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Development of an experimental procedure for energy evaluation of forest communities by calorimetry and thermal analysis

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Abstract

In 1989, Prof. Lisardo Núñez and his Research Group TERBIPROMAT designed an experimental procedure to evaluate the energy contained in Municipal Solid Waste (MSW) generated in Galicia (NW Spain) using a static bomb calorimeter in an oxygen atmosphere following the procedure described by Hubbard et al. (1958).

In the last time, this experimental procedure was developed and improved to use it in different research fields, from energetic evaluation of biomass to the determination of risk indices in forest communities.

In this paper so special, we will try to summarize the evolution of this experimental procedure and its achievements, from the design of the sampling phase to the gradual introduction of new techniques as thermal analysis or microcalorimetry.

The results obtained in these 17 years show that the experimental procedure as well as the scientific work of Prof. Lisardo Núñez and TERBIPROMAT were successful.

This paper is focused on the energetic evaluation of forest communities and the determination of risk indices to prevent and fight against forest fires.

Keywords: Calorimetry; Thermal analysis; Forest biomass; Calorific value; Flammability; Risk index map

1. Introduction

In the last 50 years, the continuous energy and social crises experienced by the humankind slowed down the economic development of even rich industrialized countries. At the same time, the excessive use of traditional fossil fuels was causing economic problems and irreparable ecological damages.

As consequence of the increase in price of fossil fuels, specially crude oil, and the fact that the fuel reserves are limited, the search of new alternative fuels satisfying the conditions of rationality and sustainability is one of the bases of the energy policy of industrialized countries, and a response to this continuous energy crisis. Nowadays, these are the principal reasons why alternative energies, and more specifically the energy obtained from biomass, are occupying a leading place in the research and development sector, making of this search a world wide top priority objective. Within these alternative energy sources, the biomass, that is the group of materials of biological origin capable of being used as xyloenergy sources, is becoming an important one.

In this paper, we are going to analyze the evolution of an experimental procedure developed to determine the energetic content of different biomass resources, from Municipal Solid Waste (MSW) to forest waste. The initial objective of this research was the energetic evaluation of different biomass resources in order to study the possibility of using these MSW as an alternative combustible in plants of cogeneration. But this experimental procedure based in the bomb calorimetry was also the basis to determine risk indices in forest formations to prevent and fight against forest fires. This evolution was achieved thanks to the improvement of sampling procedure, the realization of flammability studies, the introduction of thermal analysis or including the study of different environmental features.

2. Experimental

This paper so special summarizes the evolution of an experimental procedure developed and its main achievements during

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17 years by Prof. Lisardo Núñez and his Research Group TERBIPROMAT.

This study began in 1989 when Prof. Núñez analyzed the possibility of using the MSW generated in Galicia as a source of recovered energy. In that moment, the increases in MSW in Galicia brought irreparable environmental damages such as pollution of the surface and subterranean waters, the proliferation of sanitary vectors, stench, forest fires or the loss of fertile land. These environmental problems led the Galician government and society to consider urgent measures to avoid this situation, and one solution was to consider the thermal treatment of these waste materials produced in towns and surroundings to gain energy [1,2]. In these first studies the final samples of MSW used to evaluate the energetic were obtained directly from street containers following a statistical method in order to get a representative material of raw municipal waste The samples were reduced by coning and quartering and then separated into two fractions: fraction A (material as-received) and fraction B (resulting after sorting of the different components). The energetic evaluation was made using a static bomb calorimeter [1]. The main achievements in this paper were the design of a standard sampling procedure to obtain samples in different places, and the use of the bomb calorimetry to evaluate energetic contents of MSW. The obtained results of the low heating value (LHV) and the high heating value (HHV) fairly agreed with literature values and confirmed the possibility to use these MSW, with a LHV close to 10,300 kJ kg^{-1} [2], as an alternative fuel in energy recovery plants.

In 2001 and 2002, this experimental procedure was used with some improvements to obtain a new fuel from waste industrial mineral and synthetic oils [3]. This fuel should be used in internal combustion engines for cogeneration of electric and thermal energies [3], or as raw material for the elaboration of new oils [4].

The treatment of approximately 500,000 t year^{-1} is not only viable and adequate from the economic, but also from the ecological point of view (the cost of treatment of polluting waters, interphase, and slops is low and, the techniques are well developed at the same time. These waste industrial oils are not only disturbing in each of the three environments (air, water, or soil), but are also classified as toxic or hazardous because they are ignitable. The treatment described is highly remunerative, both as regards to cost and ecology. Used oil is subject to a low-cost process, especially if compared to its elaboration from raw materials so that the final product is very competitive from the economical point of view, especially as it is recycled, thus saving a great amount of raw material. The results obtained here constituted the basis for an industrial pilot plant of cogeneration and led to the following conclusions:

(1) The purification process can be used for treatment of different used oils with PCBs, PCTs, and halure concentrations under 50 ppm. The waste oil recovery can reach over 75% of the waste oil treated. This recovered oil is an ideal base to obtain new industrial oil [4] or alternative fuel [3].
(2) The fuel obtained after treatment has a calorific power close to 43,800 kJ kg^{-1}, very low moisture content (<0.1%), and a low amount of ashes (<0.5%). That makes it very convenient to be used in cogeneration engines [4].
(3) From the ecological point of view a correct management of these residues lead to an immeasurable benefit.

Prof. Núñez published in 1994 the first study analyzing the possibility of using forest waste biomass as a potential alternative energy source applying the same procedure as developed with the MSW [5]. In this investigation, forest residues were collected after cleaning 1 ha of forest surface chosen at random. After this step, and following the procedure presented in the previous papers [1,2], this sample was mixed and reduced by coning and quartering to get a homogeneous mass of the different species in the studied zone. The sample was divided in two fractions, A and B, and both ones were dried for 12 h at 105 °C in a natural convection stove to determine their moisture, then two fractions were processed by a cutting mill in order to make the pellet preparation easier. Fraction A was used to determine the HHV using a bomb calorimeter and following the procedure proposed by Hubbard et al. [6]. The species studied were *Sarothamnus scoparius* Link (broom), *Ulex europaeus* L. (furze), *Rubus fructicosus* L. (blackberry bush), and *Pteridium aquilinum* L. (fern). The main conclusion of this first paper was that forest waste, with a LHV close to 19,000 kJ kg^{-1}, and in this moment lost as abandoned residues, can be used as an additional fuel to be added to MSW in energy recovery plants.

In 1995, using the previous paper [5] as base, flammability data were introduced and calculated according to the model proposed by Valette [7], and the chemical analysis was improved introducing data of volatile metals. The main conclusion in this next paper was that flammability decreases with calorific values. This fact is considered as a natural defence against forest fires [8].

From this year on up to 2005 these studies continued and their results were published in further 11 papers.

First, two different zones and different forest formations typical of Galicia (NW of Spain) were studied: the coastal-hillside zone [9], and the continental high mountainous-humid Atlantic zone [10]. In these two papers, the improvements introduced were:

- That the sample was ground using two mills of different power in order to homogenize the sample as much as possible [9].
- The study of the influence of the main climatic parameters on the flammability and the calorific values. These climatic parameters are represented as bioclimatic diagrams [10].
- The study of other forest species: *Eucalyptus globulus* Labill (eucalyptus), *Pinus pinaster* Aiton (pine), *Quercus robur* L. (oak), *Castanea sativa* Miller (chestnut), *Acer pseudoplatanus* L. (maple tree), *Alnus glutinosa* (L.) Gaertner (alder), *Betula celtiberica* L. (birch), *Laurus nobilis* L. (laurel), *Salix atrocinera* L. (willow), *Taxus baccata* L. (yew), *Prunus Avium* (L.) L. (cherry tree), *Sorbus aucuparia* L. (mountain ash), *Fraxinus excelsior* L. (ash tree), and *Fagus sylvatica* L. (beech).

- The classification of the studied species according to their calorific values and flammabilities. According to our previous studies, most species with the highest HHV present the lowest flammability. This can be understood as a self-defence mechanism of nature, where the species with high calorific values present a great resistance to ignition. This behaviour can be observed analyzing the Figs. 1 and 2.

This research line reached it main objective in 2001, the study of the most important forest species in Galicia from the ecological and economic point of view. In this year, Prof. Núñez published the first paper in which he analyzed the possibility of using forest wastes originating from different forestry works as alternative fuel in wide social sectors [11]. The forest species here studied were *Eucalyptus globulus* Labill (eucalyptus) and *Pinus pinaster* Aiton (pine). The improvements introduced in this paper led to different steps of the whole study:

- *Sampling procedure:* Samples were collected from a previously chosen 1 ha of forest located in a homogeneous biomass zone in phase of exploitation of a total forest area greater than 10 ha. After being cut down, two representative individuals of the forest species to be studied were selected on the basis of their height measured by a hypsometer. In this paper, two forest species in different zones of Galicia were studied to analyze the influence of environmental parameters on flammability and calorific values.
- *Preparation of samples:* The forest waste obtained was divided into three well-differentiated classes: leaves or needles; branches having a diameter less than 3 cm; and branches with a diameter between 3 and 6 cm. After this division, residues were mixed and reduced by a coning and quartering procedure to obtain a representative bulk sample of 5–6 kg each.
- In order to study the influence of the environmental and climatic conditions on the forest waste, which was abandoned in forests "in situ" during a lot of months after forestry tasks, the final sample was divided into dead (forest residues abandoned in forest) and live matter (fresh forest residues produced immediately after cuts).
- Combining LHV obtained in this research, physico-chemical, biological, and bioclimatic parameters, energy maps were elaborated. The elaboration of these maps required a complete knowledge of the studied area as they depend not only on thermochemical parameters but also on physico-chemical properties of the different botanical species, biological characteristics, and parameters depending on physical environmental conditions.
- Different parameters of soil and the relationship between soil and forest formations were analyzed [12–14] by microcalorimetry.
- The influence of resins, essential oils and other volatile compounds on the flammability and calorific values was studied.
- At the same time, the use of these residual resources yielded a twofold benefit. On the one hand, the above-mentioned economic benefit, on the other hand, an ecological one because the removal of forest residues diminished the risk of initiation and spreading of forest fires.

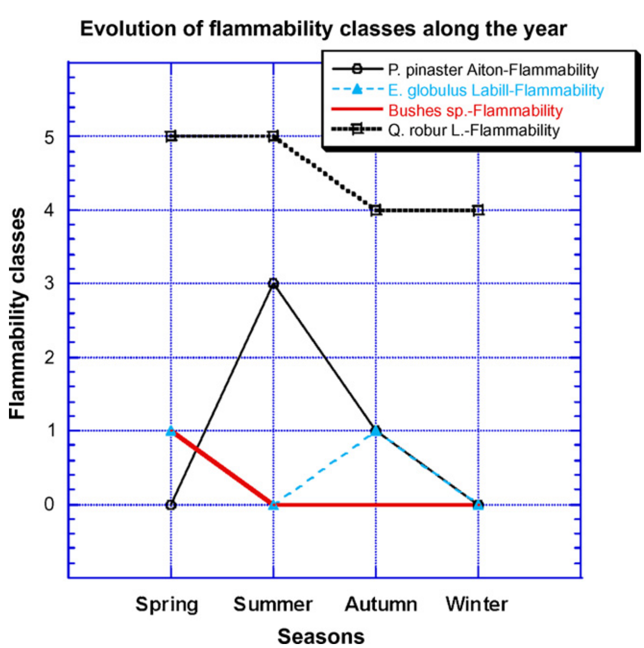

Fig. 1. Evolution of flammability classes along the year in the three main forest formations and for *Quercus robur* L. in Galicia. Flammability class—class 0: very low flammability (>32.5 s); class 1: low flammable (27.5–32.5 s); class 2: flammable (22.5–27.5 s); class 3: moderately flammable (17.5–22.5 s); class 4: very flammable (12.5–17.5 s); class 5: extremely flammable (<12.5 s). Bushes sp. corresponds to mixed formations of high size *Erica* species, *Ulex europaeus* L., *Sarothamnus scoparius* Link. and various herbaceous.

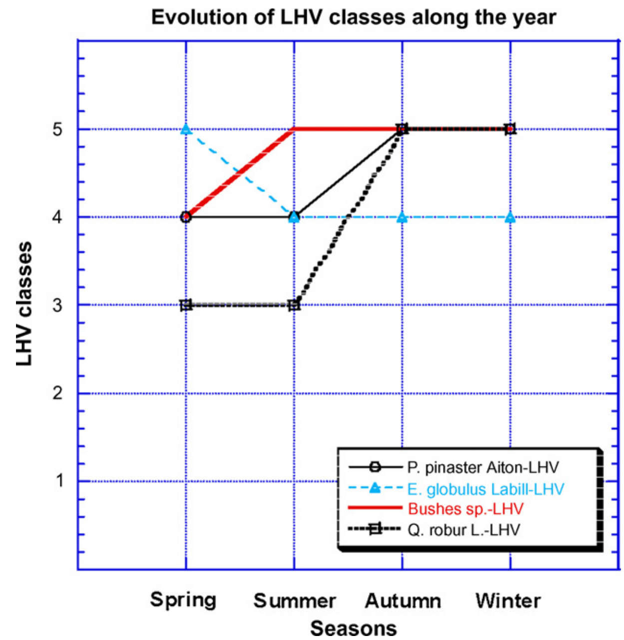

Fig. 2. Evolution of LHV classes along the year in the three main forest formations and for *Quercus robur* L. in Galicia. LHV classes—class 1: LHV < 4500 kJ kg^{-1}; class 2: LHV ≥ 4500 and <5500 kJ kg^{-1}; class 3: LHV ≥ 5500 and <6500 kJ kg^{-1}; class 4: LHV ≥ 6500 and <7500 kJ kg^{-1}; class 5: LHV ≥ 7500 kJ kg^{-1}. Bushes sp. corresponds to mixed formations of high size *Erica* species, *Ulex europaeus* L., *Sarothamnus scoparius* Link. and various herbaceous.

During the following years these improvements were applied to the study of the three forest formations most important in Galicia: eucalyptus, pines and shrubs.

As a consequence, an improved paper about energy evaluation of biomass was published by Prof. Núñez in 2002 [15]. In this paper forest wastes were sampled in seven different zones in Galicia during the year to analyze the influence of climatic conditions on calorific values. The most important conclusion was that climate conditions have no important influence on calorific values as LHV and in the mean HHV. Therefore, these calorific values remained reasonably constant over the year and in the different zones, thus allowing a sustainable exploitation all the time. An important aspect was that the data presented in this study could be used for exploitation of eucalyptus located in any other zone. This conclusion might seem different from those reported in some previous paper, but we are sure of it because in this study we have done a rigorous design of the sampling procedure and severe data analysis.

Following the same procedure, pine [16] and shrub [17] formations were studied.

In 2004, a paper with the main criteria to evaluate the energy contained in different forest formations was published [18]. These criteria are:

(1) Quantification of the surface (ha) of the forest formations available for exploitation according to economic and ecological criteria.
(2) Quantification of the forest residues generated "per year".
(3) In the case of eucalyptus, quantification of the forest waste percentage that must be abandoned from the soil surface that means about 10% of the total amount. On the other hand, it is advisable to completely remove forest waste from pine. The abandonment in situ can originate not only problems related to forest fires, but also problems derived from the fact that these residues constitute a propitious medium for many of the pine parasites. Cuts of shrub were left at a height of 10 cm to protect soil.
(4) Mean calorific value over the year. For the forest formations analyzed in Galicia, the mean calorific value was about 7400 kJ kg^{-1}.
(5) The yield of the energy transformation plant was assumed as 25%.
(6) Cuts timing for a rational and sustainable exploitation: shrub every 5 years, eucalyptus every 15 years, and pine every 20 years.

Assuming these criteria and taking account of the last studies, the final results are presented in Table 1.

Table 1
Main exploitation criteria and theoretical values of electricity production and economical income for the main forest formations in Galicia

Forest formations	Eucalyptus	Pine	Shrub
Cuts period (years)	18	25	8
Exploitation surface[a] (ha)	240,000	300,000	430,000
Occupation index (trees ha^{-1})	2500	2200	–
Forest residues[b] (kg $tree^{-1}$)	109	165	–
Biomass production (t $year^{-1}$)	3.27×10^6	4.36×10^6	2.48×10^6
Average LHV (kJ kg^{-1})	7398.43	7588.80	7358.20
Efficiency[c] (%)	25	25	25
Electricity production (kWh $year^{-1}$)	1.70×10^9	2.29×10^9	1.26×10^9
Economical income[d] (€ $year^{-1}$)	8.50×10^7	11.45×0^7	6.30×10^7

[a] Surface occupied by pine is close to 640,000 ha but, for ecological reasons, only 300,000 ha can be used for energetic exploitation. The whole surface occupied by eucalyptus can be used for energetic exploitation because nowadays this species is a key raw material for pulp production. The exploitable surface by shrub is close to 430,000 ha, and the remaining surface, approximately 500,000 ha, is kept for ecological benefit.
[b] Gross forest waste.
[c] A yield of 25% is assumed for the energy transformation in plants using biomass as a fuel.
[d] Gross receipts.

At the same time the elimination of this waste minimizes the risk of initiation and spreading of forest fires. This idea was the starting point to initiate this new research line in 1999 using the same experimental procedure as in the energetic evaluation of forest formations. That year the first paper was published [19] in which the main forest species in Galicia were classified according to their flammability and HHV values using the classes proposed by Valette and Doat [20]. With these data, it is possible to classify the species in terms of their energy content and their resistance to forest fire, that is, in terms of their risk index.

In the same year the first paper appeared in which the risk index was defined and calculated for the first time through a numerical method using the flammability and calorific values as basis [21]. This main risk number can be modified by different contributions, such as: physico-chemical properties, biological characteristics, climatic characteristics and various parameters depending on environmental conditions. These risk indices, numerical values based on experimental data of different physical, chemical, environmental and climatic parameters describing the behaviour of forest formations with respect to forest fires, are useful for drawing realistic risk index maps; with them it will be easier and more effective to prevent and fight forest fires.

From 2000 to now, the procedure to calculate this risk index was improved:

(1) In 2000, the HHV class boundary values were modified according to the range of experimental measurements for the different studied species to obtain a number more adapted to the reality of the Galician forest species [22].
(2) In 2002, the influence of various features on the risk index was modified to adjust the results better to the reality of the different forest formations [23].
(3) In 2004, the method to calculate the risk index was strongly improved [24]. The main and very important modification for the future was the exchange of the HHV class number by the LHV class number in the thermochemical parameters. The reason is that HHV is determined in the laboratory under ideal conditions, while the knowledge of LHVs of the different tree species in the forest vegetation becomes a more realistic indicator of the energetic state of the forest biomass of a zone.

The last paper of Prof. Núñez was presented in 2005 at MEDICTA 2005 [25]. The main contributions to the determination of the risk indices in this paper were:

(1) The introduction of thermal analysis in the study of forest formations. The main reason for his decision was to try to get relationships between thermal behaviour and some physical properties of forest species.
(2) The revision of the different numerical contributions of all parameters to the risk index number. This revision was not a whim, because the introduced changes were based on the different studies during the past 10 years of very hard research work with the objective of better adjusting of the final results. This revision was very important to prevent damages as the ones suffered by Galicia in July 2006 where close to 100,000 ha of forest surface were burnt in only 12 days.

Table 2 shows the risk index classification for the different forest species studied in Galicia.

The final seasonal map of the risk index for the main forest formations of Galicia can be seen in Fig. 3. Nowadays, the risk index developed by TERBIPROMAT is the only one based on real data and not on simulations, and this is its main advantage over the traditional risk indices.

The prevention of and fight against forest fires has an economic benefit too. As a sad example, the damages caused by forest fires in Galicia this year (2006) will cost more than €150 millions.

Table 2
Risk index classification of the different forest species studied in Galicia over the year [21]

Species	Spring	Summer	Autumn	Winter
Acer pseudoplatanus L. (maple tree)	3	4	5	4
Alnus glutinosa (L.) Gaertner. (alder)	2	2	2	3
Betula pendula Roth. (birch)	2	2	3	2
Shrub	2	2	3	3
Castanea sativa Miller (chestnut)	3	4	5	5
Eucalyptus globulus Labill. (eucalyptus)	3	2	2	2
F. sylvativa L. (beech)	3	5	4	4
F. excelsior L. (ash tree)	2	2	3	3
Laurus nobilis L. (laurel)	4	3	4	4
Pinus pinaster Aiton. (pine)	2	3	3	2
Prunus avium (L.) L. (cherry tree)	3	3	3	3
Pteridium aquilinum L. (fern)	1	3	5	4
Quercus pyrenaica Willd. (sessile oak)	3	5	5	4
Quercus robur L. (oak)	4	4	5	5
Rubus fructicosus L. (blackberry bush)	3	4	3	3
Sarothamnus scoparius Link. (broom)	2	2	2	2
S. atrocinera L. (willow)	2	2	3	3
Salix aucuparia L. (mountain ash)	4	4	4	4
Taxus baccata L. (yew)	4	4	4	3
Ulex europaeus L. (furze)	5	5	4	4

No risk: 1; low risk: 2; middle risk: 3; high risk: 4; extremely high risk: 5.

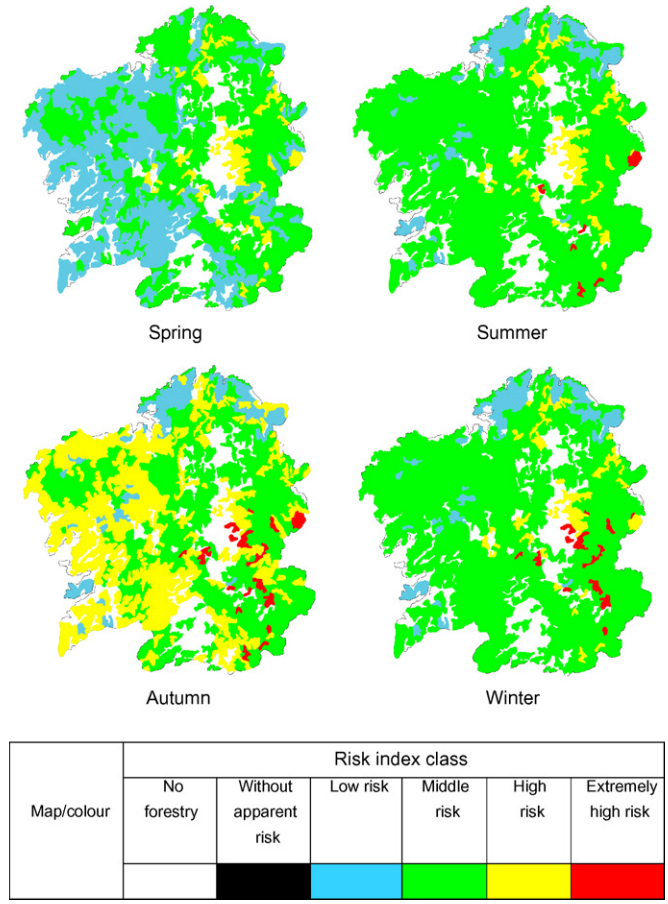

Fig. 3. General risk index map for the main forest formations in Galicia: eucalyptus, pine and shrub [21].

3. Results and discussion

In Fig. 1 the evolution of flammability and calorific values of more representative forest species in Galicia can be analyzed along the year. After 17 years studying more than 19 forest species, most of them present high flammabilities but low heating values as a natural self-defence against forest fires [24]. This natural mechanism was described for the first time in 1995 [8] and 10 years later we can confirm this behaviour in most of the forest species in Galicia.

Table 1 shows the final results of energetic evaluation of the three main forest formations in Galicia. In this Table the main exploitation criteria and theoretical values of electricity production and economical gross income are shown. These values can be considered as definitive. Nowadays, TERBIPROMAT is making new measurements to corroborate their validity, but analyzing the new results obtained we are sure that values presented in the Table 1 are correct and a reference point to use the forest wastes as an alternative energy source. Data presented in this table confirm that the experimental procedure designed and developed by Prof. Núñez and TERBIPROMAT is successful.

Fig. 2 shows the risk index map of Galicia along the year. The three main forest formations in Galicia (eucalyptus, pine and shrub species) are represented in this map. These three forest formations take up close to 1,700,000 ha of the 2,100,000 ha devoted to forestry uses in Galicia; nowadays, eucalyptus and pines are the most important species from the economical point of view contributing approximately to the 2.5% of the Gross Domestic Product (GDP).

Table 2 shows the risk index classification of the different forest species studied in Galicia. This classification was obtained after the application of the experimental procedure proposed by TERBIPROMAT [25]. These values can be corrected in the future, because we are doing improvements in this experimental procedure with the objective of adjusting the obtained results even more to the reality. This method of calculation the risk indices improves the other traditional methods nowadays.

4. Conclusions

The procedure developed by Prof. Núñez and his Research Group TERBIPROMAT was successful and ensures a rational and sustainable exploitation of the energy resources contained in the main forest formations in Galicia. This procedure is helpful to design energy transformation plants under engineering regulations using the biomass generated by forestry tasks as fuel because:

(1) It ensures the availability of enough raw materials. For this reason, the following periods between consecutive cuts, after last studies, must be designed: 18 years for eucalyptus, 25 years for pine, and 8 years for shrub (in slight deviation from the values given in 2004 [18]).
(2) LHV and mainly HHV remain reasonably constant thus allowing a sustainable exploitation over the year. This fact indicates a nonsignificant influence of the environment on these values in the different zones and seasons.
(3) The technology existing nowadays is sufficiently developed and frequently employed in industry to transform calorific energy into electric energy.
(4) These three first points ensure the achievement of economical benefits, about €2.63×10^8 year^{-1} of gross incomes. The produced electric energy of about 5.25×10^6 kWh is considered as clean and high quality energy by European Union energetic politics.

Aside of the economical benefit, the environmental benefit derived from a forest rearrangement must be also considered, because it produces a minimization of the number of forest fires, avoids phytoplagues that decrease the productive capacity of forest, and decreases of defertilizing processes.

This experimental procedure developed by TERBIPROMAT also helps to set the basis to design effective campaigns to prevent and fight forest fires through risk indices.

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