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Biomass District Heating Systems Based on Agriculture Residues

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Featured Application: Biomass District Heating Systems in Rural Areas.

Abstract: This paper presents a methodology for analyzing the regional potential for developing biomass district heating systems combining forestry biomass and agriculture residues as fuel. As a case study, this methodology is applied to the continental region of Spain. With this analysis the potential for the implementation of biomass district heating systems based on the use of agriculture residues is applied to 501 rural municipalities in Spain. The renewable forestry biomass and agriculture residues resources availability is analyzed and the biomass required for heating is assessed. The results of applying the methodology show the interest of the combination of biomass sources in a relevant number of municipalities with estimated Internal Rate of Return (*IRR*) values above 10% and for the analyzed region an *IRR* mean value of 4.3%.

Keywords: district heating; biomass; rural areas; agriculture residues biomass

1. Introduction

One of the key factors to control global warming is to improve the energy efficiency at residential areas, one of the large energy consumption sectors. Buildings are responsible of above 40% of the total energy demand, mainly covered by fossil fuels, with the associated greenhouse gases emissions. Even though technology evolution produces more efficient energy systems, the global energy consumption is continuously increasing [1]. The improvement in the quality of energy distribution is one of the great challenges facing today's society for future decades [2].

On this goal, the replacement of existing low efficiency heating systems by high efficiency district heating and cooling (DHC) facilities based on renewable sources is of the highest interest [3]. Their implementation can generate significant fuel and cost savings, reducing significantly greenhouse gases emissions [4,5]. On the other hand, despite their high interest, it is necessary the development of adequate regulatory and financial frameworks to support the large scale implementation of advanced district heating networks. It should also be noted that the development of new DH systems involves the displacement of existing heating technologies and it implies infrastructures development in public areas [6].

In Europe, the Energy Efficiency Directive (EDD-2012/27/EU) [7] establishes a common framework on measures to promote energy efficiency in the European Union. According to EED-2012/27, DHC cogeneration systems deployment is a promising pathway for reducing primary energy consumption.

However, DHC technologies are largely untapped. One of the key points addressed in EDD-2012/27/EU is that the potential for the implementation of district heating networks should be evaluated.

DHC systems will have quite different design and performance characteristics depending on their location and local resources availability. There will be different requirements to fulfil from social, legal and economic points of view depending on location that will affect to their viability and sustainability. On this sense a first general classification for DHC systems can be done in terms of the implantation area: urban, rural and industrial. Each of these types usually has common characteristics and specific requirements for viable and sustainable District Heating and Cooling systems development. Usually they have different ranges of population density, heat demand density, space availability, infrastructure development constrains, gas natural supply, local regulations development, air quality constrains, etc. Therefore, different methodologies are required in order to an adequate evaluation of their potential implantation [8].

On this purpose, previous research works have studied the potential for DHC [8,9]. In [8], a methodology is established to evaluate the potential of a large scale implementation of Combined Heat & Power District Heating (CHP-DH) systems in urban areas with natural gas network availability. The application to the continental region of Spain results in a quite efficient of CHP-DH, simultaneous thermal and electrical generation system. In [9], a procedure is established and applied to evaluate the massive implementation of DH networks in rural areas. For this case, and focused on rural areas where there is no natural gas network for continuous supply of natural gas, biomass district heating systems (BioDH) are evaluated. The use of biomass as fuel in these areas implies the use of a resource fully integrated in their environment and with capacity for reducing greenhouse gases emissions and with potential to improve the economy of the region [10].

Depending on the location, an usual situation is that rural municipalities have not all the forest biomass resources required by the BioDH systems in their own territory [9]. So, supply from neighboring municipalities is required to achieve the required biomass supply for the development of BioDH. It involves challenges in the management of the forestry biomass resource [6].

Following this research line, in this article is evaluated an option for BioDH systems in rural areas: the combined use of existing agricultural biomass residues as complementary to the forest biomass resources in the municipality. Agricultural residues have been obviated in previous studies but they present an interesting potential as fuel [11,12]. The combination of both biomass sources may improve the economic profitability of BioDH systems by using as much as possible the local biomass resources available in the area where the network is installed. In this paper is established a methodology for the assessment of the potential of a massive implementation of BioDH systems in a region. It takes into account the simultaneous evaluation of the forest and agricultural biomass resources in a given area.

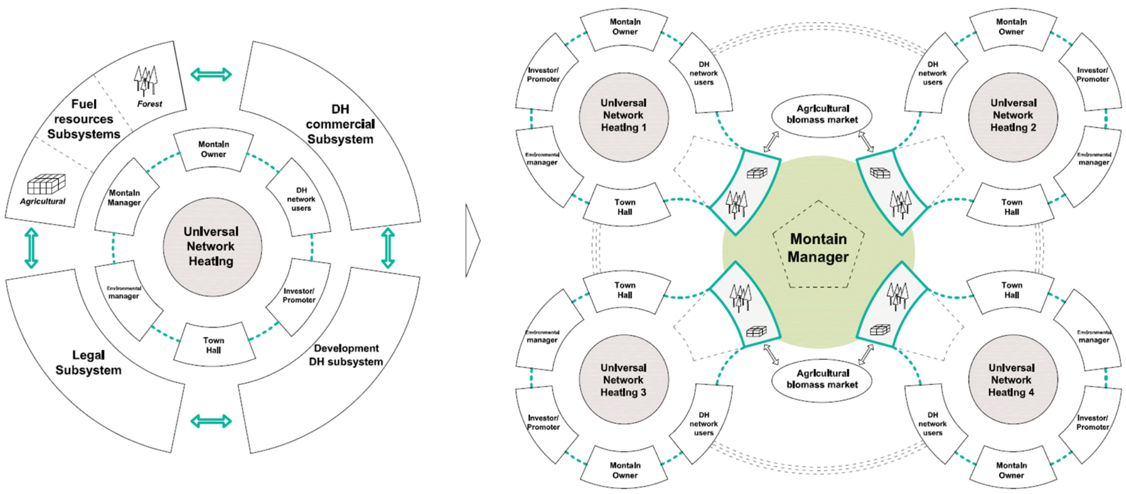
As it is oriented for the evaluation at regional scale, it will be necessary to establish a relatively fast and efficient procedure to quantify the biomass resource available in a given area, as well as to determine the costs involved in the exploitation of the different types of agricultural biomass residues. Once evaluated the available quantity of renewable biomass resource, biomass forestry and agriculture residues, and their associated costs, it is possible to evaluate the use of agricultural biomass as fuel in BioDH systems and to evaluate the associated operational expenditures.

The methodology is applied to a case study to evaluate the potential of BioDH based on the addition to renewable forestry biomass agriculture residues. The case study is carried out in the continental area of Spain, the same area in which application cases are developed in bibliography [8,9], in order to allow the comparison of results with previous studies to advance in the definition of the framework for the application of district heating systems at this region.

Before approaching the methodology, the biomass resource management model is developed in Section 2. It identifies the agents involved and the relationships among them, within the exploitation model of agricultural and forestry biomass resources. Viability and sustainability along the operation of BioDH systems with agricultural and forestry biomass depends to a large extent on the adequate identification, coordination and correct functional relationship between all the agents.

2. Forest and Agricultural Biomass Model Management for Universal District Heating

The management of biomass resources for biomass district heating system involves different stakeholders and sectors. In the case of forest biomass, from private or public dominium, the management from the forest to the final use in the biomass district heating system involves many different agents that interact in the process. In Figure 1, [6] is graphically presented how the forest biomass resource is managed in combination with the agriculture residue and the relationships between the involved stakeholders for their exploitation and use in biomass universal district heating systems.



(**a**) (**b**)

Figure 1. (**a**) Universal Network Heating model; (**b**) Integrated management between different universal heating networks of the forestry resource, extrapolated from [6].

In Figure 1 can be appreciated the complexity of the system with multiple interactions, decision agents and regulations to apply, already developed or required to be developed. If, in addition, the mountain, and the forest resource, belongs to different municipalities the management complexity is increased. All these are factors that increase the uncertainties regarding the viability and sustainability of BioDH and affects to investments.

In this sense, the consideration of local agriculture residues in the biomass district heating fuel management chain, as proposed in this work, could reduce some of these management issues increasing the local biomass resource availability. At the same time it could reduce the global system transport carbon footprint, and depending on the specific cases, with the increase of the biomass fuel resource, to reduce costs and fuel availability uncertainties.

3. Methodology

In this section is presented a methodology for evaluating the potential for forest/agriculture residues BioDH systems in a region. It evaluates the factors that affect to the viability of these systems though a top-down/bottom-up methodology integrating the renewable forest biomass energy source and complemented with agriculture residues. This global methodology is summarized in Figure 2.

The methodology analyzes the critical factors that directly affect to the economic viability of BioDH systems and their sustainability. These factors and the stages where they are evaluated within the methodology are: availability of the biomass resource (stage 5); thermal energy demand (stage 2); environmental factors (stage 3); socio-economic factors, such as energy poverty, housing occupation or the age of buildings (stage 4).

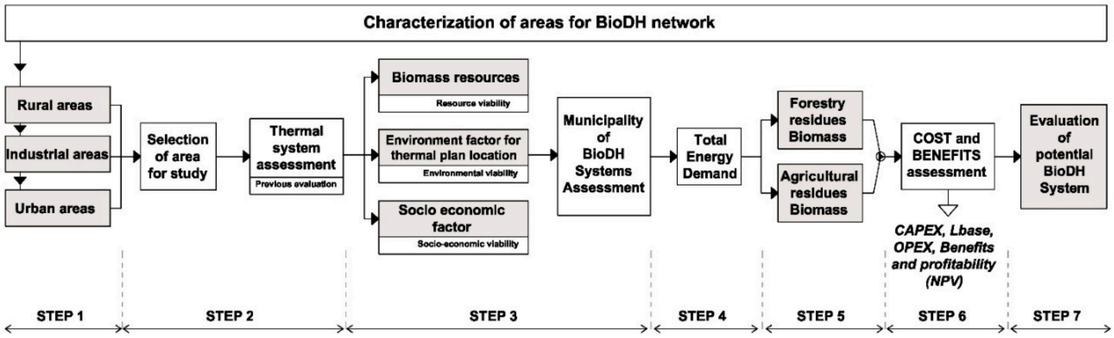


Figure 2. Methodology for evaluation of potential of BioDH System.

Step 1. Regional characterization and selection area of study

The region under study is defined through the energy characterization and available resources. In a first approach three main types can be identified for district heating analyses: (i) industrial areas, where the heat source comes from residual processes and cogeneration; (ii) urban areas, with high population density, scarcity of available spaces and, usually, natural gas network. In them the logistic associated to the use of biomass at certain scale can be complex; and (iii) rural areas where usually population density is low or moderate and biomass resource is available with a relatively easier management for logistic and supply.

Step 2. Thermal System assessment. Preliminary evaluation

It comprises the Sanitary Hot Water (SHW) and heating demands of the set of building to be connected to the heating network. The former can be estimated from adjusted estimation of the consumption rates, usually defined in local regulations. The heating demand can be evaluated through the evaluation of energy losses through buildings envelope and the contribution of internal and external heat gains [8].

Once estimated the thermal demand, the linear heat density (LHD) can be used as first approximation to the systems viability, based on a mean length of the network defined as function of the buildings density.

The BioDH systems are designed for supplying the whole thermal demand, and no auxiliary backup systems are considered for these urban heating networks. They are considered to be reliable systems and, once implanted, with lower fuel costs than those with fossil fuels. Although in some biomass district heating systems gas or diesel boilers are used for peak demand, this study has opted for full decarbonization of the heating system by using only local renewable resources, even though in some cases it may penalize the investment costs of the boilers.

Step 3. Assessment of viability factors

Rural BioDH systems require specific evaluation of the factors that directly influence their viability:

- Biomass resources: Cost and availability must be analyzed. This can be done by means of GIS tools or statistical data.
- Environmental factors for thermal plant location: this includes characteristics of available and feasible spaces for thermal station plant implementation, available area, affections, contaminants and particles dispersion and safety distances.
- Socioeconomic factors. These should include analyses of energy poverty and occupancy of dwellings.

Step 4. Municipality assessment

After the classification of potential BioDH locations in previous steps, this step goes into the detail of the specific BioDH at the selected locations. Heating demand is the main factor for the viability of the systems. It goes up to 90% of the total energy consumption in the DH. An accurate demand estimation allows an accurate prediction of incomes and system profitability. It can be done Total heating demand can be calculated as a function of internal (occupation, lighting and domestic appliances) and external (solar radiation) gains, ventilation loads and heat transmission by hourly integration of the heating power.

Besides it must be adjusted by additional factors as: (i) availability and costs of the biomass resource, that can be evaluated using GIS sources [13,14]; (ii) environmental factors for the location of the thermal plant; and (iii) socioeconomic factors, they include the ponderation of the energy poverty and houses occupation and use on the real demand [15,16]. They must be analyzed for each one of the BioDH under study.

In the specific methodology for BioDH in rural areas the following correction factors of the demand are included:

(i) Occupancy of dwellings: for permanent residences an intermittence factor for the theoretical demand of 0.78 [8] is considered, whereas for partially occupied dwellings (weekends and holidays periods), the value is set to 0.4.

(ii) Energy poverty: a correction factor for energy poverty is only applied to permanent dwellings. This information can be obtained directly through local surveys or indirectly through statistical data. For the application case surveys were used.

(iii) Age of the buildings: theoretical demand must be corrected in function of the age of buildings, with a factor that corrects the time passed since their construction or the last refurbishment. These data can be estimated through statistical data of the municipalities.

Finally, the future demand evolution must be taken into account correcting the estimated degree-days taking into account the effect of estimated temperature increase.

Network length affects directly to the investment and expected profitability of DH [17]. Besides, operational expenditures are affected of network length due to the effect of distribution losses. BioDH length can be evaluated through Equation (1):

$$L_P = 0.02 \cdot S_{DH} + 0.4 \cdot {S_{DH}}^{0.5} \quad (1)$$

And the specific network length L_{spec} for each building can be calculated as follows [18]:

$$L_{spec} = 1207.36\ {\rho_{building}}^{-0.5894} \quad (2)$$

Both can be adjusted from the evaluation of existing DH networks.

Step 5. Biomass residues evaluation

- 5.1 Biomass from forestry residues

Characteristics of the available biomass can be evaluated using existing databases and/or GIS tools, where available. They include main biomass characteristics (composition, LHV, humidity) and extraction and manipulation costs.

Forest biomass availability is calculated as a function of type Q_{m_i} and supply cost P_{m_i}. If local biomass is not able to cover the demand, it must be taken from the excess biomass in neighbouring areas, with quantities Q_{ext_i} and supply cost P_{ext_i} [€/ton]. The mean forest biomass cost per tonne for each BioDH is given by Equation (3):

$$\overline{P}_B = \frac{\sum P_{m_i} \cdot Q_{m_i} + \sum P_{ext_i} \cdot Q_{ext_i}}{\sum Q_{m_i} + \sum Q_{ext_i}} \quad (3)$$

- 5.2 Agricultural residues biomass

A procedure able to quantify and economically evaluate the available agricultural biomass in an area under study. To do this, it is recommended, where available, the use of GIS tools to determine available resources and then to use different experimental expressions to evaluate the costs of the different agricultural biomass. GIS tools can also provide economic data but they are usually less accurate than those provided by the experimental formulas adjusted to the specific cases (Figure 3).

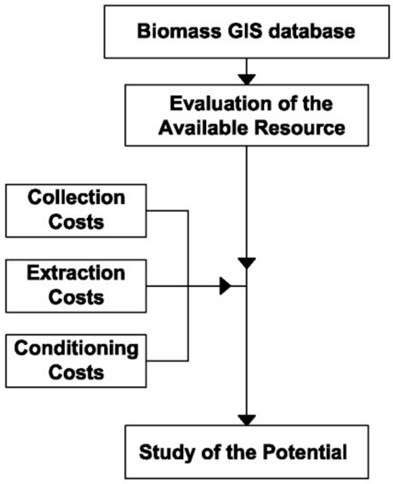


Figure 3. Agricultural Residues Biomass.

- 5.3 Extraction, collection and conditioning costs of agricultural biomass from Bionline [19]

For the application case of the methodology shown in this paper, to quantify the amount of agricultural biomass available, the Bionline web tool [19] (Figure 4) (with application for countries in South Europe) has been used. Other tools and programs with similar information are available for other regions of Europe and different regions of the World. Where no available the same procedure could be applied directly from agriculture databases. They provide data related to the extraction, collection, conditioning and transport of the biomass.

In the present article, the evaluation of costs related to cereal straw, corn borer, olive groves, fruit trees and vineyards is mainly based on the work by Esteban et al. [20].

For the application of the Bionline GIS tool the following typologies of agricultural biomass are classified in:

- Woody residues: generated from pruning of olive groves, fruit trees and vineyards.
- Herbaceous residues: mainly cereal straws and corn boletus.

The extraction, collection and conditioning costs used for each type within methodology are presented in the following subsections:

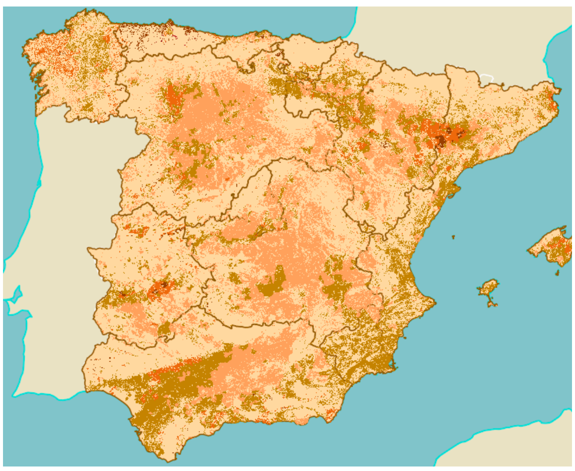


Figure 4. *Cont.*

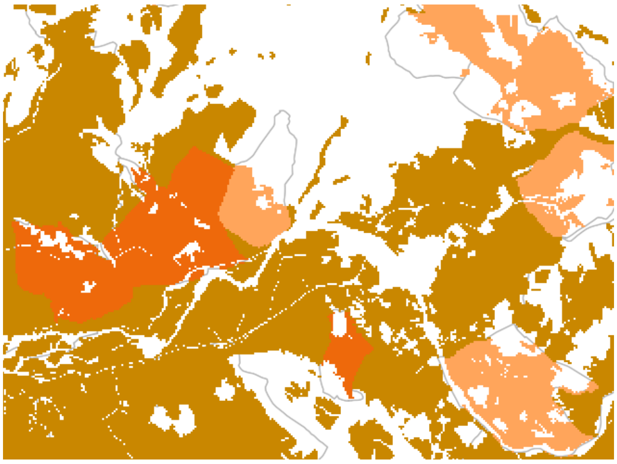


Figure 4. GIS evaluation of available resource of residues biomass (Bionline. IDAE [19]).

- 5.3.1 Straws of cereal and corn canister

For the case of cereal straws and corn the costs of collection, extraction and conditioning are presented in Table 1. They include the transport costs required to perform these tasks. It requires the evaluation of the surface biomass density [20].

Table 1. Basic costs of harvesting and forwarding annual crops in Spain [20].

Crop	Baling in Rank (€/t) (x, Surface Density in t/ha)	Baling out of Rank (€/t)	Forwarding (Max 500 m) and Piling (€/t)
Winter cereals	−4.2752x + 37.685	3.89 (x > 7.94 t/ha)	3.00
-	(2.64 > x < 7.94)	26.97 (x < 2.64 t/ha)	-
Oil crops, Maize, Cotton	−3.2064x + 38.264	2.92 (x > 8 t/ha)	3.00
-	(2.67 > x < 8)	20.22 (x < 2.67 t/ha)	-

- 5.3.2 Olive groves, fruit trees and vineyards

In this case, the costs of extraction, collection and conditioning can be directly visualized independently of the surface biomass density in the area. The costs are divided into different sub sections, finally obtaining the total costs. The transport costs required to perform these tasks are also taken into account. Data are grouped in Table 2:

Table 2. Basic costs of harvesting and forwarding woody crops in Spain [20].

Woody Crop	Alignment Machine (€/t)	Crushing (€/t)	Forwarding (Max 15 km) (€/t)	Total (€/t)
Orchard	6.00	15.03	9.02	30.05
Olive	6.00	24.00	7.20	37.20
Vineyard	6.00	24.00	7.20	37.20

These data are applicable to Spain. To extrapolate the results to other European regions different to South of Europe, correction factors based on the economic indicators of the region should be used. For countries in central and northern Europe, the results obtained in Sweden should be used as a reference. The extrapolation of the correction factors to be used in several countries are presented in Table 3:

Table 3. Correction factors used for the extrapolation of the basic costs calculated for Spain and Sweden (data extracted from [20]).

Spain as Base	Correction Factor	Sweden as Base	Correction Factor
Spain	1.000	Sweden	1.000
France	1.121	Austria	0.985
Italy	1.169	Denmark	1.124
Greece	0.851	Finland	0.979
Portugal	0.820	Germany	1.057
-	-	Norway	1.245
-	-	Poland	0.514

- 5.3.3 Straw

In the case of using straw as fuel, the process of obtaining the biomass has a different impact in the cost and in the relative effect over the total fuel cost. The transport costs required to perform these tasks are taken into account. It is also important to note that in the case of straw, there are different final geometries of packaging the biomass, and it affects to the final price in each case as it affects to the transport and management. Three different tables (Tables 4–6) [21] are presented with the differential costs for different final geometries of fuel compilation.

Table 4. Calculation of differential costs of energy use with straw prepared in small square bales [21].

Costs Category (Operation)	Costs (€/t)	Costs Structure (%)
Bailing	1.90	17.27
Materials	1.90	17.27
Loading	1.20	10.91
Transportation	3.00	27.27
Manipulation	1.20	10.91
Storage	1.80	16.36
Total costs	**11.00**	**100.00**

Table 5. Calculation of differential cost of energy use with straw collected in the form of cylinder-shaped bales is used [21].

Costs Category (Operation)	Costs (€/t)	Costs Structure (%)
Bailing	2.30	26.44
Materials	0.50	5.75
Loading	3.10	35.63
Transportation	0.60	6.90
Manipulation	0.80	9.20
Storage	1.40	16.09
Total costs	**8.70**	**100.00**

Table 6. Differential cots of briquetting per ton of briquettes produced [21].

Costs Category (Operation)	Costs (€/t)	Costs Structure (%)
Bailing	8.70	21.48
Materials	21.70	53.58
Manipulation	3.60	8.89
Storage	6.50	16.05
Total costs	**40.50**	**100.00**

This procedure can be extrapolated for the evaluation of the costs of other of agriculture biomasses.

Step 6. Cost and benefit evaluation

At the BioDH system level, viability is evaluated through a Cost-Benefit analysis [8]. It involves the analysis of:

(i) CAPEX. It includes all the required investments to start up each of the subsystems: biomass thermal power station ($CAPEX_{TP}$), distribution network ($CAPEX_N$) and energy transfer stations ($CAPEX_{ETS}$).

$$CAPEX_{BioDH} = CAPEX_{TP} + CAPEX_N + CAPEX_{ETS} \tag{4}$$

Thermal plant investment for BioDH systems is in the range of 855 €/kW to 1453 €/kW of the total plant capacity [22,23]. For a power range of 8 MW to 50 MW, higher than those expressed in [22,23], reduces the capital investment to a much lower range, 200 €/kW to 250 €/kW, due to economies of scale.

The cost of the distribution network must be evaluated according to its length and specific diameter. The specific pipe diameter for each BioDH network can be calculated using [24]:

$$d_a = 0.0486 \cdot \ln(D/L_P) + 0.0007 \tag{5}$$

where d_a is the pipe diameter (m), and L_P the network pipe length (m), together with D, forms D/L_P the linear heat density (GJ/m). According to [24], network investment can be evaluated as follows:

$$CAPEX_N = (C_1 + C_2 \cdot d_a) \cdot L_P = (C_1 + C_3 \cdot P_{th}^{0.5}) \cdot L_P \tag{6}$$

The use of plastic pipes in heating networks has reduce the costs at levels of C_1 = 120 €/m and C_3 = 750 €/m·W$^{0.5}$ evaluated from real installation within the scope of this research.

(ii) Reference Baseline definition. The baseline (L_{base}) in a BioDH project, which replaces heating and ACS generation from individual or collective boilers in buildings, is the unit cost of the useful energy, plus the depreciation and maintenance costs of the individual boiler (Equation (7)) [8].

$$L_{base} > Price_{kWh} > \frac{C_{fixed}^{BioDh} + C_a^{central} + C_a^{network} + C_E^{network} + C_{fuel}^{central}}{E_{sold}} \tag{7}$$

where C_{fixed}^{BioDh} is the network fixed cost (€), $C_a^{central}$ and $C_a^{network}$ are the central and network amortisation costs respectively, $C_E^{network}$ is the network energy cost, $C_{fuel}^{central}$ is the fuel cost and E_{sold} is the total energy sold (kWh).

The reference baseline cost for the current heating system is based on the use of individual or collective diesel boilers, with a cost of 45 €/MWh. If considering also maintenance costs and amortization of the individual boilers are added and combined with a seasonal average yield of 70%, the reference baseline cost is 85 €/MWh.

(iii) Incomes. Incomes are calculated as follows:

The price should be clearly below than the baseline price to make it attractive to the consumer avoiding to introduce additional costs to the end user.

$$I_n = D \cdot Price_{kWh} \tag{8}$$

where I_n are the incomes (€) and D the energy sold (kWh).

To promote the subscription and to give a clear benefit to the end user the sale price for the case study includes a discount on the current cost of heating of 20%, resulting in a selling price of 68 €/MWh.

(iv) OPEX. Operational Expenditures (OPEX) in the cost-benefit analysis are given by biomass cost and conveying energy consumption cost, which depends linearly on the heating demand. They must be included together with the fixed operation costs.

$$OPEX = C_{fuel}^{central} + C_E^{network} + C_{fixed}^{BioDH} \tag{9}$$

where $C_{fuel}^{central}$ is the product of the mean price of biomass $\overline{P}_B$, of each BioDH by the energy consumed by the system. Pumping cost depends on the energy demand and to a lesser extent on the topology of the network. A estimation for fixed costs C_{fixed}^{BioDH} is 5.5% of the investment [25].

(v) Viability assessment and investment return. Due to the infrastructure characteristics and the involved equipment a time horizon of thirty years is considered [5,8]. The Internal Rate of Return (*IRR*) is used as main parameter for the evaluation and comparison between projects of the interest of investment.

$$-CAPEX + \sum_{i=1}^{30} \frac{I_{ni} - OPEX_i}{(1 + IRR)^i} = 0 \tag{10}$$

Step 7. Evaluation of the potential of a BioDH system and environmental assessment

To determine the real potential of biomass district heating in an area o region a minimum viability threshold must be set, It will depend on the characteristics of the investor (i.e.,: if it is public or private). Once defined the viability criteria, for all viable BioDH networks, the avoided emissions can be evaluated by applying the conversion factor for fuel oil [26]:

$$\Delta_{CO_2} = CO_2^{Boil-dom} = \frac{D}{\overline{\eta}_{domestic\ boil}} \cdot GHG_{Diesel} \tag{11}$$

where $\overline{\eta}_{domestic\ boil}$ is the individual boiler efficiency replaced by the BioDH system, and GHG_{Diesel} is the conversion factor for diesel fuel.

4. Application of the Methodology

In this section is presented the application of the methodology to a specific region. The continental area of Spain has been selected to add new analyses to the previously presented to other DH systems in the same region but different typologies of district heating systems [8,9].

For the study of BioDH potential within this area, municipalities with a population above 1500 inhabitants and without natural gas supply were selected to apply the methodology.

Under this criteria in the area under study, there are 501 municipalities with these characteristics. In them the application of the methodology estimates that the required heating power of BioDH systems would range from 4.5 to 69 MW, with an operating range of 875 to 2619 equivalent hours, Figure 5. The energy demanded by these systems would go from 6.8 to 130 GWh per year, with a total of 12,148 GWh per year. In Figure 5 are represented for these 501 municipalities the estimated installed power for heating as function of the equivalent working hours of the heating system.

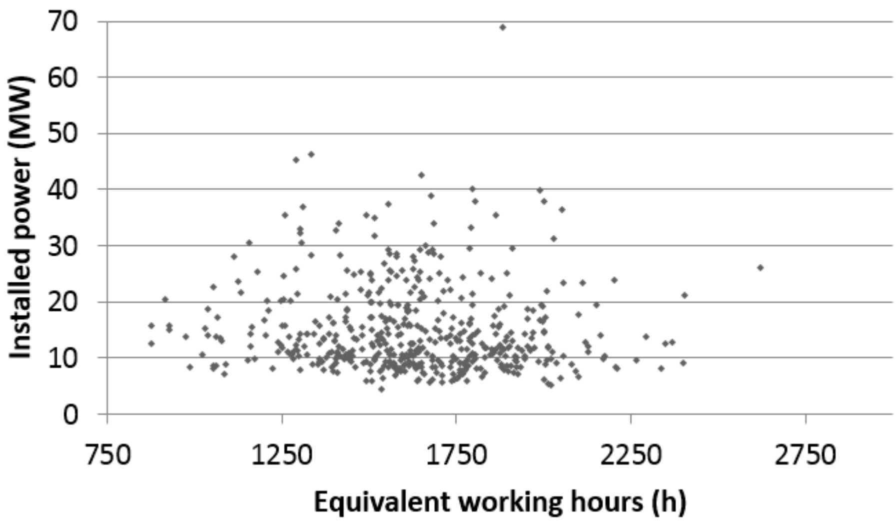


Figure 5. Installed power and equivalent working hours.

It can be seen in Figure 5 that most of the systems require a thermal power in the range of 7–20 MW, and the equivalent working hours mean value is around 1600 h.

In Figure 6 the ratio between the agricultural biomass generated in each municipality per year and the total area in that municipality is shown. It can be verified that there is not a direct linear relationship between the municipality area and the agricultural biomass that can be collected. The link between area and potential agricultural biomass is affected by other variables. Among these factors are the variety of crops that exist in the municipalities; the orography and the forest areas.

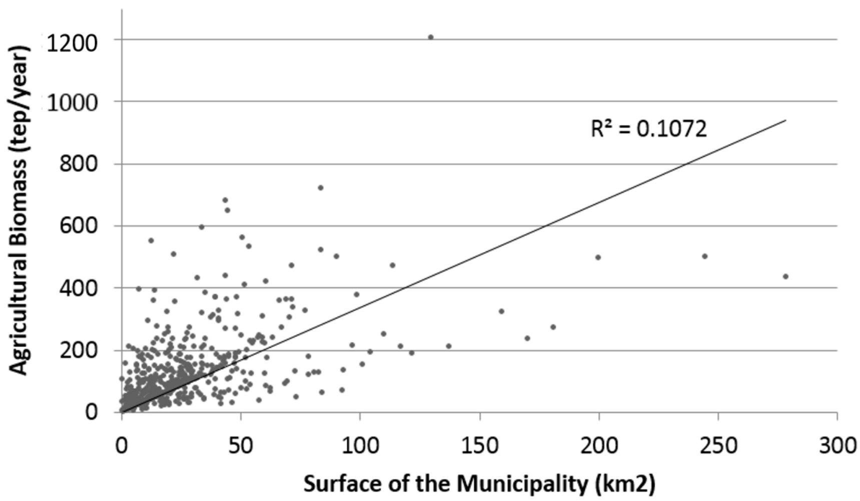


Figure 6. Agricultural biomass generated in each municipality and municipality area.

In Figure 7 are represented the total amount of forest biomass and agriculture biomass not covered with the own resources of the municipalities. The results are presented in three groups: municipalities with a population below 2000 inhabitants, municipalities with population in the range between 2000 and 5000 inhabitants and those municipalities with population above 5000 inhabitants. In the figure on the left are represented the existing biomass resources and in the figure on the right is represented the total demand. Tables and expressions presented in the methodology to quantify the agricultural biomass resource are directly applicable to this case study, as they are based on studies carried out in the continental region of Spain. For the application to other European regions the correction factors in Table 3 must be applied.

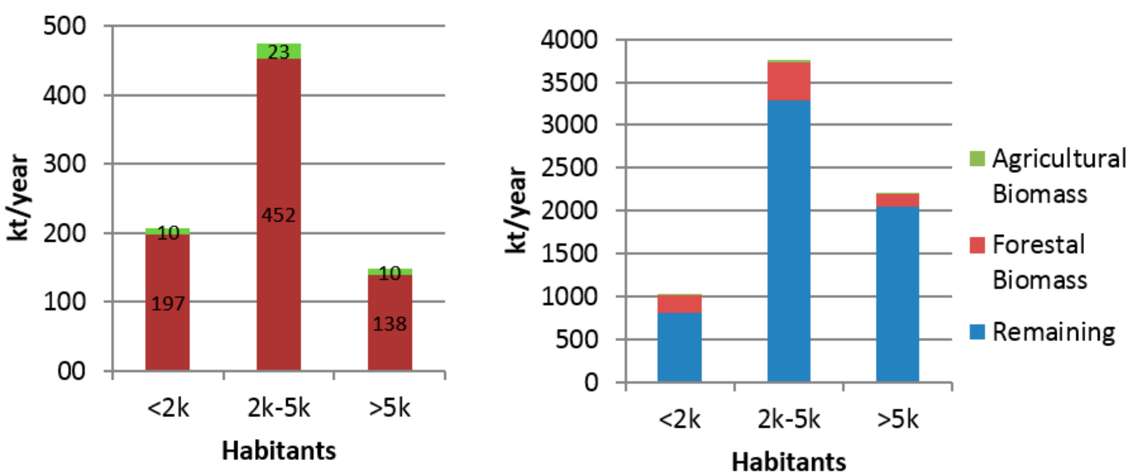


Figure 7. Agricultural, forest and remaining biomass for BioDH System.

The biomass required for the supply of these 501 systems is 6980 kt. For each of the municipalities studied, the biomass availability varies between 3.9 kt and 74.3 kt. As can be seen in Figure 7, although renewable forestry and agricultural combined resources were used, they would be insufficient to satisfy the energy requirements for the municipalities.

The percentage of agricultural biomass with respect to forest biomass in the potential contribution to the BioDH systems is 3.3% for municipalities with less than 2000 inhabitants, 4.9% for municipalities between 2000–5000 inhabitants and 6.7% for municipalities with more than 5000 inhabitants.

Figures 8 and 9 show the amount of agricultural biomass resources available in each municipality in terms of their inhabitants with respect to the total demand that they require to implement BioDH systems. It will be therefore necessary to have biomass from other municipalities, which have not been included in the study because they do not have the potential for a heating network because they have natural gas or less than 1500 inhabitants but they have biomass resources. The required percentage of agriculture biomass in order to fully satisfy the demand only with own local resources should be 80.7% for municipalities with less than 2000 inhabitants, 88.0% for municipalities with population between 2000–5000 inhabitants and 93.7% in municipalities with a population above 5000 inhabitants. If we take into account only agricultural biomass availability for the same classification of villages the percentages are 1%, 0.6% and 0.5%.

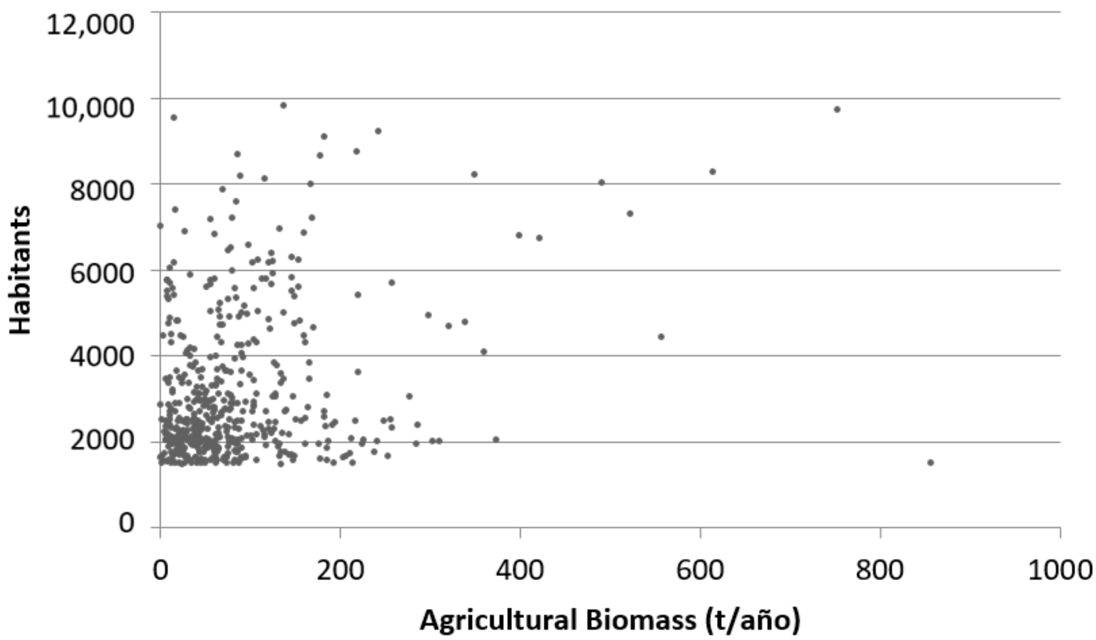


Figure 8. Agriculture biomass potential per municipality.

As shown in Figure 9, the amount of agricultural biomass varies between 0–855 t with an average for the municipalities of 85 t/year.

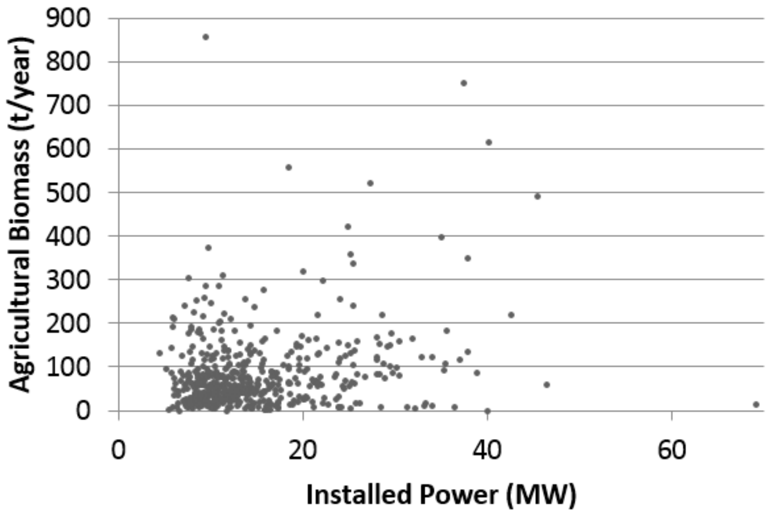


Figure 9. Agricultural biomass potential per installed power.

Regarding the contribution of agricultural biomass according to the power of the systems, the amount of biomass provided for powers ranging between 4.5 and 69 MW is shown in Figure 9. For the region under analysis only three systems have a potential for agriculture biomass supply above 500 t/year with power between 10 MW and 40 MW.

Figure 10 shows the Internal Rate of Return (*IRR*) of BioDH systems only with forest biomass in the municipalities under study.

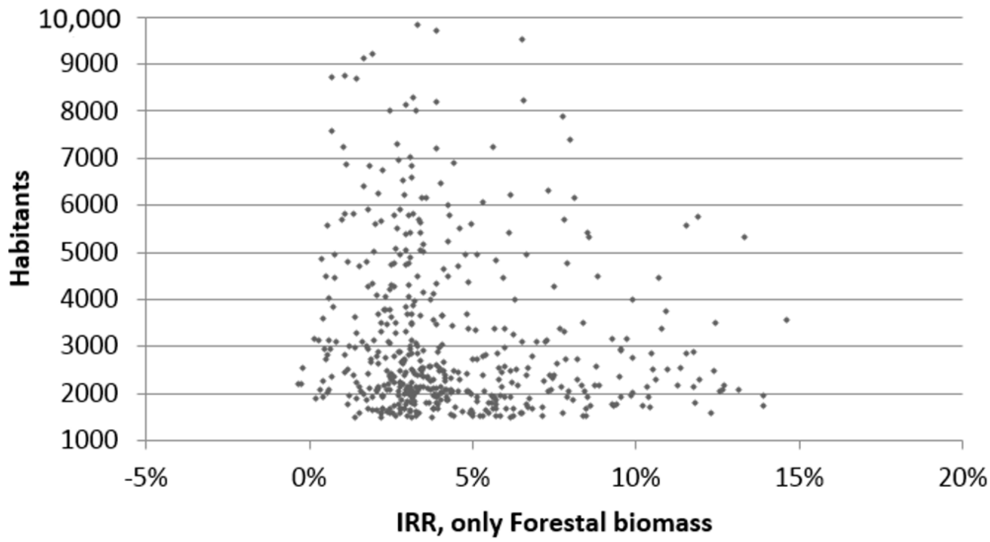


Figure 10. Internal Rate of Return (*IRR*) systems only forest biomass.

The variation of the economic profitability index (*IRR*) for facilities with only forest biomass varies between −0.4 and 14.6%, with an average profitability of 4.4%. In Table 7 are presented mean *IRR* values for municipalities classified in three groups. In those municipalities below 2000 inhabitants mean *IRR* value is 4.73, in those between 2000 and 5000 inhabitants the mean *IRR* value is 4.37 and for those above 5000 inhabitants the mean *IRR* is 3.86. Those are mean values for the classification in terms of population size. It must be highlighted that meanwhile these are mean values, there is a relevant number of municipalities with *IRR* values above 10%. These values are above the current economic return of money, therefore, it is considered an acceptable value for private investors, although the risks associated with investments of this type could require higher returns. In the case of Public Investors, profitability values are acceptable. In addition, governments can get involved in projects by assuming the investment or giving low interest financing, in this case private investors can get better project yields due to leverage.

Figures 11 and 12 show the Internal Rate of Return (*IRR*) adding the potential use of local agriculture residues. Figure 11 shows the percentage contribution of local agriculture residues and Figure 11 shows the distribution in terms of population. Considering the use of agricultural biomass and its lower price with respect to the transport of forest biomass from other municipalities, the average profitability of BioDH with mixed fuel is improves very slightly from 4.32 to 4.36% (Figures 11 and 12). This is an expected result due to the very reduced local availability of agriculture residues in this region for the municipalities that are under the criteria for analysis of BioDH. The improvement is not very appreciable because the amount of agricultural biomass of the different municipalities it smaller than the forest and, therefore, only cover a reduced fraction of the total heat demand. In addition, although that the forest biomass has cost slightly higher, the difference is not sufficient enough to show a clear variation with the very reduced available amount.

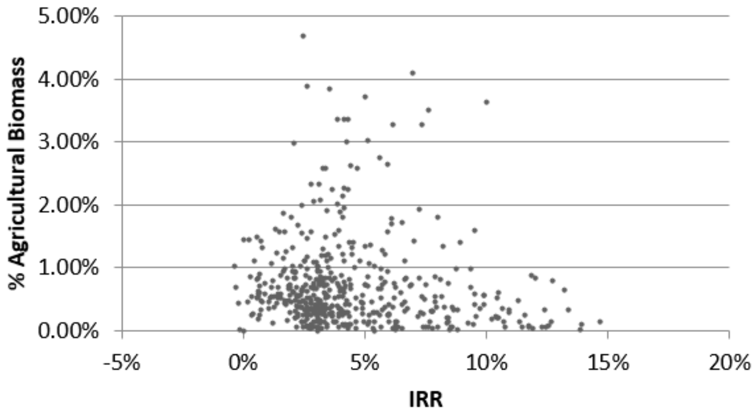


Figure 11. *IRR* per % agricultural biomass available.

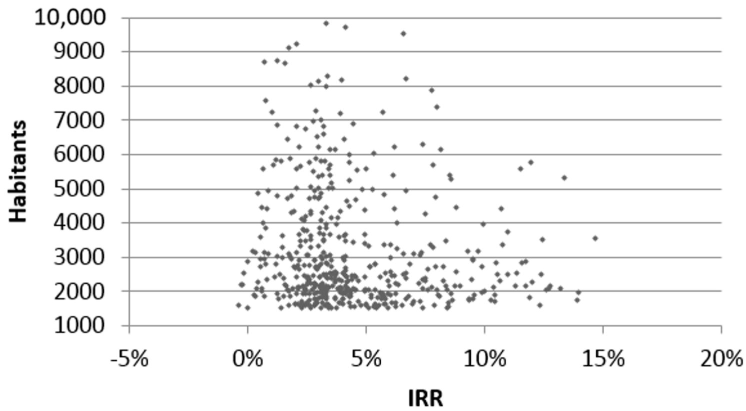


Figure 12. *IRR* per agricultural and forest biomass.

Although the increase of profitability is not high enough for the combined forest/agriculture fuel compare to the only exploitation of the forest resource in the region under study however there are points of interest associated to this combination. Among them can be highlighted that without a penalty of cost there is an increase of local biomass resource. It has an additional positive impact in the local economy with creation of new jobs and giving an additional value for the local agriculture (not evaluated in this work). Besides, and as presented in Section 2 it could give some partial relieve to forest resource management issues when many different municipalities are involved.

The summary of the global results obtained of applying the methodology to these 501 municipalities is summarized in Table 7.

As shown in Table 7, the total number of potential users that could be supplied with these systems in the region under analysis is high, 1,584,000 inhabitants. The estimated cost of fully deployment of these BioDH in this region would imply an investment of 4260 M€ meanwhile the expected mean profitability, *IRR*, would be of 4.36% combining biomass agricultural and forestry and 4.32% only with forest biomass. There is a number of population with values of *IRR* above 10% where the interest of investment is direct and others with values in the middle in which additional factors must balance the interest of the investment. The environmental benefit is clear with an estimation of potential avoided CO_2 emissions of 5406 kt.

Table 7. Main characteristics of the municipalities under study and the expected impact of BioDH.

Inhabitants	Number of Villages	Users	Invest M€	Required Biomas (t)	Available Forestal Biomass	Available Agricultural Biomass	*IRR* (%) Forest Only	*IRR* (%)	CO_2 Savings (t)
<2 k	131	228 k	635	1019 k	197 k	9.87 k	4.73	4.72	779 k
2 k–5 k	294	858 k	2372	3759 k	452 k	22.67 k	4.37	4.44	2907 k
>5 k	76	1100 k	1252	2202 k	138 k	9.88 k	3.86	3.92	1720 k
Total	501	1584 k	4260	6980 k	787 k	42.42 k	4.32	4.36	5406 k

These number are of high of interest but as mean values they don't give a clear route for a massive development under the current framework. However, the analysis identifies a number of are municipalities where the interest for the investment in BioDH is clear already under current framework. In addition there is a relevant number of municipalities in which additional activities as importing biomass from closer areas could increase these results making the investment in BioDH profitable. Same consideration could be done if policies supporting economic activity in this rural area were applied.

These results are obtained from a top-down/bottom-up methodology, so the results do not show a correlation between them, but they depend on the specific locations and characteristics within the area. As a consequence, a direct relationship cannot be established between the size of the municipalities and the economic profitability of the associated BioDH systems; although it is appreciated in the particular case of this study, the trend is that the smaller the size of the municipality, the greater the economic profitability. The municipalities with more severe climate tend to be more depopulated since people tend to move to cities in search of a better quality of life. Therefore the results cannot be generalized and profitability is not directly linked to the size of the municipality, although there is a minimum size threshold set in the methodology. It justifies the need of applying the proposed top-down/bottom-up methodology to analyze the potential of BioDH in a region.

5. Discussion

In this paper a methodology for the evaluation at regional level of the implantation of BioDH systems based on renewable biomass forestry and agricultural residues is presented.

This methodology has been applied, as case study, to the continental region of Spain in order to evaluate the potential of a BioDH network in this region and how it is influenced by considering agriculture and forest biomass. From the analysis is derived that for this region, and under the current local agriculture residues production, the profitability is not highly improved with the use of available resource of agricultural biomass. This is mainly due to the reduced availability of agriculture biomass that combined with exploitation costs of agriculture biomass not significantly lower than the forest biomass costs results in only a slight increase of Internal Rate of Return in most of the municipalities analyzed.

Therefore, for the region selected, as long as there is not a situation in which a greater amount of biomass resources are available or one in which the reuse of agricultural biomass is for some reason of a considerably lower cost, from the direct analysis of mean values it could be concluded that BioDH systems based on the combination of both resources do not provide clear benefits compared to only forest biomass. In other regions, with different patterns of agriculture production and renewable forestry biomass resources, different results would arise with the application of methodology. However, the methodology and analysis has identified a relevant number of municipalities where the integration results in values of *IRR* above 10% operating only with local biomass resource. These values for an infrastructure investment can be high enough for BioDH deployment in these municipalities.

In addition, in most of the villages under analysis there is an increase of the profitability with both fuel sources. If BioDH systems were implanted in them the combination of both biomass fuel sources would extend the availability of biomass resource of the municipalities for future scenarios. Besides with an increase of profitability, small but positive, there are additional positive impacts in the local economy. New economic activity and jobs can be created both in the agriculture and in the collection and exploitation of the biomass [27].

Any case, special attention must be paid to additional issues associate to the use of biomass multifuel. On one hand, different fuels should be stored in isolated places of other types of fuel, which would mean an increase in storage costs [28] with an increase of the complexity in the management of the storage and fuel preparation. On the other hand, special attention must be paid to the boiler selection and biomass fuel mixes preparation for an adequate performance as with several types of biomass there will be different combustion characteristics and fuel geometries (chips, pellets, etc.) [29]. These aspects must be taken into account when including agricultural biomass in BioDH systems.

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References

1. U.S. Energy Information Administration. International Energy Outlook 2016. Available online: https://www.eia.gov/forecasts/ieo/pdf/0484.pdf (accessed on 4 February 2018).
2. International Renewable Energy Agency (IRENA). *REthinking Energy 2017: Accelerating the Global Energy Transformation*; International Renewable Energy Agency (IRENA): Bonn, Germany, 2017.
3. Lizana, J.; Chacartegui, R.; Barrios-Padura, A.; Ortiz, C. Advanced low-carbon energy measures based on thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.* **2017**, *82*, 3705–3749. [CrossRef]
4. Connolly, D.; Lund, H.; Mathiesen, B.V.; Werner, S.; Möller, B.; Persson, U.; Boermans, T.; Trier, D.; Østergaard, P.A.; Nielsen, S. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy* **2014**, *65*, 475–489. [CrossRef]
5. Lizana, J.; Ortiz, C.; Soltero, V.M.; Chacartegui, R. District Heating systems based on Low-Carbon Energy technologies in Mediterranean areas. *Energy* **2017**, *120*, 397–416. [CrossRef]
6. Soltero, V.M.; Rodríguez-Artacho, S.; Velázquez, R.; Chacartegui, R. *Biomass Universal District Heating Systems*; University of Seville: Seville, Spain, 2017.
7. The European Parliament and the Council of the European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. *Off. J. Eur. Union* **2012**, *315*, 1–56.
8. Soltero, V.M.; Chacartegui, R.; Ortiz, C.; Velázquez, R. Evaluation of the potential of natural gas district heating cogeneration in Spain as a tool for decarbonisation of the economy. *Energy* **2016**, *115*, 1513–1532. [CrossRef]

9. Soltero, V.M.; Velázquez, R.; Chacartegui, R.; Carvalho, M.; Becerra, J.A. Biomass district heating systems: A solution for the directive 27/2012/EU. In Proceedings of the Ecos2015: 28th International Conference on Efficiency, Cost, Optimization, Simulation and Enviromental Impact Energy Systems, Pau, France, 29 June–3 July 2015.
10. Raslavičius, L.; Narbutas, L.; Šlančiauskas, A.; Džiugys, A.; Bazaras, Ž. The districts of Lithuania with low heat demand density: A chance for the integration of straw biomass. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3259–3269. [CrossRef]
11. Ekman, A.; Wallberg, O.; Joelsson, E.; Börjesson, P. Possibilities for sustainable biorefineries based on agricultural residues—A case study of potential straw-based ethanol production in Sweden. *Appl. Energy* **2013**, *102*, 299–308. [CrossRef]
12. Singh, J. Overview of electric power potential of surplus agricultural biomass from economic, social, environmental and technical perspective—A case study of Punjab. *Renew. Sustain. Energy Rev.* **2015**, *42*, 286–297. [CrossRef]
13. Alessandro Provaggi (Consortium Coordinator). Stratego Project. Available online: http://stratego-project.eu/reports/ (accessed on 4 February 2018).
14. Sánchez-García, S.; Canga, E.; Tolosana, E.; Majada, J. A spatial analysis of woodfuel based on WISDOM GIS methodology: Multiscale approach in Northern Spain. *Appl. Energy* **2015**, *144*, 193–203. [CrossRef]
15. Bouzarovski, S.; Petrova, S.; Sarlamanov, R. Energy poverty policies in the EU: A critical perspective. *Energy Policy* **2012**, *49*, 76–82. [CrossRef]
16. Hills, J. *Getting the Measure of Fuel Poverty—Final Report of the Fuel Poverty Review: Summary and Recommendations*; CASE Report, 72; Centre for Analysis of Social Exclusion, London School of Economics and Political Science: London, UK, 2012.
17. Reidhav, C.; Werner, S. Profitability of sparse district heating. *Appl. Energy* **2008**, *85*, 867–877. [CrossRef]
18. Gils, H.C.; Cofala, J.; Wagner, F.; Schöpp, W. GIS-based assessment of the district heating potential in the USA. *Energy* **2013**, *58*, 318–329. [CrossRef]
19. IDAE. BIONLINE. Available online: http://bionline.idae.es/biomasa/index.php?r=layers/gis (accessed on 4 February 2018).
20. Esteban, L.S.; Carrasco, J.E. Biomass resources and costs: Assessment in different EU countries. *Biomass Bioenergy* **2011**, *35*, S21–S30. [CrossRef]
21. Dodić, S.N.; Zekić, V.N.; Rodić, V.O.; Tica, N.L.; Dodić, J.M.; Popov, S.D. The economic effects of energetic exploitation of straw in Vojvodina. *Renew. Sustain. Energy Rev.* **2012**, *16*, 397–403. [CrossRef]
22. Community Energy Association. *Small-Scale Biomass District Heating Handbook, A Reference for Alberta & BC Local Governments*; International District Energy Association: Westborough, MA, USA, 2014.
23. Davies, G. *The Potential and Costs of District Heating Networks*; Pöyry Energy Ltd.: Dubai, United Arab Emirates, 2009.
24. Persson, U.; Werner, S. Heat distribution and the future competitiveness of district heating. *Appl. Energy* **2011**, *88*, 568–576. [CrossRef]
25. Hendricks, A.M.; Wagner, J.E.; Volk, T.A.; Newman, D.H.; Brown, T.R. A cost-effective evaluation of biomass district heating in rural communities. *Appl. Energy* **2016**, *162*, 561–569. [CrossRef]
26. Edwards, R.; Larivé, J.-F.; Rickeard, D.; Weindorf, W. *WELL-TO-TANK Report Version 4.0*; European Commission: Brussel, Belgium, 2013.
27. Kimming, M.; Sundberg, C.; Nordberg, Å.; Hansson, P.-A. Vertical integration of local fuel producers into rural district heating systems—Climate impact and production costs. *Energy Policy* **2015**, *78*, 51–61. [CrossRef]
28. Rentizelas, A.A.; Tolis, A.J.; Tatsiopoulos, I.P. Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renew. Sustain. Energy Rev.* **2009**, *13*, 887–894. [CrossRef]
29. Saidur, R.; Abdelaziz, E.A.; Demirbas, A.; Hossain, M.S.; Mekhilef, S. A review on biomass as a fuel for boilers. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2262–2289. [CrossRef]