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The Way Forward in Quantifying Extended Exergy Efficiency

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Abstract: Extended exergy accounting (EEA) is a methodology which estimates the extended exergy cost (EEC) of a product or a service or the extended exergy efficiency (EEE) of a country or economic sector taking into account materials, energy, labour, capital, and environmental impact. The use of EEA results for policy or planning purposes has been hampered by: (1) the lack of data to quantify the EEC of most of the inputs, making it almost impossible to quantify the EEC of a product or service and (2) the lack of a conceptual framework to quantify in a consistent way the exergy of labour and capital. In this paper, we make a review of past studies to identify, synthesize, and discuss the different EEA methods. We identified 3 different EEA methods, that we further compare using the Portuguese Agriculture, Forestry, and Fishery (AFF) sector from 2000 to 2012. The equivalent exergies of labour and capital estimated for the AFF sector vary widely among the three EEA methodologies. We propose and test a new EEA methodology to estimate EEE which accounts for these fluxes in a more restricted scope but more consistently and that includes the Environmental Benefit (EB) that represents the capability of the forestry to capture carbon dioxide. Results show that the EEE of the Portuguese AFF sector has increased by 32% from 2000 to 2012.

Keywords: exergy; extended exergy accounting; efficiency; environmental assessment; agriculture

1. Introduction

The rapid depletion of the natural environment and the will to ensure the survival of present and future generations led mankind to study and address new ways to improve the efficiency of using earth finite resources. Thermodynamic concepts widely adopted to measure the efficiency of industrial processes are being increasingly used to assess the efficiency and sustainability of other societal processes at different scales. Acknowledging that our societal relation with the global environment is above all made through physical interactions, the thermodynamic concept that is better able to measure the quality of these interactions is exergy.

In contrast to energy, which is subject to a conservation law and suitable for quantity measurements, exergy is destroyed in any real interaction process, due to irreversibilities, and is absent from conservation principles. Exergy content in a stream or in a system is an entropy free form of energy that measures the work content or the ability to produce work from that stream or system [1]. By aggregating the energy of different flows entering and leaving a system, the energetic assessment of the system tells only a partial story since the quality of such flows is not taken into account. On contrast, exergetic assessments measure all flows by taking into account their quantity and quality.

Exergetic analysis of nations, or very large complex systems, began with Reistad [2] who published an exergetic analysis for the US in 1975, using the Energy Resources Exergy Accounting (EREA) approach. Wall [3] made an exergetic analysis for Swedish society in 1980, using the Natural Resources

Exergy Accounting (NREA) methodology which extends the EREA by adding the exergetic content of natural resources and material flows. These exergetic analyses quantified only the intrinsic exergy (physical and chemical exergy) of flows. In 1987, the concept of cumulative Exergy Consumption (CExC), that quantifies the exergy of a stream as the sum of all necessary exergy to bring the stream to the specified state, was introduced by Szargut [4]. CExC was an innovative and important tool that can be used in manufacturing processes, to indicate in each step, the embodied exergy of materials and energy of inflow and outflow fluxes, highlighting the processes were most exergy destruction occurs. It also cumulatively quantifies the necessary exergy to manufacture a desired product, allowing for comparisons between different manufacturing processes and for the quantification of the impact of measures such as recycling or changes in raw materials.

The Extended Exergy Accounting (EEA) methodology quantifies additionally three immaterial streams, labour, capital and environmental impact [5] in exergy units. Sciubba [6] argued that the exergetic content assigned to input and output flows in EEA should be the embodied or cumulative, defined as the sum of its physical and chemical exergies plus all net exergies received directly or indirectly in its transformation path including all labour, capital, and environmental costs necessary along each step of the path. In its essence, on top of all energetic and physical fluxes, EEA also accounts three immaterial streams: labour, capital, and environmental remediation or avoidance exergy cost (Figure 1) to quantify the Extended Exergy Cost (EEC) of a stream. Ultimately, all material and energy streams are valued by their EEC from extraction to consumption. The resources or energy carriers which are extracted or collected from the environment are primarily valued by their intrinsic exergy and subsequently attributed an EEC when entering a new transformation process.

The EEC measures the overall societal exergy necessary to produce a product or a service. Conceptually, this result is extremely useful since we may identify the products or services with lower EEC or energy carriers with better intrinsic exergy to EEC ratio. The EEC of fluxes is useful in identifying which output environmental fluxes would need more exergy to become non-polluting and the trade-offs in exergy terms between labour, capital, and mass/energy flows.

While some of the studies developed using the EEA methodology have the aim of evaluating the EEC of a product or a service [7,8], others focus on quantifying the societal efficiency of a process [9–11]. This extended exergy efficiency (EEE), measured by the ratio between the exergy of the output fluxes and the exergy in the inputs, can have different meanings. If inputs are valued by their EEC, then the efficiency evaluates the performance of all labour, capital, and environmental impacts and of every material and energy carrier used up from extraction to the multiple transformation processes that lead to the intended output flow. In contrast, if inputs are valued by their intrinsic exergies, the efficiency refers solely to the specific transformation process under analysis. EEA societal studies don't usually refer exergy losses or destruction in their analysis except Ertesvag [9] which includes them in his input-output tables.

However, the EEA faces some challenges/difficulties. The first challenge is complexity. EEA is extremely complex if done properly. Take electricity as an example, which is used in almost every device or transformation process. The consumption matrix of the conversion sector is vast and if most of the initial carriers are imported, then the tracking of all interactions is easily lost [12].

The second challenge is the difficulty in developing a useful database for EEC values. The values obtained using the CExC methodology [4] should not be used as EEC because they only take into account energy and material flows. Thus, the EEA methodology implies the use of EEC values obtained by EEA studies in each step of the process. Additionally, the use of upstream EEC values from other publications is problematic unless they were estimated for the same region and year since labour and capital are geographically and time dependent.

The third challenge is the difficulty in ensuring consistency when applying the EEA approach. The lack of a solid EEC database led some EEA studies to use an inconsistent approach. Most studies use the intrinsic exergy content of all material and energy flows combined with a cumulative equivalent exergy for capital and labour fluxes. This inconsistency also extends to the environmental impact externality which is mainly accounted by pollutants' intrinsic exergy or by the equivalent exergy of the capital spent in trash and discharge fluxes. These inconsistencies led to EEA results where the equivalent exergies of capital and labour are the dominant flows by a large factor. This disparity between the exergy of different flows is shown in Manso et al. [13], where the results obtained by the EEA approach, using as a case study the Agriculture, Forestry, and Fishing (AFF) economic sector of Portugal from 2000 to 2012, are completely dominated by the exergies of capital and environmental impacts.

The fourth challenge is the overestimation of the EEC of a product or service because of double-counting associated with labour. This is well explained by Szargut et al. [14] that shows that accounting for the exergy of labour makes the sum of the EEC of all final useful products higher than the primary exergy used by society.

The all-embracing nature of EEA that accounts all major production factors into a transformation process is relevant for sustainability and efficiency studies. However, due to the issues already mentioned: (1) the lack of consistency in accounting for the EEC among flows, (2) the double-counting and arbitrariness in accounting for labour and capital and (3) the lack of an EEC database, its use is problematic. These issues have to be addressed in order to improve the usefulness of EEA for policy purposes.

In this paper, we review past studies to identify, synthesize, and discuss the different methods used to quantify exergy with a special focus on the three immaterial production factors of EEA (labour, capital, and environmental impact) and compare the several EEA methodologies using the Agriculture, Forestry and Fishing (AFF) economic sector of Portugal from 2000 to 2012 as a case study, with the aim of providing understanding and clarity for EEA practitioners. The case study and initial dataset is the same used in Manso et al. [13], but here it is used to compare the multiple EEA methodologies while in Manso et al. [13], it was used to compare the exergy efficiency obtained using the EREA, NREA, and one of the EEA approaches. Additionally, this paper addresses the challenge of improving the estimation of EEA externalities, labour, capital, and environmental impacts for sectorial studies. Based on our review, we propose an Intrinsic Extended Exergy Accounting (IEEA) approach to estimate the Extended Exergy Efficiency (EEE) of products/services or sectors that (1) values labour and capital flows more consistently and (2) does not need an EEC database.

2. EEA Methodologies: Review and Synthesis

Literature reviews on exergy accounting of nations have already been made by Utlu and Hepbasli [15] and Sousa et al. [16]. Among the studies collected by these reviews, only one applies the Extended Exergy Accounting (EEA) methodology [9]. In this paper, we focus only on EEA studies that either discuss methodological issues or apply EEA to nations or societal economic sectors. Table 1 highlights the analogies and differences between the methodologies used in published EEA studies focusing on (1) the use of intrinsic or cumulative exergy data in their analysis, (2) the methodology applied to labour, capital, and environmental impact and (3) the exergetic evaluation of the outputs.

2.1. Input and Output Exergies for Material and Energy Flows

EEA theory defends a cumulative approach to all streams that enter a transformation process to find the EEC of the output streams. From the studies presented in Table 1 we would like to highlight the studies by Ptasinski et al. [17] which used the EcoChem software to translate chemical exergy to CExC and Rocco et al. [18] which used the Ecoinvent database [19] to compute their inputs. No study was able to include inputs with their extended exergy cost and few studies were able to offer extended exergy cost values to a database for EEA use, despite its low utility for studies on other regions or years. Examples include the environmental remediation cost values of carbon monoxide, mono-nitrogen oxides, and sulphur dioxide published by Dai et al. [20] and from carbon dioxide, nitrous oxide, and methane by Seckin et al. [21]. The extended exergy cost values of municipal wastewater and sludge abatement are also known for Turkey in 2006 [8].

When assessing the efficiency of an economic sector, many authors opted to evaluate their input flows by their intrinsic exergy, even for fluxes leaving a sector to enter the following. The main proposal was to quantify the sector's performance and if cumulative data was introduced, the efficiency would reflect the cumulative performance of all sectors that transformed the flows under analysis (Figure 1). The EEA approach was not initially designed to measure efficiencies at the middle of the transformation chain, but to ascertain the final cumulative resource and societal exergetic consumption. When the aim is to estimate the efficiency, the correct approach is to quantify the input, including only the intrinsic or physical and chemical exergies. This modified Extended Exergy Analysis methodology was used by Ertesvag [9], Milia and Sciubba [22], Sciubba et al. [23], Gasparatos et al. [10], Chen and Chen [24], Bligh and Ugursal [25], and by Seckin et al. [11] for material and energetic fluxes (Table 1).

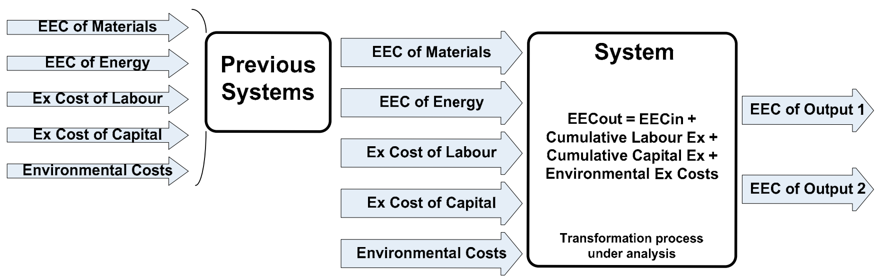

Figure 1. Upstream systems included in the EEA methodology.

2.2. Labour

Human labour is an essential production factor in any conversion system, and although not a novelty in energetic assessments, its correct introduction is controversial [26].

Sciubba [6] estimated the equivalent exergy of labour (E_L) as the total exergy input to society (E_{in}) and the specific exergy of labour (ee_L) as the labour exergy per working hour (Table 1). The exergetic input into the economy of a region in a given year is taken from the environment as resources (natural, renewable, or non-renewable) that travel a partial or complete route along primary sectors, to manufacturing, and finally to tertiary and domestic. Some resources and products are exchanged with other countries, where the total exergy E_{in} is the result of all environmental inputs plus imports and less exports (Appendix B). This exergetic input sustains all metabolic necessities, all generation of labour, all manufacturing and transportation abilities, as well as all recreational and leisure activities.

By assuming $E_L = E_{in}$, the author assumes that all gathered exergy E_{in} is used to fuel labour. But, labour itself is only one of the outputs of E_{in} and this creates a major problem when assessing the domestic sector. Ertesvag [9], Gasparatos et al. [10], Chen and Chen [24], and Bligh and Ugursal [25] followed this methodology and found efficiencies higher than 100% for the domestic sector.

Ptasinski et al. [17] studying the Dutch energy sector, based on EEA, proposed a different labour methodology. The study adds three components, a man-power equivalent exergy ($E_{L,W}$) which was 300 GJ a year per person (which represents the total exergy inflow per capita for Sweden in 1975 [27]), a skill component ($E_{L,Skill}$) comprising compensation of employees (gross wages and salaries) and a social component based on the monetary flows of social cost accounts ($E_{L,SA}$). The man-power contribution was almost negligible, while the monetary values of skills and social accounts, converted to exergy by a capital conversion factor, represented respectively around 90% and 10% of E_L that varied between 153 MJ/h for central electricity production and 501 MJ/h for refineries. Such different values of equivalent labour exergy factors (over three times more), on two branches of the energy sector, result from directly relating labour exergy with wages.

Agricultural sustainability for OECD countries was studied by Hoang and Alauddin [28] in a combination of EEA and cumulative exergy extraction from the natural environment (CEENE) [29] from 1990 to 2003. In their analysis, the equivalent exergy of labour was accounted as $E_L = F_e \cdot N_w \frac{t_w}{t_t}$, where F_e is the daily metabolizable food energy per worker, N_w is the number of workers in the sector and t_w/t_t is the fraction of daily time spent working. The equivalent exergy of labour represented 0.25% off all inputs in the agricultural sector. In contrast to previous studies where the labour exergy flux depends on the lifestyle of a population or wages, the authors assumed that the equivalent exergy of labour was the energy obtained from food, by the workers in the sector, needed to fuel metabolism, during working hours. However, the authors also assume that all hours in a day are fueled by the same number of calories, regardless of whether the person is working or resting.

Aware of the imbalance of the domestic sector caused by the methodology that he proposed for labour, Sciubba [30] reviewed the calculation of both capital and labour fluxes. A postulate for labour was created that states that only a fraction, α, of all the incoming exergy E_{in} is used to support the workers: $E_L = \alpha E_{in}$ or $ee_L = \alpha E_{in}/n_{workhours}$. To obtain α, Sciubba [30] introduced the following equation for the equivalent exergy of labour $E_L = f \cdot e_{surv} \cdot N_p$ that takes into account the population (N_p), the minimum exergy (e_{surv}) required to maintain healthy metabolic needs (2500 Kcal/day per person or 1.05×10^7 J/day·person) and f is an enlargement factor that describes the societal exergy needs over the survival mode. To measure the societal amplification factor (f), the author opted to correlate it with the Human Development Index (HDI) [31] where $f = HDI/HDI_0$ being HDI_0 the Human Development Index of a pre-industrial society ($HDI_0 \approx 0.055$). By proposing this equation, Sciubba asserts that the embodied exergy into labour is linearly dependent on HDI, which is the geometric mean of three dimensions: life expectancy and healthy life, knowledge and education, and standard of living and national income [31].

In contrast to the first methodology, where all exergy that entered society was attributed to the labour flux, the new methodology relates both quantities by a factor (α). Figure 2 relates each country's, E_{in*}, with E_L predicted by HDI, for 121 countries. The value for E_{in*} is estimated only with the energy obtained from the International Energy Agency [40]. This accounts only for energy carriers and it is not the total energy that enters a specific country E_{in}; it misses the extraction of non-energy carriers, the production from the agricultural sector and their energetic balance of imports minus exports. Thus, E_{in} is higher than E_{in*}. Also, the energy carriers are valued by their energetic content and not by their quality or exergy. However, the exergy factors are all bigger than the unity except for thermal fluxes, meaning that the total exergetic content, in energy carriers, entering the nation should be slightly higher than the energetic one represented by the dots in Figure 2.

Table 1. Methodologies used for the labour, capital, and environmental impact of published EEA studies. The aim of the study may be the process or sector efficiency[1] or the EEC[2] of a flux or process; the equivalent exergy of environmental impact is usually the trash and discharge (T&D)[3] intrinsic exergy or the equivalent exergy of capital for garbage and waste (G&W)[4] processing.

Study, Region and Year	Input Exergy	Aims	Labour Methodology	ee_L (MJ/h)	Capital Methodology	ee_k (MJ/$)	Environmental Impact Method
Sciubba (2001) [6] Italy 1994	Intrinsic exergy	Efficiency[1]	Equivalent Exergy of Labour (J): $E_L = E_{in}$ Specific exergy of labour (J/h): $ee_L = E_L/n_{workhours}$	52.7	Equivalent Exergy of Capital (J): $E_k = C \cdot ee_k$ Specific exergy of capital $(J/\$)$: $ee_k = E_{in}/M2$	18.2	3 times intrinsic exergy
Sciubba (2003a) [32] Italy 1998	Intrinsic exergy	Efficiency[1]		235.5		18.2	Discharge intrinsic exergy
Sciubba (2003b) [33]	-	-		-		-	Theoretical
Sciubba (2004) [7] Italy 1998	Not explicit	Efficiency[1] EEC[2]		235.5		18.2	T&D intrinsic exergy[3]
Ertesvag (2005) [9] Norway 2000	Intrinsic exergy	Efficiency[1]		525.8		20.1	T&D intrinsic exergy[3]
Milia and Sciubba (2006) [22] Italy 1996	Not explicit	Efficiency[1]		198.5		18.2	T&D intrinsic exergy[3]
Sciubba et al. (2008) [23] Italy 2000	Intrinsic exergy	Efficiency[1]		253.0		16.0 (€)	T&D intrinsic exergy[3]
Gasparatos et al. (2009) [10] UK 2004	Intrinsic exergy	Efficiency[1]		248.3		10.0 (£)	T&D intrinsic exergy[3]
Chen and Chen (2009) [24] China 2005	Intrinsic exergy	Efficiency[1]		71.9		23.7	G&W processing cost[4]
Dai and Chen (2011) [34]	Not explicit	EEC[2]		-		-	G&W processing cost[4]
Bligh and Ugursal (2012) [25] Canada 2006	Intrinsic exergy	Efficiency[1]		406.5		20.7 (C$)	T&D intrinsic exergy[3]
Ptasinski et al. (2006) [17] Netherlands, 1996	CExC, Intrinsic exergy	Efficiency[1]	$E_L = E_{LW} \cdot \mathrm{N}_w + \left(\frac{E_{LSkill}+E_{LSA}}{ee_k}\right)$	-	$E_K = C \cdot ee_k$ $ee_k = NREA_{in}/IC$	197–621 (€)	G&W processing cost[4]
Hoang and Alauddin (2011) [28]	CExC, Intrinsic exergy	Efficiency[1]	Equivalent Exergy of Labour (J): $E_L = F_e \cdot \mathrm{N}_w \frac{t_w}{t_t}$	-	-	-	Not applied.
Sciubba (2011) [30]	-	-	Equivalent Exergy of Labour (J): $E_L = \alpha E_{in} = f \cdot e_{surv} \cdot N_p$ Specific exergy of labour (J/h): $ee_L = E_L/n_{workhours}$	-	Equivalent Exergy of Capital (J): $E_k = M2 \cdot ee_k$ Specific exergy of capital $(J/\$)$: $ee_k = \frac{\alpha \cdot \beta \cdot E_{in}}{M2} = \frac{E_L}{S}$	-	Not applied.
Sciubba (2012) [35]	-	-		-		-	Theoretical
Dai et al. (2012) [36]	Not explicit	EEC[2]		-			G&W cost[4] and T&D exergy[3]
Sciubba (2013) [37]	-	-		-		-	Theoretical.
Dai et al. (2014) [20]	Manufacture cost	EEC[2]		-		-	EEC of CO, NO_X and SO_2.
Chen et al. (2014) [38] China 2000–2007	Intrinsic exergy	EEC[2]		52–76		42–23	G&W processing cost[4]
Jawad et al. (2015) [39]	Intrinsic exergy	EEC[2]		-		-	G&W processing cost[4]

Table 1. *Cont.*

Study, Region and Year	Input Exergy	Aims	Labour Methodology	ee_L (MJ/h)	Capital Methodology	ee_k (MJ/\$)	Environmental Impact Method
Seckin et al. (2012) [11] Turkey 2006	Intrinsic exergy	Efficiency [1]		153.9	Equivalent Exergy of Capital: $E_k = (M2 - S) \cdot ee_k$ Specific exergy of capital $(J/\$)$: $ee_k = \frac{\alpha \cdot \beta \cdot E_{in}}{M2 - S} = \frac{f \cdot e_{surv} \cdot N_p}{S} = \frac{E_L}{S}$	25.5	G&W processing cost [4]
Seckin et al. (2013) [21] Turkey 2006	Intrinsic exergy	Efficiency [1]		153.9		25.5	EEC of CO_2, N_2O and CH_4.
Seckin and Bayulken (2013) [8] Turkey 2006	Intrinsic exergy	EEC [2]		153.9		25.5	G&W cost [4] and intrinsic exergy
Rocco et al. (2014) [18]	CExC	EEC [2]		-		-	Theoretical.

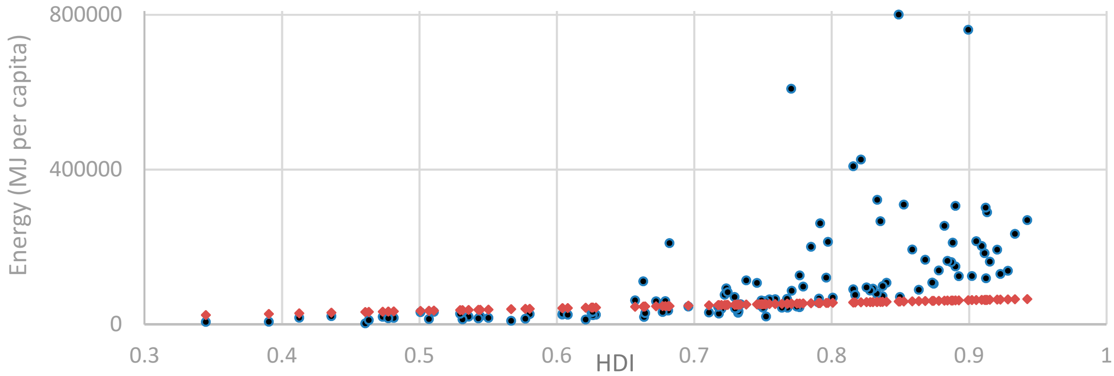

Figure 2. Comparison between country's energy use by energy carriers, E_{in*} (in blue), and country's predicted energy use by HDI (2013), E_L (in red).

For HDI values lower than 0.65, $E_L > E_{in*}$, with a high probability of being higher than E_{in} (for South Sudan, labour flux from HDI is 13 times higher than all energy from energy carriers). For HDI values between 0.65 and 0.78, $E_L > E_{in*}$ for some countries while $E_L < E_{in*}$ for others. For HDI values higher than 0.78, $E_L < E_{in*}$, as expected. Nevertheless, there is no observed linearity between HDI and E_{in*} and for lower HDI countries $E_L > E_{in*}$ which is problematic.

Rocco et al. [18], in their theoretical reassessment of EEA, also referred the lack of linearity between HDI and the real energy consumption of a region and highlighted how the equivalent exergy of labour tends to rise with lower employment rates.

Human labour has a physical component which may be easily measured by its energy expenditure while working and an intellectual component comprising planning, managing, and all related intellectual activities which cannot be accounted in energy terms [41]. Number of workers and hours worked are usually available in labour statistics. These quantities measured by number of persons and hours need conversion factors if one wants to reflect on them as energetic or exergetic streams. Table 2 presents several options of accounting for exergy embedded on human labour (E_L). The first line is the extra physical expenditure of energy while working while the second line includes also the basal metabolic rate. The third line considers the survival energy (or human energy requirements [42]) which is the average food energy required to satisfy energy expenditure, maintain body size (adult) or physical growth (child) and be healthy while the fourth considers the metabolizable food energy intake during working hours (first column), total time (second column) and for total population (third column). These approaches are independent of the type of work. Approaches synthesized in the first column cannot be considered as cumulative approaches because they only account for the power that workers are "spending" during working hours.

Sciubba [30] chose a cumulative approach for labour energy, concluding that labour is only possible by the presence of all population and used a conversion factor, from energy to exergy, based on the current HDI index over a preindustrial one. The HDI comprises lifestyle, education, and national income in one index.

According to the EEA methodology, the economy is divided in seven sectors (Extraction, AFF, Conversion, Industry, Transportation, Tertiary, and Domestic) plus two open systems responsible for flux exchanges (Environment and Abroad). Human labour is the only output flow from the Domestic sector which produces working hours that enables all sector's economic activities.

The exergy needed to fuel society comes from the relation between the Environment and three economic sectors (Extraction, AFF, and Conversion) plus exergy trades with abroad. The exergy surplus from these three sectors is consumed in the remaining four plus the abroad exergy trades. The total primary exergy inflow to the society should be equal to the sum of all products' CExC cost. Adding more exergy flows will double-count them. To deal with this issue, Rocco and Colombo [43] have suggested a methodology to internalize labour in the economic system by assigning a fraction of the domestic sector's final demand to leisure activities and the rest to human labour which can provide a way around the double-counting issue if only the goods assigned to leisure activities are considered "final useful products". In the first EEA methodology reviewed in this section, the equivalent exergy of labour will introduce double-counting in the EEC because it increases the EEC of products in two ways (directly and via labour). In the other methodologies, the existence or absence of double-counting depends on whether the exergy used to fuel labour is also directly attributed to useful products.

Table 2. Embedded energy in human labour (N_w—Number of workers; N_p—Total population; E_w—Exergy expenditure during labour; E_b—Exergy expenditure at rest; t_w—working time; t_t—total time; e_{surv}—survival energy ≈ 2500 kcal/d; F_e—Food nutritional energy).

	Working Time	Total Time	Total Population
Net energy cost of labour [44]	$N_w \cdot (E_w - E_b) \cdot t_w$	-	-
Total energy expenditure [45]	$N_w \cdot En_w \cdot t_w$	-	-
Survival energy	$N_w \cdot e_{surv} \cdot \frac{t_w}{t_t}$	$N_w \cdot e_{surv}$	$N_p \cdot e_{surv}$
Metabolized food energy	$N_w \cdot F_e \cdot \frac{t_w}{t_t}$	$N_w \cdot F_e$	$N_p \cdot F_e$

2.3. Capital

Translating capital to an exergy flux is also a challenging task. Seen as an input factor, the capital flux represents all capital services provided by tangible and intangible assets that depreciate their ability to perform work over their lifetime. To quantify the equivalent exergy of capital, E_k, in the EEA methodology, two issues are addressed: (1) how to quantify the production factor capital in monetary units, C, and (2) how to quantify the specific exergy of capital needed to convert monetary units to exergy units, ee_k.

We will start with the conversion of monetary to exergy units exploring a simple analogy between financial accounting and EEA (Figure 3). Three flows have a direct relation between a monetary flow and energy as represented in Figure 3: intermediate consumption (IC), compensation of employees (S), and output.

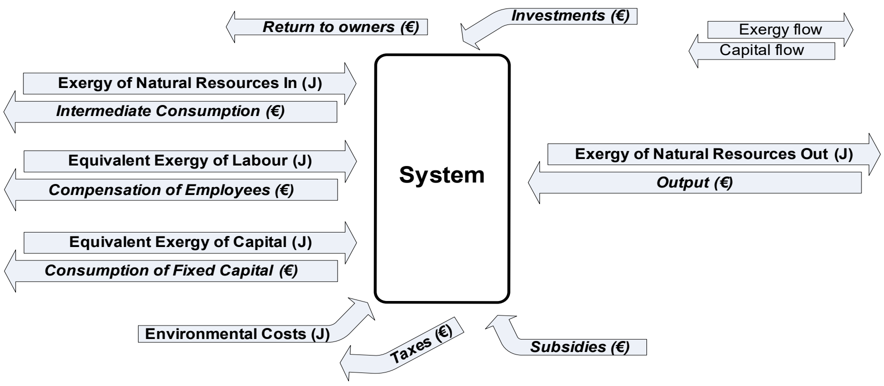

Figure 3. Simplified analogy between financial accounting and Extended Exergy Accounting.

Intermediate consumption (IC) consists of the monetary value of services and products consumed as inputs and transformed or used up by a production process [46]. In the Natural Resources Exergy Accounting (NREA) methodology, this flow is quantified as an exergy flow, representing all matter and energy plus services that enter the system [13]. If the ratio between these flows was used to obtain the specific exergy of capital than $ee_k = \frac{NREA_{in}}{IC}$, where $NREA_{in}$ stands for all material and energy flows measured by their intrinsic exergy.

Compensation of employees (S) is the total remuneration payable in cash or in kind of wages, salaries, and social insurance contributions. In the EEA methodology, this flow, measured as exergy, is the equivalent exergy of labour, E_L. When the specific exergy of capital is obtained with these flows, $ee_k = \frac{E_L}{S}$, which is the relationship proposed by Scuibba (2011) and Seckin et al. (2013).

Output is the monetary value of goods and services produced within a system for final use. This flow is also quantified by its exergy in the NREA methodology. In this case, $ee_k = \frac{NREA_{out}}{Output}$.

From the previous analogy, three relations are possible: one based on the labour flow, $ee_k = \frac{E_L}{S}$; the other on the intermediate consumption of input goods and energy $ee_k = \frac{NREA_{in}}{IC}$ and finally the output relation $ee_k = \frac{NREA_{out}}{Output}$. The ee_k based on the IC or Output may be optimal for systems were the fluxes are all easily measured by their exergetic content. The ee_k based on output would have lower values since manufactured products have lower exergy than the sum of inputs but higher economical value. The ee_k based on labour uses the exergetic content of labour measured in a non "thermodynamic" way and provides values that depend on the economic context of the region under study.

To relate a monetary value to an exergy quantity, Sciubba [6,32] used a specific exergy of capital $ee_k = E_{in}/M2\ (J/\$)$ and introduced the equivalent exergy of capital flow: $E_k = C \cdot ee_k\ (J)$ where C is the monetary flow under evaluation (Table 1). M2 is an intermediate monetary aggregate which reflects the currency under circulation plus the liquid deposits (maturity up to 2 years and redeemable up to 3 months) [47]. This approach to the equivalent exergy of capital is not related to financial accounting and is a macroeconomic value that may not be specified for each sector or subsector.

Ertesvag [9] followed Sciubba [32] to quantify ee_k, the exergetic capital flow input, $E_{k,in}$, and the exergetic capital flow output, $E_{k,out}$. To quantify capital $E_{k,in}$, Ertesvag [9] used the sum of output, gross investment, and net subsidies as the "capital input" and the sum of intermediate consumption, compensation for employees, net taxes, return to owners, and consumption of fixed capital as "capital output". To estimate the EEA efficiency, the author added "capital input" to other inputs and "capital output" to other outputs. Ertesvag was a pioneer since he applied, for the first time, the EEA approach for a nation, detailing all economic sectors and explaining all steps towards the exergetic assessment. It has become a reference study and most EEA researchers followed his methodology. However, by accounting for all monetary values entering and leaving the economic sectors, Ertesvag is double counting all material and energetic flows by their exergetic content and by their monetary value (Figure 3). This leads to incorrect values for the EEA efficiency (Table A20).

The novelty of EEA is the inclusion of two fluxes, labour and capital, plus the exergy accounting of harmful environmental externalities. All three flows are regarded as inputs (production factors) except labour which also represents the output of the domestic sector (the NREA efficiency of the domestic sector only accounts recycling materials and is practically nil). In all other economic sectors, the NREA efficiency should be superior to the EEA efficiency since it doesn't account for the equivalent exergy of harmful emissions as a virtual input nor the equivalent exergy of capital, representing the degradation of the capital stock or the capital services, or the equivalent exergy of labour. However, in the Ertesvag study [9], the opposite happened. Take as an example the Norwegian transportation sector, where the equivalent exergy of capital entering the sector is 64% of all input fluxes and an equivalent exergy of capital output was considered with almost the same amount. Adding such large numbers in both sides of the output-input equation ratio led to an overall increase of efficiency from 18.7% in NREA to 62.8% for EEA. The same behaviour was observed for all other economic sectors.

Milia and Sciubba [22] analysed the exergetic efficiency of Italian society, for 1996, using the methodology proposed by Sciubba [6,32]. In this study, for the agricultural, industrial, and tertiary sectors, $E_{k,out} > E_{k,in}$, providing no explanation of the monetary flows that were used to quantify C_{out} and C_{in}. Sciubba et al. [23] applied the same methodology [6] to the Siena province. Here, the industry and transportation sectors also had more exergetic capital output than input, which, as in the previous study, may be related with the accounting method for C_{out} and C_{in}. Bligh and Ugursal [25], studying the economy of Nova Scotia, accounted C_{out} for the domestic sector as the sum of net subsidies, depreciation, and value of production while C_{in}, from the other sectors is the sum of intermediate consumption, capital expenditures, and return on investment to owners. This methodology led to $E_{k,out} > E_{k,in}$ for all sectors except the domestic and conversion. The relative size of capital exergetic fluxes when compared with the other flows led to higher Efficiency for EEA. Appendix C presents the capital input-output relations and the efficiencies' relations between NREA and EEA of all economic sectors and societal studies.

Ptasinski et al. [17] assumed that: $ee_k = NREA_{in}/IC$ and that the C in $E_k = C \cdot ee_k$ was measured by the capital stock plus the short-term investment monetary values times the specific exergy of capital. Capital stock is the company's capital (common and preferred stock a company is authorized to issue) and short-term investments is the money spent on tangible assets on that year.

In his revision of the EEA methodology, Sciubba [30] assumed a proportionality between the equivalent exergies of capital and labour, $E_k = \beta \cdot E_L$, where β is given by $\beta = M2/S$. In this new method, the equivalent exergy of capital is smaller than the incoming global exergy $E_k = \alpha \cdot \beta \cdot E_{in}$ and that the new specific capital exergy is: $ee_k = \frac{E_k}{M2} = \alpha \cdot \beta \cdot \frac{E_{in}}{M2} = \frac{E_L}{S}$. The novelty is the relation between the specific exergy of capital and the specific exergy of labour: $ee_k = ee_L \frac{n_{workhours}}{S}$. With this relationship, the specific exergy of capital can be easily estimated from the specific exergy of labour for individual sectors.

Seckin et al. [21], in their assessment of the Turkish transportation sector, introduced a slightbut meaningful change to the specific exergy of capital $ee_k = \frac{E_k}{M2-S}$. Total salaries (S) were removed from the total current societal money ($M2$) because labour exergy was already accounted for. This change removed the issue of double-counting labour inputs. In Seckin et al. [21], the relationship, $ee_k = \frac{E_L}{S} = ee_L \frac{n_{workhours}}{S}$ was verified.

In the first EEA methodology reviewed in this section, the equivalent exergy of capital will introduce double-counting in the EEC because it increases the EEC of products in two ways (directly and via capital). In the other methodologies, double-counting is also an issue because all materials and energy for each sector are double counted by their intrinsic exergy and by their monetary (translated into exergy) cost. To avoid double-counting, a methodology is need to internalize capital, so that capital (a production factor) is also a product of the system.

2.4. Environmental Impact

Environmental impact is defined by the EEA, as the exergy needed for the treatment process, taking into account all materials, energy, labour, and capital necessary, to avoid the pollutants emission or bring all pollutants to a dead state. EEA does not value harmful emissions by their physical and chemical exergies because these do not value the pollutants' toxicity nor the devastating effects on our environment. However, real processes to completely avoid or treat effluents are non-existing or scarce. Although the specific exergy cost of pollutants is solely based on the exergetic resource consumption and independent of pollutants' proprieties, the approach is a valuable step towards the societal cost of avoiding its environmental effects. For example, the value obtained for the EEC of biomass-based electricity would be lower than the EEC of coal-based electricity because the latter would take into account the exergy needed to remove the CO_2 emissions associated with the combustion of coal.

This lack of real processes presents a difficulty to EEA studies in their environmental assessment and allows multiple interpretations (Table 1). Two trends were followed to evaluate the trash and discharge fluxes to the environment. The first quantified their intrinsic exergies due to the lack of extended exergy cost values. The second converted the monetary costs associated with waste and pollutants management into exergy using the capital conversion factor. Three studies obtained the extended exergy cost of major atmospheric pollutants and wastewater. The environmental remediation cost values of carbon monoxide, mono-nitrogen oxides, and sulphur dioxide were published by Dai et al. (2014) [20] while carbon dioxide, nitrous oxide and methane were studied by Seckin et al. (2013) [21]. The extended exergy cost values of municipal wastewater and sludge abatement were obtained for Turkey in 2006 [8].

3. EEA Methodologies: A Case Study

We compare the EEA methodologies that were collected in Table 1 to estimate the efficiency of the Portuguese Agriculture, Forestry, and Fisheries (AFF) sector from 2000 to 2012. The exergy flow diagram followed the one presented in Figure 4 [13], where all available fluxes in the respective databases were accounted for and converted to energetic and exergetic fluxes. Data sources and values gathered for this study are available in Appendixs A and B.

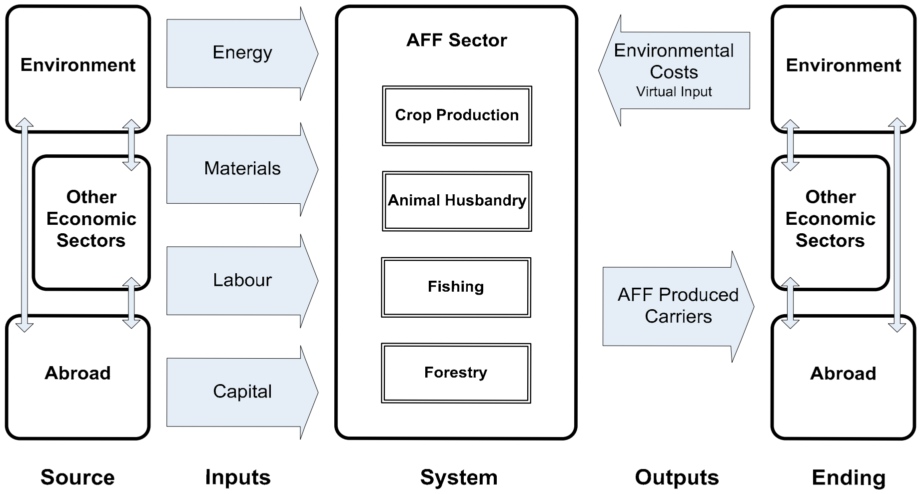

Figure 4. EEA flow diagram applied to the Portuguese AFF sector [13].

Previous agricultural studies accounted for all agricultural produced fluxes as an output from the environment and as an input to the agricultural sector. In this study, we consider that all renewable fluxes produced within the agricultural boundaries are an output from the sector and are not extracted from the environment. The reason is that, if no agricultural activities occurred, the agricultural produced fluxes would be almost negligible. The same thinking was applied to forestry (and aquaculture) but not to fisheries, since there are no human related activities within the fisheries subsector to feed and eventually protect the fishes. Fishing is an extraction from the natural environment like metals or minerals. This methodology inevitably leads to an efficiency which is much lower than the efficiency obtained for forestry or agriculture since fish catch appears as an output and also as an input.

The estimation methods for labour, capital, and environmental costs are the ones synthesized in Table 1. Table 3 summarizes the equations used to estimate the AFF equivalent exergies. The equivalent labour exergy of each subsector is defined as the fraction of workers in that sector times the equivalent labour exergy of society. In EEA1, no output monetary fluxes were considered and the only monetary input, representing the assets used in the AFF sector, was the consumption of fixed capital (CFC). In EEA2, the AFF money aggregate $M2_{AFF}$ is estimated as being proportional to M2 where the proportionality coefficient is the ratio of AFF gross value added to aggregated gross added value. All equations presented in Table 3 are for the AFF economic sector but were also used for each individual subsector (Agriculture, Forestry, and Fishing).

As environmental remediation costs for the three EEA methodologies, this study considers the major atmospheric pollutants emitted by the AFF sector and the respective specific exergy to clean or prevent them. These specific exergy values were measured as an extended exergy cost so they include the regional labour and capital considered in Refs. [20,21].

Table 3. EEA Methodologies applied to the AFF Portuguese sector (IEEA—Intrinsic Extended Exergy Accounting; M&E—Mass and Energy; EI—Environmental impact and EEC—Extended exergy cost).

EEA Method	AFF Labour Exergy	AFF Capital Exergy	AFF Mass, Energy and Environmental Impact Exergies
EEA 1	$E_{L,AFF} = E_{in} \cdot \frac{n_{AFF,workers}}{n_{total,workers}}$ $ee_L = E_{L,AFF}/n_{workhours,AFF}$	$E_{k,AFF} = CFC_{AFF} \cdot ee_k$ $ee_k = \frac{E_{in}}{M2}$	*M&E-Intrinsic Exergy* *EI-EEC*
EEA 2	$E_{L,AFF} = f \cdot e_{surv} \cdot N_p. \frac{n_{AFF,workers}}{n_{total,workers}}$ $ee_L = E_{L,AFF}/n_{workhours,AFF}$	$E_{k,AFF} = M2_{AFF} \cdot ee_k$ $ee_k = E_{L,AFF}/S_{AFF}$ $M2_{AFF} = M2 \frac{GVA_{AFF}}{GVA}$	*M&E-Intrinsic Exergy* *EI-EEC*
EEA 3		$E_{k,AFF} = (M2_{AFF} - S_{AFF}) \cdot ee_k$ $e_k = E_{L,AFF}/S_{AFF}$ $M2_{AFF} = M2 \cdot \frac{GVA_{AFF}}{GVA}$	*M&E-Intrinsic Exergy* *EI-EEC*
IEEA	$E_{L,AFF} = e_{surv} \cdot n_{AFF,workers} \cdot \frac{t_w}{t_t}$	$E_{k,AFF} = CFC_{AFF} \cdot ee_k = CFC_{AFF} \cdot \frac{\mathrm{NREA_{in}}}{\mathrm{IC}}$	*Intrinsic Exergy*

In these EEA approaches, energy and material fluxes are valued by their intrinsic exergy while the three immaterial ones are valued using arbitrary assumptions that were not fully justified.

We define a new methodology (IEEA) to measure the capital, labour, and environmental impact flows. This methodology evaluates all fluxes by an intrinsic approach in order to allow more consistent efficiency measurements of single processes.

The equivalent exergy of labour is considered to be an output of the domestic sector and fed by some of the incoming exergy to the sector. It is measured by the worker's survival exergy while working. The energy needed to sustain the workers is just for working days (235 days yearly considered) and during work hours (8 h daily). To maintain consistency with the remaining input fluxes, the equivalent exergy of capital is considered to be the "consumed" intrinsic exergy of capital assets. However, since it is impossible to measure this flux by physical proprieties, we will use the consumption of fixed capital multiplied by the specific exergy of capital (Table 3), $ee_k = NREA_{in}/IC$. The consumption of fixed capital (CFC) represents the lifetime share of the tangible and intangible assets used as a production factor, while the choice of ee_k is based on the assumption that the specific intrinsic exergies of intermediate consumption and fixed capital are similar. Mass and energy flows can be easily converted from energy to exergy (Appendix A). Environmental impact follows the same approach (Table 3).

In the IEEA, the environmental impact methodology is extended to include carbon dioxide sequestration from the forestry subsector. This will reflect the importance of the AFF sector not only in its ability to nourish all humankind but also through its remarkable ability to convert carbon dioxide into carbohydrates. Carbohydrates will produce cellulose (based on carbon), a primary component of plant cells. Although the carbon dioxide concentration in the atmosphere just recently surpassed 0.04% [48], it is increasing and may be related to global warming and climate changes. Once carbon dioxide is considered a harmful pollutant when released, it should also be considered an environmental service when sequestered. Thus, the AFF sector produces an environmental virtual output service, an environmental benefit (EB) that has to be taken into account. The environmental benefit (EB) is estimated by multiplying the CO_2 sequestered by the EEC (in EEA methodologies) or the specific exergy (in IEEA).

Since crops, vegetable, and fruits are intended for human consumption and our metabolism frees the ingested carbon, we will not account it as an exergetic sequestered flux. However, wood follows a commercial or industrial path mainly as a resource or energy carrier. If wood is used for furniture or construction it maintains its carbon content; if used in combustion processes as an energy carrier or in the paper industry, the released carbon dioxide should be attributed to the related activity.

4. Results, Comparison, and Discussion

4.1. The Exergy of Material Fluxes

Figure 5 presents the amount of intrinsic exergy in materials and energy entering the AFF sector [13]. These exergetic fluxes take into account the mass and energy magnitudes and the specific exergy values as explained in Appendix A. Feed is the main contributor with more than half of all exergy into the sector, followed by energy carriers. The intrinsic energy of seeds, fertilizers, pesticides, and fish is almost negligible.

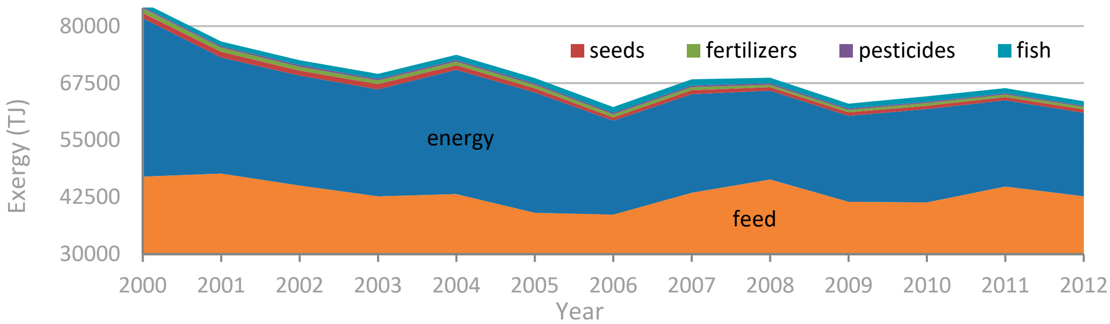

Figure 5. Exergy of all materials and energy entering the AFF sector [13].

4.2. The Exergy of Immaterial Fluxes with EEA1, EEA2, and EEA3

The exergy of environmental impact, common to EEA methodologies, presents the two atmospheric pollutants that have the highest overall EEC: carbon dioxide and methane (Figure 6) [13]. The other pollutants: ammonia, carbon monoxide, hydrofluorocarbons (CO_2 equivalent), nitrous oxide, nitrogen oxides, and sulphur oxides are barely visible. Also, the agriculture subsector represents 77% to 87% of the total virtual exergy. Methane emissions follow the trend line of animal husbandry production (almost constant) and carbon dioxide follows the decreasing consumption trend of energy resources on all three subsectors. Over the 13-year period, forestry reduced its virtual exergy consumption by 60%, fisheries by 40%, and agriculture by 10% which resulted in an overall reduction of 18% (Figure 6).

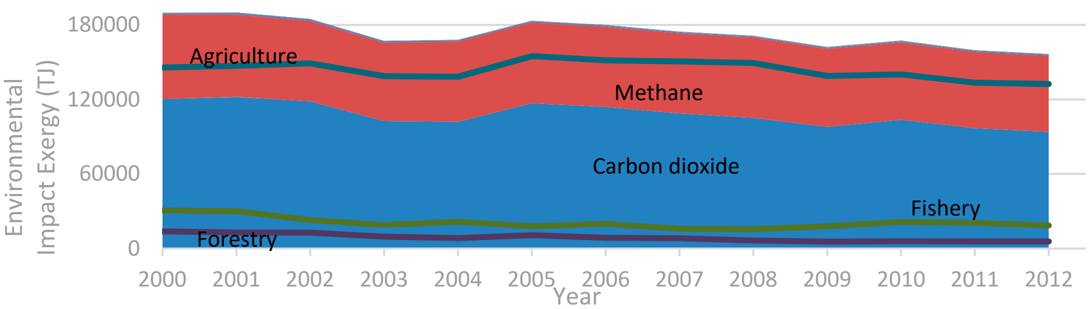

Figure 6. The virtual exergy input due to pollutant emissions into AFF subsectors [13].

The equivalent exergy of labour has two different methodologies (Table 3). In EEA1, E_L is the total amount of exergy entering the society (E_{in}) while in EEA2,3 it is only a fraction of E_{in} which explains the higher values obtained for EEA1 for all subsectors (Figure 7). The decrease in labour exergy from EEA1 since 2005 is mainly due to a decrease in E_{in} (Appendix B). The difference between subsectors is a direct result of the number of workers.

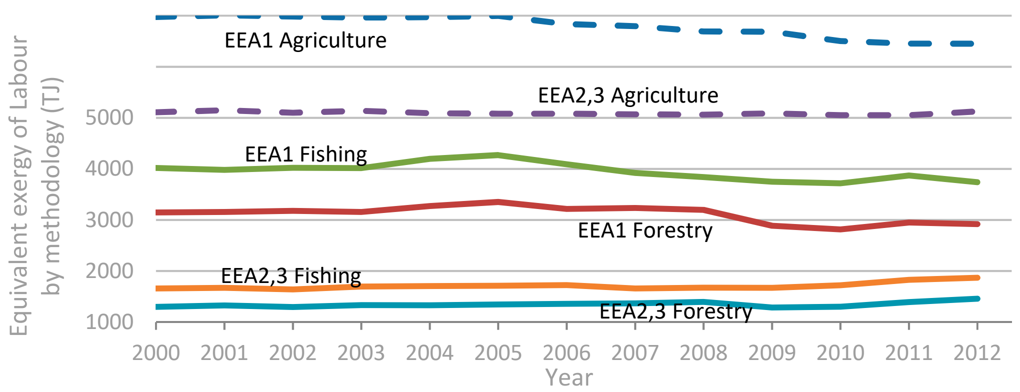

Figure 7. Equivalent exergy of labour per EEA methodology and subsector (full lines on the left axis and dashed lines on the right axis).

The specific exergy of labour, ee_L, which is the exergy needed to sustain one hour of labour is increasing for EEA1 and EEA2,3 (Figure 8). The number of workers per subsector is almost constant (except for agriculture which is slightly decreasing) but the annual working hours per worker are decreasing. From 2000 to 2012 there was a 30% decrease in agriculture, 3% in forestry, and 13% in fisheries. Since the average work hours per worker is lower in agriculture, its ee_L is higher (30% in 2012) than in the other subsectors.

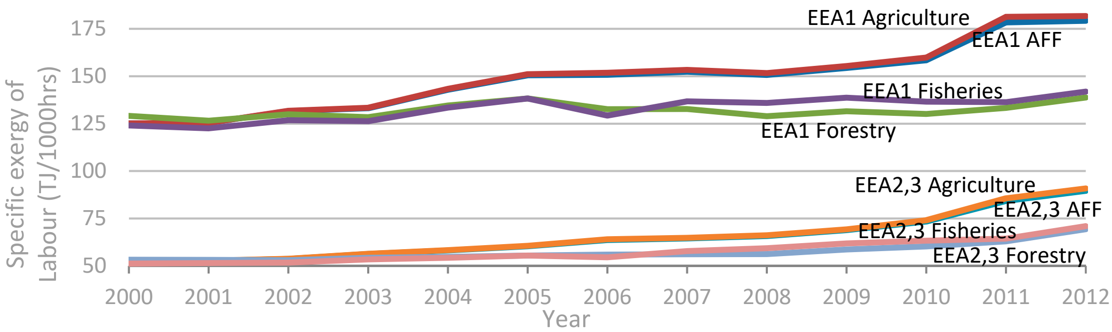

Figure 8. Specific exergy of labour per EEA methodology and subsector.

The differences between the equivalent exergies of capital, between the EEA methodologies, are very significant (Figure 9). The equivalent exergy of capital in agriculture in EEA2 is 26% to 47% higher than in EEA3 (14% to 18% higher in forestry and 51% to 68% higher in fishery). The equivalent exergy of capital in EEA1 is several times lower than in the other methodologies. Not only is the specific exergy of capital lower in EEA1 (Figure 10), but the monetary flux is also lower for all subsectors (CFC < M2).

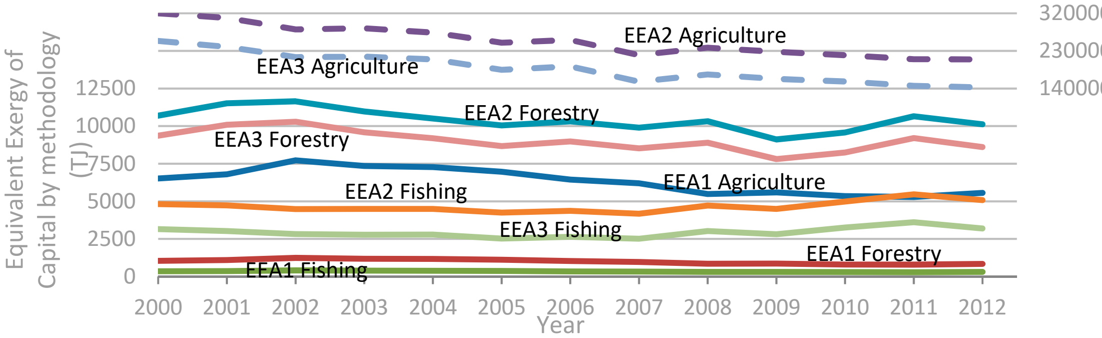

Figure 9. Equivalent exergy of capital per EEA methodology and subsector (full lines on the left axis and dashed lines on the right axis).

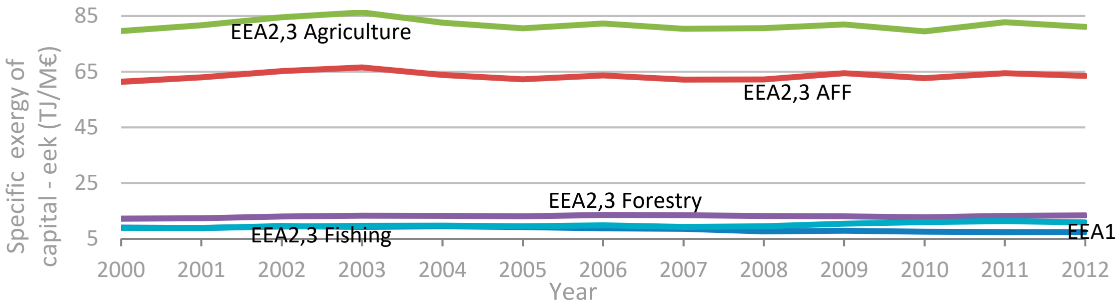

Figure 10. Specific exergy of capital per EEA methodology and subsector.

The differences among the specific exergies of capital values are high (Figure 10). While in EEA1 there is only one ee_k for all subsectors, $ee_{k1} = E_{in}/M2$, in EEA2 and EEA3 it is possible to estimate $ee_{k2,3} = \frac{E_L}{S}$ for each subsector. A worker in the agriculture subsector earns about 8 times less than in fisheries and 6 times less than in forestry (Figure 11). These differences are reflected on the specific exergies of capital. The average annual salary for agriculture is low because many farmers have no declared salaries. Both fishing and forestry annual salaries are more realistic in the Portuguese economic context.

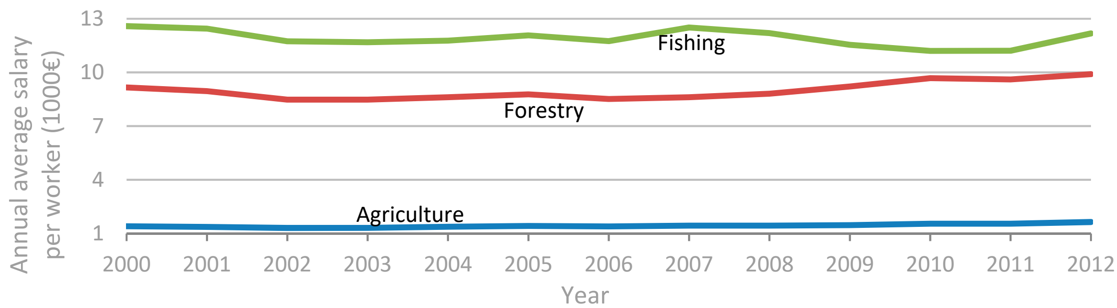

Figure 11. Annual average salary per worker and subsector.

The equivalent capital exergy of forestry is substantially higher than fisheries (Figure 9) because it has a higher equivalent exergy of labour (higher number of workers) and a higher fraction of M2 (higher GVA). Figure 12 presents the ratio of gross value added to annual salaries per subsector and explains the higher equivalent exergy of capital in forestry. In forestry, for every monetary unit spent on salaries, 6 to 9 units become value-added. The decreasing slopes are due to a decrease in GVA for all subsectors.

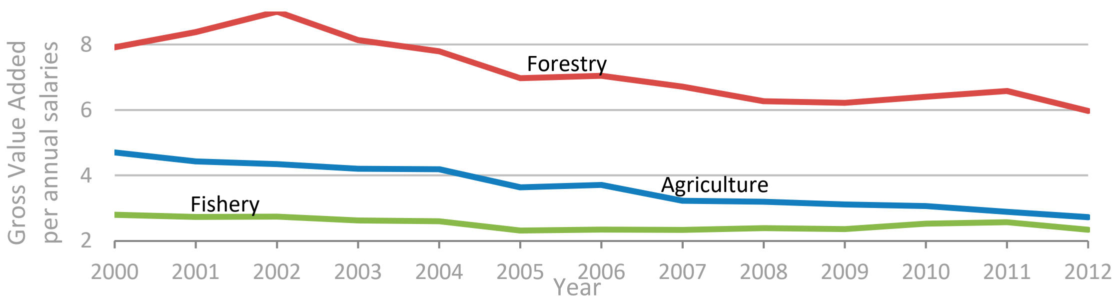

Figure 12. Ratio of gross value added by annual salaries per subsector.

4.3. The Additional Immaterial Flux: The Environmental Benefit (EB)

The environmental benefit (EB) of sequestering carbon dioxide by wood removal is 2.2 to 3.3 times larger than the entire environmental impact of the AFF sector (Figure 13). The EB value is larger than all inputs of the sector and reflects its importance which was, until now, neglected in these studies.

In Portugal, due to the strong paper industry, the difference between removals of non-coniferous wood and coniferous wood almost tripled from 2000 to 2012, the total remaining almost constant.

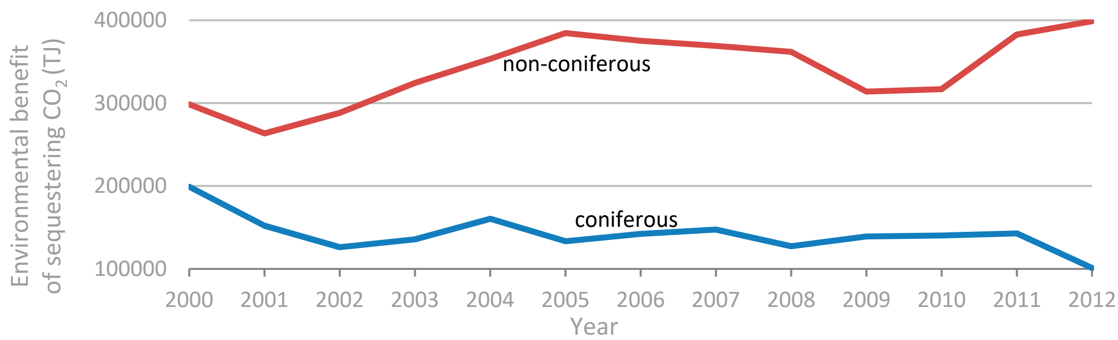

Figure 13. Environmental benefit of sequestering carbon dioxide by trees.

4.4. The Exergy of Immaterial Fluxes—Comparison between IEEA and EEA1, EEA2, and EEA3

With the IEEA methodology, the overall intrinsic exergy of atmospheric pollutants is much lower, representing on average 7% of the environmental impact measured by the EEC of emissions. Methane represented 81 to 83% of all exergy emissions (mostly due to animal husbandry), while agriculture is responsible for 98 to 99% of the sector's atmospheric pollutants. The low intrinsic exergy of carbon dioxide makes it negligible (Figure 14).

The equivalent exergies of labour and capital in IEEA have a lower share of the exergy of inputs compared with the other EEA methodologies (Figure 15). Although the agriculture and forestry subsectors need equipment, they are fixed assets and usually noncurrent assets with a long lifetime. Also, their utilization is not as intensive as in industry. The need for intangible assets is also scarce for the sector. Labour is also less intensive than in other economic sectors, at least in crop, vegetables and fruit production and forestry.

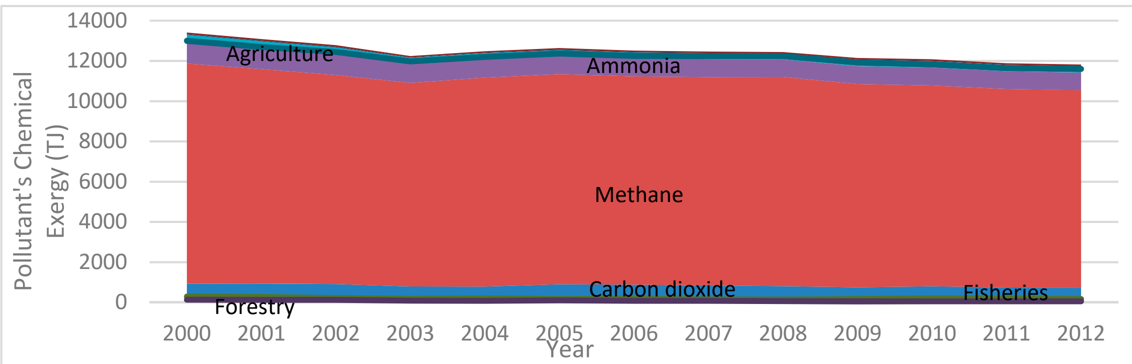

Figure 14. Chemical exergy of atmospheric pollutants from the AFF sector.

For agriculture and forestry, in EEA1, the sum of immaterial fluxes is on average 5 times higher than the materials and energy fluxes (Figure 15). The main reason is the accounting method of these fluxes. While the immaterial fluxes are evaluated with a cumulative approach, mass and energy flows are measured by their intrinsic exergy.

In EEA2, while the equivalent exergy of capital largely increased, the equivalent exergy of labour decreased. Nevertheless, both are measured with a cumulative approach and all three exergetic immaterial fluxes represent, on average, 88% of all inputs (Figure 15). In EEA3, all immaterial fluxes represent on average 86% of all inputs.

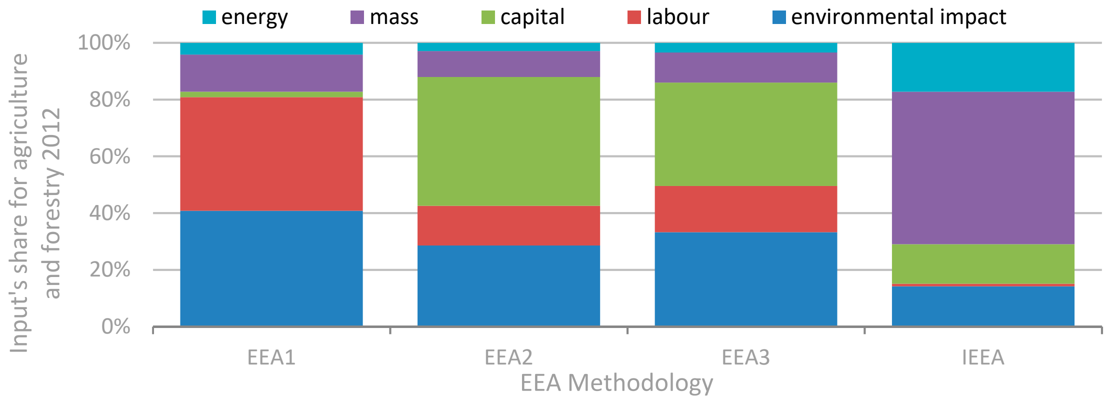

Figure 15. Input's exergy share for agriculture and forestry (2012).

In IEEA, material and energy fluxes represent two thirds of all inputs while the equivalent exergy of labour represents the lowest flux.

The share of each exergy flux in the inputs and the overall efficiency of each subsectors depends on the EEA methodology being used (Figure 16). While in NREA the exergy of outputs is up to 2.6 times higher than the exergy of inputs, in EEA (without the environmental benefit) the output–input relation is always below 0.5. From 2000 to 2012, the efficiency increased by 36% in NREA and by 17%, 28%, 33%, and 32% in EEA1, EEA2, EEA3, and IEEA, respectively (Figure 16), and by 21%, 32%, 37%, and 32% if EB is included.

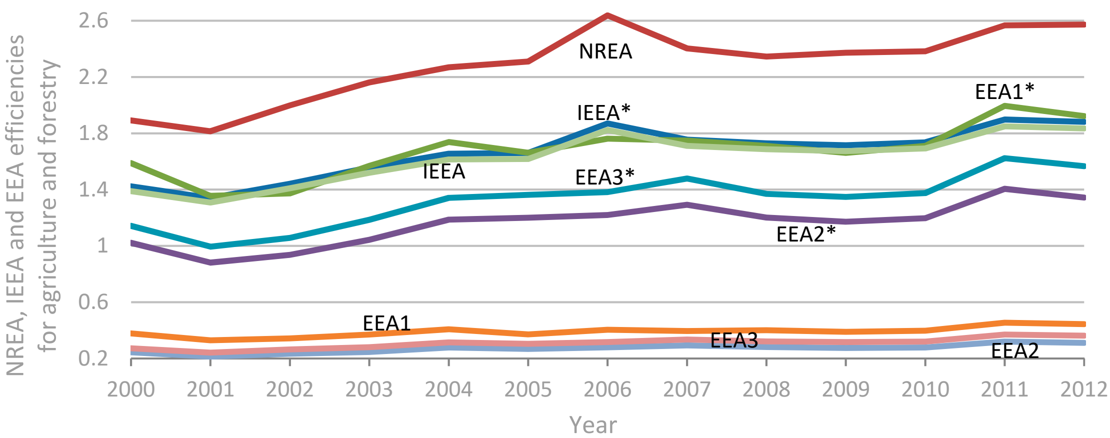

Figure 16. NREA, IEEA, and EEA output–input ratios for agriculture and forestry (* includes Environmental Benefit).

For the fishery subsector, the material and energy inputs represent less than 20% of all inputs in EEA1,2,3, while in IEEA, these fluxes represent close to 80% of all inputs (Figure 17). The fishery subsector is highly dependent on fossil combustibles which emit carbon dioxide in the internal combustion diesel engines of vessels. The EEC of removing carbon dioxide is 130 times bigger than its intrinsic exergy [21], making the environmental impact flow greater than the input energy in EEA1, EEA2, and EEA3 (Figure 17).

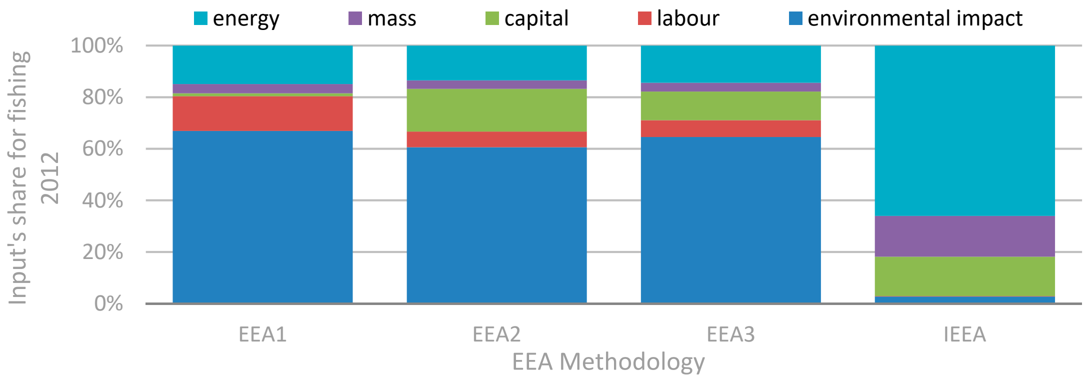

Figure 17. Input's exergy share for fishing (2012).

The NREA, IEEA, and EEA efficiency curves for fishing have different magnitudes and shapes. The NREA and IEEA efficiency are gradually decreasing due to an increasing consumption of energy carriers. The fish caught is regulated by European quotas and their mass and energetic content is almost constant over the years. However, since the energy needed to catch them is increasing, the efficiency decreased by 42% (NREA) from 2000 to 2012. Considering the EEA methodologies, the main input is, by far, the equivalent exergy of the environmental impact (Figure 17). However, a 48% exergy reduction in the environmental impact (EI) from 2000 to 2007 caused a doubling in efficiency in the same period, despite the increase in energy carriers. From 2007 to 2012, the EI stabilized and the EEA curves began to reflect the higher usage of energy carriers (Figure 18). A greater energy needed to sustain the fishery subsector, with the same energetic content of fish caught, may indicate that fish populations are decreasing and the vessels have to travel more to catch the same amount.

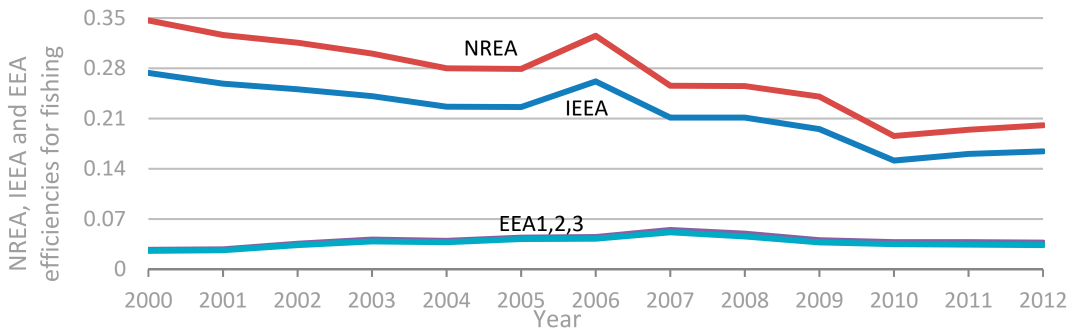

Figure 18. NREA, IEEA, and EEA output–input ratios for the fishery sector.

The IEEA efficiency is lower than NREA and higher than EEA (Figure 18). It follows the NREA shape and gets close to it at the end of the period due to a higher share of the energetic flow. The IEEA efficiency dropped 39% from 2000 to 2012.

5. Conclusions

We have reviewed past studies to identify, synthesize, and discuss the different Extended Exergy Analyses (EEA) methods. In this set of studies, the estimation of the Extended Exergy Cost (EEC) of services and products was not done in a consistent way due to the lack of a solid database of EEC for inputs and the arbitrariness and double-counting associated with the methods used to quantify the exergy of labour and capital. The lack of an EEC database is not relevant for studies whose aim is the estimation of exergy efficiency of sectors and countries because, in this case, the use of an intrinsic approach to estimate the exergy of all energy and material input flows is the correct option. If the input flows were valued by their EEC (cumulative exergy), then the estimated efficiency would not characterize the specific system or economic sector, rather all that intervene to produce the output flows.

We have classified the different approaches into 3 distinct EEA methods. The main differences are related to the methods used to estimate the equivalent exergy fluxes of labour and capital. The equivalent exergy of labour is equal to the overall input of exergy into society in EEA1 (the first EEA methodology) while in EEA2 and EEA3 (the second and third EEA methodologies), it is proportional to the population, the Human Development Index (HDI), and the per capita survival energy. The specific exergy of labour for all methodologies is the equivalent exergy of labour per working hour. The equivalent exergy of capital is the product of a monetary flow and the specific exergy of capital that is needed to convert monetary units to exergy units. In EEA1, the specific exergy of capital is the ratio of exergy input into society to a societal monetary aggregate (M2) while in EEA2 and EEA3, it is the ratio of the equivalent exergy of labour to the compensation of employees. The monetary flow is the consumption of fixed capital in EEA1, M2 in EEA2, and M2 minus compensation of employees in EEA3.

In the case studies where these methodologies were applied, materials and energy flows are valued by their intrinsic exergy while, in contrast, labour and capital are valued using approaches that estimate their cumulative exergy cost. Additionally, our case study shows that results obtained for the equivalent exergy of labour and capital vary widely among these 3 methodologies, which makes the results obtained with the EEA approaches unreliable and easy to manipulate.

We propose an additional method, the IEEA (Intrinsic Extended Exergy Accounting), that estimates the labour and capital inputs using an intrinsic approach, thereby contributing to the build-up of a consistent EEA methodology that can be used to estimate exergy efficiency. The IEEA is more restricted in its understanding of capital and labour fluxes than other EEA methodologies but more inclusive than the Natural Resources Exergy Accounting (NREA) methodology. It quantifies the physical and chemical exergies of the labour and capital flows consumed in the process. For labour, this is the exergy of food needed to fuel it and for capital is the estimated physical and chemical exergies of capital (machines among others) consumed in the process.

The IEEA considers that for capital, the relevant monetary flux is the consumption of fixed capital (CFC) and that the intrinsic exergy of this flow is obtained assuming that the specific intrinsic exergies of intermediate consumption and capital consumed are similar. For labour, the IEEA assumes that the relevant flow is the number of hours worked and that the intrinsic exergy of this flow is the exergy of the food that is needed to maintain the workers during this time period.

To account for the environmental impact (EI), the IEEA considers the intrinsic exergy of each atmospheric pollutant. In this case, it would be more consistent to consider the exergies needed to remove the pollutants from the environment or to avoid them. However, these estimations were not available in the literature. Additionally, the IEEA proposes a new category of exergy flows: the environmental benefit. For environmental benefit (EB), this methodology considers the intrinsic exergy of the carbon dioxide removed from the atmosphere.

We compare the EEA methodologies (including the IEEA) using the Portuguese Agriculture, Forestry, and Fishery (AFF) sector from 2000 to 2012. For the agriculture and forestry subsectors, all methodologies estimate (1) an improvement in exergy efficiency that ranges from 17% to 37% and (2) an exergy surplus if the EB is taken into account. The NREA and IEEA methodologies also estimate an exergy surplus without the EB. The equivalent exergy of labour represented, on average, 40%, 12%, 14%, and 1% of inputs for EEA1, EEA2, EEA3, and IEEA, respectively, and 2%, 48%, 41%, and 15% for the equivalent exergy of capital.

For the fishery subsector, the results are contradictory: the NREA and IEEA methodologies estimate a decrease in efficiency of 42% and 40%, respectively, while the three EEA methodologies estimate an increase in efficiency of 37%, 31%, and 34%, respectively. This contradiction is mostly explained by the environmental impact (EI). This input exergy flow, which corresponds to more than 60% of the inputs in the three EEA methodologies, has been reduced by 40% from 2000 to 2012. The equivalent exergy of labour represented, on average, 14%, 6%, 6%, and 0.2% of inputs for EEA1, EEA2, EEA3, and IEEA, respectively, while the equivalent exergy of capital represented 1%, 15%, 10%, and 15%.

EEA is a valuable methodology; however, the lack of an EEC database and rigorous guidelines (ex. on how to correctly include capital fluxes) make it very difficult to apply the EEA without accounting for inconsistencies. The IEEA is the first attempt to move forward from a cumulative thinking into an intrinsic one, allowing correct extended efficiency metrics and providing flux accounting guidelines. The extended exergy efficiency obtained with the IEEA takes into account all the intrinsic exergies of input and output mass and energy fluxes considered with the NREA methodology plus the physical work of humans (and working animals) and the intrinsic exergy of the capital dissipated in the process. These additional flows are important to identify processes/sectors or periods of time when the dissipation of capital or human work is higher. For our case study, the IEEA extended exergy efficiency is lower than the NREA efficiency, as expected. This difference is significant for both subsectors, which means that the consumption of exergy associated with physical labour and dissipated capital is relevant but it does not have a clear trend for the time period under analysis. It is more relevant for agriculture and forestry (AF) compared to the fisheries subsector, which means that the AF subsectors are either more labour intensive and/or dissipate more capital.

The IEEA methodology proposed in this paper was developed to estimate extended-exergy efficiencies. However, the IEEA approaches for labour and capital can be applied to estimate the EEC of products, avoiding double-accounting. The approach proposed for labour avoids double-counting if the food consumed to fuel working hours does not exit the system as a "useful product". In this case, the increase in EEC of all useful products due to the labour input is compensated by a lower amount of useful products exiting the system. The same reasoning can be applied to the capital methodology; in this case, the capital goods used as production factors do not exit the system and the exergy used to produce them will increase the EEC of useful products as dissipation of capital occurs. Thus, our paper also contributes to improving the method to estimate EEC in the scope of EEA. Issues that have to be addressed in future research to promote the use of EEA results for policy and planning purposes include: the development of an EEC database and a discussion on the spatial and temporal boundaries that should be considered for different cases.

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Abbreviations

The following abbreviations are used in this manuscript:

AFF	Agriculture, Forestry and Fisheries
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExC	Cumulative Exergy Consumption
CFC	Consumption of Fixed Capital
EB	Environmental Benefit
EEA	Extended Exergy Accounting
EEC	Extended Exergy Cost
ee_K	Specific Exergy of Capital
ee_L	Specific Exergy of Labour
EI	Environmental Impact
E_{in}	Exergy entering the society
E_K	Equivalent exergy of Capital
E_L	Equivalent exergy of Labour
EREA	Energy Resources Exergy Accounting

GVA	Gross Value Added
HDI	Human Development Index
IC	Intermediate Consumption
IEEA	Intrinsic Extended Exergy Accounting
M2	intermediate monetary aggregate
NREA	Natural Resources Exergy Accounting
S	Compensation of Employees

Appendix A. Data Sources and Values for the AFF Sector

Fluxes that were directly produced and consumed inside the AFF sector were not considered and only fluxes between sectors that have economic relevance were accounted for. Although feed, incubations and seed are produced by the sector, they were considered to leave the agricultural sector to other economic activities (ex. industry and/or tertiary) and returned as an input. However green fodder, straw and manure (used as a fertilizer in crop production) that are internal outputs and inputs of activities within the sector were not accounted for.

Solar radiation, vital for crop production, and water, essential for crops and livestock, were not included in the study. Sun radiation is not an anthropogenic controlled flux and it can be seen as a flux from the environment with no economic value. Water from rain follows the same thinking as it is not an anthropogenic activity but irrigation water should have been an input although the lack of trustworthy data prevented its use in the study.

The food (and feed) energy content was considered equal to the metabolizable energy as defined by the USDA National Nutrient Database [49]. The energy content (combustible or gross energy) of the ingested food should be measured by a bomb calorimetry. However, foods are not fully digested and absorbed by the organism. From the ingested or gross energy, some is lost as faeces (faecal energy) and gases (combustible gas), the rest is the digestible energy. Subtracting from the digestible energy, the energy that is lost is urine and heat results in metabolizable energy [50]. Data available from the United States Department of Agriculture [49] for food energy is based on the Atwater system which is equivalent to the metabolizable energy. The choice to use the metabolizable energy was mainly due to the lack of a complete database of combustible or gross energy. Nutritional energy values assigned to each food element, in its raw state, are from USDA National Nutrient Database [49]. Moisture content of all food items was considered to be equal between USDA and Eurostat databases.

Some data presented gaps in one or more years of the study. To fill in the gaps for a given resource or product, in a year or more, data was interpolated (between known values) or extrapolated (in extremes of the data set) by a linear regression made from all the other known values.

Beginning with the inputs of the sector, energy carriers fluxes are available from the statistical office of the European Union, Eurostat [51] in energy units. The energy of energy carrier's fluxes is the lower heating value (LHV) and the exergy factors for the energy carriers are the ratio of the standard chemical exergy of the organic fuels to the LHV. Table A1 presents these factors, which were obtained from Ref. [52–54]. However, the consumption matrix of energy carriers is only available in two branches, with the first being the agricultural plus the forestry subsectors and the second being the fisheries subsector.

Table A1. Exergy factors for energy carriers.

Energy Carrier	Factor	Energy Carrier	Factor	Energy Carrier	Factor
Biodiesels	1.11	Gasoline	1.07	Natural gas	1.04
Derived Heat	0.6	Kerosene	1.07	Solid biofuels	1.107
Electrical Energy	1	Liquified petroleum gas (LPG)	1.07	Total fuel oil	1.07
Gas/Diesel Oil	1.07	-	-	-	-

Fertilizer data was downloaded from Eurostat [51], in mass units and desegregated by main nutrient or compound. The chemical exergy values (Table A2) were estimated with the corresponding chemical formula, multiplying molecular mass by the standard chemical exergy (values from [53] or alternatively [55]).

Table A2. Fertilizers' chemical exergies.

Fertilizer	Chemical Formula	Molecular Mass g/mol	Exergy kJ/mol	Exergy kJ/kg	Alternatively [55]	Exergy kJ/kg
Potassium/Potash	K_2O	94.203	413.1	4385		4400
Nitrogen	NH_4NO_3	80.04348	294.8	3682		3680
Phosphorus /Phosphate	P_2O_5	141.9446	319.5	2251		2700

Pesticide data was also available from the Eurostat [51] in mass units and divided by function. Chemical exergy values were adopted from [55,56] being the herbicides value the average of six known herbicides and the insecticides value the average of three insecticides active substances (Table A3).

Table A3. Pesticides' chemical exergies.

Pesticide Type	Exergy kJ/kg	Reference
Fungicides and bactericides	27,900	[55]
Herbicides, haulm destructors and moss killers	24,100	[56]
Insecticides and acaricides	19,900	
Molluscicides, total	19,900	
Other plant protection products	24,100	
Plant growth regulators, total	24,100	

Seeds are harvested from the crop production subsector and enter the same subsector in next sowings. This flux was included in the study since future seeds are accounted as production crops that follows a route to industry and tertiary sectors. Seeds used in agriculture are available in mass units for each plant type from the Food and Agriculture Organization of the United Nations, Faostat [57]. Specific exergy values are presented in Table A4 and available from the USDA National Nutrient Database [49,58].

Table A4. Specific Nutritional Energy (SNE) in kJ/100 g for seeds [49].

Seed	SNE	Seed	SNE	Seed	SNE	Seed	SNE
Barley	1473	Cow peas, dry	1432	Oats	1628	Sesame seed	2399
Beans, dry	1427	Grain, mixed	1455	Oilseeds	1800	Sorghum	1377
Broad and horse beans	1436	Groundnuts	1733	Peas, dry	1448	Soybeans	614
Buckwheat	1381	Hempseed	1800	Poppy seed	2231	Sunflower seed	1289
Cabbages and brassicas	150	Lentils	1448	Potatoes	321	Taro (cocoyam)	360
Canary seed	1624	Linseed	2076	Pulses	1423	Triticale	1406
Castor oil seed	1800	Lupins	1633	Rapeseed	2068	Vegetables, fresh	150
Cereals	1455	Maize	1527	Rice, paddy	1172	Vetches	1360
Chick peas	1499	Millet	1582	Rye	1414	Wheat	1418
Cottonseed	1059	Mustard seed	1963	Safflower seed	1314	Yams	422

Food given to animals is only accounted for by feed, since green plants that animals forage don't exit the sector. Feed is available from Faostat [57] in mass units for each of the constituents. Specific exergy values were taken from Refs. [49,58] and presented in Table A5.

Table A5. Specific Nutritional Energy (SNE) in kJ/100 g for feed components.

Feed Product	SNE	Feed Product	SNE	Feed Product	SNE	Feed Product	SNE
Apples	218	Fats, Animals, Raw	3257	Oil crops, Other	1639	Rye	1414
Aquatic Plants	180	Fish Body Oil	3776	Olive Oil	3700	Sesame seed	2399
Bananas	371	Fish, Liver Oil	3776	Onions	166	Sesame seed Oil	3700
Barley	1473	Freshwater Fish	400	Palm kernels	2152	Sorghum	1377
Beans	368	Fruits, Other	203	Peas	339	Soya bean Oil	3700
Butter, Ghee	3001	Groundnuts	1733	Pelagic Fish	400	Soya beans	614
Cassava	667	Maize	1527	Potatoes	321	Sugar beet	293
Cephalopods	343	Marine Fish Other	400	Poultry Meat	979	Sugar cane	135
Cereals Other	1488	Meat, Other	858	Pulses	354	Sunflower seed	1289
Coconuts	770	Milk	353	Rape and Mustard Oil	3700	Sweet potatoes	359
Cottonseed	1059	Millet	1582	Rape and Mustard seed	2068	Tomatoes	74
Crustaceans	300	Oats	1628	Rice	1548	Vegetables Other	226
Demersal Fish	400	Offal, Edible	486	Roots Other	449	Wheat	1418
Eggs	682	Oil crops, Oil, Other	3700	-	-	-	-

Incubating egg data is available from Eurostat [51] in number of units for each bird type. For each egg unit an average mass [59] was considered to estimate his energy. Nutritional values taken from the USDA database [49] and presented in Table A6.

Table A6. Specific Nutritional Energy (SNE) in kJ/100g and average mass for eggs.

Eggs	SNE	Mass (g)	Eggs	SNE	Mass (g)	Eggs	SNE	Mass (g)
Duck Eggs	776	70	Guinea fowl eggs	663	9	Turkey eggs	716	79
Geese Eggs	775	144	Hen eggs	599	53			

As output of the AFF sector, the harvested crops include cereals, root crops, industrial crops, fibre crops, vegetables, fruits, nuts, vineyards, and olive trees. Overall nutritional energy values are obtained by multiplying each crop mass production by their specific nutritional energy. Table A7 presents all crop specific nutritional energies [49] of all products in the production database [51].

Table A7. Specific Nutritional Energy (SNE) in kJ/100 g for each harvested crop.

Crop	SNE	Crop	SNE	Crop	SNE	Crop	SNE
Almonds	2423	Mushrooms	130	Oranges	197	Radishes	66
Apples	218	Eggplants	104	Other berries	225	Raspberries	220
Apricots	201	Eggplants	104	Other brassicas	150	Red pepper	166
Bananas	371	Endives	71	Other citrus fruits	180	Rice	1548
Barley	1473	Figs	310	Other fresh vegetables	100	Rye and maslin	1414
Beans	368	Garlic	623	Other fruits	369	Sour cherries	209
Black currants	264	Grain maize	1527	Other leafy or stalked vegetables	117	Spinach	97
Broad and field beans	1377	Hazelnuts	2629	Other nuts	2170	Strawberries	136
Cabbage (white)	103	Kiwis	255	Other pulses	354	Sugar beet	293
Carrots	173	Leeks	255	Peaches	165	Sunflower seed	1289
Cauliflower and broccoli	140	Lemons and acid limes	126	Pears	239	Tomatoes	74
Celeriac	176	Lettuces	65	Peas	339	Triticale	1406
Cherries	263	Melons	141	Plums	192	Vineyards	288
Chestnuts	891	Oats and mixed grain	1628	Pomelos and grapefruit	134	Walnuts	2738
Chicory	96	Olive trees	481	Potatoes	321	Watermelons	127
Courgettes	80	Onions	166	Quinces	238	Wheat	1418
Cucumbers	65	-	-	-	-	-	-

Meat production is available in mass units from the Eurostat database [51] and nutritional energy values [49] were chosen as a raw mix of meat for each animal type (Table A8).

Table A8. Specific Nutritional Energy (SNE) in kJ/100 g for each slaughtered meat.

Meat	SNE	Meat	SNE	Meat	SNE
Meat of Bovine Animals	979	Meat of rabbits	569	Pig meat	995
Meat of Horses, Asses, Mules, or Hinnies	556	Meat of sheep and goats	1067	Poultry meat	979

Fish catch is available by catching zones, fish families, and individually in Eurostat [51]. Table A9 presents the specific nutritional energy [49] considered for each fish, the average of their nutritional values if a family or an assumed average if in a fishing zone. The same table is used to account all energetic flux produced by aquaculture.

Table A9. Specific Nutritional Energy (SNE) in kJ/100 g for fish.

Fish	SNE	Fish	SNE	Fish	SNE
Abalones, winkles, conchs	439	Lobsters, spiny-rock lobsters	469	Mussels	360
Aquatic mammals	462	Marine fishes not identified	500	Oysters	213
Carps, barbels, and cyprinids	531	Miscellaneous aquatic animals	500	River eels	770
Clams, cockles, arkshells	360	Miscellaneous coastal fishes	500	Salmon, trout, smelt	594
Cods, hakes, haddocks	343	Miscellaneous demersal fishes	500	Scallops, pectens	289
Crabs, sea-spiders	364	Miscellaneous diadromous fishes	650	Shads	824
Flounders, halibuts, soles	294	Miscellaneous freshwater fishes	465	Sharks, rays, chimaeras	544
Freshwater crustaceans	300	Miscellaneous marine crustaceans	300	Shrimps, prawns	297
Herrings, sardines, anchovies	661	Miscellaneous marine molluscs	330	Squids, cuttlefishes, octopuses	343
King crabs, squat-lobsters	377	Miscellaneous pelagic fishes	500	Tunas, bonitos, billfishes	602

Milk collection is available from the Eurostat database [51] in mass units by animal type. Specific nutritional values (Table A10) are for unprocessed milk at the producer level [49].

Table A10. Specific Nutritional Energy (SNE) in kJ/100 g for milk.

Milk	SNE	Milk	SNE	Milk	SNE
Cows' milk	268	Ewes' milk	451	Goats' milk	288

FAOSTAT [57] provided the produced amount of honey in mass units which has a specific nutritional energy of 1272 kJ per 100 g of product [49].

Produced eggs is available from the Faostat database [57] in mass units for hen eggs and for other birds' eggs. Table A11 presents the specific nutritional energy of hen eggs and an average for other birds' eggs [49].

Table A11. Specific Nutritional Energy (SNE) in kJ/100 g for eggs.

Eggs	SNE	Eggs	SNE
Hen eggs	599	Other bird's eggs	776

Wood removals are available from the Eurostat database [51] in volume units considered as under bark with a moisture content of 20%. Specific exergy values (Table A12) obtained from Dewulf et al. [38] with densities of 450 kg/m^3 for softwoods and 650 kg/m^3 for hardwoods.

Table A12. Wood exergies per type of wood [38].

Wood	Exergy (MJ/kg)	Exergy (GJ/m^3)	Wood	Exergy (MJ/kg)	Exergy (GJ/m^3)
Coniferous	17.688	7.9596	Non-coniferous	17.608	11.4452

Animal skins production data [57] (including wool) is only available for goats and sheep but the absence of a specific exergetic value for skins lead us to consider only the wool production flux that has a specific exergy of 5850 kJ/kg [12].

Environmental remediation exergy costs were estimated by multiplying the pollutant air emission (obtained in mass units from Eurostat [51]) by the specific extended cost of removing the pollutant from the atmosphere. Seckin et al. [21] created a virtual process to find the environmental extended exergy cost of carbon dioxide, methane and nitrous oxide while Dai et al. [20] determined the specific environmental remediation exergy cost of carbon monoxide, nitrogen oxides and sulphur oxides. For ammonia, the chemical exergy [53] was used as the extended exergy cost of removing the pollutant since no study is available in the literature (Table A13).

Table A13. Specific environment remediation exergy cost (SEEC) and chemical exergy (Ex,ch) in kJ/kg for each atmospheric pollutant.

Pollutant	SEEC	Ex,ch	Pollutant	SEEC	Ex,ch	Pollutant	SEEC	Ex,ch
Ammonia	19,841	19,841	methane	322,400	51,810.7	nitrous oxide	10,600	2430
Carbon dioxide	57,600	442.6	nitrogen oxides	3610	2963	sulphur oxides	5890	4892
Carbon monoxide	11,800	9825	-	-	-	-	-	-

Labour data [51] is available in number of workers per AFF subsector as well as all country population (Table A14).

Table A14. Population and workers allocated to each AFF subsector (thousands).

	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Population	10,514	10,557	10,573	10,568	10,558	10,542	10,522	10,503	10,483	10,458	10,419	10,362	10,289
Agriculture	497.2	489.8	508.8	534.3	542.2	546.2	556.9	557.3	566.7	591	585.9	604.3	584.6
Forestry	10.9	10.9	10.6	10.7	12.0	11.8	11.8	11.7	11.7	11.8	11.7	11.9	11.6
Fishery	14.0	14.3	14.0	13.9	14.4	14.3	15.0	14.9	15.0	15.0	14.8	15.0	14.8

All economic values such as compensation for employees, agricultural gross value added (GVA), monetary aggregate M2, and gross domestic product (GDP) [51] (Table A15) were obtained at current prices and converted to constant euro GDP prices through a GDP price deflator obtained from the economic and financial affairs of the European commission (Ameco) [60] (Table A16). The GDP price deflator is referenced to 2010 and measures the ratio between real GDP and the nominal GDP, providing a measure of inflation over the period.

Table A15. Monetary values of all sectors and AFF sector at constant 2010 prices (Billion Euro for Total values and Million Euro for subsectorial values). Total—All sectors, GVA—gross value added, Wages—Compensation of employees.

	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Total GVA	141	149	151	149	151	151	147	146	148	145	147	147	145
Total M2	163	174	173	170	179	163	159	157	150	147	147	153	151
Agriculture GVA	2224	2184	2413	2440	2497	2538	2887	2891	3272	3260	3337	3655	3869
Agriculture M2	2585	2537	2765	2776	2946	2735	3113	3097	3312	3294	3327	3784	4019
Agriculture Wages	817	756	787	784	782	787	778	795	780	775	768	825	823

Table A15. *Cont.*

	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Forestry GVA	647	689	657	613	662	682	708	716	785	814	893	893	841
Forestry M2	752	800	753	697	782	735	763	767	795	822	890	924	874
Forestry Wages	108	104	102	98	105	101	100	102	100	100	99	106	106
Fishery GVA	399	412	396	378	419	418	413	416	459	459	476	509	521
Fishery M2	464	478	454	430	494	450	445	446	464	464	474	527	541
Fishery Wages	170	160	156	160	175	178	176	179	176	175	173	186	186

Table A16. Price deflator values referenced to 2010.

2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
99.333	99.730	100	99.360	98.283	96.604	93.809	90.913	87.984	85.925	83.068	79.714	76.859

The Human Development Index (HDI) for Portugal is presented on Table A17.

Table A17. HDI values for Portugal.

2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
0.827	0.824	0.818	0.812	0.809	0.804	0.797	0.793	0.79	0.792	0.789	0.788	0.782

Appendix B. Exergy Input to Society

In EEA1, the equivalent exergy of labour and capital is equal to the total amount of exergy that enters the region in a given year. To measure the overall input exergy, referred as domestic consumption, we will account all primary products that are internally processed. Domestic consumption is the domestic production plus imports less exports. The primary products considered are the outputs from agriculture (cereals, roots, sugar crops, pulses, nuts, oil crops, vegetables, fruits, fibers, fodder crops, and grazed biomass), the output from the fishery (fish catch) and forestry (wood) subsectors, the output from the extraction sector, including minerals (marble, granite, sandstone, chalk and dolomite, slate, salt, limestone and gypsum, clays and kaolin, sand and gravel) and metal ores (iron, copper, zinc and bauxite and other aluminium). Animal husbandry outputs were not included because the exergy to feed the cattle was already taken into account as fodder crops or grazed biomass. The total exergy of energy carriers was also accounted for (solid fuels, petroleum products, gas, renewable energies, and electrical energy).

Data from the extraction sector as well as trades with other countries were downloaded from the Eurostat database [51] in mass units. All specific exergy values for minerals and metal ores were obtained from Ref. [12] and present in Table A18.

Table A18. Specific Exergy values for minerals and metal ores.

Mineral	Exergy kJ/kg	Metal Ore	Exergy kJ/kg
Marble, granite, sandstone	820.96	Iron	79.77
Chalk and dolomite	81.88	Copper	523.09
Slate	131.49	Zinc	1237.83
Salt	244.7	Bauxite and other aluminium	1114.16
Limestone and gypsum	49.95	-	-
Clays and kaolin	697.99	-	-
Sand and gravel	131.49	-	-

Exergy factors presented in Table A19 which are the ratio of the standard chemical exergy of the organic fuels (or energy carrier in electrical and heat flows) to the LHV were retrieved from Ref. [52–54].

The sum of all exergy of primary products consumed in the country is calculated by the product of each flux by the specific exergy or exergy factor. The sum of all exergetic fluxes is presented in Figure A1.

Table A19. Exergy factors for energy carriers.

Energy Carrier	Factor	Energy Carrier	Factor	Energy Carrier	Factor
Biodiesels	1.11	Electrical energy	1	Natural gas	1.04
Biogas	1.04	Gas works gas	1	Petroleum products	1.07
Biogasoline	1.11	Geothermal energy	0.6	Solar photovoltaic	1
Bituminous coal	1.06	Hydro power	1	Solar thermal	0.25
Charcoal	1.11	Industrial wastes	1.1	Solid biofuels	1.107
Coke oven coke	1.05	Liquid biofuels	1.11	Waste (non-renewable)	1.1
Coking coal	1.06	Municipal waste	1.1	Wind power	1

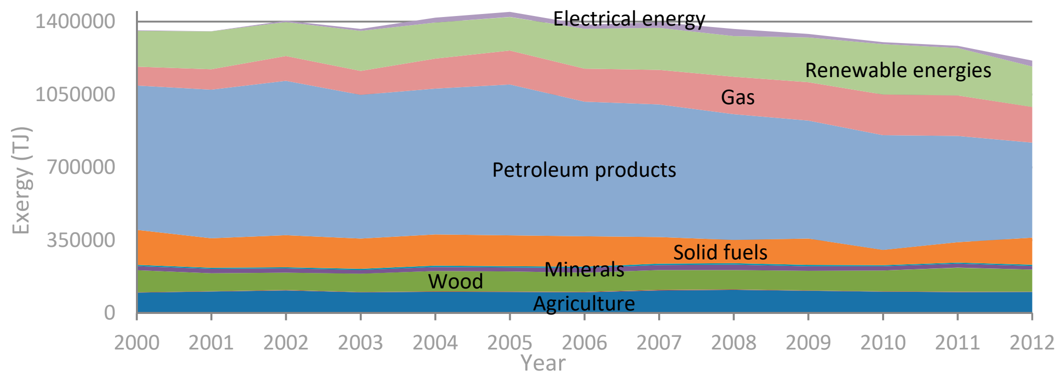

Figure A1. Exergy of primary fluxes consumed by society (fisheries and metals are barely visible).

Overall, the exergy consumption decreased by 11% from 2000 to 2012 mainly due to a 66% reduction in petroleum products in the same period from 51% of all inputs in 2000 to 38% in 2012. Food from agriculture and fisheries represented 8.4% in 2012, a little less than wood which represented 8.8% of all inputs. The combined domestic consumption of metals and minerals is below 2%. The energy flows used for energy conversion represented 83% of all exergy consumption in 2000 and 81% in 2012. Renewable energies and gas have been increasing their share, while petroleum products and solid fuels are decreasing. Metal and fish are barely visible since their exergetic contributions are too low.

Figure A2 shows the ratio between the domestic production to consumption for each primary flux. Portugal is completely dependent on fossil fuels because it does not extract them from the natural environment. In contrast, for wood, minerals, metals, vegetables, nuts, fodder crops, and eventually fruits, production is higher than consumption. The country is dependent on fish, roots, pulses, and cereals and imports almost all of its consumption of oil crops, fibers, and lately sugar crops. The total ratio of domestic production vs. consumption (including energy carriers) slightly increased from 25% in 2000 to 30% in 2012 which is explained by a 11% decrease in consumption and a 4% increase in production.

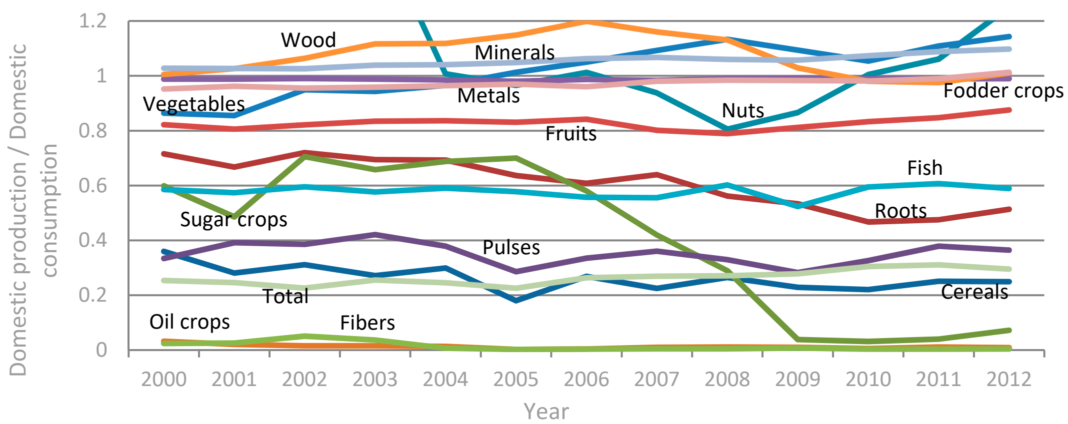

Figure A2. Exergy ratio of domestic production vs. domestic consumption by all society.

Appendix C. NREA and EEA Efficiencies of Previous Studies

Table A20 synthesizes the equivalent exergy of capital input–output relations plus NREA versus EEA Efficiency for the several economic sectors obtained by the referenced studies.

Table A20. Comparison of exergetic input and output capital fluxes (E_k) and Efficiency (NREA exergy Efficiency—ε_{NREA} vs. EEA Efficiency—ε_{EEA}) of societal studies.

Study	Agriculture	Extraction	Conversion	Industry	Transport	Tertiary	Domestic
[10]	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < 1 < \varepsilon_{EEA}$
[22]	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} = \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} = E_{k,out} = 0$ $0 = \varepsilon_{NREA} << \varepsilon_{EEA}$
[23]	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $0 = \varepsilon_{NREA} << \varepsilon_{EEA}$
[11]	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	- -
[24]	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} > \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in}>E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out} = 0$ $\varepsilon_{NREA} << \varepsilon_{EEA}$
[25]	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA} \approx 1$	$E_{k,in} = E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,out}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} < E_{k,out}$ $\varepsilon_{NREA} < \varepsilon_{EEA}$	$E_{k,in} > E_{k,out} = 0$ $\varepsilon_{NREA} < 1 < \varepsilon_{EEA}$

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