Chapter

Case Study: Pathways from Forest to Energy in a Circular Economy at Lafões

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Abstract

The present case study deals with new pathways in demand for forest residues disposal in the Lafões region (Portugal), since this biomass is presently regarded as a residue and eliminated through open air burning. Different biomass-to-energy conversion systems have a high sustainability value and, thus, the energy potential of the biomass supplied by the forest of Lafões was assessed, using GIS-based methods and assumptions from the literature. The Lafões region produces large amounts of chicken manure from which energy can be recovered through anaerobic digestion. The energy potential held by the effluent of the several classes of the poultry industry of Lafões was assessed, using IPCC 2006 guidelines to estimate their biomass and methane production potential. Furthermore, integrated solutions were pursued. The present challenge is to explore complementarities between effluents for anaerobic digestion to achieve improved energy and waste management system performances. The complementarity between the residues from maritime pine forest management and from broiler production was assessed through bench-scale anaerobic co-digestion assays, leading to increased methane production when compared to those achieved with single substrate anaerobic digestion. This result highlights the interest of further research concerning complementarities between other effluents in the Lafões region.

Keywords: forest residues, chicken manure, anaerobic digestion, substrate complementarity, energy potential assessment

1. Introduction

The damage to ecosystems generated by the current consumption patterns and associated energy demand, as well as by many of the current waste management systems, has been driving the scientific community to develop research on the mitigation of this damage through integrated and more sustainable energy and waste management systems.

Alongside, decision makers, non-governmental organizations and even market agents (both from supply and demand sectors) are concerned with current consumption impacts. They demand new or improved services and products, paying attention to all their supply chain impacts, including the energy and waste management systems required to provide them.

The present case study had the collaboration of some of the entity types mentioned above, in order to pursuit more sustainable energy and waste management systems for the region of Lafões, a region of the Viseu district, located in the centre of Portugal. Its area corresponds to the earlier Lafões municipality and presently comprises three municipalities, namely, Oliveira de Frades, São Pedro do Sul and Vouzela. **Figure 1** depicts the official administrative map of Portugal [1] and the region of Lafões, with the borders of the three municipalities and their location in Portugal.

The Lafões region is characterized by large forest areas. In the last decade, its forests have been severely affected by wildfires which also endanger food crops, industrial facilities and households. The promoter of the research here reported was the Lafões rural development association (ADRL), a certified forest management entity (EGF—*Entidade de Gestão Florestal*) responsible by two forest management units (UGF—*Unidade de Gestão Florestal*) in the region of Lafões, which is responsible for two main activities, namely, fire preventive forestry and surveillance during fire hazard periods.

ADRL is presently much concerned with the disposal of the forest residues generated by its fire preventive forestry management operations, which include thinning, pruning and sometimes harvesting, generating large amounts of biomass presently disposed of by open air burning. Regarding this effluent no longer as a residue and using knowledge on environmental management systems and technologies with a higher sustainability value, ADRL brought together local key actors and entities, to work on the common goal of finding new integrated energy systems to jointly deal with their effluents.

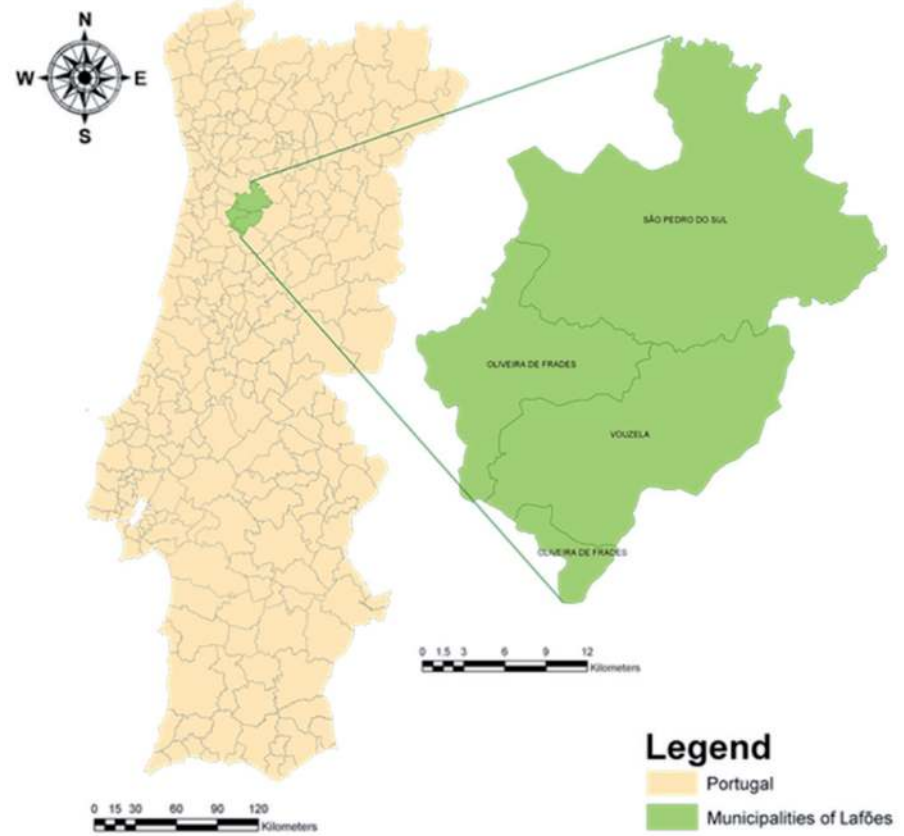

Figure 1.
Official administrative map of Portugal with the location of the Lafões region municipalities [1].

The Lafões region is also the home of a large poultry industry sector (15.9% of the Portuguese production, according to [2] and the directorate-general of food and veterinary (DGAV) of Viseu), which produces large amounts of waste. The present case study thus aims to explore complementarities in the joint valorisation of the effluents from this activity with those of the forest management operations. The challenge is then to quantify the production of these effluents in the Lafões region and to identify promising ways to convert them into energy, in a circular economy, integrated strategy. To tackle this challenge, ADRL sought the contribution of the institutions to which the authors belong.

The decision on the most promising biomass conversion processes depends on many factors, including the type and quantity of available biomass, the desired end-uses, the relevant governmental policies, environmental standards and economic conditions, as well as project specific factors. The available biomass types is one of the most determinant factors [3]. In the present case, the ADRL challenge, involving such different biomasses (forest residues and chicken manure), is not an easy one.

Since it is hardly biodegradable and carries low moisture content, forest residues are a suitable substrate for thermochemical conversion. Within thermochemical conversion process options, namely, combustion, pyrolysis, gasification and liquefaction, the combustion of residues in small-scale decentralized facilities can be considered the most promising present option for forest residues exploitation. This is due to the fact that other options involve technological challenges that remain unsolved and somewhat uncertain investment costs [4].

Chicken manure, a more easily biodegradable substrate with higher moisture content, is adequate for biochemical conversion processes. There are different possible routes within biochemical processes, mainly through fermentation and anaerobic digestion. The first is widely implemented to produce ethanol from sugar- and cellulose-rich crops and the second is frequently used for the direct conversion of manure to biogas [5].

Anaerobic digestion can provide a "major contribution to the safeguarding of energy supplies in future" [6], as stated by the head of the "Anaerobic Processes" research focus area of the German biomass research centre (DBFZ). As he also states, "biogas plants must become more flexible in terms of their substrates and energy delivery". This thus became a core issue of the present case study, in order to recover as much as possible of the energy potential of the two biomass types in consideration, through integrated solutions.

Many assessments of the biomass and energy potentials of forest [4, 7–10], chicken manure [11–15] and overall organic residues [2, 16–19] can be found in the literature, considering different boundaries (local, regional, national or worldwide levels) and different plant scales (small, medium and large). For forest and manure biomasses, the assessment of the energy potential starts with the assessment of the biomass potential. This done, it is possible to obtain their theoretical energy potential and, according to the conversion process specifications, the associated technical energy potential.

In addition to the mentioned assessment levels (biomass potential, theoretical and technical energy potentials), three more levels theoretically remain to be considered (economical, implementation and sustainable implementation) [19], however they are beyond the scope of this preliminary case study.

Concerning forest residues, it is common to rely on GIS-based methods for supply quantification, using geo-referenced data derived from remote sensing imagery, taking into account important constrains such as slope, accessibility, and land use conflicts. The theoretical energy potential is subsequently obtained using the lower heating value of each biomass species and the technical energy potential is obtained using the conversion efficiency of the selected process.

The chicken manure biomass potential assessment starts by the quantification of the number of birds in the covered industrial facilities, which is usually available through local or national statistics offices. For the present case study, this information was readily provided by the DGAV of Viseu, which has been struggling to promote sustainable standards in the local poultry sector, through inspections and guidance provided to the producers.

The Tier 2 methodology of the IPCC Guidelines 2006 [11] allows the calculation of the volatile solids and methane emissions per bird, which can then be used to return the Lafões biomass and methane potentials per poultry class. The theoretical and technical energy potentials can then be obtained as described for forest residues, using the lower heating value of methane and the technical specifications of the implemented system.

Up to this point, only the energy potentials for the separate conversion of the two types of biomass are obtained and an integrated solution remains to be assessed. Since the aim of the present case study is to estimate the increment in energy potential that can be obtained when an integrated solution is implemented, two bench-scale biomass-to-energy conversion systems (BTES) were assessed: chicken manure anaerobic digestion and anaerobic co-digestion of chicken manure and forest residues.

There are scarce results in the literature from computing the energy potential of the joint digestion of biomass from plant and animal origins, and those available are case specific, as, for example, in [20–24]. The values for this case study were thus measured experimentally and choices had to be made concerning the classes of the two types of biomass to be used as substrates. The details of the methodological procedures employed in this case study, the discussion of the results and some conclusions that can be drawn from the results, are presented in the following sections.

2. Assessment of the energy potential of the two biomass-to-energy conversion systems

The energy potential of the two BTES was assessed in three main steps. In the first step, the available classes of both types of biomass were examined and one class from each was selected to feed the bench-scale BTES assays. This selection was based on the theoretical energy potential (ThEP) for the forest classes and on the theoretical methane production (MP) from manure for the poultry classes. The second step was conducted to experimentally assess the methane production capacity of both BTES using the selected substrates. With the third step, the energy potential of each BTES was finally estimated.

These three assessment steps are presented in the following sections and the discussion concerning the energy potential increment between the two considered BTES is presented in Section 3.

2.1 Selection of biomass classes

2.1.1 Selection of the forest species

For the assessment of the ThEP of the forest residues, the analysis of geo-referenced data obtained through GIS-based methods is largely accepted and, thus, ArcGIS version 10.5 was used to map the several forest class areas. Subsequently, the annual residue productivity (RP) and the percentage of the land covered by the horizontal projection of the vegetation (HPV) were considered to assess the biomass potential of each forest class. Finally, the lower heating value (LHV) was used to obtain the ThEP of each forest class. Between the two forest classes with higher ThEP, the one with higher C:N ratio was selected, since it favors the methane potential in anaerobic digestion. This methodology is applied as described in detail subsequently.

After defining the Lafões region area (**Figure 1**), which was obtained from the official administrative map of Portugal [1], all areas with land uses other than forest were eliminated from the land use cover map [25] of the region. When mapping the forest area, land use conflicts with nature conservation areas must be considered [7, 18], which can be located in the geocatalogue of the nature and forest conservation institute (ICNF) [26].

Nevertheless, because of the fire hazard threatening nature conservation areas (rendering fire preventive biomass removal mandatory) and since the residue fraction that needs to be left on the soil for environmental purposes is taken into account in the subsequent calculations, these areas were not subtracted from the forest area to be considered.

When quantifying the biomass supply area, accessibility must also be considered, since there are technical difficulties with the collection of forest residues from steep slope areas. Due to environmental concerns like soil erosion, but also to allow mechanization and to reduce collection costs, only areas with slopes of less than 20% [4] were selected from the terrain digital model [27] of Lafões.

To further meet accessibility criteria, technical restrictions imposed by large distances to roads or passable tracks must also be taken into account. Thus areas at distances of less than 3 km were to be selected [4] from the forest road maps of Oliveira de Frades [28], São Pedro do Sul [29] and Vouzela [30]. Dense road coverage of the entire region was observed, thus, no area was subtracted concerning this technical restriction to biomass collection, since no point in the map is at a distance to a road greater than 3 km.

With all the mentioned assumptions, the available and accessible supply area for each forest class was obtained. Those areas are illustrated in **Figure 2** and the forest class nomenclature used is in accordance with the technical specifications in [31].

The forest biomass residues potential (FBP) present in the residues was estimated, multiplying the selected areas by the RP for each forest class and the percentage of land covered by the HPV of the predominant species of each forest class, as suggested in [10]. Finally, to calculate the ThEP, the LHV of the predominant species of each forest class, taken from [4], was multiplied by the FBP. All the input data used is shown in **Table 1**, as well as the results for the FBP and the ThEP.

As observed from the results, the eucalyptus forest and the maritime pine forest are those with the highest ThEP in the region of Lafões, 601 TJ/year and 374 TJ/year, respectively. According to [32], the C:N ratio values for pine and hardwood are 73:1 and 39:1, respectively, and since high C:N ratios favor the methane potential in anaerobic digestion of chicken manure, maritime pine was the selected residue source.

2.1.2 Selection of the poultry class

The assessment of the ThEP of the chicken manure in the region of Lafões was implemented in three stages: (1) data collection on the number of birds in the region's industrial units; (2) calculation of the biomass potential of each poultry class using volatile solids excretion rate (VS); (3) estimation of the theoretical methane potential using the maximum methane production capacity (B_o) of each poultry class. The methodological assumptions, procedures and results in each stage are subsequently explained in detail.

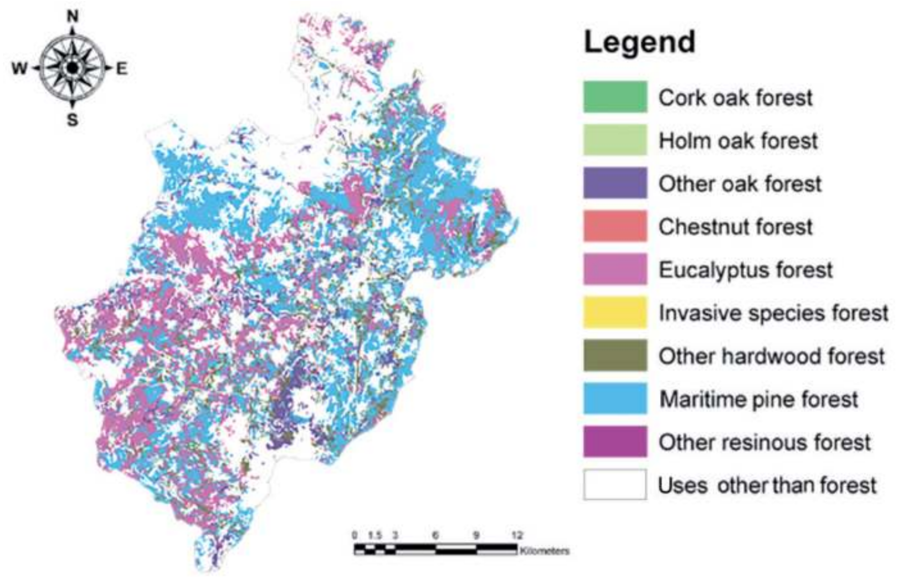

Figure 2.
Map of the forest land cover of the Lafões region.

To start the computation of the chicken manure production in the region of Lafões, the first collected input data was the number of birds in the industrial sector of the region. The number of birds existing in the three municipalities of Lafões in February 2020 was registered and provided by DGAV. A total of 328 producers and 5,716,945 birds were registered, distributed among four classes of poultry industry, namely, broilers, laying hens, reproductive hens and turkeys. **Table 2** shows the number of birds of each class registered in the three municipalities of Lafões.

With the information on the number of birds, calculation of the biomass potential is usually done considering the chemical oxygen demand (COD) or volatile solids (*VS*) content of the chicken manure. The methodology applied in this case study is that suggested in the IPCC guidelines [11]. In this, the assessment uses the volatile solids excretion rate, calculated through Eq. (1) for each class of bird.

$$VS = \left[GE \times \left(1 - \frac{DE}{100}\right) + (UE \times GE)\right] \times \left[\frac{1 - ASH}{18.45}\right] \quad (1)$$

where *VS* is the volatile solids excreted by an average bird [kg VS/(bird.day)]; *GE* is the gross energy intake in the feed for an average bird [MJ/(bird.day)]; *DE* is the digestibility of the feed [%]; *UE* is the urinary energy expressed as mass fraction of *GE*; *ASH* is the ash content of manure calculated as mass fraction of the dry matter in the feed intake; 18.45 is the conversion factor for dietary *GE* per kg of feed dry matter [MJ/kg].

The results of the estimation of the *VS* per bird class, as well as all the input data (taken from [2]) are presented in **Table 3**. The calculation of the gross energy intake (*GE*), which depends on the recommended metabolic energy ingestion and metabolisability, is explained in detail in [11]. The presented values are class specific, except for that of *UE* (no value available for poultry) for which the value given for other livestock (cattle, sheep and goats) was used.

In the third stage, the value obtained for the *VS* in the second stage was multiplied by the maximum methane production capacity (B_o) from manure, specific for each bird class, all taken from [2], resulting the methane production (MP) per bird. The total MP was calculated on a basis of 365 days/year and using the number of birds in each poultry class presented in **Table 2**. The values of B_o and the results

Forest class	A^T [ha]	*RP* [t residue/(ha.year)]	*HPV* [%]	*FBP* [t residue/year]	*LHV* [GJ/t residue]	*ThEP* [GJ/year]
Cork oak forest	15	0.48	20	1	14	20
Holm oak forest	24	0.48	20	2	14	33
Other oak forest	4453	0.50	65	1447	15	21,710
Chestnut forest	30	0.50	65	10	15	145
Eucalyptus forest	70,077	0.88	65	40,080	15	601,300
Invasive species forest	85	20.00	65	1106	14	15,480
Other hardwood forest	4989	0.75	65	2432	15	36,480
Maritime pine forest	33,868	1.00	65	22,010	17	374,200
Other resinous forest	29	0.85	65	16	15	241

Table 1.
Forest biomass residues potential (FBP), theoretical energy potential (ThEP) and input data used for their estimation: total area (A^T) of the forest class; annual residue productivity (RP) of the forest class [10]; percentage of land covered by the horizontal projection of the vegetation (HPV) of the predominant species of the forest class [10]; lower heating value (LHV) of the predominant species of the forest class [4].

Poultry class	Oliveira de Frades	São Pedro do Sul	Vouzela	Total
Broiler	1,869,294	1,734,020	1,361,166	4,964,480
Laying hen	102,108	46,607	27,027	175,742
Reproductive hen	201,149	0	209,200	410,349
Turkey	75,919	63,055	27,400	166,374

Table 2.
Number of birds registered by class and municipality (data from February 2020).

Poultry class	*GE* [MJ/(bird.day)]	*DE* [%]	*UE* [kg/kg]	*ASH* [kg/kg]	*VS* [kg VS/(bird.day)]
Broiler	1.56	68	0.04	0.020	0.03
Laying hen	2.2	64	0.04	0.048	0.05
Reproductive hen	2.15	64	0.04	0.048	0.04
Turkey	4.75	68	0.04	0.026	0.09

Gross feed energy intake (GE), digestibility of the feed (DE), urinary energy expressed as mass fraction of GE (UE) and manure ash content (ASH) [2].

Table 3.
Volatile solid excretion rate (VS) calculated for each poultry class in the Lafões region and its input data.

of the estimation of the MP potential of the several poultry classes of Lafões are presented in **Table 4**.

According to the calculations, the poultry class that contributes the most to the MP potential of the Lafões region is the broilers (77.3%) and was therefore selected for the experimental study.

2.1.3 Selection of the broiler litter type

The characterization of the litter practices in the region was provided by a company that integrates 73 producers, representing a sample of 26.8% of the total population of producers in the region of Lafões. Within this sample, 88% of the producers use straw litter for the bed of the broilers, 10% use sawdust litter and 2% use rice chaff litter. Straw litter is thus the favorite and, therefore, a poultry production facility that uses this litter type was selected to provide the sample used to feed the bench-scale BTES assays.

2.2 Estimation of the methane production capacity of the two BTES

After the residue class selection, samples were collected, submitted to a pre-treatment and characterized. With these, different compositions of mother suspensions were prepared to feed bench-scale digestion assays. The methane productivity results obtained from the assays were then used to compute the experimental and technical energy potentials of the two BTES being assessed.

The samples collected are identified as follows: straw litter chicken manure (CM) from the poultry breeding pavilion; maritime pine forest biomass residues (FB) containing residues of woody tissues (with diameter smaller than 6 mm) and leaves; wastewater (WW) from the cleaning of the poultry pavilion; inoculum (I) from an anaerobic digester treating wastewater sludge.

Both CM and FB were collected in triplicate, from a broiler production pavilion and from a maritime pine forest area, respectively, in the region of Lafões. The WW was collected from a drain usually connected to a septic tank, in the facility that provided the CM sample, while the inoculum (I) was obtained at the wastewater treatment plant of Quinta do Conde (SIMARSUL, Setúbal, Portugal).

At the laboratory, all the samples were submitted to a pre-treatment and subsequently characterized. For both the CM and FB samples, the collected triplicates were hand homogenized together in a single large container. After this, the CM was slightly chopped and shifted to produce particles with an approximate diameter lower than 5 mm, while the FB was crushed in a mill to produce particles less than 0.5 mm in diameter. No pre-treatment was applied to the WW and I samples. Characterization of the four substrates was performed in duplicate using standard methods [33] for volatile solids (VS*) and bulk density. Results are presented in **Table 5**.

To experimentally assess the methane potential of the anaerobic digestion and co-digestion options, four mother suspensions were prepared: chicken manure (CMms); chicken manure and forest biomass (CM + FBms); forest biomass (FBms); and inoculum (Ims).

The CMms was used to determine the methane production capacity from the CM substrate and the CM + FBms was used for the same purpose regarding co-digestion of the CM and FB substrates. Inoculum was added to both CMms and CM + FBms, at a concentration of 0.3 mL per mL of mother suspension. The preparation of these mother suspensions also incorporated the wastewater from cleaning of the poultry pavilion (WW). For this, a volumetric proportion between the liquid and solid substrates of 1:4.5 was considered, the average value among those provided by several poultry production facilities in the region.

The other two mother suspensions, Ims and FBms, were included in the study with the intention of measuring their individual methane production capacity

Poultry class	B_o [m^3 CH_4/kg VS*]	MP [10^3 m^3 CH_4/year]
Broiler	0.36	19,460
Laying hen	0.39	1136
Reproductive hen	0.39	2592
Turkey	0.36	1974

Table 4.
Methane production (MP) and maximum methane production capacity (B_o) per poultry class [2].

Sample	VS* [g/g]	Bulk Density [g/mL]
Straw litter chicken manure (CM)	0.519 ± 0.001	0.3 ± 0.01
Maritime pine forest biomass residues (FB)	0.767 ± 0.001	0.21 ± 0.02
Wastewater from the poultry pavilion cleaning (WW)	0.0016 ± 0.0001	0.97 ± 0.02
Inoculum (I)	0.0133 ± 0.0003	n.d.

The values presented are average ± standard deviation from duplicate measurements using standard methods [33].

Table 5.
Values for the characterization parameters of the substrates used in the anaerobic digestion experiments, volatile solids (VS) and bulk density.*

(in the absence of CM). The same inoculum concentration was used in these two (0.3 mL I/mL mother suspension) and distilled water was added to complete the assay volume, instead of poultry wastewater. The composition of the four mother suspensions is summarized in **Table 6**.

From each 400 mL of mother suspensions, 40 mL were taken to feed each of three 70-mL reactors, leaving a headspace of 30 mL. The reactors were operated in batch mode under temperature control at 37 ± 1°C, thus in mesophilic conditions.

The assay had a duration of 48 days and during this period biogas production was monitored every day with a pressure transducer and the methane content in the biogas was monitored every week by gas chromatography (Varian 430-GC). The cumulative methane production results after the incubation period are presented in **Table 7** and their evolution along time is illustrated in **Figure 3**. The step increase episodes that can be observed correspond to gas sampling for chromatographic analysis.

Considering the methane production achieved from each mother suspension (**Table 7**), the value from the inoculum alone (Ims) was subtracted from the CMms and the CM + FBms values. The resulting methane volume was then used in Eq. (2), together with the volatile solids content and the density of the CM (**Table 5**) and the volume of CM added to mother suspensions CMms and CM + FBms (**Table 6**), to compute their average maximum methane production capacity achieved from the added CM, resulting in values of 0.01 and 0.2 m^3 CH_4/kg VS*, respectively (@STP).

$$B_{o\_ms} = \frac{Vol_{CH_4\_CM}}{VS^*_{CM} \times Vol_{CM} \times \rho_{CM}} \tag{2}$$

where B_{o_ms} is the average methane production capacity from the VS* in the CM residue [m^3 CH_4/kg VS*]; $Vol_{CH_4\_CM}$ is the average accumulated methane production from the reactors carrying the CM [m^3 CH_4]; VS^*_{CM} is the volatile solids content of the CM [kg VS*/g CM]; Vol_{CM} is the volume of CM added to the reactors [mL]; ρ_{CM} is the CM density [g/mL]. All methane volume values are expressed at STP.

2.3 Estimation of the theoretical and technical energy potential of the two BTES

The estimation of the energy potential of the two BTES starts with the estimation of their average methane production (MP), using the biomass supply of the broiler production of Lafões, considering the average B_o calculated in the previous section and using Eq. (3) presented below. This equation was adapted from the one suggested in [11] to estimate methane emissions from chicken manure. The methane density value was expressed at STP, corresponding to the experimental methane volume values.

Mother suspension	CM [mL]	FB [mL]	WW [mL]	I [mL]	Water [mL]	Total [mL]
CMms	228.8	0.0	51.2	120	0	400
FBms	0.0	228.8	0.0	120	51.2	400
CM + FBms	114.4	114.4	51.2	120	0	400
Ims	0.0	0.0	0.0	120	280	400

Substrates were straw litter chicken manure (CM), maritime pine forest biomass (FB), wastewater from poultry pavilion cleaning (WW), and inoculum (I).

Table 6.
Composition of the mother suspensions.

Mother suspension	Methane production [mL CH_4 @STP]
CMms	36.5 ± 4.5
FBms	0.10 ± 0.03
CM + FBms	356.8 ± 25.0
Ims	2.6 ± 0.03

The values presented are average ± standard deviation from triplicate digestion runs.

Table 7.
Total methane production in the anaerobic digestion reactors using the mother suspensions chicken manure (CMms), chicken manure and forest biomass (CM + FBms), forest biomass (FBms) and inoculum (Ims).

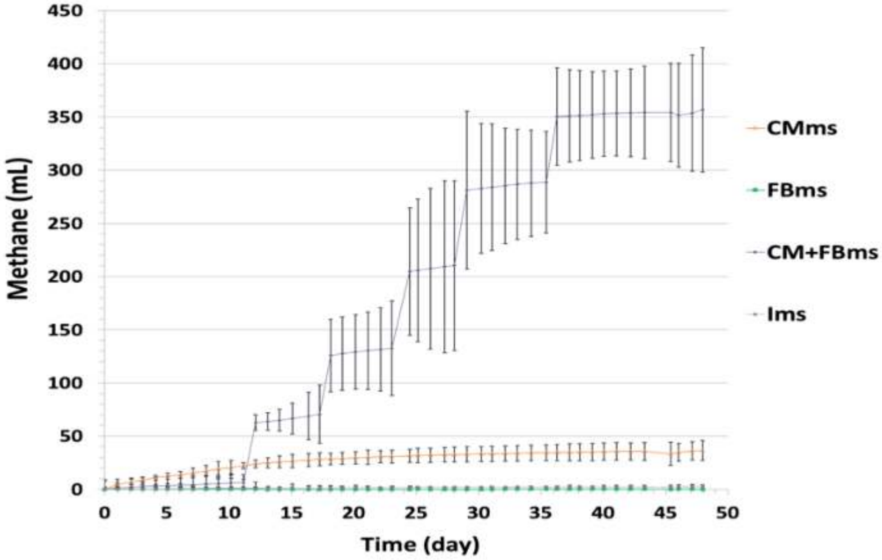

Figure 3.
Time course of cumulative methane production (in mL@STP) in the anaerobic digestion reactors using the mother suspensions chicken manure (CMms), chicken manure and forest biomass (CM + FBms), forest biomass (FBms) and inoculum (Ims). Average values are given, with standard deviation (error bars) from triplicate runs.

$$MP_i = VS \times B_{o\_i} \times 0.71 \quad (3)$$

where MP_i is the methane production achieved by the BTES i [$kgCH_4$/(bird.day)]; VS is the volatile solids excretion rate obtained with Eq. (1) [kgVS/(bird.day)]; B_{o_i} is the maximum methane production capacity of the BTES i [m^3 CH_4/kg VS excreted]; 0.71 is the conversion factor of m^3 CH_4 to kg CH_4 at STP; i stands for the anaerobic digestion or anaerobic co-digestion BTES.

The total MP for each BTES was calculated on a basis of 365 days/year and using the number of birds in the broiler poultry class presented in **Table 2**. The obtained values of MP were 369 t CH_4/year and 7719 t CH_4/year, for anaerobic digestion and co-digestion BTES, respectively. Multiplying the MP of each BTES by the methane LHV of 50 MJ/kg [34], the theoretical energy potential (ThEP) values of 18,450 TJ/year and 386,000 TJ/year for anaerobic digestion and co-digestion, respectively, were obtained.

Finally, the technical energy potential (TeEP) of the two BTES was estimated. The methane losses that occur in different unit operations of the anaerobic digestion process, namely, pre-storage, digestion and digestate storage, as well as the conversion yield of methane into energy, were taken into consideration.

The methodology proposed in [35] accounts for the methane conversion (emissions to the atmosphere) during manure pre-storage and the gastight storage of the digestate, as well as methane losses in its recovery from the digester. Using Eq. (4) and the input data presented in **Table 8**, the value of 0.011 m^3/m^3 was obtained for the overall effective methane conversion factor (*MCF*) that represents the total losses during the digestion process of both BTES. The value is then used, multiplying by the ThEP value previously calculated, to compute methane energy losses in the three mentioned system components, resulting in 212 TJ/year and 4433 TJ/year for the anaerobic digestion and co-digestion BTES, respectively.

$$MCF = MCF_{ps} + \left(1 - MCF_{ps}\right) \times \left[\left(1 - \mu_{rg}\right) \times L_{prod} + \mu_{rg} \times MCF_{digestate}\right] \qquad (4)$$

where *MCF* is the effective methane conversion factor for the combination "pre-storage + digester + storage" [m^3/m^3]; MCF_{ps} is the methane conversion factor for pre-storage [m^3/m^3]; μ_{rg} is the relative potential of residual gas, in relation to B_o (with $0 \le \mu_{rg} \le 1$ [m^3/m^3]); L_{prod} is the leakage rate of the digester (with $0 \le L_{prod} \le 1$ [m^3/m^3]); $MCF_{digestate}$ is the methane conversion factor for the gastight storage of the digested manure [m^3/m^3].

It is assumed, according to [36], that the biogas recovered from the digester of both BTES is conveyed to a combined heat and power (CHP) plant with electrical and thermal yield values of 35% and 43%, respectively, and the remaining 22% are taken as overall losses in the co-generation process. Still according to [36], some

Parameter	Value
μ_{rg} [m^3/m^3]	0.046
MCF of the pre-storage [m^3/m^3]	0.0015
L_{prod} [m^3/m^3]	0.01
MCF of the digestate [m^3/m^3]	0.01
MCF of the overall process [m^3/m^3]	0.011

Table 8.
Process specific methane conversion factors (MCF), relative potential of residual gas (μ_{rg}) and leakage rate of the digester (L_{prod}) values [35] used for the calculation of the overall MCF for methane losses in the anaerobic digestion process.

Parameter	Anaerobic digestion energy [10^3 TJ/year]	Anaerobic co-digestion energy [10^3 TJ/year]
Methane losses in the digestion process	0.2	4.4
Electricity produced	6.3	135.0
Heat produced	7.8	165.9
Electricity for internal use	0.6	27.0
Heat for internal use	1.6	33.2
Overall losses in the co-generation process	4.0	83.9
TeEP	**12.0**	**241**

Digestion processes losses, co-generation balance and energy diverted for internal use are also given.

Table 9.
Technical energy potential (TeEP) of the anaerobic digestion and co-digestion BTES.

internal use of the produced energy is assumed, namely, 10% of the generated electricity is used for digester agitation and material conveying operations and 10% of the produced heat is used for temperature control in the digester.

The first value concerning internal electricity use was adopted for the anaerobic digestion BTES, but for the anaerobic co-digestion BTES the value was increased to 20%, since there are energy requirements associated to the pre-treatment of the maritime pine biomass. The second value, heat used internally, was increased to 20% for both BTES, anticipating less efficient heat conservation systems in Portugal.

The technical energy potential of both BTES, TeEP, is given by Eq. (5). **Table 9** presents the results of the above assumptions and the total TeEP values, 12 PJ/year and 241 PJ/year (presented in bold in the table) for the anaerobic digestion and co-digestion BTES, respectively.

$$TeEP = ThEP \times (1 - MCF) \times \left[\eta_{el}(1 - int.el.use) + \eta_{th}(1 - int.th.use)\right] \quad (5)$$

where $TeEP$ is the technical energy potential of the BTES [TJ/year]; $ThEP$ is the theoretical energy potential of the BTES [TJ/year]; MCF is the methane conversion factor for losses in anaerobic digestion systems [m^3/m^3]; η_{el} is the electrical yield of the CHP [%/100]; $int.el.use$ is the electricity fraction used internally [%/100]; η_{th} is the thermal yield of the CHP [%/100]; $int.th.use$ is the heat fraction used internally [%/100].

3. Energy potential increment due to the exploitation of substrate complementarities

The results obtained experimentally allow an optimistic perspective on the performance of the BTES handling forest residues and chicken manure together. With the BTES running on complementary substrates it is possible to achieve an increment of 229 PJ/year, one order of magnitude from the value for the BTES running only on chicken manure.

It can however be argued that the overall efficiency values considered for the two BTES are unrealistic since much higher internal use fractions for electricity and heat should be considered to account for the pre-treatment. Dividing the TeEP by the ThEP of each BTES, overall yield values of 65% and 62% are obtained for the anaerobic digestion and co-digestion BTES, respectively. A more realistic comparison would require further knowledge on energy demand for these pre-treatment options.

Nevertheless, the obtained results allow the conclusion that, even considering further technical differences, the anaerobic co-digestion BTES is likely to achieve better performance levels than the single substrate chicken manure BTES, since a clearly improved methane production capacity can be obtained through its complementarity with the maritime pine biomass.

4. Conclusions

The main conclusion that can be drawn from this case study is that integrated solutions, such as anaerobic co-digestion of complementary substrates, can be appealing from the point of view of their theoretical and technical energy potentials.

The large production of chicken manure in the Lafões region is presently handled through solid storage or pasture solutions, therefore emitting methane into the atmosphere. This is a waste of its energy content and contributes to climate change. Thus, this residue class presents itself as a strong candidate to create synergies in the implementation of integrated systems, in a circular economy concept, whereby complementary effluents are managed together to produce value gains in the region.

It is advisable to perform assessments on further levels, namely in terms of the economical, implementation and sustainable implementation energy potentials. Even within the scope of the assessment levels addressed in the present case study (theoretical and technical), the total energy potential is yet to be determined, since the classes from both biomass types that were left out in this preliminary study must also be tested in terms of their complementarity.

More research has also yet to be carried out concerning the forest residues supply needed to run the anaerobic co-digestion, since only the small size fraction was used in the BTES assay. The total amount of available residues was estimated, but the amounts corresponding to this faction remain unknown.

Finally, another aspect needing further research concerns the biochemical mechanisms responsible for the increment in methane production when substrate complementarities in co-digestion are exploited. The physicochemical composition of the different effluents generated by the industrial activities of Lafões must be analyzed in more detail and their possible combinations must be experimentally assessed, in order to develop new pathways from forest to energy.

Acknowledgements

The authors would like to acknowledge Associação de Desenvolvimento Rural de Lafões (ADRL) for introducing this challenging topic of research, and Fundação para a Ciência e a Tecnologia for PhD studentship SFRH/BD/146002/2019.

For their extensive support, the authors would also like to acknowledge the poultry sector integrating company and the DGAV of Viseu, who provided the data and intermediated the contacts with poultry producers. The producers who provided the samples are also gratefully acknowledged.

The three municipalities of Lafões (Oliveira de Frades, São Pedro do Sul and Vouzela) must also be acknowledged for providing the data necessary for the forest residues assessment. Acknowledgments are also due to the forest sappers for sharing their knowledge concerning the Lafões forest.

Nomenclature

AD	anaerobic digestion
ADRL	Lafões rural development association
B_o	maximum methane production capacity
BTES	biomass-to-energy conversion systems
CHP	combined heat and power
CM	straw litter chicken manure
CM + FBms	chicken manure and forest biomass mother suspension
CMms	chicken manure mother suspension
DBFZ	German Biomass Research Centre
DGAV	Directorate-General for Food and Veterinary
EGF	forest management entity
FB	maritime pine forest biomass residues
FBms	forest biomass residues mother suspension

FBP	forest biomass residues potential
GIS	Geographical Information Systems
HPV	horizontal projection of the vegetation
I	inoculum
ICNF	Instituto da Conservação da Natureza e das Florestas
Ims	inoculum mother suspension
IPCC	Intergovernmental Panel on Climate Change
LHV	lower heating value
MCF	methane conversion factor
MP	methane production
RNAP	national network of protected areas
RP	residues productivity
TeEP	technical energy potential
ThEP	theoretical energy potential
VS	volatile solids excretion rate
VS*	volatile solids
UGF	forest management units
WW	wastewater from poultry pavilion cleaning

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References

[1] Direção-Geral do Território. In: Carta Administrativa Oficial de Portugal (CAOP 2019); 2019. Available from: http://www.dgterritorio.pt/cartografia_e_geodesia/cartografia/carta_administrativa_oficial_de_portugal_caop/caop__download_/carta_administrativa_oficial_de_portugal___versao_2019__em_vigor_/ [Accessed: 27 June 2020]

[2] Pereira T, Amaro A, Borges M, Silva R, Pina A, Canaveira P. Portuguese National Inventory Report on Greenhouse Gases, 1990-2017. Submitted under the United Nations Framework Convention on Climate Change. Amadora: Portuguese Environmental Agency; 2020. p. 751

[3] McKendry P. Energy production from biomass (Part 2): Conversion technologies. Bioresource Technology. 2002;**83**(July):47-54. DOI: 10.1016/S0960-8524(01)00119-5

[4] Lourinho G, Brito P. Assessment of biomass energy potential in a region of Portugal (AltoAlentejo). Energy. 2015;**81**:189-201. DOI: 10.1016/j.energy.2014.12.021

[5] Ferreira S, Moreira NA, Monteiro E. Bioenergy overview for Portugal. Biomass and Bioenergy. 2009;**33**(11):1567-1576. DOI: 10.1016/j.biombioe.2009.07.020

[6] Kornatz P. Introduction Statement of the Anaerobic Processes Research Focus Area [Internet]. 2020. Available from: https://www.dbfz.de/en/research/researchfocusareas/anaerobicprocesses/ [Accessed: 20 April 2020]

[7] Quinta-Nova L, Fernandez P, Pedro N. GIS-based suitability model for assessment of Forest biomass energy potential in a region of Portugal. IOP Conference Series: Earth and Environmental Science. 2017;**95**(4):1-7. DOI: 10.1088/1755-1315/95/4/042059

[8] Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Applied Energy. 2010;**87**(8):2551-2560. DOI: 10.1016/j.apenergy.2010.02.007

[9] Mateos E, Garrido F, Ormaetxea L. Assessment of biomass energy potential and forest carbon stocks in Biscay (Spain). Forest. 2016;**7**:75. DOI: 10.3390/f7040075

[10] Rocha JT, Malico I, Gonçalves AC, Sousa AMO. Análise do potencial de biomassa residual no Algarve, Portugal, baseada em SIG. Ciência da Madeira (Brazilian Journal of Wood Science). 2020;**11**(1):42-52. DOI: 10.12953/2177-6830/rcm.v11n1p42-52

[11] Dong H, Mangino J, McAllister T. Chapter 10: Emissions from livestock and manure management. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. 2006. p. 87

[12] Bao W, Yang Y, Fu T, Xie GH. Estimation of livestock excrement and its biogas production potential in China. Journal of Cleaner Production. 2019;**229**:1158-1166. DOI: 10.1016/j.jclepro.2019.05.059

[13] Bhattacharya SC, Thomas JM, Salam PA. Greenhouse gas emissions and the mitigation potential of using animal wastes in Asia. Energy. 1997;**22**(11):1079-1085. DOI: 10.1016/S0360-5442(97)00039-X

[14] Tańczuk M, Junga R, Kolasa-Więcek A, Niemiec P. Assessment of the energy potential of chicken manure in Poland. Energies. 2019;**12**(7):1-18. DOI: 10.3390/en12071244

[15] Amon BJW, Hutchings N, Dämmgen U, Sommer S. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019. Technical Guidance to Prepare National Emission Inventories 2019. p. 26. ISSN: 1977-8449

[16] Roberts JJ, Cassula AM, Osvaldo P, Dias R, Balestieri JAP. Assessment of dry residual biomass potential for use as alternative energy source in the party of General Pueyrredón, Argentina. Renewable and Sustainable Energy Reviews. 2015;**41**:568-583. DOI: 10.1016/j.rser.2014.08.066

[17] Mosaddek M, Sazedur AHM, Kabir AS, Faruque MM, Ahmed S. Systematic assessment of the availability and utilization potential of biomass in Bangladesh. Renewable and Sustainable Energy Reviews. 2017;**67**:94-105. DOI: 10.1016/j.rser.2016.09.008

[18] Vieira A, Franco C, Marques F, Rosa F, Monsanto M. Avaliação do Potencial de Biomassa da Região do Algarve. Lisboa: INETI; 2006. p. 114

[19] Papilo P, Kusumanto I, Kunaifi K. Assessment of agricultural biomass potential to electricity generation in Riau Province. In: IOP Conference Series: Earth and Environmental Science, Volume 65, International Conference on Biomass: Technology, Application, and Sustainable Development; 10-11 October, 2016; Bogor, Indonesia; 2017. DOI: 10.1088/1755-1315/65/1/012006

[20] Marques IP. Anaerobic digestion treatment of olive mill wastewater for effluent re-use in irrigation. Desalination. 2001;**137**(1-3):233-239. DOI: 10.1016/S0011-9164(01)00224-7

[21] Damaceno FM, Buligon EL, Restrepo JCPS, Chiarelotto M, Niedzialkoski RK, Costa LAM, et al. Semi-continuous anaerobic co-digestion of flotation sludge from broiler chicken slaughter and sweet potato: Nutrients and energy recovery. Science of the Total Environment. 2019;**683**:773-781. DOI: 10.1016/j.scitotenv.2019.05.314

[22] Li C, Strömberg S, Liu G, Nges IA, Liu J. Assessment of regional biomass as co-substrate in the anaerobic digestion of chicken manure: Impact of co-digestion with chicken processing waste, seagrass and Miscanthus. Biochemical Engineering Journal. 2017;**118**:1-10. DOI: 10.1016/j.bej.2016.11.008

[23] Begum S, Ahuja S, Anupoju GR, Ahuja DK, Arelli V, Juntupally S. Operational strategy of high rate anaerobic digester with mixed organic wastes: Effect of co-digestion on biogas yield at full scale. Environmental Technology. 2020;**41**(9):1151-1159. DOI: 10.1080/09593330.2018.1523232

[24] Batool N, Qazi JI, Aziz N, Hussain A, Shah SZH. Bio-methane production potential assays of organic waste by anaerobic digestion and co-digestion. Pakistan Journal of Zoology. 2020;**52**(3):971-976. DOI: 10.17582/journal.pjz/20190322170334

[25] Direção-Geral do Território. In: Carta de Ocupação do Solo (COS'2018); 2018

[26] Instituto da Conservação da Natureza e das Florestas. Nature Conservation Areas Geocatalogue. Available from: https://geocatalogo.icnf.pt/ [Accessed: 20 April 2020]

[27] ESRI-PT. Digital Terrain Model 30 m Portugal (ETRS89); 2009

[28] Gabinete Técnico Florestal da Câmara Municipal de Oliveira de Frades. Forest Roadmap of Oliveira de Frades Municipality. 2020

[29] Gabinete Técnico Florestal da Câmara Municipal de São Pedro do Sul. Forest Roadmap of Oliveira de Frades Municipality. 2020

[30] Gabinete Técnico Florestal da Câmara Municipal de Vouzela. Forest Roadmap of Oliveira de Frades Municipality. 2020

[31] Caetano M, Marcelino F. Especificações Técnicas da Carta de Uso e Ocupação do Solo (COS) de Portugal Continental para 2018. Technical Report. Direção-Geral do Território; 2019

[32] Fenn ME, Bauer LI, Hernandez-Tejeda T. Urban Air Pollution and Forests: Resources at Risk in the Mexico City Air Basin. Springer Science & Business Media; 2012. p. 394

[33] APHA, AWWA, WEF. Standard Methods for the Examination of Water and Wastewater. 2012

[34] Engineering ToolBox. Fuels—Higher and Lower Calorific Values [Internet]. 2003. Available from: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html [Accessed: 20 April 2020]

[35] Rösemann C, Haenel H-D, Dämmgen U. Calculations of gaseous and particulate emissions from German agriculture 1990-2013. 2015. p. 406. DOI: 10.3220/REP_27_2015

[36] Oehmichen K, Thrän D. Fostering renewable energy provision from manure in Germany—Where to implement GHG emission reduction incentives. Energy Policy. 2017;**110**(August):471-477. DOI: 10.1016/j.enpol.2017.08.014