

Article

Reusing Pruning Residues for Thermal Energy Production: A Mobile App to Match Biomass Availability with the Heating Energy Balance of Agro-Industrial Buildings

Carlo Bisaglia ¹, Massimo Brambilla ¹, Maurizio Cutini ^{1,*}, Antonio Bortolotti ², Guido Rota ³, Giorgio Minuti ³ and Roberto Sargiani ³

¹ Consiglio per la Ricerca in Agricoltura e L'analisi Dell'economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroindustriali, via Milano 43, 24047 Treviglio (BG), Italy; carlo.bisaglia@crea.gov.it (C.B.); massimo.brambilla@crea.gov.it (M.B.)

² Bortolotti Group Srl, via Leonardo Da Vinci 21, 41014 Castelvetro di Modena (MO), Italy; bortolottigroup@caebinternationaldistributor.it

³ CAEB International s.r.l., via Botta Bassa, 22, 24010 Petosino di Sorisole (BG), Italy; g.rota@caebinternational.it (G.R.); g.minuti@caebinternational.it (G.M.); r.sargiani@caebinternational.it (R.S.)

* Correspondence: maurizio.cutini@crea.gov.it; Tel.: +39-0363-49603

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Abstract: Using the pruning residues of woody crops can be beneficial in many ways (e.g., excellent energy balance, a net reduction in pollutant emission and a positive contribution to global warming control). This article describes the background work and development of a new support tool that will allow the user to know the amount and quality of pruning residue required to meet the energy requirements to heat both residential and agro-industrial buildings (e.g., greenhouses). Knowing the average amount of pruned biomass ($t_{d.m.} ha^{-1}$), the average lower heating value of wood ($4.00 kWh kg^{-1}$) and the average efficiency of a woody biomass boiler (90%) enabled the overall available net energy yearly amount ($kWh year^{-1}$) to be determined. This was compared to the overall energy requirements ($kWh year^{-1}$) of agro-industrial buildings, which are a result of their main features (e.g., maximum heatable surface, building energy classification and the climatic zone). Depending on user needs, the tool suggests the amount of required biomass and, if not entirely available, what amount of fossil fuels are required to fulfill the energy requirement. The algorithm output was compared with the results of two case studies carried out on seven farm buildings and nine greenhouses. Knowing the amount and energy potential of the available biomass allows for planning and evaluation of the planned benefits.

Keywords: decision support tool; biofuel supply chain; fruit tree; logistics

1. Introduction

Agricultural residues possess a significant unused potential in renewable energy, where their exploitation may be achieved by raising awareness among local stakeholders [1,2]. To date, research has tackled the issue of their utilization, highlighting both the positive and weak points connected to their usage and providing recommendations for the proper set up of the logistic chain [3–6]. Supporting such a business is therefore fundamental and decision support systems (DSS) and decision support tools (DST) can assist stakeholders. DSTs can be dynamic software tools that suggest the optimal decision path as user inputs vary by acting as information sources [7]. Mobile communication technologies and tools, with the subsequent availability of cloud-based data storage integration and retrieval, make the

inventory and monitoring of data almost instantaneous [8]. Computational analysis or monitoring tools are becoming increasingly readier to use [9] and also enable the involvement of farmers in the research process [10,11].

The management of woody crops (orchards, olive groves and vineyards), produces significant quantities of woody residues [12]. These are usually windrowed between the rows of trees to then be chipped/ground for mulching into the orchard or taken apart for on-site combustion. Both options are an extra cost for the farmer, ranging from 100 € ha⁻¹ to 200 € ha⁻¹ [13], making them more of a disposal problem than an opportunity for additional revenue. Just as for forest residues, collecting and using woody residues from agriculture as fuel results in an excellent energy balance, a net reduction in pollutant emission and a benefit for global warming control [14,15]. Moreover, several studies confirm agricultural residues in general, and vineyard by-products in particular, may represent a targeted source of fuel in European countries [16], such that the development of dedicated harvesting equipment enhances the technical sustainability of fuel procurement systems based on woody crops [17,18]. As aforementioned, to date, bioenergy production has not considered biomass from fruit tree plantations because of unsolved technical problems in harvesting or a lack of information on the amounts and the qualities of the residues. Harvesting and logistics account for the most expensive costs in this biomass supply chain. Knowing the real amounts, the characteristics and the places of the available residual biomass in each orchard, would therefore enable more specific planning and cheaper logistics operations.

This work presents the background studies to develop an app in which the aim is to provide a technical support tool to help farmers understand the heating potential of pruning and to enable them to organize data from their own orchards. The app enables assessment of the energy potential of the pruning within the frame of the farm energy balance, sharing this information at a district level to match the availability of biomass with the heating energy balance of agro-industrial buildings (e.g., barns, warehouses, greenhouses). A local supply chain can be created that would greatly benefit from a traceable system that could be used for quality control and the effective management of pruning residues. The result would be an improved efficiency of the whole system through actions taken to promote using agricultural residues for renewable energy production [19], leading to an increased level of sustainability at the district level (i.e., cooperatives, typical production areas, agricultural production companies, etc.) [20]. Indeed, it has been reported that:

- Sharing data and information among the actors of the supply chain has a fundamental role [21];
- projects at both district and household level are vital towards sustainability because of the ability to scale-up their impacts [22];
- exploiting woody biomass for self-consumption is a valid alternative to conventional heating systems [23].

Starting from the building energy consumption, the DST calculates the biofuel required, and if needed, the additional biofuel or conventional fossil fuels to be purchased outside the district to cover the requirement. At the current development stage, to achieve the full optimization of the supply chain, the DST requires the end user to know the energy consumption of the building; nevertheless, being able to deal with different levels of uncertainty creates a way to indicate potential drawbacks during the setup of the supply chain.

2. Materials and Methods

To allow the matching of biofuel availability with the energy required to heat the buildings, the tasks of the research are to:

- Identify residual biomass availability;
- Assess available thermal energy;
- Define the heatable surface area of buildings (residential and industrial) and greenhouses;
- Possibly extend the tool to other European countries.

2.1. Identification of the Residual Biomass Availability

Several factors (i.e., the planting pattern, the variety, the shape of the plants, the use of irrigation, plant age and size and the frequency of pruning) affect the quantity of residual biomass from pruning operations. To assess the quantity of available biomass, the average quantities of biomass (metric tons of dry matter (d.m.) per hectare) resulting from the annual pruning of fruit trees were considered. Table 1 reports the average quantities of pruning residues from eight woody crops together with the related sources.

Table 1. Fruit trees with the average amount of biomass available from pruning.

Fruit Tree	Average Amount of Pruning Residues (t _{d.m.} ha ⁻¹)	Source
Grapevine	1.45	[24,25]
Olive	1.34	[16,24,26]
Apple	1.90	[24,25]
Pear	1.58	[25,27]
Peach	1.43	[27,28]
Citrus	1.08	[27]
Almond	1.02	[27]
Walnut	1.42	[27,29]

These data were organized in a drop-down menu: After selecting the species they are interested in, the user can input the area of surface (hectares) the crop grows on. Regarding the harvesting efficiency, it varies greatly in relation to machine type, pick-up settings and the cultivated plant (0.4 to 18%) [30,31]. Because of this, the default value of 90% was chosen. Calculations then automatically assess the quantity of available biomass (t year⁻¹) with the moisture level set at 15%.

2.2. Assessment of Available Thermal Energy

The Lower Heating Value (LHV) of woody biomass ranges between 4.1 and 4.3 kWh kg⁻¹ [32,33]. Given this, to take into account all of the possible differences among the diverse biomasses resulting from the natural variability of the growing conditions, together with the worst-case scenario, the constant value of 4.00 kWh kg⁻¹ was chosen as the reference LHV for all the considered crops. This value, multiplied by the yearly available biomass (t year⁻¹), results in the annual potential energy available from pruning (kWh year⁻¹).

The efficiency of a biomass wood boiler has been considered equal to 90%, a value adopted since current regulatory assessment in Italy on the efficiency of a woody biomass boiler specifies two levels of subsidies on varying the Nominal Power (NP) of the heating plant. Following the certification of heating plants in compliance with the UNI EN 303-5 standard [34], it is possible to obtain a 50% fiscal subsidy if the boiler efficiency is >70% [35]. This subsidy may increase up to 65% if the boiler efficiency is greater than 87 + log (NP) [36]. Accordingly, retaining the boiler size class lower than 100 kW as appropriate at the farm level, it seems fundamental that boiler efficiency is at least 90%. A flowchart was created to better describe this phase (Figure 1).

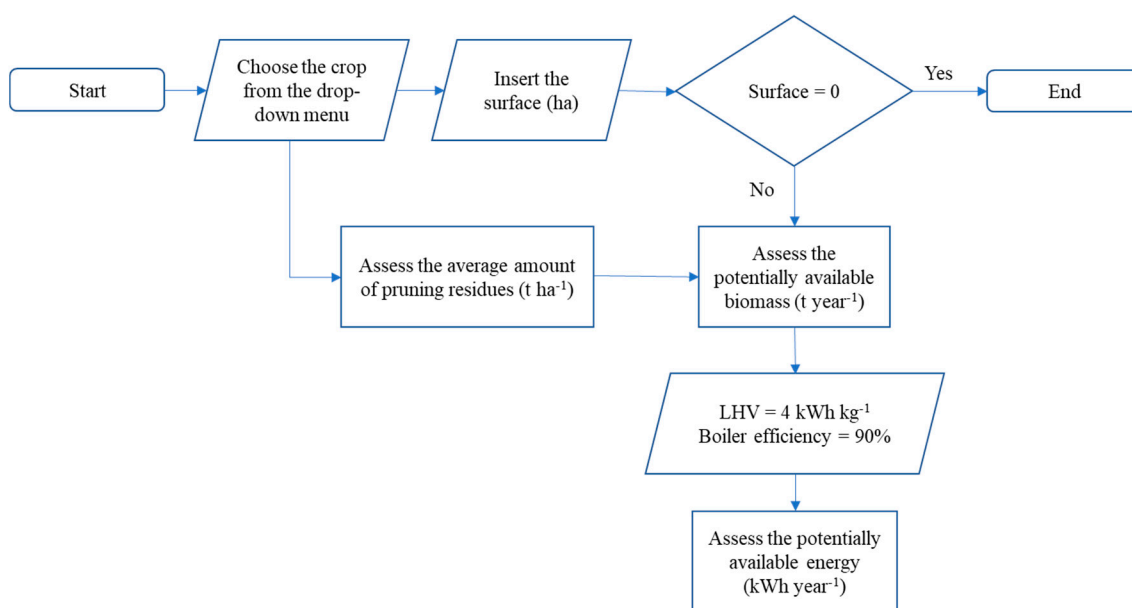


Figure 1. Flowchart of input data processing to assess the potentially available energy.

2.3. Definition of the Heatable Surface Area of Buildings (Residential and Industrial) and Greenhouses

Starting from the amount of energy potentially available from pruning residues, the first step the tool makes is to calculate the maximum surface area the user can heat without any use of fossil fuels in buildings (both residential and industrial) and greenhouses.

2.3.1. Residential and Agro-Industrial Buildings

For a given house or apartment, the maximum heatable surface results from two parameters: The apartment or building energy classification and the Heating Degree Day (HDD) of the specific municipality the home is located in. In detail, the indications of the Italian Decree n. 192 of 19 August 2005 (“Buildings classification”) [37], helped in calculating the energy requirements per square meter on the basis of the surface/volume (S/V) ratio defined by the outside dispersing surface (S, m²) and the total heated volume (V, m³). The S/V ratio ranges from 0.2 to 0.9 and because of this calculations were made considering the average S/V value of 0.55. Building energy classification prescribes eight classes (from A+, for the best insulation, to G when insulation is very low). To improve the user interface and simplify the tool application, the eight classes have been summarized into three insulation levels:

- Low: The mean value for a building in class G and F;
- Average: A mean value between C, D and E;
- High: The mean value of A+, A and B.

The outcome of this stage was refined further by considering the HDD value (the number of degrees that a day’s average temperature is below 18 °C, namely the temperature below which residential buildings need to be heated). Increasing values of HDD define six climatic zones (labelled from A for the lowest to F for maximum heating need) [38]. Table 2 shows the results of these calculations.

Table 2. Energy requirements ($\text{kWh year}^{-1} \text{ m}^{-2}$) of residential buildings with varying climatic zones and insulation levels.

Building Insulation Level	Climatic Zones					
	A	B	C	D	E	F
Low	54.20	64.20	91.50	128.80	173.60	213.80
Average	26.00	30.70	43.80	61.60	83.10	102.30
High	8.90	10.50	15.00	21.10	28.50	35.10

A drop-down menu in the spreadsheet organises the list of all the municipalities in Italy together with their HDD value and with the label of the climatic zone. The DST is therefore preloaded with a list such that when the user chooses the name of the municipality where the building is located, the tool automatically gives the following information:

- Province;
- Altitude (m a.s.l.);
- Heating Degree Day (n°);
- Climatic classification (from A to F);
- Thermal energy requirement on varying the climatic zone and the insulation level (see Table 2);
- Maximum heatable surface (m^2) for any of the three considered insulation levels.

For industrial buildings, the organisation of calculations follows the same steps. The difference is that the tool reports the energy requirement for the heatable volume ($\text{kWh year}^{-1} \text{ m}^{-3}$, Table 3) instead of the surface area, considering the greater height variability in agro-industrial buildings.

Table 3. Energy requirements ($\text{kWh year}^{-1} \text{ m}^{-3}$) of industrial buildings with varying climatic zones and insulation levels.

Building Insulation Level	Climatic Zones					
	A	B	C	D	E	F
Low	10.04	11.89	16.94	23.85	32.15	39.59
Average	4.81	5.69	8.11	11.41	15.39	18.94
High	1.65	1.94	2.78	3.91	5.28	6.50

If the climatic zone of the municipality and the insulation level play the same role as before, it is not possible to operate the same standardization because of two reasons, firstly the different heights these buildings may have and secondly the differences in the performed working tasks that sometimes cause the building to stay open or cool down. Here, the well-being temperature for sedentary activities is usually between $20\text{--}23\text{ }^\circ\text{C}$, but in the case of standing or heavy work it can range from $12\text{--}19\text{ }^\circ\text{C}$ [39]. Because of this, based on the experience of technicians, an approximate quantification of the maximum heatable volume was achieved considering that the energy requirement of an industrial building is twice that of a residential unit (to be considered merely indicative).

As described above, the information is attainable from the drop-down menu. Once the user selects the municipality, all the information related to it (province, HDD, climatic zone and thermal energy requirements for low, medium and high insulation levels) appears.

2.3.2. Greenhouses

Greenhouses are a special kind of agro-industrial building. Regarding the heating of greenhouses, the standard reference used in this research is the annex 40E to the Italian Republic Official Journal of 2 January 2013 (Ministry of Economic Development, 2013) [40]. Here, the energy consumption for greenhouses is reported as equivalent to diesel fuel and they have a thermal plant efficiency of 0.9. We took as reference unit a square meter of the heated greenhouse. The assessment of the energetic

requirement considers the Ac/As ratio that results from the division of the covering surface (Ac) with the ground surface (As) of the greenhouse (Equation (1)):

$$Q = \left(\frac{Ac}{As} \right) U (Ti - Te) \frac{h}{\eta_c} 10^{-3} \quad (1)$$

where Q is the required thermal energy ($\text{kWh year}^{-1} \text{ m}^{-2}$), Ac is the surface area cover (m^2), As is the ground surface (m^2), U is the global coefficient of thermal dispersion ($\text{W m}^{-2} \text{ K}^{-1}$), Ti is the temperature inside the greenhouse ($^{\circ}\text{C}$), Te is the outside air temperature ($^{\circ}\text{C}$), h is the greenhouse operating hours duration, η_c is the boiler efficiency, which for simplification purposes is considered to be 0.9 even though the standard uses simplified tables for the diesel fuel consumption of traditional greenhouses chosen for reference. Relating these requirements to the energy of 1 t of biomass at a 15% moisture level enabled the compiling of Table 4 which shows the maximum surface that can be heated with such an amount of biomass.

Table 4. Representation of the amount of greenhouse surface (m^2) that 1 t (dry mass, d.m.) of biomass at a 15% moisture level can heat, varying the covering surface (Ac)/ground surface (As) ratio, the cover material and the heating degree days.

Covering Material	Ac/As Ratio	Heating Degree Days				
		600–900	900–1400	1400–2100	2100–3000	>3000
Plastic Film	<1.5	73.5	46.0	15.2	8.5	8.3
	1.5–1.8	55.4	35.1	11.58	6.5	6.3
	>1.8	48.4	30.6	10.0	5.6	5.4
Polycarbonate	<1.5	123.3	76.4	25.3	14.3	13.7
	1.5–1.8	93.2	58.8	19.1	10.8	10.4
	>1.8	81.3	51.0	16.6	9.4	9.1
Glass	<1.5	67.0	42.0	13.8	7.8	7.5
	1.5–1.8	51.0	31.8	10.4	5.9	5.7
	>1.8	43.9	27.7	9.1	5.1	4.9
Double layer plastic film	<1.5	119.06	75.50	24.57	13.82	13.40
	1.5–1.8	91.04	57.32	18.65	10.49	1.01
	>1.8	77.39	49.13	16.12	9.10	8.79
Glass + plastic film	<1.5	73.70	46.90	15.32	8.65	8.37
	1.5–1.8	61.91	35.58	11.64	6.56	6.33
	>1.8	49.13	30.95	10.08	5.69	5.50
Double pane glass	<1.5	99.85	63.17	20.92	11.77	11.38
	1.5–1.8	77.39	48.37	15.79	8.92	8.62
	>1.8	67.29	41.83	13.76	7.76	7.50

In this case, the user enters the municipality where the greenhouse is located and the greenhouse surface, then the tool automatically gives information about the province, the climatic zone and the heating degree days, indicating the amount of biomass required to autonomously heat the given surface with the available energy (see Sections 2.1 and 2.2).

2.4. Comparison with Real Data

The output of the set of codes was tested against some case studies whose findings have been published by the Italian ENAMA (Ente Nazionale per la Meccanizzazione Agricola) [41]. Overall, fifteen case studies were examined: Six were related to using woody biofuel to heat residential buildings, while the remaining nine reported its use for greenhouse heating.

There was a great deal of uncertainty with these specific situations since none reported the hectares of wood crops producing the pruning residues and also, even if they were self-sufficient, the amount of the thermal energy required was not noted. Given this, the functioning of the DST was

tested by focusing on the used amount of biomass per square meter of greenhouse ($t_{d.m.} \cdot m^{-2}$) and its usage (i.e., residential or industrial). In the case of residential buildings, the comparison was carried out considering the surface to be heated. Moreover, the used dataset includes the production of warm water, however the app does not take this into account in its current form. Data underwent statistical processing by means of Minitab statistical software and Microsoft Excel Spreadsheet using Pearson's correlation coefficient r , the coefficient of determination R^2 , the root mean square error (RMSE) and the percentage bias of prediction (PBIAS) dimensionless index [42,43] for the evaluation.

3. Results

The application has been developed to allow the user an initial approach without logging on. It can be used in English or Italian and has five choices (Figure 2): (1) Energy availability in the field; (2) heatable building surface; (3) saving in money; (4) energy balance; and (5) technical solutions.

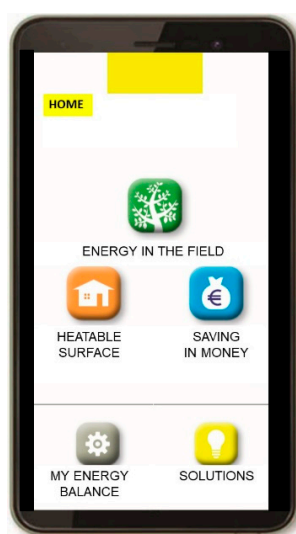


Figure 2. The main interface.

3.1. First Approach

The first three options (the energy availability in the field, the heatable surface and the savings in money) indicate what the user wants to know. Selecting any of these options opens the first interface; in practice, this chooses which data must be inserted and what the output will be. The pages that open are shown in Figure 3. If the user selects “Energy in the field”, the app requires the user to choose the cultivar and the field surface. The first output on the same page is the available thermal energy. The calculation of available thermal energy is automatic because the LHV is set at 4.00 kWh kg^{-1} and the boiler efficiency to 0.9. Scrolling the screen, the application then shows the heatable surface of a residential or industrial building or a greenhouse related to the level of insulation and the climatic classification. The other output is the equivalent in methane, diesel or LPG requirements. In this way, knowing the pruning amount as a quantification of thermal energy and its potential “equivalent” in money is immediately apparent. Thanks to this information, it can instantly be seen that 30 ha of olive trees gives an equivalent energy of $18,000 \text{ m}^3$ of methane.

In the same way, the user can select “heatable surface” or “saving in money” and input the surfaces to heat. The relevant outputs are the requirements of energy in kWh and the equivalent hectares of pruning. The equivalent in methane, diesel and LPG may also be reported. If “Saving in money” is chosen, the user can insert their fossil fuel consumption and the outputs are the required amount of energy and the equivalent hectares of pruning.

Doing so, the heatable surface is instantly correlated with the hectares used for cultivation (Figures 4 and 5).



Figure 3. A first approach at the main options.

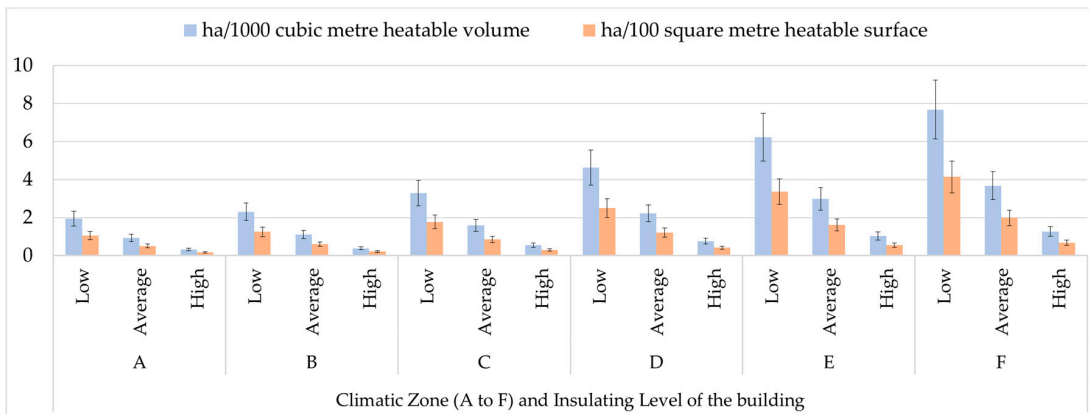


Figure 4. Heatable surfaces and volume with hectares of cultivation.

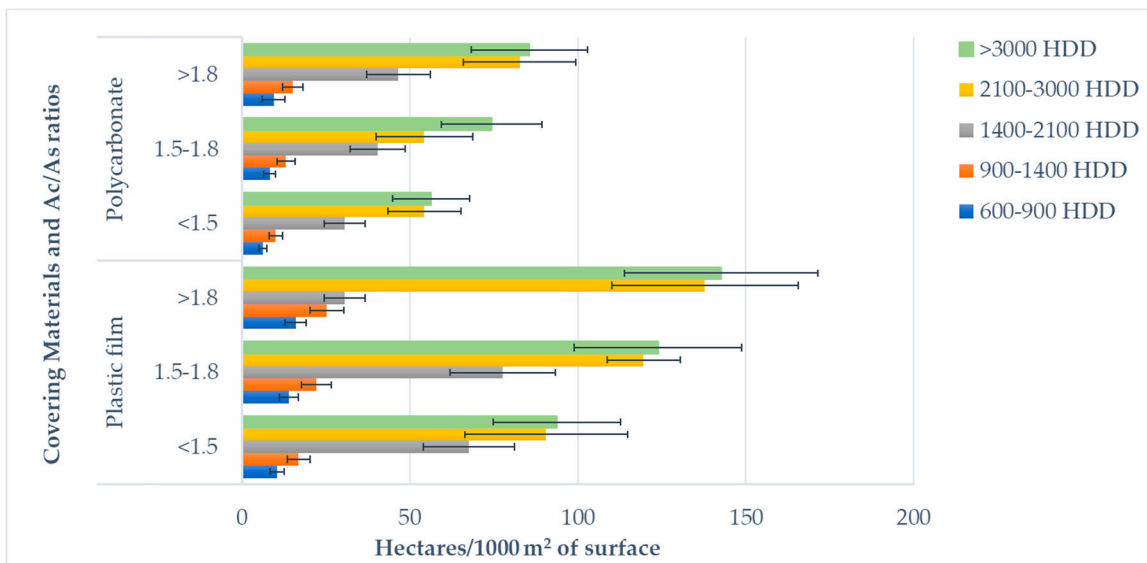


Figure 5. Hectares of woody crops required to heat 1000 m² of greenhouse surface with varying cover material.

3.2. My Energy Balance

The most interesting and perhaps valuable selection, in line with the main aim for a technical support tool to help farmers understand the heating potential of pruning, is the page “My energy balance”. This part of the application requires the user to log in. Now the information of the municipality is required so that the results will be applicable to the user.

Three pages similar to the first three options must be filled. These pages represent the energy in the field, the heatable surface and saving in money. The user should insert the right cultivar and the relevant hectares, the surfaces actually heated and the real annual fuel consumption. The output is the farmer energy balance which is a comparison between the actual energy requirement and the energy available in the field thanks to pruning.

The user interface is shown in Figure 6. Obviously, the balance could present a surplus or a lack of energy available in the field. If a surplus, the tool indicates how much surface can be heated, if a lack of energy, once again the three pictures of Figure 2 indicate how many hectares are needed of the specific cultivar or fuel to achieve the balance, or otherwise how much surface it is not possible to heat.

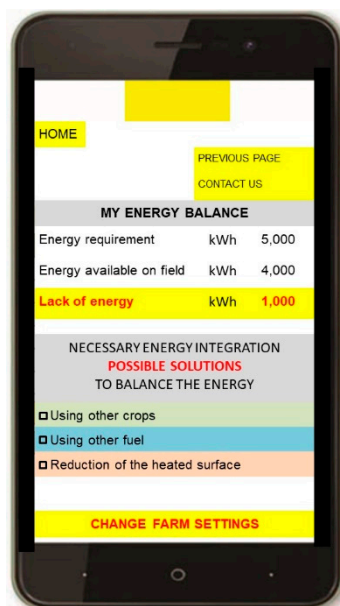


Figure 6. Example result of “My energy balance”.

3.3. Solutions

The last option in the app, “solutions”, shows some technical solutions to collect and burn the biofuel. The complete production process, starting from baling, chipping or pruning till arriving at the specific boiler for heating production is described in this option (Figure 7).

The main aim of “solutions” is to indicate what the tool has determined technically feasible. Since the calculations within the app have followed technical norms, a focused study on the farm is still necessary, both as a pruning evaluation and as an energy need evaluation, in order to choose the correct line of mechanization. For this reason, the technical solutions are presented but are not technically connected with the “energy balance” section.

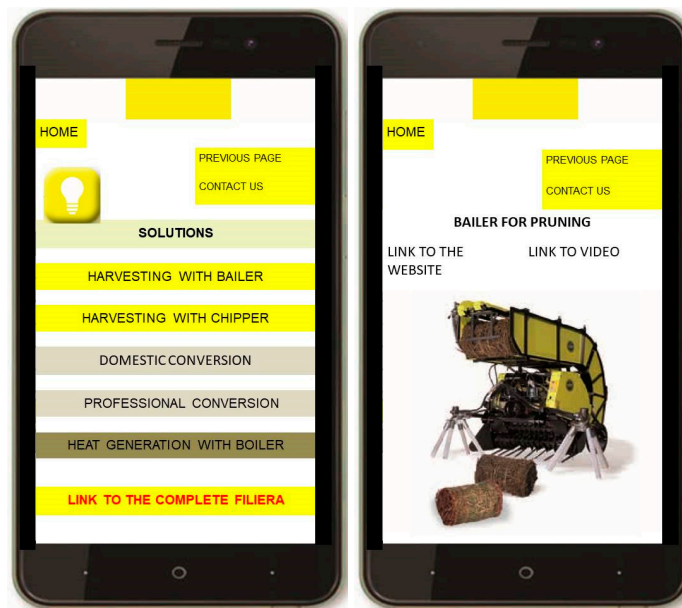


Figure 7. Technical solutions from harvesting to the boiler.

3.4. Comparison with Real Data

Evaluation of the app performance in all cases revealed an overall correlation coefficient of 0.79 and a coefficient of determination (R^2) equal to 0.62 (rises to 0.92 for residential buildings). If the average bias of the estimate is about 20% for residential buildings, things change when greenhouses are considered. As a matter of fact, the comparison between the estimated and observed data results in an RMSE of 0.08 t_{d.m.} but the bias reaches a value of -51.8%, since for normal greenhouses the values seem to be evenly distributed above the equality line (Figure 8). It is important to note that this does not happen in the case of insulated greenhouses, so that data appears to be more comparable (with a bias of -14%).

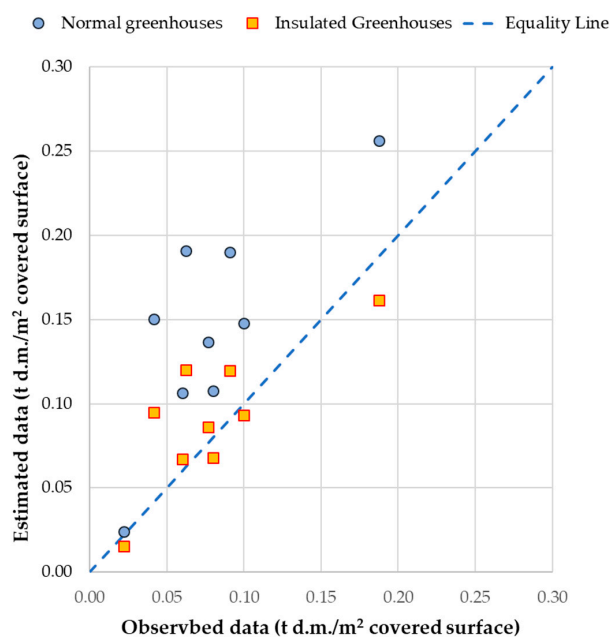


Figure 8. Scatterplot representing the estimated amounts of biomass plotted vs. the amounts reported in the case studies on the greenhouses.

In detail, the r and R^2 indexes indicated that the app calculations reproduce the trends in the observed data quite well [44]. Nevertheless, the PBIAS value is quite far from the optimal (optimum PBIAS is 0), indicating that there is something that the app currently does not consider, such that its estimations based on the heating requirements are higher than those observed (particularly in reference to greenhouses). This means that some building parameters (e.g., for greenhouses, what the coverings are made of) have insulating performances that the code, set up with the current regulatory assessment, does not include.

This is the reason why the average overestimation of 94% occurs. In practice, the app requires double the effective wood consumption. However, it is worth noting that these case studies have undergone a complete revision of their heating management, so if we consider the coefficient regarding an insulated greenhouse then a 32% overestimation of the needed chipped biomass occurs.

Since the app was developed based on regulatory assessments, its output should be considered as a reference. The differences shown above highlight the need for having data on as many farming systems as possible to correlate the specific energy requirements with the proper required quantities of pruning residues.

For the first phase of releasing the app, it has been decided to adopt the values reported in Table 4. In any case, the adoption of “my energy balance” solves the question entirely, suffice for farmers inserting the fossil fuel consumption they currently have. Moreover, it must be considered that one of the main aims of the app is to involve farmers in the research process by collecting data and sharing it with researchers. To this end, a focused approach on the type of farm and the available pruning has been started.

4. Conclusions

Pruning residue may represent an important source of energy biomass, but the process of evaluating the energy availability, adapting the heating system, harvesting, recovering and preparing the biomass for the boiler, means the viability in terms of avoiding costs of residue management and eventual benefits are not immediate. Therefore, pruning residues are harvested by forwarding them to a collection point, shredding the residue and collecting it into bins, a method that offers all the benefits of rapid handling, or by baling with the advantage that stored bales incur minimal dry matter losses compared to shredded residues, which allows the maximization of the energy potential of pruning.

This research paper has presented a new tool designed to indicate to any potential user the amounts and quality of pruning residues needed to cover the energy requirements for the heating of both residential and agro-industrial buildings (i.e., greenhouses). The tool suggests the amounts of required biomass, and in case they are not fully available, how much fossil fuels (diesel oil, methane or Liquid Petroleum Gas (LPG)) are needed to complete the energy requirement.

Knowing the real amounts and the energy potential of the available residual biomass in the orchard therefore allows planning and evaluation of the benefits. Currently, many data related to pruning quantities and cultivated surfaces are available and there are also case studies on the use of pruning residues as biofuel but there is a lack of information bridging these data. Even the case studies do not explain the features of the heated buildings and this problem arises following the great deal of uncertainty that the comparison with real data highlighted.

This mobile application will allow creating a link between the local biomass availability with the energy requirements for heating buildings. On one hand, this enables the end user to be aware of the energetic potential of pruning, while on the other, farmers can become involved in the research process by collecting data and sharing it. The app introduces a focused approach on the type of farm and available pruning by matching energy requirements with the biofuel from pruning. It offers policy makers new modes of planning and the possibility of decentralized and self-contained systems, provided that adequate development and support programs are regulated at the district or community level.

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Abbreviations

DSS	Decision Support Systems
DST	Decision Support Tools
LHV	Lower Heating Value
NP	Nominal power
HDD	Heating Degree Day
S/V	Surface/Volume ratio
Ac/As	Greenhouse covering surface/Ground surface ratio
RMSE	Root Mean Square Error
PBIAS	Percentage bias of prediction

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