing tendency to house the livestock. Extensive livestock husbandry systems and their traditional use of pastures have been substituted by high livestock density or even landless systems with an intensive diet. These systems are dependent on the globalized supply of corn and soybean or other grains produced by export monocultures in lands that could be used to provide human food or occupied by old-growth forests functioning as irreplaceable

carbon sinks [1]. This intensification has led to a separation of livestock and territory, a process that is interrupting nutrient flows and causing soil organic matter depletion in the territories where animal feed is originally produced, often also generating pollution in the place where the livestock is housed [2]. Direct environmental impacts of this process include groundwater pollution, the increase of anthropogenic greenhouse gas emissions [3,4], concentration of polluting waste [5], and growth of energy consumption [6]. Indirect impacts, most of them related to animal feeding, are also to be considered, including deforestation, soil erosion, and loss of biodiversity [7], particularly in the main intensive agricultural regions [8]. Therefore, the initial hypothesis of the present work is that the global disconnection of crops and livestock from pasturable resources implies a lack of efficiency in the use of natural resources and a greater environmental impact of confined livestock farming [9].

Within the debate on sustainability, energy is a central and cross-cutting element affecting all economic activities [10–12], especially in a context of oil depletion and climate change [13], that urges a move toward food provision systems based on renewable energy, low energy intensity, and rates of energy return above the unit [14]. Therefore, the fostering of decision-making processes favoring energy sustainability require to develop new analytical methodologies and indicators that allow understanding and evaluating, in a comparative way, the energy-environmental implications of technology and production-related decision-making within farms. Energy indicators, as well as sustainability indicators, operate to make visible the potential environmental benefits derived from energy efficiency, and consider energy and material flows that are usually neglected. These tools need to be particularly adaptable to management specificities in the agro-livestock systems that are being analyzed [15].

This paper develops and implements a series of indicators specifically designed for the study of goat farming sustainability (Final energy return on investment—EROI, NR Final EROI, Food/feed EROI, etc.). These indicators allow the energy implications of the different types of management associated with this activity to be assessed and compared, focusing mainly on the role of animal feeding and the use of pasturable resources. The livestock farm, understood as a techno-productive and economic decision-making entity, is therefore the unit of analysis. An agroecological approach is applied that views stockbreeding as part of a complex agroecosystem exchanging energy flows with other natural and social systems [16,17]. From this point of view, the socialized output is a fraction of the total output intended to meet human needs mostly through the market. However, the total output is a broader factor that includes internal energy flows, some of them with no direct human-oriented purpose, but potentially contributing to ecological balance, like manure. This agroecological approach allows bringing to light and analyzing the internal energy flows between pastoral agroecosystems and the use of manure, both of which are central elements of the energy and biophysical metabolism of livestock husbandry, even if they have no market value or direct and immediate human-oriented use. In addition, from an ecological economics approach, new indicators are proposed to identify and make visible the avoided energy costs associated with pastoralism (“avoided energy cost of manure” AEC_M or “avoided energy cost” and “avoided energy land cost” of natural pasture AEC_P and ALC_P).

Energy analyses based on indicators, such as the EROI (energy return on investment), allow measuring of the energy efficiency of agriculture. This important analytical tool provides valuable information on the energy cost of producing food and feed [18,19]. However, different authors have recently criticized the insufficiency of this conventional approach, which reproduces the cost-benefit logic in terms of energy and treats agricultural systems as unexplored black boxes, ignoring internal energy flows that do not enter the market, but are crucial for the ecological balance of the agroecosystem [17]. In the case of livestock husbandry, for instance, pastoralism enables using the biomass produced by agroecosystems and largely reincorporating it into the systems in the form of organic fertilizer. These internal energy flows, which are not usually taken into consideration, contribute to maintaining the structure and functions of the ecosystem and, therefore, sustain the flow of ecosystem services [20]. In particular, manure is a central element of the nutrient flow within the agroecosystem and of the soil structure, despite the loss of energy in the form of heat

during the decomposition process. Manure is a crucial contribution to the net primary biomass and energy production of the agroecosystem in different production cycles over time. To overcome economicism, recent agrarian energy studies have suggested the implementation of an agroecological approach to analyze the complexity of the systems' biophysical interactions, exchange of flows with the environment, and potential environmental benefits, independent of their market orientation, as well as to widen the understanding of the recirculation of internal flows generated by agroecosystems (see [16]). However, even if some previous studies have analyzed the use of energy in livestock husbandry activities [21,22] and in the production of cow milk [6,23,24] or goat milk [25], very few works have adopted this agroecological approach to evaluate the use of energy in livestock farming systems [26].

On the other hand, the scarcity of energy resources in economic processes is a central element in the analysis of energy viability. By applying an ecological economics approach [27], this scarcity can be analyzed in terms of "biophysical opportunity cost". The concept of opportunity cost, proposed by the Austrian marginalist school at the end of the 19th century, refers to the benefit or monetary revenue that is waived when choosing one use among the different possible uses of a resource. Thus, the biophysical opportunity cost is especially relevant in conflicts between alternative human uses, whether there is a monetary value attached to them or not [28]. For instance, in energy analyses of agriculture, the solar energy used during photosynthesis is often considered a "free" input, i.e., a resource with no opportunity cost that cannot be depleted or degraded by human use [29]. This "free-of-charge" concept of solar energy introduces a moderate anthropocentric bias in energy use analyses and allows the EROI to reach a value that is above the unit. Along those lines, the energy input of natural pasture, contributed through grazing, has no biophysical opportunity cost and may also be considered a free input because it is not digestible for human beings and its use for livestock feeding is not competitive in these terms. However, in contrast with the solar flux, an improper management of pastures, for instance through overgrazing, may indeed deplete or degrade the resource by exceeding its bearing capacity. In this sense, pastures should not be considered unlimited and freely available economic resources, but the biomass generated by them and used by the livestock can be conceptualized as a resource without any human biophysical opportunity cost in relation to the food/feed debate.

On the contrary, the use of grains for animal feeding has a clear human biophysical opportunity cost, given that grains can be destined to human consumption. Thus, food/feed competence is one of the central debates around the sustainability of livestock husbandry [30]. Devoting energy resources that are edible for human beings to livestock feeding reduces the energy efficiency of animal food production as compared to that of agricultural systems. On average, the net energy used by ruminants for maintenance, milk production, and fattening amounts to 41%, 34%, and 25% of the gross energy ingested by them, respectively [31]. In addition to the energy cost, the production of fodder has a biophysical opportunity cost in terms of territory. The livestock breeding industry is not only responsible for 18% of the greenhouse gas emissions [32,33], but it also accounts for 80% of the total anthropogenic land use, with grazing land for ruminants covering about 70% of the global agricultural land, and feed crops occupying 34% of the global cropland [34].

Finally, another relevant concept to be integrated in energy analyses of livestock husbandry is the "avoided cost". The avoided cost allows the identification of the benefits derived from choosing one alternative instead of another. In the field of environmental economics, this concept was initially proposed as a monetary indicator [35] and it has been recently reinterpreted from the biophysical perspective of ecological economics. Thus, for instance, Arto et al. [36] have measured the emissions avoided by international trade in Spain, while Ruisheng et al. [37] have quantified the avoided environmental impacts of recycling wood waste in Singapore. The present work suggests applying the concept of avoided cost to manure and natural pasture. The use of manure as fertilizer avoids the environmental cost of using the energy equivalent of inorganic fertilizers [29]. The energy accounting of manure is, in addition, a measure of the potential environmental benefit of incorporating biomass

to the agroecosystem. The use of natural pastoralism avoids the energy costs associated with the production of livestock feed [38], in addition to reducing pressure on the cropland.

This article has the general objective of proposing new energy sustainability indicators for livestock husbandry, particularly goat farming, according to the above-defined theoretical premises. More specifically, it proposes indicators that allow the highlighting and assessing of the potential environmental benefits derived from the sustainable use and management of manure as organic fertilizer and from animal feeding based on the sustainable use of pastures. Empirical evidence is presented for the three productive goat farms studied. Analyzing these farms, located in the Sierra de Cádiz Natural Park, and presenting different levels of extensiveness makes it possible to demonstrate the analytical possibilities of the sustainability indicators proposed.

2. Materials and Methods

2.1. System Boundaries and Functional Unit

The energy analysis performed in this work applies a “cradle-to-farm gate” approach. The livestock standard unit (LSU) (one goat = 0.15 LSU) and one liter of milk are the two reference units selected to express the results. The analysis is articulated into three levels of study (adapted from [39,40]) (Figure 1). Level 1 measures the consumption of indirect energy, particularly the energy cost of producing and transporting the inputs and capital used during the livestock production process. More specifically, the indirect energy associated to the consumption of feed concentrates, fodder, electricity, diesel, lubricants, phytosanitary materials, plastics, tools, fertilizers, and seeds has been quantified. As for capital, the energy related to the amortization of machinery and the repairing and maintenance of fixed capital has also been calculated. Level 2 quantifies the energy directly consumed at the farm: (a) The one associated to the consumption of diesel, electricity, feed concentrates, fodder, and labor; and (b) the one related to intra-farm consumption or internal energy flows (manure, feed, grazing inputs, etc.). Level 3 corresponds to the farm’s socialized energy output.

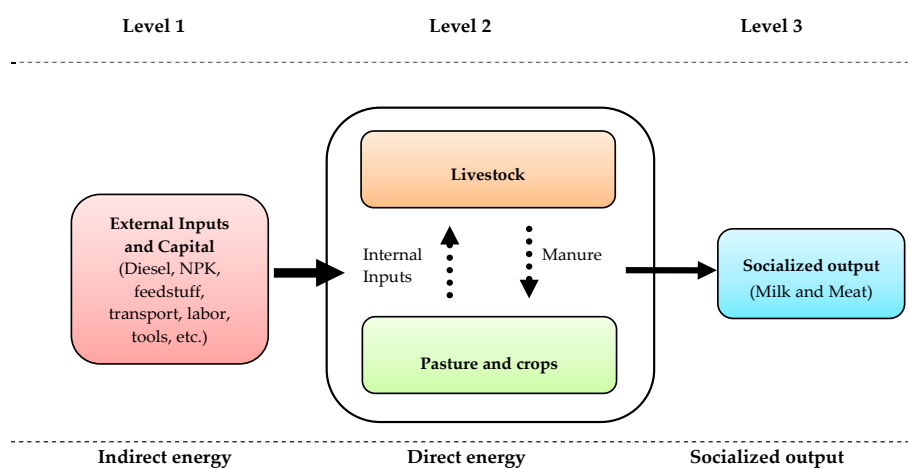


Figure 1. System boundaries of the energy analysis: Cradle-to-farm gate approach.

2.2. Indicators of the Use of Energy in Livestock Farms

2.2.1. EROI and Energy Input-Output in Livestock Systems: Conventional Approach

Following the agricultural analysis approach and using animal science definitions (Appendix A), the gross energy contained in commercialized livestock products (milk and meat) is taken as a reference to estimate the energy output (Equation (1)). Regarding the inputs, the external energy input includes the energy coming from outside that is directly or indirectly used in livestock husbandry systems (Equation (2)). Direct energy is that which, although generated outside the farm, is consumed in it

during the livestock production process (electricity, diesel, human labor, feed, etc.), while indirect energy stands for the energy cost of fabricating the consumable goods employed in the management of the farm (fodder, diesel, fertilizers, etc.). Efficiency in the use of external inputs in relation to the socialized output is measured through the indicator, “external EROI” (Equation (3)).

$$\text{Socialized output} = \sum \text{Livestock output}_{(p)} \text{ (kg LSU}^{-1}\text{)} \times \alpha_{(p)}^{-1} \text{ (MJ kg}^{-1}\text{)} \quad (1)$$

$$\text{External energy input} = \sum \text{External input}_{(j)} \text{ (unit LSU}^{-1}\text{ or L}^{-1}\text{)} \times \beta_{(j)} \text{ (MJ unit}^{-1}\text{)} \quad (2)$$

$$\text{External EROI} = \text{Socialized output (MJ LSU}^{-1}\text{)} \times \text{External energy inputs}^{-1} \text{ (MJ LSU}^{-1}\text{)} \quad (3)$$

where livestock output_(p) = milk + meat; $\alpha_{(p)}$ is the energy equivalent of the product, p (MJ kg⁻¹); external input_(j) = feed concentrates, fodder, electricity, diesel, lubricants, phytosanitary material, plastics, tools, fertilizers, seeds, machinery, and labor; and $\beta_{(j)}$ is the energy converter, including the direct and indirect energy of the input, j .

2.2.2. Energy Indicators for Livestock Systems: An Agroecological Approach

Indicators 1, 2, and 3 analyze the energy inputs and outputs of farms considered as “black boxes” because the internal energy flows, i.e., the intra-farm consumption of biomass is excluded [17]. In the specific case of livestock farming, the following energy flows are neglected: (a) The increase/decrease in the number of livestock units and manure, which can in fact be included as part of the energy output of the livestock system (Equation (4)); and (b) the farm’s own crops (whether consumed indoors or through grazing) and natural pasture consumed during grazing, which can be accounted as part of the input (Equation (5)). Manure is considered an energy output due to its potential use as fertilizer, either directly during grazing or through management and reincorporation in the case of housed livestock. In systems where manure cannot be used, it should not be considered. In all cases, the energy costs associated with manure management must be accounted (transportation, labor, capital, etc.). The agroecological redefinition of output, input, and energy efficiency is thus reflected in Equations (4) and (5), which generate a new energy indicator, the “final EROI” (Equation (6)). In addition, and keeping in mind these very specifications, the percentage of the livestock’s gross energy requirements covered with purchased feed is an additional energy indicator (“external feed dependence”) that allows identifying the level of intensiveness/extensiveness of the livestock management and, consequently, the level of energy dependence/autonomy of the farm [40] (Equation (7)).

$$\begin{aligned} \text{Total energy output} &= \text{Socialized output (MJ LSU}^{-1}\text{)} \\ &+ \text{Energy recovery of manure (MJ LSU}^{-1}\text{)} \\ &+ \text{Energy increase/decrease in the number of livestock units (MJ LSU}^{-1}\text{)} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Cumulative energy demand (CED)} &= \text{External energy inputs (MJ LSU}^{-1}\text{ or L}^{-1}\text{)} \\ &+ \text{Internal energy inputs (MJ LSU}^{-1}\text{ or L}^{-1}\text{)} \end{aligned} \quad (5)$$

$$\text{Final EROI} = \text{Total energy output (MJ LSU}^{-1}\text{)} \times \text{Cumulative energy demand}^{-1} \text{ (MJ LSU}^{-1}\text{)} \quad (6)$$

$$\begin{aligned} \text{External feed dependence} &= \text{Gross energy of external feed (MJ LSU}^{-1}\text{)} \\ &\times \text{Gross energy requirements of the livestock}^{-1} \text{ (MJ LSU}^{-1}\text{)} \times 100 \end{aligned} \quad (7)$$

where internal energy inputs = energy contribution to animal feed of fodder and grains grown within the farm (consumed during grazing or indoors) (MJ LSU⁻¹ or L⁻¹) + energy contribution to animal feed of natural pasture consumed during grazing (MJ LSU⁻¹ or L⁻¹).

In energy analysis, it is relevant to differentiate renewable and non-renewable energy. Renewable energy includes biomass, labor, and the proportional share of renewable energy (mainly wind, hydraulic, and solar) used to produce agrarian inputs, which are estimated based on the information provided by Aguilera et al. [41], the Instituto de Diversificación y Ahorro Energético (Institute for

Energy Diversification and Savings) [42], and the Spanish Ministry of Industry and Tourism [43]. Bearing this distinction in mind, the external energy input and CED are recalculated according to the use of non-renewable (NR) energy; hence, the energy indicators, “NR external EROI” and “NR final EROI”.

2.2.3. Efficiency Indicators and Avoided Costs Related to Management: An Agroecological Economics Approach

From an agroecological economics perspective, it is possible to estimate the avoided cost associated with the reuse of manure and the natural pasture consumed during grazing and to design new energy sustainability indicators for livestock systems. Thus, the indicator, “avoided energy cost of reusing manure” (AEC_M), is estimated as the energy cost of industrially synthesizing the equivalent amount of nitrogen (N) (Equation (8)) (adapted from [29]). The indicator, “avoided energy cost of natural pasture consumed during grazing” (AEC_P), is calculated by adding to the gross energy provided by natural pasture the indirect energy costs that would have been incurred to obtain the same amount of energy from cultivated crops (Equation (9)).

$$\begin{aligned} \text{Avoided energy cost of manure (AEC}_M) &= \text{Reused manure (kg LSU}^{-1}) \\ &\times \text{N manure (kg N kg}^{-1}) \times \text{Indirect energy of N (MJ kg}^{-1}) \end{aligned} \quad (8)$$

$$\begin{aligned} \text{Avoided energy cost of natural pasture consumed during grazing (AEC}_P) & \\ = \text{Energy contribution of natural pasture consumed during grazing (ECNP) (MJ LSU}^{-1} \text{ or L}^{-1}) & \quad (9) \\ + \text{Indirect energy of substituting the ECNP by cultivated crops (IE ECNP) (MJ LSU}^{-1} \text{ or L}^{-1}) & \end{aligned}$$

Livestock consume biomass to meet their metabolic needs and maintain growth and productivity. As argued before, the biomass consumed by livestock can be divided into that which has a biophysical opportunity cost (grains and other feed concentrates) because it can be used as human food, and that which has no such cost (fodder and natural pasture). The “food/feed EROI” indicator (Equation (10)) measures the energy efficiency of transforming edible human food into edible energy in the form of meat and milk. The use of natural pasture to feed livestock reduces competition on grains and other feed concentrates that can be included in the human diet, reducing the pressure on the cropland as well. In this sense, Equation (11) allows estimation of the last indicator, “avoided land cost of natural pasture consumed during grazing” (ALC_P), in terms of usable agricultural area (hectares) under extensive livestock management. This avoided land cost has been calculated based on the agricultural area required to produce the feed (grains, feed concentrates, and cultivated fodder) that would be necessary to substitute, in terms of energy, the contribution of natural pasture consumed by grazing.

$$\begin{aligned} \text{Food/feed EROI (F/F EROI)} &= \text{Socialized output (EO) (MJ LSU}^{-1}) \\ &\times \text{Gross energy of grains/feed concentrates}^{-1} \text{ (MJ LSU}^{-1}) \end{aligned} \quad (10)$$

$$\begin{aligned} \text{Avoided land cost of natural pasture consumed during grazing (ALC}_P) \text{ (ha)} & \\ = \text{ECNP (MJ LSU}^{-1} \text{ or L}^{-1}) & \quad (11) \\ \times \text{Energy yield of the substituted crops (j)}^{-1} \text{ (MJ ha}^{-1}) & \end{aligned}$$

where (j) = composition of the substituting crops; and energy yield = yield of the substituting crops (j) (kg ha^{-1}) \times energy equivalent (j) (MJ kg^{-1}).

2.3. Case Study, Information Gathering, and Elaboration of the Inventory

Andalusia (south of Spain) is the first goat milk-producing region in Spain and the second in Europe. According to data provided by the Spanish Ministry of Agriculture, Fisheries, Food and environment [44], it has a population of 489,814 milking goats (39% of the national population) and the 205 million liters of goat milk they produce represent 42.8% of the total Spanish production [44]. In Spain, the management of dairy goat farms has been notably intensified, although there are still a

great variety of production models, ranging from highly intensive indoor systems to pastoral systems with different levels of extensiveness [45]. Andalusia is one of the Spanish regions where there are still an important number of pastoral dairy goat farms. This production model is predominant in the Sierra de Cádiz, in particular. The sierra, which includes a natural park within its territory, lies between 36°55' and 36°41' latitude North and 5°33' to 5°11' longitude West. Its relief includes craggy areas with steep inclines and undulating areas with shallow inclines. The climate is Mediterranean, with ombroclimates ranging from sub-humid (C2B' 3s2a') to humid (B2B' 2s2a'). The average annual rainfall is 1221 mm, and the average annual temperature is 16.9 °C.

In this area, farms are mostly family-run and have an average population of 371 goats (the autochthonous Payoya breed is the genetic base). Goats kid once a year and have an average lactation period of between six and eight months. The animals are milked once a day, according to their production level. Independent of the availability of pasture and the stocking rate, the goats of this area graze throughout the whole year, although grazing intensity is higher in the spring. Herd feeding management is based on the grazing of natural grasslands, namely pastures, shrubs, and trees, but the annual average of energy requirements covered by feed provided indoors (concentrates plus fodders) varies greatly, presenting values of 41% for high-intensity grazing farms, 61% for medium-intensity grazing farms, and 91% for low-intensity grazing farms [46].

To perform a comparative analysis with the methodology presented in the previous section and to show the analytical potential of this methodology, three goat farms located in the Sierra de Cádiz, Andalusia were selected according to expert criteria focused on the non-statistical representation of the area. Farm 1 (F1) is a semi-intensive livestock farm that depends on feed purchased outside the farm and provided indoors, even though its goats are taken out to graze in cultivated pasture. Farm 2 (F2) is a semi-extensive farm where the dependence on purchased feed provided indoors is not so high and which, in addition, grows its own crops to be consumed by the livestock through grazing. Farm 3 (F3) is a semi-extensive farm that does not grow its own crops. Data were collected through monthly monitoring and personal visits to the farmers during 2011. This information was completed with data provided by the cooperatives and associations to which the farmers purchase their consumable goods and sell their products. The areas, livestock density, and inventory of the three farms are synthesized in Tables 1 and 2. Natural pasture areas are those covered with natural grassland, while mountain areas are higher and mainly covered with shrub.

Table 1. Areas and livestock density of the goat farms analyzed.

Particular	Unit	Farm 1	Farm 2	Farm 3
Area of natural pasture	ha	7	70	70
Mountain area	ha	15	665	20
Crops ⁽¹⁾	ha	6	96	-
LSU ⁽²⁾	unit	34	108	39

Where (1) cultivated area for grazing; (2) LSU = livestock standard unit, one goat equals 0.15 LSU.

Farm 1 has six hectares cultivated with a commercial blend of seeds, including *Avena sativa*, *Hordeum vulgare*, and *Triticosecale aestivium*. Farm 2 has 96 hectares where a mix of *Avena sativa* and *Vicia angustifolia* is grown. Regarding external feeding, F1 provides the animals a mixed-grain concentrate with a high protein value during the kidding period (December to February). This mix consists mainly of corn (25%), lima beans (21.8%), sunflower seeds (20%), and oats (20%). During the rest of the year, the farmer uses a high-fiber concentrate mainly composed of short-fiber dehydrated alfalfa (25%), corn distillate (15.5%), and soybean hulls (15%). As for the fodder, hay is provided between December and May, when the intensity of grazing is lower due to the kidding period, when the grazing hours are reduced, and to lower vegetation productivity. During the kidding period, cereal straw is also provided. The short-fiber dehydrated alfalfa included in the high-fiber concentrate supplied during the whole year should also be considered as fodder. Farm 2 provides the same type of concentrate as

Farm 1 all year round, although during the summer (when the energy requirements are lower because the goats are at the end of the lactation period or already dry), the contribution of this concentrate is reduced and broad beans are supplied. With respect to the use of fodder, this farm provides hay between January and June, the months during which grazing is less intensive. Farm 3 provides two types of feed during most of the year: The same concentrate used in the other two farms and another one mainly composed of barley (24.4%), wheat (20%), corn distillate (15%), soybean hulls (10%), and soy (9%), except during the spring, when pastures are most productive and only the second type of feed is supplied. This farmer does not provide any fodder throughout the year.

Table 2. Inputs and capital used during one year for the production of the goat livestock analyzed.

Particular	Unit	Farm 1	Farm 2	Farm 3
(a) Output				
Liters of milk	L LSU ⁻¹	3236	2558	2350
Kilograms of meat	kg LSU ⁻¹	47.2	40.8	43.0
(b) Livestock inputs				
Feed concentrates ⁽¹⁾	kg goat ⁻¹	453	282	330
Fodder ⁽¹⁾	kg goat ⁻¹	147	33	-
Electricity	kW	12,458	6209	5630
Diesel (Management + Crops)	L	702	2140	669
Lubricants	L	30	53	38
Phytosanitary material	Kg	375	264	90
Plastics	Kg	20	15	16
Tools	€	2401	3711	2593
Fertilizers (46-15-15)	Kg	1410	2334	-
Seeds	Kg	2520	825	-
Labor	h LSU ⁻¹	120	235	101
(c) Capital				
Tractor I (amortization in 10 years)	Hp	90	90	100
Tractor II (amortization in 10 years)	Hp	64	-	-
Other machinery (trailer, harrow, others)	Kg	150	1500	963

Where (1) refers to feed concentrates/fodder provided indoors.

For reasons of space, the additional information, methodological assumptions, and energy converters used to estimate the output, input, and energy sustainability indicators of the livestock farms analyzed are presented in the methodological Appendixes A–C.

3. Results and Discussion

3.1. Making the Hidden Outputs and Inputs of Goat Rearing Visible

The results show how the semi-intensive farm (F1) is the one that obtained the largest energy output, both total and socialized (33.08 and 10.79 GJ LSU⁻¹), while the semi-extensive farm with natural pasture consumed through grazing (F3) produced the smallest outputs (25.01 and 7.76 GJ LSU⁻¹ for, respectively, the total and the socialized output) (Table 3). The semi-extensive farm growing its own crops (F2) occupied an intermediate position. In the three cases studied, manure multiplied by three the value of the energy output of milk and meat, and represented, on average, 68.8% of the total energy output (Figure 2). The remaining 32.2% corresponded to the marketed output: Most of it as milk (95.8%) and the rest, in a much smaller amount, as meat (4.2%). As pointed out before, manure is a fundamental energy and biomass contribution in extensive pastoral systems; it helps maintain the long-term ecological balance and the production capacity of these agroecosystems. However, conventional energy analyses usually exclude manure from the accounts because it is not marketed.

This economist bias distorts the understanding of biophysical processes by not including one of the main internal energy flows of livestock husbandry systems [16].

Table 3. Energy outputs and inputs of goat husbandry in Andalusia.

Particulars/Units	Farm 1		Farm 2		Farm 3	
	GJ LSU ⁻¹	%	GJ LSU ⁻¹	%	GJ LSU ⁻¹	%
(A) Total energy output (a + b + c)	33.08	100	27.23	100	25.01	100
(a) Socialized output	10.79	32.6	8.36	30.7	7.76	31.0
(b) Livestock increase/decrease	−0.17	−0.5	−0.02	−0.1	−0.09	−0.4
(c) Reused biomass (manure)	22.45	67.9	18.89	69.4	17.34	69.3
(B) CED (d + e)	123.93	100	94.26	100	85.64	100
(d) External inputs	94.10	75.9	58.37	61.9	50.69	59.2
(e) Internal inputs	29.84	24.1	35.89	38.1	34.95	40.8
NR External input	26.48	21.4	15.15	16.1	13.09	15.3

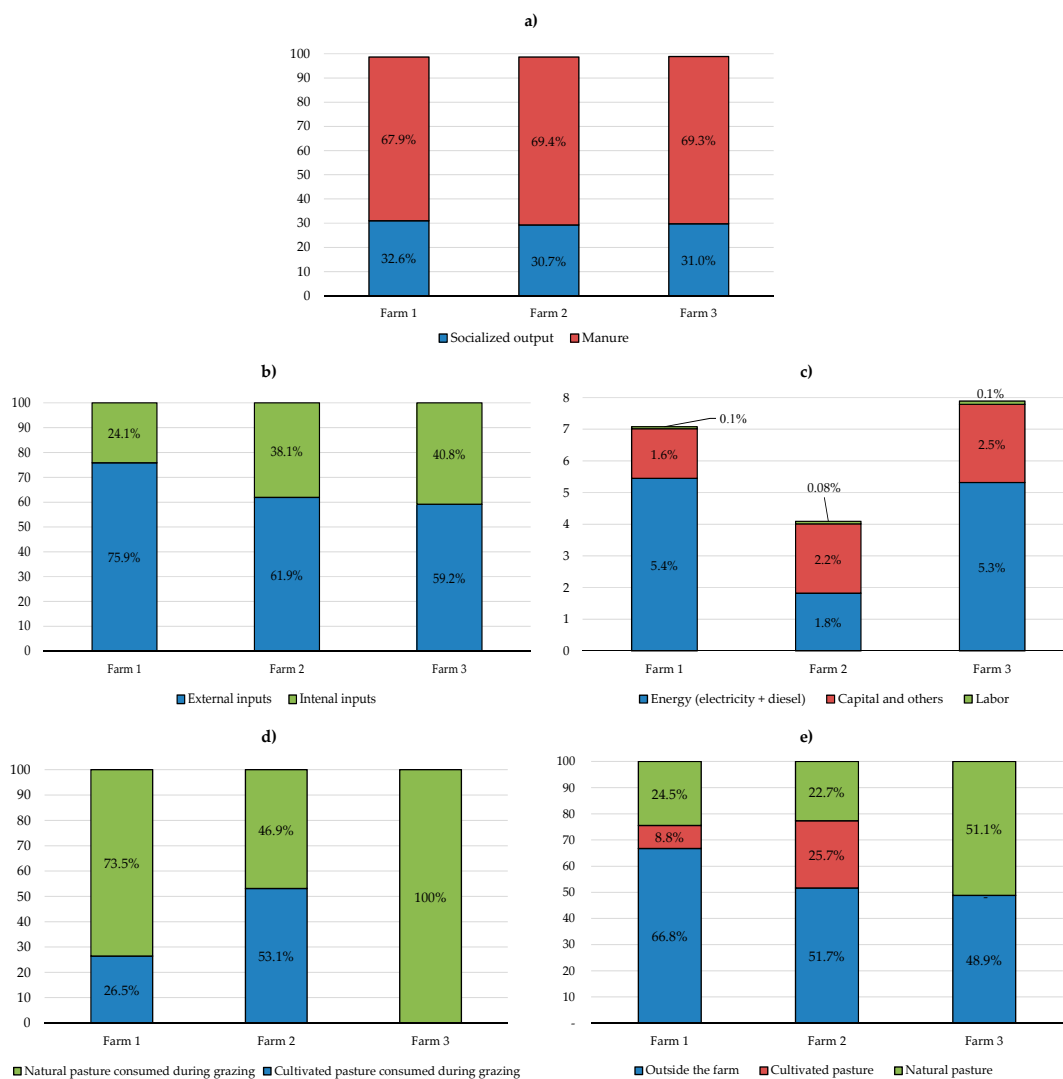


Figure 2. Composition of the: (a) Total energy output (excluding the variation in the number of livestock units); (b) cumulative energy demand; (c) external inputs (excluding animal feed); (d) internal inputs; and (e) animal feed (gross energy consumed) (%). Unit: %.

When grazing is not accounted, the total CED is estimated at 123.93, 94.26, and 85.64 GJ LSU⁻¹ for F1, F2, and F3, respectively. After including the internal inputs of the livestock husbandry system, the CED increases very significantly between 31.7%, in the case of F1, and 69%, in that of F3, rendering the energy contribution of grazing visible. The data per unit of the three cases show that, despite the higher intensity of grazing in F3, this farm is the one presenting the lowest CED LSU⁻¹ (Table 3). Consequently, high-intensity grazing may be associated with lower energy requirements, even when the energy contribution of pastures is accounted. This is a relationship worth studying in greater detail. The most intensive farm (F1) presented a CED LSU⁻¹ that was 44.7% higher than that of the semi-extensive farm with natural pastures (F3). F1 also required more energy per liter of milk produced than F2 and F3, although the difference between the farms analyzed was smaller in this case (38.29, 36.86, and 36.44 MJ L⁻¹, respectively) (see also Table 4). The internal energy flows derived from the contribution of grazing to feed, whether pastures are cultivated or not, ranged from 24% (F1) to 40.8% (F3) of the CED LSU⁻¹ (Figure 2). Like manure, these internal flows are usually neglected in conventional energy analyses, thus, distorting the understanding of the energy metabolism of livestock husbandry systems.

Likewise, the results obtained in the farms studied show how the use of pastures, whether natural or cultivated, can reduce dependence on external energy, especially on the most important energy input: Animal feed purchased outside the farm. The energy cost associated with the external purchase of feed is estimated at 87.43, 55.98, and 46.69 GJ LSU⁻¹, representing 70.5, 59.4, and 46.7% of the CED of F1, F2 and F3, respectively. This result is consistent with those obtained by Pérez Neira et al. [40], who estimated the weight of animal feed at 71.3% of the CED for organic goat rearing in Andalusia. The use of natural and cultivated pastures is also related with smaller requirements of non-renewable energy, which in F3 and F2 are comparatively lower than in the more intensive F1 (13.09 and 15.15, as compared to 26.48 GJ LSU⁻¹). The NR CED accounted for 21.4, 16.1, and 15.3% of the total energy consumed in F1, F2, and F3, respectively. These data point to the possibility of reducing the need for non-renewable energy as the use of grazing increases. In future analyses, this positive relationship should be one of the most important sustainability criteria applied for the assessment of livestock sustainability.

Table 4. Energy efficiency indicators of goat husbandry in Andalusia.

Particulars	Unit	Farm 1	Farm 2	Farm 3
1. Economic approach				
External input	MJ L ⁻¹	29.07	22.82	21.57
NR External input	MJ L ⁻¹	8.18	5.92	5.57
External EROI	-	0.11	0.14	0.15
NR External EROI	-	0.41	0.55	0.59
2. Agroecological approach				
CED	MJ L ⁻¹	38.29	36.86	36.44
NR CED	MJ L ⁻¹	8.18	5.92	5.57
Final EROI	-	0.27	0.29	0.29
NR Final EROI	-	1.25	1.80	1.91

3.2. Energy Efficiency from a Conventional and Agroecological Approach

The measurement of the energy efficiency of livestock breeding systems changes, both in quantitative and conceptual terms, when the hidden flows of manure and grazing are considered (Table 4 and Figure 3). Conventional energy analysis, which integrates an economic-mercantile approach [20], focuses on the energy valuation of the external input and the external EROI according to the socialized output. In relation to these indicators, the data per liter of milk and per LSU evidence that the semi-extensive system (F3) and the semi-extensive system with cultivated pastures (F2) demands less external inputs than the more intensive farm (F1) (21.57 and 22.82 as compared to

29.82 MJ L⁻¹). The same happens in relation to the use of non-renewable energy, with an estimated NR CED of 8.18 MJ L⁻¹ for F1 and 5.92 and 5.57 MJ L⁻¹ for F2 and F3, respectively. Although these data correspond to cases with no statistical representation, the results are consistent with those of previous works. For example, studying France and its goat milk production, Kanyarushoki et al. [47] calculated an average consumption of non-renewable energy (7.9 MJ L⁻¹) that is similar to the one obtained here for F1. According to these authors, the average consumption of feed concentrate per goat was 546 kg, a figure that is also close to the one obtained for the semi-intensive F1. In the case of cow milk, Pagani et al. [6] estimated an energy cost that ranged between 2.73 and 6.0 MJ L⁻¹.

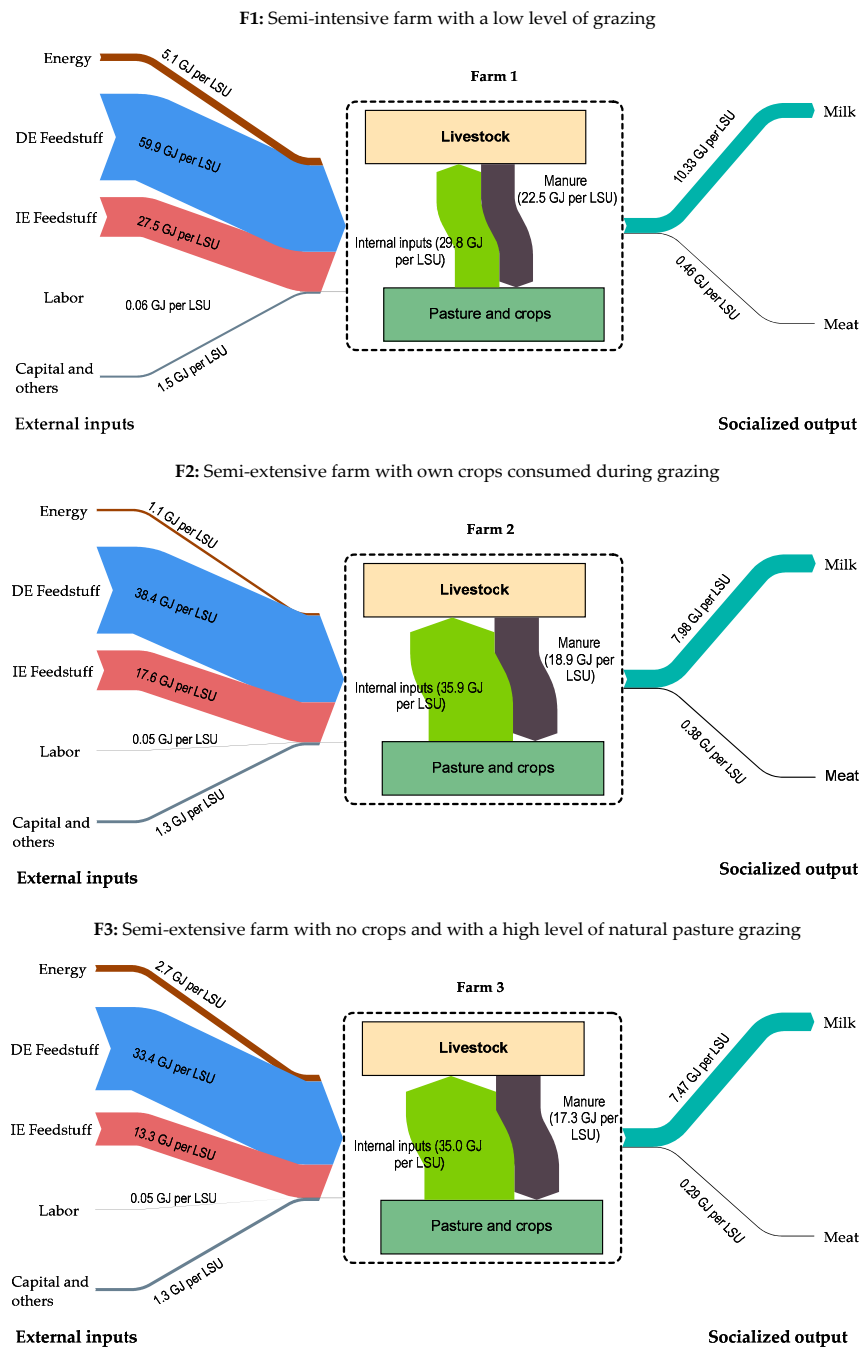


Figure 3. Energy metabolism of the three farms analyzed (F1, F2, and F3) (Where energy includes diesel, lubricants, and electricity; others = operational expenses).

The external EROI indicates greater energy efficiency in the semi-extensive F2 and F3 (0.14 and 0.15), where the animal feed strategy is based on pastoralism (on cultivated and/or natural pastures), although the values are indeed very low. However, there is a contrast with F1, which presents a higher level of intensiveness, more external requirements (0.11), and, consequently, an even lower energy efficiency. Efficiency slightly improves when non-renewable inputs are accounted. The NR external EROI of F2 and F3 is very similar (0.55 and 0.59), with the former complementing natural pasture with its own crops and the latter using only natural pasture. In turn, F1 obtained a lower NR external EROI (0.41) because of its greater requirements of non-renewable external energy, which are not compensated with increments in productivity. Despite its higher output, and due to production intensification, F1 requires a larger contribution of energy inputs that translate into a higher energy cost of production [48].

Measuring energy efficiency from the agroecological perspective proposed in this work implies considering manure as part of the energy output, and the natural pasture consumed through grazing as part of animal feed and, consequently, of the energy inputs incorporated to the process. In other words, a change in the conception of energy efficiency in livestock husbandry is thus suggested to take into consideration such flows as those of manure and grazing, which can contribute to the improvement of sustainability in both agroecosystem management and human food provisioning. The resulting indicator is the final EROI, which, in addition to reflecting the differences in energy efficiency between farms with different levels of intensiveness efficiency is slightly higher in extensive farms, can reach a value that doubles the conventional measure of external EROI, although still well below the unit. This higher energy efficiency is the result of valuing the environmental benefits associated with the provision of manure by the agroecosystem, with manure considered to be part of the energy output. When energy efficiency is measured according to the non-renewable energy used in the system (NR final EROI), the values obtained are above the unit, with differences that depend on the level of intensiveness. The farm that uses more natural pasturable resources (F3) is therefore the most efficient one in these terms (1.91 for F3 and 1.80 for F2, as opposed to 1.25 for F1). The NR final EROI indicates that, for every MJ of non-renewable energy used, 1.25 and 1.91 MJ of energy are obtained in F1 and F3, respectively. These results show the capacity of pastoral livestock systems to efficiently provide useful energy resources (milk, meat, and organic fertilizers) when agriculture, livestock husbandry, and forestry are integrated and properly managed, profiting from the potential use of manure as fertilizer and guaranteeing the sustainable management of pastures.

3.3. Avoided Costs and Agroecological Measurement of the Energy Efficiency of Animal Feed

This article proposes a complementary measure to the final EROI: The avoided cost that implies using manure instead of conventional fertilizers. In the farms analyzed in this paper, this avoided cost (AEC_M) is estimated at between 4.17 and 3.49 GJ LSU^{-1} , figures that reflect the amount of non-renewable energy that would have been required to industrially synthesize the N-equivalent provided by the livestock. This avoided energy cost is a measure of the environmental benefit of incorporating manure into the agroecosystem, thus, contributing to its ecological balance and future production capacity. Grazing guarantees the incorporation of manure into the agroecosystem, even though proper management is also required for the resource to be sustainable. In farms where the livestock are housed, the management comprises labor and energy (including locomotion), two factors that must be considered and analyzed separately. Therefore, the avoided energy cost of manure is a measure of the potential environmental benefits of livestock husbandry that needs to be secured with proper management.

The natural pasture consumed during grazing is another internal energy flow generating an, usually invisible, environmental benefit. Grazing reduces the contribution of feed and, consequently, the energy cost of the crops and of the long-distance transportation of resources that, in addition, might be used directly for human consumption with higher energy efficiency. In the cases analyzed, the energy cost avoided using natural pasture (AEC_P) was estimated at 30.41, 23.32, and 48.44 GJ LSU^{-1}

for F1, F2, and F3, respectively (Table 5). Up to 27.8% of this cost corresponds to the use of non-renewable energy to produce feed substituting natural pasture. Thus, the non-renewable energy cost avoided by natural pasture would be equivalent to 32.0, 42.9, and 103.3% of the NR CED of F1, F2, and F3. Natural pasture, as compared to cultivated pasture, is a renewable alternative with no energy opportunity cost in terms of human food.

Table 5. Avoided costs and energy efficiency of animal feed.

Particulars	Unit	Farm 1	Farm 2	Farm 3
3. Degree of dependence on external animal feed	%	66.8	51.7	48.9
4. Energy costs avoided by				
(1) Manure (AEC _M)	GJ LSU ⁻¹	4.17	3.77	3.49
(2) Natural pasture consumed through grazing (AEC _P)	GJ LSU ⁻¹	30.41	23.32	48.44
	MJ L ⁻¹	9.40	9.12	20.61
5. Animal feed efficiency				
Food/feed EROI	-	0.20	0.22	0.23
Land cost avoided by natural pasture consumed through grazing (ALC _P)	ha LSU ⁻¹	1.93	1.48	3.08
	ha 1000 L ⁻¹	0.60	0.58	1.31

Given the potential positive relation between the use of pasturable resources and energy efficiency in pastoral husbandry systems [49], the indicator measuring the dependence of livestock breeding systems on external feed becomes relevant. In the present case study, this indicator is estimated at 66.8% for F1, revealing a high level of external dependence because only 33.2% of the animal feed consumed in the system comes from resources with no opportunity cost in terms of human food. In contrast, F3 has a dependence rate of 48.9%, indicating that over half of the animal feed comes from natural pasture consumed during grazing and that, consequently, the farm enjoys a high level of autonomy, something that is still uncommon in dairy goat farming in Andalusia [45].

Livestock contributes to food security by providing essential macro and micronutrients. However, in terms of energy, it has a low capacity to transform feed into food, especially in the case of ruminants [30]. In this sense, the feed/food EROI allows the measurement of the energy efficiency of using feed with a biophysical opportunity cost in relation to human food. In the present case studies, the values calculated for this indicator range between 0.20 for F1 and 0.23 for F3, with F2 in an intermediate position. This means that, for every energy unit of animal feed with a biophysical opportunity cost, 0.20–0.23 units of edible output are obtained. These figures confirm the high energy cost of human food based on animal proteins. In the United States, Shepon et al. [38] have estimated an energy efficiency of 17% in the use of energy to feed livestock and produce milk, a figure that is below those obtained for the three cases analyzed here.

Despite this, the use of properly managed natural pasture could help reduce dependence on non-renewable energy associated with feeding [40] and alleviate the pressure on croplands. A possible measure of this environmental benefit would be the agricultural area required to grow alternative animal feed to pasture, i.e., the avoided land cost of natural pasture consumed during grazing. Thus, in the present study, the natural pasture of the semi-extensive F3 had an avoided land cost (ALC_P) that doubled the one of the semi-intensive F1, reaching 1.36 and 0.60 hectares per 1000 L of milk produced, respectively. This shows that goat farms in which animal feed is based on natural pasture can potentially reduce the total requirements of agricultural area as compared to more intensive systems, which is relevant considering that feed crops occupy 34% of the global cropland is considered [34]. Finally, it is important to point out that no significant differences have been found between F1 and F2 in relation to the avoided land cost, even though F2 has a much larger area of natural pasture. This proves that, sometimes, natural pasture is not properly managed, and that this is an aspect that deserves some improvement in territory-based goat rearing farms.

4. Conclusions

Including an agroecological economics perspective in the energy analysis of livestock husbandry helps reveal the internal energy flows of livestock systems, which generate important environmental benefits and are usually neglected in conventional analyses. Reformulation of the concept of output shows the relevance of manure in terms of energy, which in the cases analyzed is estimated at 68% of the total output. This contribution of energy and biomass is essential for the balance and productivity of agroecosystems based on forestry and pastoralism. The contribution of grazing represents between 17 and 40% of the cumulative energy demand (CED) depending on the farm's level of extensiveness, showing how the use of pasturable resources can reduce dependence on external feed, which is, nevertheless, the main energy consumption component in the three cases studied (between 54 and 87% of the CED). This potential positive relation between the use of pasturable resources and energy efficiency must be valued and developed. In the cases studied here, the agroecological economics measurement of energy efficiency shows how the most extensive farm (F3) was 53% more efficient than the semi-intensive farm (F1) in terms of energy and non-renewable energy use. This was calculated through the final EROI and the non-renewable (NR) final EROI. A new measure of energy efficiency based on the final EROI and taking into consideration both manure and grazing is thus required.

The avoided costs associated with grazing and with the organic fertilization linked to it highlight, in terms of energy, the environmental benefits of the interaction between extensive livestock systems and agroecosystems. These two agroecological energy indicators make it possible to evaluate livestock husbandry sustainability by taking into consideration certain aspects of the management that are usually neglected by conventional sustainability analysis. The energy cost avoided by manure in the cases analyzed represents between 15.7 and 26.7% of the NR CED of the farms. The natural pasture consumed through grazing provides between 24.5 and 51.1% of the gross energy required by the livestock, depending on the farm's level of extensiveness, and the avoided cost of natural grazing is estimated at 35.5, 60.19, and 157.4% of the NR CED of the three farms, from the least to the most extensive one. The reduction of territorial pressure on the cropland resulting from the use of grazing is estimated at between 0.60 and 1.31 hectares per 1000 L of milk. These results point out that the global disconnection between crops and livestock, on the one hand, and pasturable resources, on the other, can lead to inefficiency in the use of natural resources.

The quantitative results of the three cases studied have been used to demonstrate the analytical potential of the new energy indicators proposed. However, this information should be treated with caution and should not be generalized as it is highly context-related. The main objective of this article was to reinforce the idea that it is necessary to widen and sophisticate the conventional vision of energy analyses on agricultural and livestock systems. For this purpose, it is necessary to incorporate the assessment of the internal energy flows associated with grazing and organic fertilization to adequately value the energy efficiency and environmental benefits of livestock farming systems. This work aims at contributing to this objective by proposing new synthetic energy indicators for the assessment of goat farming sustainability.

Author Contributions: Conceptualization: D.P.-N. and M.S.-M.; Methodology: D.P.-N., M.S.-M. (energy analysis and indicators), Y.M.-G. and R.G.-P. (specific questions on pastoral goat husbandry); Formal Analysis: D.P.-N. and M.S.-M.; Data Curation: R.G.-P. and D.P.-N.; Writing-Original Draft Preparation: D.P.-N. and M.S.-M.; Writing-Review and Editing: D.P.-N., M.S.-M. and Y.M.-G.; Supervision, project administration and funding acquisition: Y.M.-G.

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Appendix A. Energy Output

Agricultural energy analyses are based on the study of gross energy flows. The complementary data adding to empirical data required to calculate the gross energy flows associated with both the energy output and the energy input have been gathered from the bibliographical references mentioned in the following appendices.

Appendix A.1. Meat and Milk

First, to estimate the gross energy contained in meat, the carcass weight of kids (1–3 months-old), juveniles (4–11 months-old), adult females (12 months-old or more), and males (12 months-old or more) of commercialized Payoya goats [50] is calculated, assuming a channel performance of 50%. Secondly, the energy content of meat is calculated from its nutritional composition, assuming that 1 kg of goat meat contains 65% of protein, 5% of fat, and 30% of bone [51,52]. From the energy coefficients of proteins, fat, and carbohydrates estimated by Moreiras et al. [53], an average value of 6.6 MJ kg⁻¹ of carcass meat is obtained. Similarly, the gross energy of milk is estimated as per its nutritional composition, its average content of protein, fat, and lactose being 3.5, 4.3, and 4.6%, respectively. The energy coefficient of milk, which allows the transformation of physical data into homogeneous energy units, is estimated at 3.19, 3.12, and 3.18 MJ L⁻¹, depending on the fat and protein content of each farm's production (adapted from [53]).

Appendix A.2. Manure

To estimate the energy content of manure, it is necessary to take into consideration that: (1) 30% of the gross energy of the feed consumed by ruminants is lost in the form of feces [31], and (2) one adult goat and one kid produce, respectively, 0.62 and 0.15 tons of manure per year [54,55]. The energy coefficient of manure is thus estimated at 4.49 MJ kg⁻¹ (adapted from [40,56]).

Appendix A.3. Accumulated Biomass (Livestock Population)

For estimating this concept, the difference in the live weight of the livestock population between the beginning of the year and the end of the year is calculated, as is the corresponding carcass weight. Following the methodological steps detailed in Appendix A.1, the energy content of the carcass meat of the increase/decrease in livestock population is thus estimated.

Appendix B. Energy Input

Appendix B.1. External Inputs Except Feed

When measuring inputs in energy analyses, energy coefficients ($\beta_{(j)}$) are a key factor because they significantly influence the results. However, they are not always well defined. Aguilera et al. [41] have provided a coherent database that includes the direct and/or indirect energy of the main agricultural inputs at the maximum disaggregation level available. Along those lines, Pérez Neira et al. [40] made a selection of energy coefficients to study ecological agriculture and livestock breeding in Andalusia. In this work, the coefficients related to the use of diesel, plastics, iron, and fertilizers (NPK) were taken from Aguilera et al. [41], while the ones for oil and lubricants, electricity, labor, tools, wood, seeds, crop protection, and machinery were taken from Pérez Neira et al. [40,56].

Appendix B.2. Livestock Feeding

Livestock feeding is the most important energy input in livestock husbandry. Goat feeding was calculated by adding: (1) The gross energy contributions to the livestock (purchased feed + own crops + natural pasture); and (2) the energy cost of producing the feed meeting the livestock's gross energy requirements, where applicable. The gross energy of food and feed is the heat generated when the organic matter contained in it is burnt off. In other words, it is the chemical energy stored in the

molecular bonds of the organic matter contained in food and feed. The net energy is the amount of energy available after the digestive process has concluded. It is calculated by subtracting from the gross energy the energy that is lost in feces, gases, urine, and other transformations prior to its use in cellular metabolism [31]. Livestock feeding can be divided into three categories:

Appendix B.2.1. Energy Contribution of Purchased Feed

The feed purchased outside the farm and consumed by the goats indoors has been divided into two groups: Fibrous feed and feed concentrates. The energy content of both types of feed is estimated from data taken from Moreiras et al. [53] and FEDNA (Spanish Foundation for the Development of Animal Nutrition) [57]. Net energy has been transformed into gross energy following the general scheme on the use of energy by ruminants described on INRA (French National Institute of Agronomy Research) [31]. The energy cost of producing the two types of feed is calculated based on data taken from Naredo and Campos [29] and Pimentel [58]. More specifically, the energy cost of producing hay is assumed to be 2.5 MJ kg⁻¹, while for oats, barley, sunflower, peas, broad beans, corn, soya, and wheat, the energy cost of production is estimated at 4.3, 4.2, 5.4, 4.4, 4.7, 4.1, 5.9, and 4.9 MJ kg⁻¹, respectively (adapted from [40,56]). In the case of flour/oil cakes, the expenses of cleaning, mixing, and packing (0.36 MJ kg⁻¹), and, additionally, milling (0.46 MJ kg⁻¹) need to be added to the energy cost of fodder (adapted from [59,60]). The distances travelled by the different types of feed are calculated from the information provided by the Cooperativa Nuestra Señora de los Remedios, located in the town of Olvera (Cádiz, Andalusia), which supplies most of the fodder and feed concentrates used in the area. On average, fodder travels 175 km by road and, when imported, 2400 km by boat [61]. The coefficients that allow the estimation of the energy consumed in transportation have been taken from these same authors.

Appendix B.2.2. Energy Contribution of Feed Grown in the Farm

The feed obtained from the farm's own crops is divided into two groups: Fibrous feed to be consumed through grazing, and fibrous feed or feed concentrates to be consumed indoors.

Although none of the farms studied in this article grow crops to be provided indoors because this is not a usual practice in the area [46,62], it has been considered important to include this option in the methodological proposition. The energy provided by the crops consumed during grazing has been estimated from the average productions in the area, their dry matter content, and their net energy value [56,63] (Table A1). The transformation of net energy into gross energy has been made following the general scheme on the use of energy by ruminants described on INRA [31]. The energy cost of producing the feed is estimated from the consumption of energy associated with the use of machinery, fossil fuels, fertilizers, phytosanitary material, and labor in the farm.

Table A1. Estimation of cultivated pasture for consumption during grazing.

Farms	Area (ha)	Type of Crop	Yield (kg MS/ha) *	UFL kg MS ⁻¹ **	Total Net Energy Provided (UFL Year ⁻¹) ***
F1	70	Mixed-grass pasture	6000	0.70	23,520
F2	96	Winter cereals mix	6000	0.70	241,920
F3	-	-	-	-	-

Where * own elaboration from data taken from [63]; ** own elaboration from data taken from [57]; UFL = *unité fourragère lait* or milk fodder unit, which, according to the French system [31], is the amount of net energy for milk production containing one kilogram of reference barley; *** the use of it by the livestock has been estimated at 60% for F1 and 80% for F2, in accordance with the farmer's management of the pastures.

Appendix B.2.3. Energy Contribution of Natural Pasture

The energy contribution of natural pasture consumed through grazing has been calculated by subtracting the net energy provided by purchased feed, plus the net energy provided by cultivated pasture, from the goats' annual net energy requirements (estimated according to the animals' maintenance, locomotion, and production requirements, following the methodology described by

Nahed et al. [64], Ruiz et al. [62], and Mena et al. [45]). Synthetically, it could be expressed as: Energy contribution of natural pasture consumed through grazing (MJ LSU^{-1}) = Net energy requirements of the goats—Net energy of purchased feed—Net energy of crops grown in the farm and consumed during grazing or indoors (MJ LSU^{-1}). The transformation of net energy into gross energy is made according to the general scheme on the use of energy by ruminants described by INRA [31].

Appendix C. Energy Sustainability Indicators of Livestock Husbandry

Appendix C.1. Avoided Energy Cost of Manure

To estimate this energy cost, an annual excretion of 7.39 and 3.25 kg of nitrogen (N) per adult goat and kid, respectively, was calculated [54,55]. Additionally, the work by Aguilera et al. [41] was taken as a reference to calculate the non-renewable energy required to industrially produce one kilogram of N. The assumed value was 51.5 MJ kg^{-1} of N.

Appendix C.2. Avoided Energy Cost of Pasture

Appendix C.2.1. Direct and Indirect Energy Costs

The avoided direct cost of pasture is equivalent to the energy contribution of the natural pasture consumed during grazing (Appendix B.2.3). In the study area, the fibrous feed provided indoors by the farmer to compensate for the lack of pasture during certain periods over the year is usually composed of 35% of hay, 40% of short-fiber fodder, 15% of straw, and 9% of fibrous sub-products [46]. From these data and from the references mentioned in Appendix B.2.1, a ratio of 0.55 MJ of indirect energy per MJ of energy provided by natural pasture in the form of biomass has been estimated.

Appendix C.2.2. Land Costs

To calculate the land cost, the following yields, adapted to the territorial reality of the comparative case study, were assumed: $2750 \text{ kg of dry matter ha}^{-1}$ for hay; 3500 kg ha^{-1} for straw (assigning 50% of the area to grains and 50% to straw); and 4000 kg ha^{-1} for other byproducts [63].

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