

*Research article*

## **Economic feasibility of a wood biomass energy system under evolving demand**

**Giorgio Guariso \* and Fabio de Maria**

Department of Electronics, Information, and Bioengineering, Politecnico di Milano, 20133 Milano, Italy

\* **Correspondence:** Email: [giorgio.guariso@polimi.it](mailto:giorgio.guariso@polimi.it); Tel: +39-02-2399-3559;  
Fax: +39-02-2399-3412.

**Abstract:** In some European regions, particularly in mountainous areas, the demand for energy is evolving due to the decrease of resident population and the adoption of energy efficiency measures. Such changes are rapid enough to significantly impact on the planning process of wood-to-energy chains that are supposed to work for the following 20–25 years. The paper summarizes a study in an Italian pre-alpine district where some municipality shows a declining resident population together with increasing summer tourism. The planning of conversion plants to exploit the local availability of wood is formulated as a mathematical programming problem that maximizes the economic return of the investment, under time-varying parameters that account for the demand evolution. Such a demand is estimated from current trends, while biomass availability and transport is computed from the local cartography, through standard GIS operations. Altogether, the mixed integer optimization problem has 11 possible plant locations of different sizes and technologies taking their feedstock from about 200 parcels. The problem is solved with a commercial software package and shows that the optimal plan changes if one considers the foreseen evolution of the energy demand. As it always happen in this type of biomass-based plants, while the problem formulation is general and may be applied to other cases, the solution obtained is strongly dependent on local values and thus cannot be extrapolated to different contexts.

**Keywords:** Wood biomass; mountainous areas; mixed-integer programming; GIS analysis

---

### **1. Introduction**

The use of wood biomass for combined heat and electricity production is expanding in Europe

as well as in many other countries. Wood biomass can in fact be considered as almost carbon neutral (the amount of carbon released during combustion is assumed to equal that absorbed during the vegetative growth) and thus may play a key role in the reduction of greenhouse gas emissions. Though the overall carbon balance is not strictly zero (accumulation takes years while release is very rapid, collection and transportation of feedstock to the conversion facilities emits additional carbon) the expansion of biomass-fired energy production is presently foreseen as a relevant component of several national and European climate policies.

Indeed, according to the Solid biomass barometer 2014 [1], energy production from solid biomass grew by 6.1% in Europe between 2012 and 2013, and this trend will probably continue, to reach 100 Mtoe of heat and 155 TWh of electricity by 2030. Italy ranks fifth in Europe for wood biomass consumption with a power generation of 3.7 TWh in 2014 and a heat production of 7.2 Mtoe. The exploitation of wood biomass is also interesting because it can foster the restoration of abandoned land, the maintenance of forests, the creation of new jobs (see, for instance [2]), i.e. contribute to the solutions of problems that are presently very important in many European areas.

Parallel to the expansion of biomass use for energy, the scientific literature has consistently expanded in this sector. Google Scholar catalogued about 700 documents on the optimization of wood biomass for energy use in year 2000, but around 4000 in 2014. Many of these papers deal with the availability of biomass (see, for instance [3] for a recent study, or [4] for an Italian case study). Others are concerned with the optimization of the energy conversion processes itself (e.g. [5]) or with other aspect of the production chain, like transport or comminution (e.g. [6]).

Another relevant portion of the scientific literature is devoted to the design of a wood-to-energy chain (see, for instance, [7-9] or the review in [10]). These works try to determine the optimal location, characteristics and capacity of the conversion facilities and are important to support local administrations in designing developing plans to increase the use of this renewable resource for energy production. The main characteristic of biomass is indeed to be a local resource, strictly linked to the specific territory, that may allow a distributed production of energy at reasonable costs with rather simple conversion facilities. This implies that both the availability of feedstock and the demand for energy must be carefully estimated on the territory, taking into account its specific features. Most studies in this area assume however a constant energy demand based on some average parameter. This approach was justified in a situation where energy demand was continuously expanding, as it was the case almost everywhere in the world till few years ago. On the contrary, the economic crisis, the expanding attention to energy saving measures, and, last but not least, the decreasing population may reduce the demand especially of thermal energy in some specific context. These changes are rapid enough to impact on the traditional 20–25 years planning horizon of district heating plants and thus must be thoroughly evaluated to define an efficient forest wood exploitation plan.

This paper provides an example of this situation studying an Italian pre-alpine district around Lake Como in Northern Lombardy. The area is reach in forests and thus may enjoy a relative abundant supply of wood residues to feed small energy conversion units for district heating and electricity production. Where such units can be located and how they can be fed are the decision variable of a usual mixed-integer linear programming problem, the formulation of which is presented in the next section. Section 3 presents the territory used for the case-study and discusses how the availability of biomass and the evolution of the energy demand have been estimated, while section 4 gives all the other details necessary to implement the model in the specific context. Finally, section 5

presents the results that can be derived from the solution of the model.

## 2. Materials and methods

### 2.1. The wood-to-energy planning model

To define a network of conversion plants to transform residual wood in an area into thermal and electrical energy to satisfy the local demands, we have to determine [7,8,11]:

- The number, location, technology and size of energy conversion facilities
- The amount, type, and location of the feedstock.

The first operation needed is thus to identify the candidate locations for energy units (they must represent urban areas with sufficient population and density to justify the installation of a district heating network) and to subdivide the territory into a number of parcels, inside which the vegetation can be considered homogeneous and with a unique management method [6].

We will assume that the purpose of the plan is the maximization of the net present value of the income over the planning period. Other economic performance indexes of the overall plan such as the payback time could have been used, as well.

Finally, we need to foresee the demand of thermal energy in the candidate locations for the planning horizon. One can in fact consider that electric energy, whatever its amount, can always be sold either locally or to the national grid, while thermal energy can be sold only up to the local demand.

The constraints to be satisfied are related to the sustainability of the wood collection [13,14], the efficiency of the energy conversion, the uniqueness of facilities in each location.

The problem can be formulated moving along the lines proposed in the recent literature [9,10]. Assume that the number of possible energy plants is  $Np$  in locations  $p = 1, \dots, Np$ , while a binary variable  $u_{pk}$  indicates whether or not (1 or 0) a plant with technology  $k$  exists at location  $p$ ; and the number of parcels for feedstock collection is  $Nw$ , in locations  $w = 1, \dots, Nw$ . The decision variable  $z_{wp}$  will thus represent the amount of wood collected in parcel  $w$  and shipped to the plant in  $p$ . Note that the technology  $k$  may indicate both the type of plant (e.g. combined Organic Rankine Cycle, ORC) and its size, since only a finite set of plant dimensions is actually available on the market.

#### 2.1.1. The optimization objective

The objective  $J$  of the problem can be formulated as the maximization of the net present value of the difference between benefits and costs [10]. Benefits from the plant in  $p$  can in turn be written as the sum of two terms, the return from the energy sold  $P_p(t)$  (with  $t$  representing the year within the planning horizon), and the return from reduced CO<sub>2</sub> emissions (carbon emission permits, green certificates, or similar)  $E_p(t)$ , while costs are due to plant construction and maintenance  $M_p(t)$ , feedstock harvesting  $H_p(t)$  and transportation  $T_p(t)$ . That is, the yearly return  $R_p(t)$  is

$$R_p(t) = [P_p(t) + E_p(t) - M_p(t) - H_p(t) - T_p(t)]u_{pk} \quad (1)$$

and

$$J = \sum_{t=1}^{25} \sum_{p=1}^{N_p} \frac{R_p(t)}{(1+r)^t} \quad (2)$$

where  $r$  is the discount factor and the planning horizon is assumed to be 25 years.

For the  $p$ -th plant in year  $t$ , the term  $P_p(t)$  can be written as

$$P_p(t) = C_{el} EN_{p,el}(t) + C_{th} EN_{p,th}(t) \quad (3)$$

Where  $EN_{p,el}(t)$  and  $EN_{p,th}(t)$  represent the amount of electrical and thermal power sold in year  $t$  at prices  $C_{el}$  and  $C_{th}$ , respectively. As already anticipated,  $EN_{p,el}(t)$  corresponds to the total power production, whatever its value, since electricity can always be sold to the national grid. On the contrary,  $EN_{p,th}(t)$  equals the thermal energy produced only until  $EN_{p,th}(t) \leq D_p(t)$ , i.e. the heat demand at location  $p$  in year  $t$ , since the excess thermal energy possibly produced has no market.

The CO<sub>2</sub> emission reduction term is [17]

$$E_p(t) = V_c \left( ef_{el} EN_{p,el}(t) + ef_{th} EN_{p,th}(t) - \sum_{w=1}^{N_w} ef_{hw} z_{wp} - ef_{tr} \sum_{w=1}^{N_w} d_{wp} z_{wp} \right) \quad (4)$$

where  $V_c$  is the value of a ton of CO<sub>2</sub> emission;  $ef_{el}$ , and  $ef_{th}$ , are the emission factors of a unit of electric or thermal energy produced by fossil source (methane, in our case study), and  $ef_{hw}$ , and  $ef_{tr}$  represent the emission for the harvesting of one ton of feedstock (that may depend on the specific parcel  $w$ , for instance when it is difficult to access) and for its transportation over a unit distance, being  $d_{wp}$  the distance along the road network from the parcel  $w$  to the plant  $p$ . The monetary value of a ton of CO<sub>2eq</sub> emitted (or spared) is determined in Europe by the Emission Trading System (EU ETS). It is the biggest international system for trading greenhouse gas emissions, presently covering more than 11,000 power stations and industrial plants in 31 countries, and including airlines. The EU ETS is based on the ‘cap and trade’ principle: a limit is set on the total amount of greenhouse gases that can be emitted by the factories, power plants and other installations. Within the cap, companies can buy allowances which they can trade on the emission market, presently mainly through auctioning. About two billion tons per year have been traded under this scheme since its institution in 2005. With several other countries (e.g. China, US East Coast, S. Korea) experimentally adopting similar schemes, the traded amount in the world is deemed to reach 4.5 billion by the end of 2015 [18]. Italy is within the largest markets of emission allowances in Europe. Its average price in 2015 has been around 8€ per ton of CO<sub>2eq</sub>, similar to that in the rest of EU, with a clear increasing trend [19].

From the cost side, the formulation is, in a way, similar.  $M_p(t)$  represents the yearly cost of the conversion plant and of the district heating network, including operation and maintenance;  $H_p(t)$  is the cost of harvesting operations, that can again be written as

$$H_p(t) = \sum_{w=1}^{N_w} C_{hw} z_{pw} \quad (5)$$

where  $C_{hw}$  is the cost of harvesting a unit biomass in parcel  $w$ , that, as already noted, may depend on the difficulty of forestry activities in the specific parcel. In the same way

$$T_p(t) = C_{tr} \sum_{w=1}^{N_w} d_{wp} z_{wp} \quad (6)$$

where  $C_{tr}$  is the cost of transporting a unit biomass over a unit distance. From the previous formulation, it appears that we assume all coefficients as constant along the planning horizon and thus the last two cost terms do not depend explicitly on time. One can obviously assume time-varying emission factors or unit costs, but the purpose of this work is to show the role of time dependent thermal energy demand and thus we considered them as fixed. This is obviously true also for the decision variables; it is clear that, once the plan is decided (i.e. energy plants and feedstock supply) they will remain fixed for the whole plan duration.

### 2.1.2. The energy production constraints

The constraints of the problems are very simple. From each parcel we can withdraw no more biomass than the sustainable amount  $W_w$  (less than the primary productivity), i.e.

$$\sum_{p=1}^{N_p} z_{pw} \leq W_w \quad \forall w \quad (7)$$

The amount of feedstock supplied to each plant must be compatible with its size [18]:

$$u_{pk} S_k (1 - m_k) \leq \eta_k \sum_{w=1}^{N_w} LHV_w z_{pw} \leq u_{pk} S_k (1 + M_k) \quad \forall p \quad (8)$$

where  $\eta_k$  and  $S_k$  are the efficiency and nominal size of the  $k$ -th plant technology, while  $m_k$  and  $M_k$  are two values indicating how much under or over supply can be tolerated for technology  $k$  with respect to the nominal plant size.  $LHV_w$  is the lower heating value of the feedstock coming from parcel  $w$ . Such a constraint can in principle be written for either thermal or electric energy, but here we focus on thermal energy and thus electricity is seen only as a beneficial side-effect. Indeed, the electric energy produced (and sold) by each plant is

$$EN_{p,el}(t) = \eta_{k,el} \sum_{w=1}^{N_w} LHV_w z_{pw} \quad (9)$$

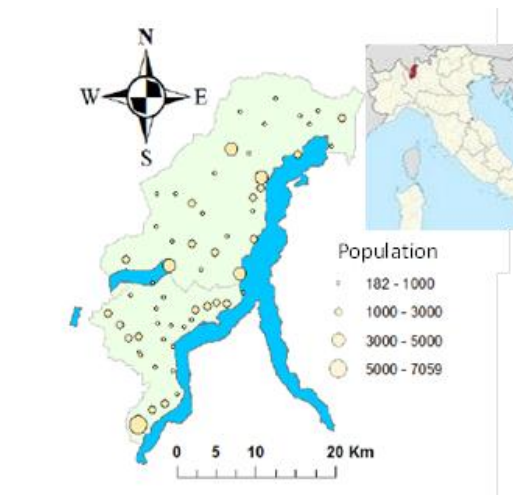
where  $\eta_{k,el}$  is the conversion efficiency of technology  $k$  in terms of electric energy, and thus does not depend on time. On the contrary, the thermal energy sold does depend on time and is:

$$EN_{p,th}(t) = \begin{cases} \eta_{k,th} \sum_{w=1}^{N_w} LHV_w z_{pw} & \text{if } \eta_{k,th} \sum_{w=1}^{N_w} LHV_w z_{pw} \leq D_p(t) \\ D_p(t) & \text{otherwise.} \end{cases} \quad (10)$$

Finally, all the  $z_{pw}$  variables must be non-negative and the  $u_{pk}$  variables are binary.

## 2.2. The Northern Como province: Energy demand and wood availability

The study area encompasses the western side of Lake Como, going from the lakeshore to Lake Lugano and the border of Switzerland. The zone is mountainous and today summer tourism represents the most important economic resource. The area involved is about 800 km<sup>2</sup> and includes 57 municipalities and urbanized areas for a total of about 70,000 residents with tourist structures (hotels, campsites, second houses) for up to 22,000 guests (shown in Figure 1).



**Figure 1. Location of urban areas.**

Only few of these urban areas have the population and the density necessary to justify the building of a biomass fired plant and a district heating network. To identify them, two threshold values have been assumed: at least 500 residents and at least a urban density (inhabitants over urban area) of 1500 residents per square kilometer. The adoption of these values resulted in the selection of the 14 possible plant locations shown in Figure 2.



**Figure 2. Possible plant locations.**

Furthermore, the urban areas of Domaso and Gravedona, Dongo and Musso, Porlezza and Carlazzo, though being classified as separated municipalities, are practically connected to each other with a continuity of buildings. Thus, they will be considered as single entities in the following, and the possible locations considered for biomass plants will be only 11. Altogether, they cover a population of 38,000 residents plus at most 16,000 summer tourists.

### 2.2.1. Energy demand

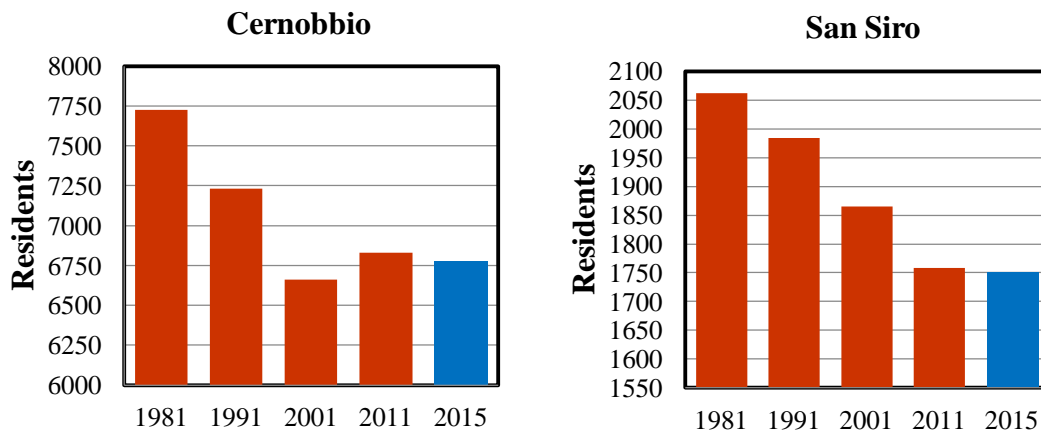
The estimation of thermal and electric energy demand of the eleven potential plant sites has gone through a relatively complex process. As for thermal energy, the regional cadaster (land register) provides the surface of all houses, while the Energy Register [21] provides an estimation of the thermal energy used by each square meter of residents' houses. The average value is about 232 kWh/m<sup>2</sup> per year, a rather high value, that reflects the old age of most houses in the area, resulting in a residential demand per unit surface four times that of modern energy conservative buildings. The same Energy Register provides an estimation of the energy used for hot water, which allows the computation of the total energy demand in each potential plant site. The total values of yearly thermal demand and the demand per inhabitant are reported in Table 1. The sensible differences among the specific heat demand of the various urban centers can be explained with the different elevations (Schignano is at 650 m a.s.l. while Dongo is at 208 m) and building age.

The energy demand is undergoing substantial changes due to two main factors: on the one side, the energy saving measures that are being implemented in many buildings due to more stringent regulations and various forms of incentives; on the other side, the slow, but continue decrease in resident population that is taking place in many small municipalities. As to the first aspect, the regional energy website [22] provides the energy consumption in the residential sector in each municipality for the last years. It shows a yearly decrease of about 2.4%. If we assume this trend will continue, the heat energy demand will go down from the current value to about 130 KWh at the end of the planning horizon: a figure which is still relatively high.

**Table 1. Energy demand in the potential plant sites.**

Potential plant locations	Surface (10 <sup>3</sup> m <sup>2</sup> )	Winter heat demand (gwh)	Hot water demand (gwh)	Total thermal demand	Inhabitants	Per capita heat demand (mwh)
Domaso Gravedona	58.4	5.90	1.48	7.38	5743	1.3
Dongo Musso	29.8	3.57	0.76	4.33	4436	1.0
San Siro	25.7	3.94	0.91	4.86	1757	2.8
Porlezza Carlazzo	74.8	8.31	1.90	10.21	7916	1.3
San Bartolomeo	10.0	2.35	0.46	2.81	1038	2.7
Valsolda	27.7	4.78	0.98	5.76	1592	3.6
Pellio Intelvi	10.0	2.71	0.46	3.17	1016	3.1
Schignano	10.0	3.10	0.46	3.56	851	4.2
Griante	12.8	1.45	0.33	1.77	628	2.8
Laglio	15.9	2.61	0.57	3.17	926	3.4
Cernobbio	95.0	15.49	3.38	18.87	6849	2.8

Figure 3 compares, for instance, the historical evolution in the resident population in two candidate locations: Cernobbio and San Siro. It is evident that, while Cernobbio, the largest municipality in the set, after a short decrease period has been substantially constant in the last 20 years, San Siro will continue losing residents, so that the population may go down to 1500 inhabitants within 2040.

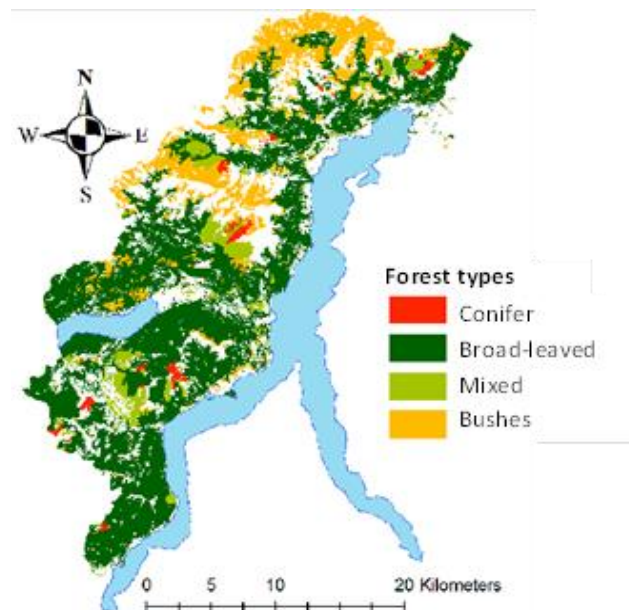


**Figure 3. Resident population evolution in Cernobbio (left) and San Siro (right).**

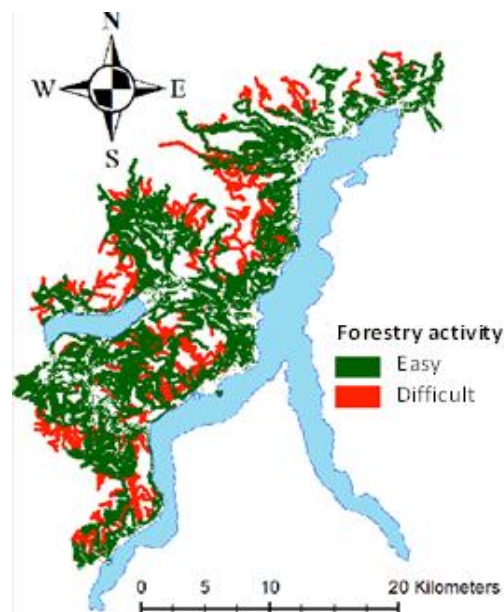
As for the electric energy, again official data from the regional website show a slight decrease in the last years of the demand per resident to a current value of 3 MWh per resident per year, but this is compensated in some areas (e.g. Porlezza) by an increase of the population and in general by an increase in tourist activities that is currently growing at a rate of about 3% per year [23]. Tourists are currently estimated to have a demand of 600 kWh per person per year, concentrated in summer, but with no need of air conditioning in most of the considered area. Altogether, we can assume that these effects compensate each other and thus the demand of electric energy will remain substantially constant.

#### 2.2.2. Available feedstock

Evaluating the sustainable feedstock that can be used in the potential energy system is again a rather complex process that exploits a lot of local information elaborated through GIS. The first step is the categorization of wood composition and extension. Figure 4 shows the situation as derived from the regional cartography [24]: there are basically only four relevant classes of vegetation: conifers (2% of the surface), broad-leaved (84%), mixed (8%) and bushes (6%). Not all the forest surface can however be exploited for biomass collection. This can be performed only if there is a mountain road that can be accessed by a tractor or some other specialized vehicle. And only the wood in a limited buffer around the road can be conveniently collected. So we have to intersect the map of the forest with that of the mountain road network with a suitable buffer (here assumed to be 150 m) and we can further classify the harvesting and collection operations as being easy (larger and not very steep roads) or difficult (small and steep paths) to obtain a map like that in Figure 5. The overall surface where forestry activities are easy is about 27,000 hectares, whereas that requiring a bigger effort is 9,000 hectares.

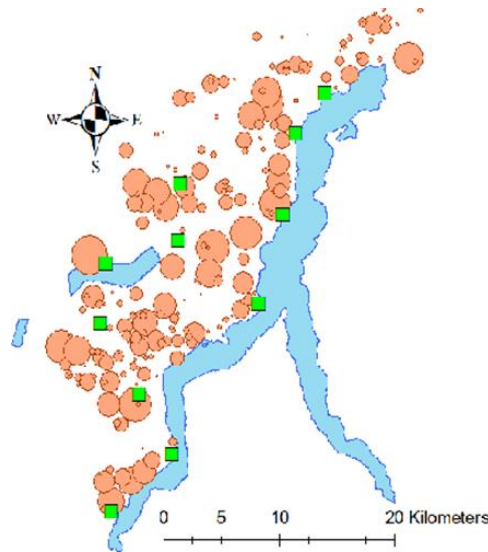


**Figure 4. Forest composition.**



**Figure 5. Map of easy (green) and difficult (orange) forestry activities.**

Now, intersecting these areas with the layer of municipality boundaries we obtain about 200 polygons, of which we can compute the barycentres and thus determine, through the suitable GIS function, a matrix containing the distance of each of them from each potential plant site (so a matrix of  $200 \times 11$  distances, for the case at hand). The final step is the calculation of how much wood can be sustainably collected by each of these parcels. These values were taken from a previous study [25] and are presented in Table 2. This gives an overall biomass availability of about  $53,000 \text{ Mg dm y}^{-1}$  distributed on the territory as shown in Figure 6.



**Figure 6. Feedstock parcel centers (pink circles proportional to availability) and potential plant sites (green squares).**

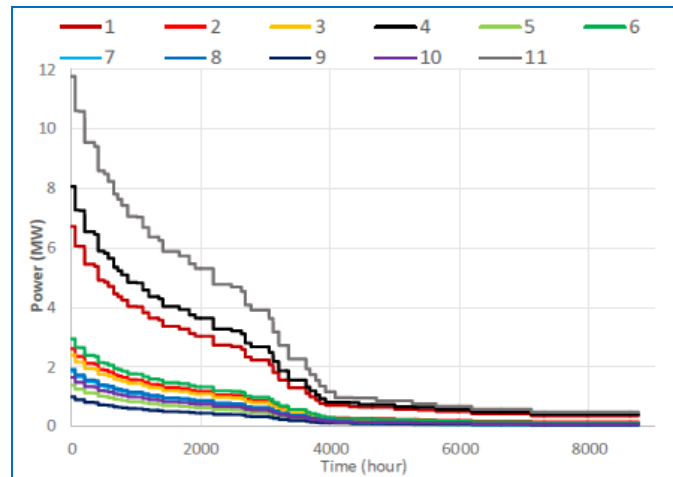
**Table 2. Feedstock types and availability.**

Type of tree	Exploitable surface (ha)	Harvest rate ( $\text{m}^3 \text{ dm y}^{-1} \text{ ha}^{-1}$ )
Broad-leaved	30,240	3.40
Conifer	720	5.52
Mixed	2880	5.32
Bushes	2160	3

### 2.3. Plant network configuration

Before implementing the model presented in Section 2 to the case described in the preceding section, some additional details have to be fixed.

The most important one is related to the evaluation of the plant investment costs, that are normally defined in terms of plant power and not of energy production. Indeed, in practice, both the demand of thermal and electric energy are characterized by a load curve that defines for how many hours a year a given energy is required. Figure 7 shows, for instance, the load curve of the thermal demand for the 11 potential plant sites. It clearly highlights the effect of the winter season, when domestic heating requires peak power of almost 12 MW in Cernobbio and 8.1 MW in Porlezza, while, after about 4000 hours, the demand goes practically to zero everywhere. So, if for instance, we decide to completely cover the current heat demand in Porlezza using a plant with 8.1 MW of thermal power, we will produce more heat than required by the district network 99% of the time. This means that a relevant portion of the thermal energy produced will be lost, because it cannot be sold. On the contrary, when building a cogeneration plant, the electric energy produced could always be sold either locally or to the national grid. The following results were obtained considering energy facilities able to cover 80% of the peak thermal power demand, that was assumed to maintain the same shape even when the total annual energy was decreased (or increased).



**Figure 7. Thermal load diagrams of the potential plant sites (1: Domaso; 2: Dongo; 3: san Siro; 4: Porlezza; 5: San Bartolomeo; 6: Valsolda; 7: Pello; 8: Schignano; 9: Griante; 10: Laglio; 11: Cernobbio).**

Other essential assumptions refer to the set of possible technologies and sizes that have been considered [26]. They are listed with their basic characteristics in Table 3.

**Table 3. Plant technologies characteristics.**

Technology	$\eta$ electric	$\eta$ thermal	Plant size MWe <sub>l</sub>	Plant size MW <sub>th</sub>	Quality of the raw material
Gasification	0.31 ÷ 0.36	0.50 ÷ 0.60	0.5	≅ 0.8	Good
Pyrolysis	0.30 ÷ 0.40	0.45 ÷ 0.50	0.5	≅ 0.6	Good
ORC	0.12 ÷ 0.18	0.74 ÷ 0.80	0.25 ÷ 2	1 ÷ 8	Poor
Chips system (only heat)		0.78 ÷ 0.85	0	1 ÷ 8	Poor

All these technical data were derived for a recent report [27] that reviewed the performances of a set of existing plants already in operation in Italy. As to the “Quality of the raw material”, it refers to the quality (homogeneity, humidity, dimension) of the feedstock that obviously has higher prices when more preprocessing is needed before utilization [28]. Investment costs have also been taken from the same report and go from about 1500 €/kW<sub>th</sub> for chips systems, to about 2600 €/kW<sub>th</sub> for gasification and pyrolysis plants. The cost of installing a district heating network has to be added to these values whenever a heat distribution system is not already in place, as for all the potential sites considered here. Such a cost has been in the past about 40–50% of the cost of the plant, but can be discounted on a longer period (40–50 years). Yearly O&M costs oscillates from about 5% of ORC systems to about 13% for pyrolysis plants. As it is apparent from Table 3, data on gasification and pyrolysis technologies are still difficult to find, since they are relatively new. Given these values, we have decided to test only one possible size for these technologies and we have subdivided the possible sizes of ORC and chips plant into 1, 2, 4, 6, 8 MW<sub>th</sub> values. The overall number of binary decision variables  $u_{pk}$  is however much smaller than 11 (sites) × 12 (technologies/size) since, as it clearly appears from Figure 7, only three potential sites out of 11 may need a thermal power larger

than 2 MW<sub>th</sub>.

Other numerical values have been taken from a report by the Energy and Strategy Group, Politecnico di Milano [29] and concern the cost of “good” (100€ Mg<sup>-1</sup>dm) and “poor” (50€ Mg<sup>-1</sup>dm) raw material and by the National Agency for Gas and Electricity [30] for the current selling prices of electricity (16€/MWh) and heat (10€/MWh). Finally, a value of 10€ Mg<sup>-1</sup> CO<sub>2</sub> has been used to compute the economic impact of the reduction of carbon emissions with respect to the use of fossil fuels.

The problem has been solved using the software What’s Best by Lindo Systems, which works as an add-on of Excel, under a number of different assumptions and values.

### 3. Results

First, the solution has been determined using the traditional approach, i.e. fixing the current heat demand for the entire planning horizon. The solution is outlined in Table 4, as to the type and location of plants.

**Table 4. Optimal solution with constant demand.**

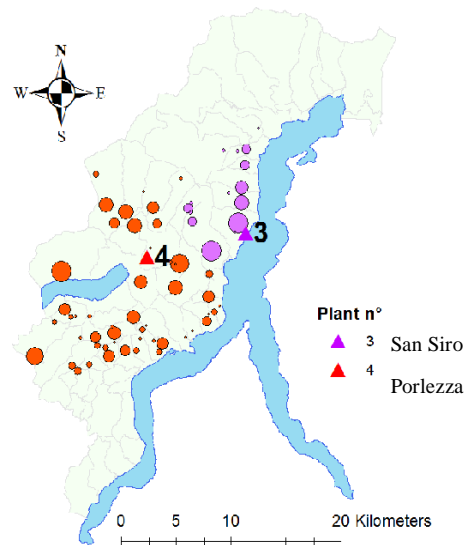
Plant	Technology	Thermal energy (% demand)	Electric power (MWeI)
San Siro	ORC	100%	0.37
Porlezza Carlazzo	ORC	100%	1.26

Figure 8 provides instead the other part of the solution, i.e. which wood parcels would provide the feedstock to each plant. The overall plan has a positive economic output that can be estimated at around  $1.5 \times 10^6$  € with a reduction of 18 Gg CO<sub>2</sub> in comparison to the use of fossil fuels (methane, in the present case). The return time of the investment is around 9 years which is close to other similar estimates for biomass-fired plants in Italy. The two plants may satisfy slightly more than 12% of the electric energy demand by using 53% of the available wood biomass. Most of the costs are related to the feedstock collection and pre-treatment, while transportation costs are limited to only about 4% of the revenues, given that the average hauling distance is only about 7 km.

### 4. Discussion

Unfortunately, for the other potential plant locations an economic feasible solution does not seem to exist within the assumptions adopted in the study. This may be due to several different factors, like for instance the limited choice of technologies for very small demands (peak values around 1–2 MW<sub>th</sub>) as in several of the considered locations.

Another relevant factor may be the low value attributed to the reduction of GHG emission. Indeed, while the current value of carbon emission permits is lower than 10€ Mg<sup>-1</sup>, many studies foresee considerable increases in the future [31]. If we assume a value of 30€ Mg<sup>-1</sup>, four plants become feasible using all the available feedstock, with a total revenue of  $2.6 \times 10^6$  € and satisfying over 23% of the local electric demand.



**Figure 8. Feedstock origins for the two optimal plants.**

The solution indeed differs if one considers the variation of the heat demand outlined in Section 3. The Porlezza-Carlazzo plant is still convenient and shows a positive return around  $10^6\text{€}$  (the increase of population in Porlezza partially compensates for the decrease of the individual demand), while in San Siro no plant with the assumed technology can reach feasibility. This solution would use slightly more than 40% of the wood biomass with an emission reduction of about 14 Gg  $\text{CO}_2$ . This means that the investment of  $7.12 \times 10^6 \text{€}$  in the Porlezza-Carlazzo plant (and heating network) is still justified, but that of  $2.12 \times 10^6 \text{€}$  in the San Siro plant would not be reasonable if the assumptions taken here will hold.

## 5. Conclusions

The planning of biomass fired plant networks requires a careful analysis of both the local availability of sustainable feedstock and of the local energy demand, when wood is to be used for heat production or for cogeneration with electricity. The estimation of wood availability requires detailed GIS analyses and forestry knowledge, but has been deeply studied and has already been applied in many cases. On the other side, the evolution of energy demand has not been carefully examined because the demand has always been increasing in the past years and thus investments could always be justified on the basis of current demand values. On the contrary, in some European countries the situation is rapidly changing due to demographic evolution and the widespread adoption of energy efficiency measures. These effects are so fast that they may significantly impact on the planning of energy systems, that are supposed to last for the next 20–25 years. In the case of the Northern Como province, the consideration of demand trends suggests the realization of a single plant instead of the two, that would be optimal in case the demand is assumed constant.

There are many other physical and economic trends that may have significant impacts on the planning process. Some of them, like global warming, can lead to an increased summer demand for air conditioning, and can be presently foreseen with a reasonable accuracy, while others, like new energy efficiency regulations and incentives, or selling prices of electricity are definitely difficult to forecast and thus extensive sensitivity analyses are needed to understand the robustness of any given

solution. Additionally, optimal technical solutions may differ substantially in different local contexts, thus they always require detailed local analyses in both space and time.

### Conflict of interests

All authors declare no conflicts of interest in this paper.

### References

1. EurObserv'ER (2015) Solid biomass barometer 2014. Available from: [www.eurobserv-er.org](http://www.eurobserv-er.org). Last accessed Dec 2, 2015.
2. Kopetz H (2013) Renewable resources: Build a biomass energy market. *Nature* 494: 29-31.
3. Kosinkova J, Doshi A, Maire J, et al. (2015) Measuring the regional availability of biomass for biofuels and the potential for microalgae. *Renew sust energ rev* 49: 1271-1285.
4. Sacchelli S, De Meo I, Paletto A (2012) Bioenergy production and forest multifunctionality: A trade-off analysis using multiscale GIS model in a case study in Italy. *Appl energ* 104: 10-20.
5. Sartor K, Quoilin S, Dewallef P (2014) Simulation and optimization of a CHP biomass plant and district heating network. *Appl energ* 130: 474-483.
6. Zamora-Cristales R, Sessions J, Boston K, et al. (2015) Economic Optimization of Forest Biomass Processing and Transport in the Pacific Northwest USA. *Forest sci* 61: 220-234.
7. Andersen F, Iturmendi F, Espinosa S, et al. (2012) Optimal design and planning of biodiesel supply chain with land competition. *Comput chem eng* 47: 170-182.
8. Čuček L, Lam HL, Klemeš JJ, et al. (2010) Synthesis of regional networks for the supply of energy and bioproducts. *Clean technol environ policy* 2: 635-645.
9. Leão RRCC, de Campos CL, Hamacher S, et al. (2011) Optimization of biodiesel supply chains based on small farmers: A case study in Brazil. *Bioresource technol* 102: 8958-8963.
10. Sharma B, Ingalls RG, Jones CL, et al. (2013) Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. *Renew sust energ rev* 24: 608-627.
11. Freppaz D, Minciardi R, Robba M, et al. (2004) Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass bioenerg* 26: 15-25.
12. Fiorese G, Guariso G (2010) A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environ modell softw* 25: 702-711.
13. Evans A, Strezov V, Evans TJ (2010) Sustainability considerations for electricity generation from biomass. *Renew sust energ rev* 14: 1419-1427.
14. Lähinen K, Myllyviita T, Leskinen P, et al. (2014) A systematic literature review on indicators to assess local sustainability of forest energy production. *Renew sust energ rev* 40: 1202-1216.
15. Pérez-Fortes M, Láinez-Aguirre JM, Arranz-Piera P, et al. (2012) Design of regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach. *Energy* 44: 79-95.
16. Fiorese G, Gatto M, Guariso G (2013) Optimisation of combustion bioenergy in a farming district under different localisation strategies. *Biomass bioenerg* 58: 20-30.
17. Baglivi A, Fiorese G, Guariso G, et al. (2015) Energy and GHG Emission Assessments of Biodiesel Production in Mato Grosso, Brazil, In: Bhardwaj AK, Zenone T, Chen J (Eds.) *Sustainable Biofuels*, Berlin: De Gruyter, 267-294.

18. Newell R G, Pizer W A, Raimi D (2014) Carbon Market Lessons and Global Policy Outlook. *Science* 343: 1316-1317.
19. GSE (Gestore Servizi Energetici) (2015) Rapporto sulle aste di quote europee di emission (in Italian) Available from: [http://www.gse.it/it/Gas e servizi energetici/Aste CO2/Pagine/default.aspx](http://www.gse.it/it/Gas_e_servizi_energetici/Aste_CO2/Pagine/default.aspx).
20. Frombo F, Minciardi R, Robba M, et al. (2009) A decision support system for planning biomass-based energy production. *Energy* 34: 362-369.
21. CEER (2014) Certificazione energetica regionale, Regione Lombardia (in Italian). Available from: <http://certenergy.it/certificazione-energetica-lombardia/502-lombardia-catasto-energetico-regionale-accessibile-a-tutti.html>.
22. Regione Lombardia (2015) Sistema Informatico Regionale Energia (in Italian). Available from: <http://sirena.cestec.eu>.
23. ISTAT (2015) Database: Servizio Turismo (in Italian). Available from: <http://www.istat.it>
24. Regione Lombardia (2015) Cartografia regionale (in Italian): Available from: <http://www.geoportale.regione.lombardia.it>.
25. Fiorese G, Guariso G (2013) Modeling the role of forests in a regional carbon mitigation plan. *Renew energy* 52: 175-182.
26. Rentizelas A, Karellas S, Kakaras E, et al. (2009) Comparative techno- economic analysis of ORC and gasification for bioenergy applications. *Energ convers manage* 50: 674-681.
27. Dept. of Energy, Politecnico di Milano (2013) Costi di produzione di energia elettrica da fonti rinnovabili (Electric energy production costs from renewable sources), AEEGSI Report (in Italian).
28. Mosier N, Wyman C, Dale B, et al. (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource technol* 96: 673-686.
29. Energy and Strategy Group (2013) Biomass Executive Energy Report, Dipartimento di Ingegneria Gestionale, Politecnico di Milano (in Italian).
30. AEEGSI, Italian National Energy Authority (2015) Statistical Data. Available at: <http://www.autorita.energia.it>.
31. Moiseyev A, Solberg B, Maarit A, Kallio I (2013) Wood biomass use for energy in Europe under different assumptions of coal, gas and CO<sub>2</sub> emission prices and market conditions. *J forest econ* 19: 432-449.



AIMS Press

© 2016 Giorgio Guariso et al., licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>)