POLITECNICO DI MILANO

School of civil, Environmental and Land Management Engineering

Master of Science in Environmental and Geomatic Engineering

OPTIMIZATION MODEL FOR BIOMASS HARVEST AND ENERGY PRODUCTION

The Lake Como case study

Supervisor: Prof. Giorgio Guariso

Master Thesis by:

Fabio De Maria Id 786817

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Abstract

The main objective of this work is to evaluate the economic feasibility of a distributed energy system, supplied with a renewable source: the wood biomass. The system is composed by 11 potential locations and we want to determine which is the most convenient configuration in terms of technology adopted, power size and the position where to harvest the raw material. For every possible plant, it has been found the thermal load diagram using the values from the CEER cadastre, namely the administrative database containing the performance index parameters for buildings acclimatization. The technologies adopted are the Organic Rankine Cycle, the Gasification and the Pyrolysis. The territory, where it is possible to harvest the biomass, it comprehends two Highland Community bordering on Lake Como. Thanks to environmental data related to the tree species and a sustainable harvest rate per hectare, it is possible to obtain the total amount of wood available in the study area. The cost of harvest has been modelled as a function of the technology adopted by the model itself. The zone where it is possible to yield the biomass, it has been divided into 200 georeferenced parcels and after the creation of a road network it has been possible to define the distance between the parcels and the possible plants in a GIS software. The system is constrained to be economically feasible, in terms of having a payback period lower than 10 years. This way to look at the energy production from renewable sources it still needs incentives throw the green certificates.

Chapter 1

Global scenario

Climate change has been defined the most important environmental challenge of all time. Enlarging the horizon to a context of human population growth and to a stockpile depletion of fossil fuel, global warming brings up serious doubts about the wellbeing of future generations. The most important greenhouse gas (GHG) is carbon dioxide (CO_2), which at normal concentration is fundamental for life on earth but an excess of it is causing an overheating of the earth's surface. The superfluous content is mainly due to the combustion process that uses fossil fuel but also due to human activities (such as intensive agriculture, land use change, deforestation, etc.) that reduces the overall forest surface and releases carbon previously stocked in the trees and soil. Other important GHGs are:

- Methane (CH_4), released by organic matter decomposition from anaerobic bacteria;
- Nitrous oxide (N_2O), released mainly by chemical fertilizer used in agriculture (Mosier et al. '98 e Kroeze et al. '99).

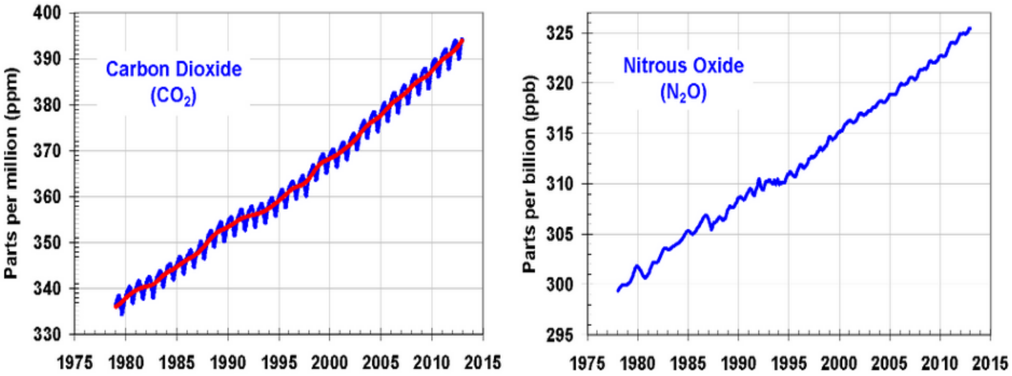


Figure 1.1 Highest greenhouse gases concentration (Source: NOAA, 2013).

Nitrous oxide emissions are an unwanted consequence of the nitrous fertilizer used in intensive agriculture because a yearly process of the ground (ploughing) is needed, as well as a high quantity of fossil fuel energy in the form of agricultural input for fertilization and weed control. NO_2 arises particular worries because its warming potential is 296 times bigger than CO_2. The IPCC (Intergovernmental Panel on Climate Change, 2007) predicts that increases in global mean temperature of less than 1.8 to 5.4 degrees Fahrenheit (1 to 3 degrees Celsius) above 1990 levels will produce beneficial impacts in some regions and harmful ones in others. Net annual costs will increase over time as global temperatures increase. Hereafter some expected regional impacts:

- **North America**: snow cover reduction of the Eastern mountain range; from 5% to 20% of harvesting growth of agricultural products that require a lot of water; increase in the frequency, intensity and durability of periods of extreme heat for cities that usually suffer from this problem.

- **Latin America**: gradual substitution of the tropical forest with savannah in the Eastern Amazonia; risk of significant biodiversity losses in the tropical areas; significant changes of water availability for human use, agriculture and power generation.

- **Europe**: Increase of rapid continental floods; more frequent coast overflow and greater erosion due to storm and to higher sea level; rapid glacial melting; Snow cover and winter tourism reduction; extensive loss of animal and vegetal species; harvest reduction in the southern part.

- **Africa**: since 2020, between 75 and 250 million people will be exposed to an increase of water scarcity; several farm products could be reduced by 50% in some regions; agricultural production which includes the food access, could be harshly compromised.

- **Asia**: availability of fresh water will decrease until 2050; coastal areas will be in danger, caused by floods; the mortality rates caused by dry periods will tend to rise.

Figure 1.2 demonstrates the global carbon balance. It can be seen that every year the total amount of carbon dioxide entering the atmosphere exceeds about 19 Tg of the amount exiting. The increasing rate is uncontrolled, caused also by the economic growth of several world populations, such as India, China and Brazil. The global carbon dioxide emissions rose from 18 to 27 Tg since 1980 to 2007, this value represents a growth of thirteen times the emission during 1900 (2 Tg).

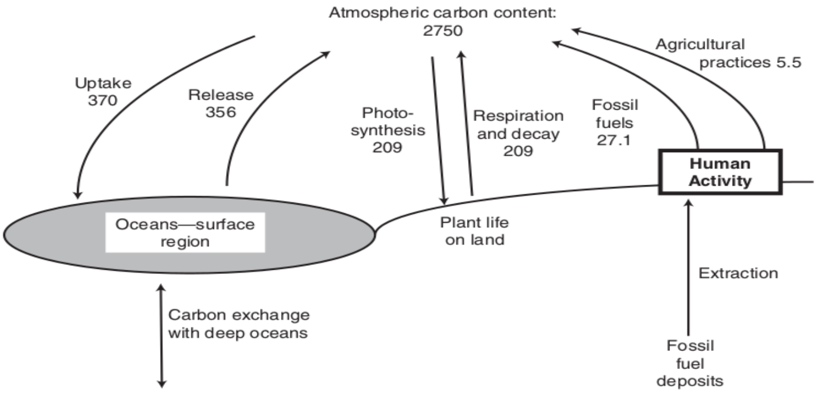


Figure 1.2 Global carbon fluxes (10^9 Mg CO_2) between anthropogenic activities, atmosphere, vegetation and ocean. (Source: Vanek, 2012).

IMPACTS	Probability
Area reduction covered by snow, permafrost unfreeze, reduction of polar glaciers' extension	90%
Frequency increase of extreme heat, heat waves and strong precipitations	90%
Intensity increment of tropical storms	66%
Precipitation increase at high latitude	90%
Precipitation decrease in subtropical regions	90%

Table 1.1 Forecasted impacts of the increase of greenhouse gases on future climate change (Source: NOAA, 2007).

1.1 How to mitigate the climate change

A correct management of forests, agriculture and breeding farms can contribute a lot towards reducing CO_2 emissions and other GHGs in the atmosphere. The consequent climate change can also be slowed down in a different manner inside the various social and geographic reality of the world (Kirschbaum, 2003). In the forestry and agronomic sector, the change from annual intensive single-crop farming to diversified farming (rich in biodiversity with a reduced input of chemical fertilizer) is able to contribute to the achievement of the global target of GHGs emission mitigation. When evaluating the energy-crop contribution (short rotation forestry) that energy cultivation can provide towards the request of renewable energy (ensuring at the same time a reduced environmental impact) two priorities have to be considered:

- the quantity of fossil fuel needed to produce every unit of renewable energy;
- the GHGs that are emitted directly or indirectly as a consequence of the cultivation of energy-crop species (Liebig, 2008).

As an example of short rotation forestry, either poplar cultivation with a rotation of 10 ÷ 15 years or a short rotation coppice can recreate a stable forest (even though this is not comparable to forestation and reforestation actions with high trunk species at long rotation). If correctly managed, they can in any case be positive in the climate change mitigation and in soil erosion reduction, also if compared to set-aside soil, or to annual cultivation that needs high energy input, like corn. Obviously, a traditional poplar forest (e.g. coppice management, Short Rotation Forest) it is able to adsorb a smaller amount of carbon then a mixed forest due to several aspects (e.g. number of species, density, tree size, age, etc.). Moreover, the logistic curve that models the population growth applied to an ecosystem says that a young species during the growing phase is able to adsorb more carbon than a similar system that is stable and mature. Several studies began, both at European level (CCR, Ispra) and inside individual countries. The final balance (direct and indirect emissions) is shifted through a net absorption (figure 1.3). For every Mg of CO_2 used for all the harvest operations, 16.8 ÷ 18.1 Mg of carbon dioxide has been removed from the atmosphere.

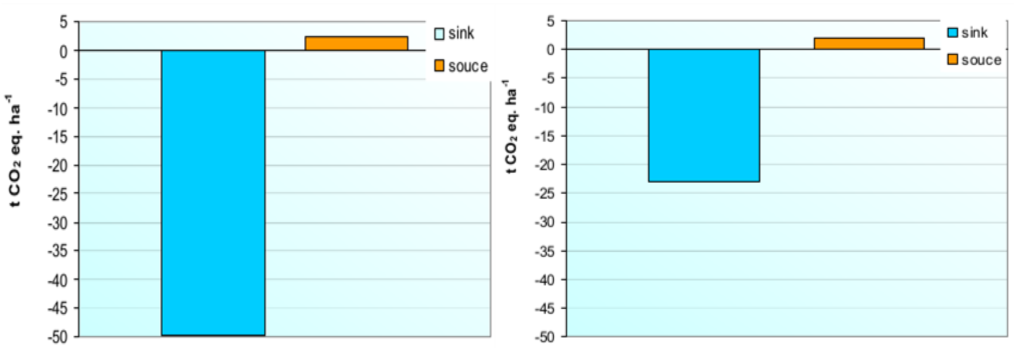


Figure 1.3 GHGs balance during the first years of cropping in the same system of poplar (on the right) and reed (on the left). Thanks to the high productivity, reed stores in the over-ground part (epigeous) a quantity of CO2 equivalent higher than poplar (Source: CRA, 2011)

1.2 Equivalent emissions

It is possible to avoid greenhouse gas emissions in the atmosphere farming type of tree species (e.g. black locust-Robinia) that does not need exaggerated energy input but able to store a high quantity of carbon in the tissue (hypogeum and epigeous) and in the soil. Moreover, the wood can be used for energy production through processes like combustion, gasification and production of second-generation biofuel. In this way, it is possible to put solely the quantity of CO_2 previously absorbed and stored during growth into the atmosphere. It is important to clarify the points arrived at during calculation inside the entire life cycle assessment. One such starting point could be the operation for the preparation of the scion for poplar and rhizome for reed, ending with the biomass load and transport at the energy conversion plant. The direct emissions are those generated during soil preparation or fertilizer production. Whereas the indirect are the consequences of the soil preparation, such as the CO_2 release caused by bacteria respiration or the emissions caused by fertilizer absorption. Figure 1.4 shows the direct and indirect emissions of different farming operations done in the first two years of a poplar coppice and in the first three years of a reed implantation. Poplar has a two-year cycle rotation whereas reed rotates every year but during the first year, the production is very low and often is not harvested. The farming methods can be more or less incidental on the balance depending on the adopted management. The cut and the harvest are generally very influential, due to the high-powered machinery used. Nevertheless, based on the farming method (e.g. tree age, soil type) other equipment could become necessary with different consequences on fossil fuel consumption. The root apparatus, which is not extracted from the soil during the subsequent harvests, stores (during the growing phase) a quantity of carbon around 40% to 60% of the total carbon absorbed from the plant as carbon dioxide (Venturi, 2005). Just a small part of the carbon is exchanged with the soil through thin root turnover. The environmental benefits of the biomass life cycle production are of undoubted value but can be widely different due to environmental condition of the system (water availability and soil fertility) and moreover to the intensity of the farming methods.

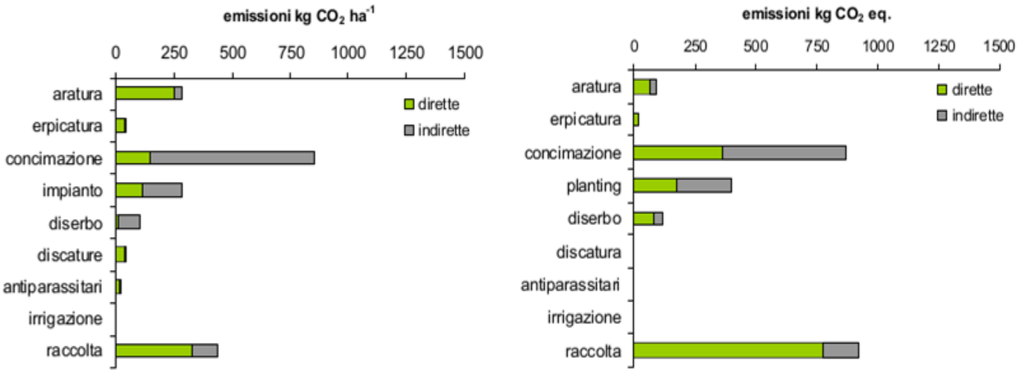


Figure 1.4 Direct and indirect emissions from farming methods management, on the left a poplar coppice while on the right the reed (Source: CRA SUSCACE, 2011).

1.3 Soil contribution to the stock of CO_2

The type of soil plays an important role on its balance, emissions and capture of atmospheric CO_2. Ground ploughed yearly tends to have a high carbon mineralization of organic carbon and organic nitrogen. Ground do not ploughed and controlled with weed-killing tends to increase its organic carbon and nitrogen content (available for the food chain) with positive effects on the global warming mitigation. Even from this point of view, the role that perennial biomass species can develop is of primary interest. Since perennial cultivation (herbaceous as well as woody) do not need further groundwork and can actually promote the carbon sequestration in the soil (Rowe, 2009). The amount of carbon released and stored plays a key role in the carbon balance evaluation related to the overall opinion on environmental sustainability of the farm system intended to produce energy (Righelato, 2007). During the ages, the substitution of grassland and natural forest with agricultural farming caused a consistent reduction of the carbon content in the soil. Around 30% of the stock, till 100 cm deep, is lost in 30-50 years since the soil use has changed (Post, 2000). It has been proved that, 450 Tg of carbon has been emitted by the historical agricultural expansion of which 320 Tg in the preindustrial era and 130 subsequently. (Lal, 2004).

If managed properly, storing carbon in high-impoverished soils is possible with an extraordinary potential. Texture, climate and previous usage can affect the speed and the quantity of carbon accumulation in the soil. Concerning this aspect, it is important to highlight that carbon can be stored in a labile form, returning quickly in the atmosphere or better in a stable form with a life cycle of centuries. The carbon increase in the soil affects not only greenhouse gas reduction but also has a positive effect on land fertility and on the reduction of the desertification risk because it allows a more efficient water retention and even the drought periods could be better managed.

1.4 First conclusions

Carbon sequestration is the key to the sustainable use of fossil fuel in the long run. In the short-term, it is possible to sequester carbon emitted into the atmosphere by enhancing natural processes such as forest growth, and using biomass as a source of energy, replacing fossil fuels.

Carbon sequestration can be done in three methods:

- Indirect. Forest development looks to be the shortest and cheapest path to implement. However, it is limited by surface availability.
- Geological storage. The potential amount of CO_2 that can be stored using this option is higher than the first. This method is called carbon legacy, because the carbon dioxide is not intentionally converted into another more stable mixture.

- Carbon dioxide conversion to inert compound. This option is the most permanent and expensive. Carbon dioxide is not only separated from the combustion soot but also converted into others geologically stable compounds.

All of the above techniques are potentially useful for the carbon sequestration of the soil and for climate change mitigation and pollution. Generally, we can focus on different methods, which involve (Tonon, 2004):

- an increase in the residual biomass that remains on the land during harvest;
- soil work reduction;
- better water and nutrient conservation;
- an improvement of the soil texture;
- an improvement of biodiversity, especially the pedofauna activity.

Chapter 2

Local renewable sources for a zero energy miles production

After the considerations done in the previous chapter, it is clear that for lowering down the GHGs emission rate, the human population necessarily has to:

- Produce energy from renewable sources.
- Increase the carbon stock into the soil. In this way, it is possible to decrease the CO_2 concentration in the atmosphere and the desertification risk. Nevertheless, the soil capacity to store fresh water.
- Make use of clean conversion technology. Namely with low pollution emission for every unit of energy produced (e.g. particulate matter, nitrous oxide, hydrogen sulphide, radioactive waste).
- Change from an intensive and single-crop agriculture to an organic one. Reducing as much as possible the farming works impacts on the soil (ploughing, weed control, fertilization) and the distance between consumers and farmers (zero food miles).

Among the different renewable sources, wood biomass combustion it is a practice done by the human being since its arrival on the hearth. Nowadays, the positive aspects of this old practice are evident:

- It is renewable. Providing that a forest can grow back to its previous flora and fauna characteristics in few years (assessment).
- A correct and careful management of forest sources is able to accumulate stable carbon into the soil.
- It offers an energetic production stable and flexible because it is not influenced by meteorological aspects as others renewable sources (wind, solar).

- Using the waste products from others supply chain (e.g woodworking, gardening, pruning) it can give an economic value to a matter that need to be disposed.
- The waste from its proper supply chain (the ash) it can be used as fertilizer for acid soil or as a component for making the lisciva (a soap used in ancient time by for example Romans and Egyptians).

In this chapter, we define the characteristics of the energy demand. We want to find a methodology able to define the amount of energy that has to be produced by renewable sources.

2.1 Renewable sources in the Italian municipalities

In Italy during 2013, the clean energy production from renewable sources it covered the 32,9% of the electrical demand and the 15% of the whole demand (Legambiente, 2013). From 2000 until today, 49 TWh of energy from renewable sources it has been added to the several but passé hydroelectric and geothermal plants. The firsts have already reached the whole potential on the territory concerning high power production plants (a lot could be done for the management). We should pay more attention to the realization of micro turbine for low flow rates. The latter, geothermal or heat pump at low and high enthalpy, have a great room of improvement. Even with expensive geological survey to determine the costs and the benefits. However, for the first time it has been overcame a wall that seemed to be unsurmountable: 104 TWh of energy made from clean sources. In the recent years in a scenario that changes continuously regardless of the traditional way to look at the energy and the relationship with the surroundings, thousands of installed plants (small, big, from different sources) they are giving a new shape to the model for the distributed power generation. The most interesting innovation it is in the different development path that each plant has to follow. Because the sources present in every area and the possibilities to exploit them they are dissimilar. In a context that intersects the diverse productive sectors, the green segment can be the key to restart the economy. It is necessary to consider the energy demand in the way to understand the specific needs, giving an answer to the questions that are in the middle of the Italian energy debate:

- Increasing energy bill cost;
- Energy dependency from foreign countries and safety supply;
- Carbon dioxide emission and pollution.

Italy imports millions of oil barrels every year and millions of tons of natural gas and coke. We have the interest to follow this direction of change. In some places of the United Kingdom, this political approach has the name of resilience network (or transition network). Several cities are becoming independent from the global market in terms of having a food and energy supply as much as dependent from its proper territory.

Legambiente (League for the Environment) is the most widespread environmental organization in Italy, with 20 Regional branches and more than 115,000 members. It is known as "association of environmental interest" by the Ministry of the Environment. It represents the UNEP National Committee for Italy and it is one of the leading member of EEB ("European Environmental Bureau") the, Federation of European environmental organization and of IUCN - the World Conservation Union. Since 2006, it provides a picture of the renewable sources development. The Legambiente database is obtained throw a questioner compiled by the main Italian authorities (e.g. Region, Province, Municipality, etc.) and crossing the answers with others associations (GSE, Enea, Itabia, Fiper, ANEV). Today plants from renewable sources are present in all the 8'054 Italian municipalities (table 2.1); the installations are on the rise. The progression is stable; they were 3'190 in 2008. Until ten years ago, the clean sources were involving just the internal areas of the country only by hydroelectric and geothermic. Today the renewable sources are present in the 100% of the municipalities. Even in 2013, the diffusion is increasing and for all the parameters considered (e.g. solar PV, solar thermal, hydroelectric, geothermal at high and low enthalpy, biomass plant and biogas integrated with district heating). Moreover, these changes show a fact: the capacity of these plants to produce energy in relation to the demand, especially for the families. This green-contribution is fundamental to answer directly to the electricity demand because they shorten the net and integrate it with other efficient plants. Thanks to the new sources, the Italian energetic balance is becoming cleaner and less dependent from others countries. In one word: modern. Because it is distributed on the territory.

ANNO	SOLARE TERMICO	SOLARE FOTOVOLTAICO	EOLICO	MINI IDROELETTRICO	BIOENERGIE	GEOTERMIA	TOTALE
2006	108	74	118	40	32	5	356
2007	268	287	136	76	73	9	1.262
2008	390	2.103	157	114	306	28	3.190
2009	2.996	5.025	248	698	604	73	5.591
2010	4.064	6.311	297	799	788	181	6.993
2011	4.384	7.273	374	946	1.136	290	7.661
2012	6.256	7.708	450	1.021	1.140	334	7.896
2013	6.260	7.854	517	1.053	1.494	360	7.937
2014	**6.652**	**7.906**	**628**	**1.123**	**1.529**	**372**	**8.054**

Table 2.1 Renewable municipalities' increment from the report "Comuni rinnovabili 2014" (Source: Legambiente, 2014)

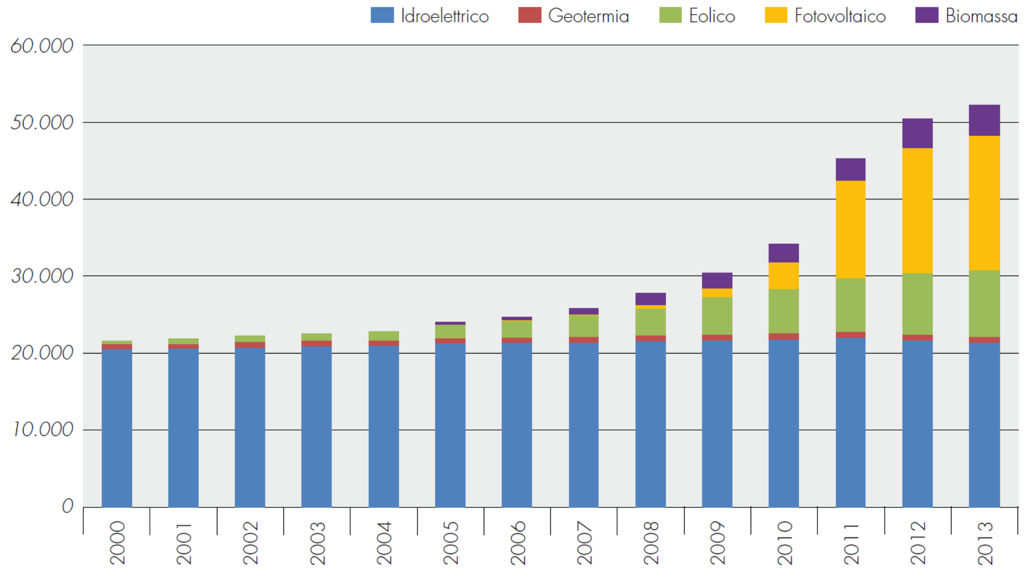


Figure 2.1 Renewable power increment (MW) in Italy (Source: Legambiente, 2014)

The crisis and the energy production increment from renewable sources determined a deep change in the Italian energetic system. The information obtained during 2013 shows in figure 2.1 an increment of installation (*power*) from several renewable sources: 1'236 MW by solar PV, 450 MW by wind, 144 MW by mini hydro, 100 MW by biomass plants and 21 MW by geothermic at low enthalpy.

The contribution in terms of *energy production* it is even more important. The production has reached the 32.9% of the entire Italian electric consumption (28.2% in 2012) and about 15% of the total energetic consumption (5.3% in 2005). The European target for 2020 is at 17%. Wind production is increasing, which contributed with 14.8 TWh (+11.6%). Solar PV had the best performance (22.1 TWh, +18.9%). Biomass, biogas and bio liquids increased as well (15 TWh, +11.3%). We denote also a slight increase by geothermic, with an increment of 1% (the calculation is done without the several heat pumps at low enthalpy). Figure 2.2 shows the renewable contribution for the Italian electric consumption. It is possible to estimate that during 2013 hydroelectric contributed with 16.5%, solar PV 6.9%, wind 4.7%, biomass 4.7% and geothermic 1.6%.

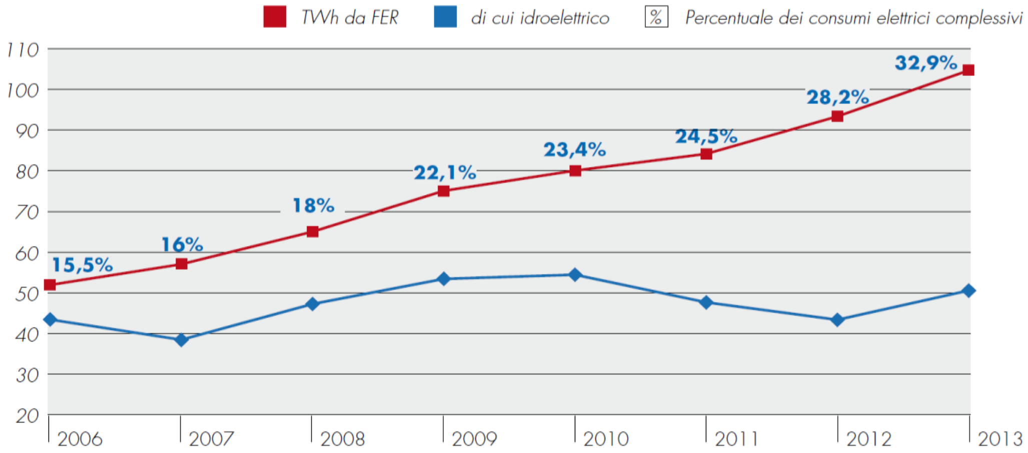


Figure 2.2 Renewable sources contribution in relation to the Italian electrical consumption (Source: Legambiente, 2014).

These results are defining significant benefits:

- The production by thermoelectric it is decreasing.
- It is diminishing the import of fossil fuel from foreign trade.
- The Italian CO_2 emissions are diminishing (just a small part of the whole world actually). Italy reached the national target of emission reduction wrote on the Kyoto protocol.
- The production from renewable and in particular from solar PV it is coincident with the peak demand.
- In the renewable sector, the employees are growing. According to the Gse (energetic sector manager) in 2012, 137 thousands of people have found a

job in the new plants of clean energy and 53 thousands in the management of the existing ones.

2.2 Energetic demand per sector and source

During 2013, the electric consumption diminished (-3.4%) and in spite of 2007 the contraction has been around 6.9%. The same for mobility fuel consumption that for gasoline decreased about 5.7% and 4.7% for diesel. The economic crisis is the main reason, but we do not have to underestimate the change in the industrial and energetic sector as well as the variation of the demand composition. Some changes are already structural, caused by the rearrangement and the delocalization processes of the industrial production. However, it is also a consequence of the growing investment in the service and residential efficiency. As showed in the electric balance for source in figure 2.3, we have a nearly complete exit of oil reduced at 2.3% and replaced gradually by natural gas.

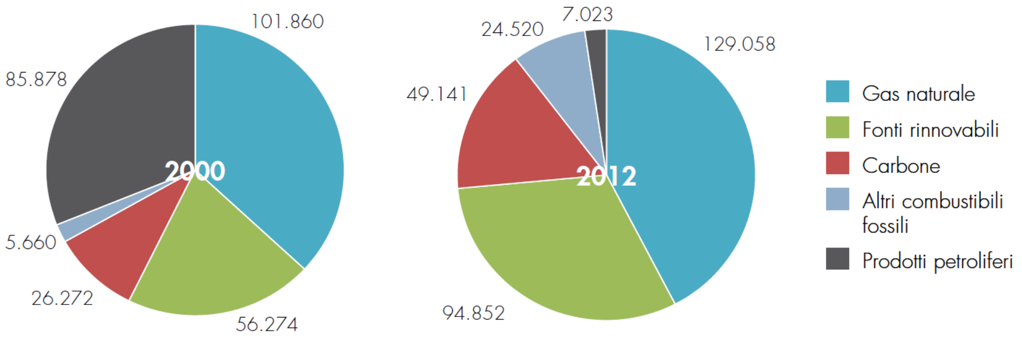


Figure 2.3 Electric production per source (GWh) (Source: Legambiente, 2014).

Concerning the electric energy consumption per sector (in figure 2.4), it is possible to highlight that the demand shifted from the industry to the residential and service sector that today account for 55.3% of the total Italian demand of electric energy.

While the total consumption per source in figure 2.5 shows the oil consumption decrement but it is still significant due to transport. Without any sustainable mobility policy, Italy added others 5.5 million of cars to the total amount (around

30 million). Unfortunately, it increased also the enormous importance of the road transport in spite of the rail one (94% for the first and 6% for the latter).

As we can see from figure 2.6 on the final energetic consumption divided by sector, it is important the role of natural gas for civil consumption purpose (e.g. heating and cooking). The best usage of natural gas is the electric energy production (turbo gas and combined cycle are the most efficient system) but it is good for heat production too (condensation boiler). A long debate could be done about which is the best set up of the entire energetic system taking into account also heat pump technology, but the question would take a longer time. The civil usage is growing faster than the others sectors.

Renewable sources are becoming important in the Italian energetic balance because they have a significant role in the electricity production and in the total consumption per source. Funds in the energetic network are an essential condition to give a future to the distributed generation. The electric grid is the backbone for the good operation of a system that must be smart. It has to be able to manage energy fluxes (irregular and bidirectional) and information (consumptions and local production). This is the reason why today it is becoming fundamental to rule the system equilibrium considering the cycle production from different sources. Funding on the electric network strengthening and on the electric energy stockpile becomes obvious to overcome the actual problem of the excess load in some part of the country, getting closer the demand to the production, and the leaks reduction on the electric network (in 2012 at 21 TWh, around 6% of the total amount). Funds are also necessary to update the electric and thermic distribution network, creating the conditions for realize districts heating in the urbanized areas. In the prospective of a more efficient management, it can help the exchange with the grid and the accumulation, approaching the concept of the smart grid. Just in a vision of this kind, it will be possible to carry the renewable sources to a further rise. In particular, we should pay more attention to the plants able to guarantee the peak load (not linked to the production wavering) and flexible on the management according to the grid demand.

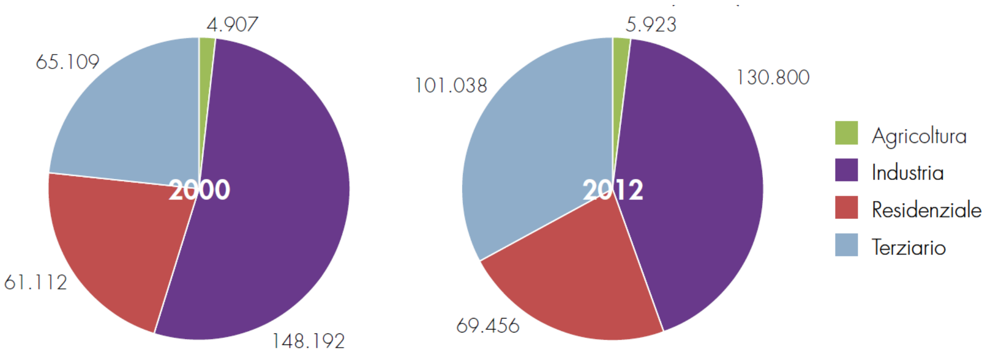


Figure 2.4 Electric consumption per sector (GWh) (Source: Legambiente, 2014)

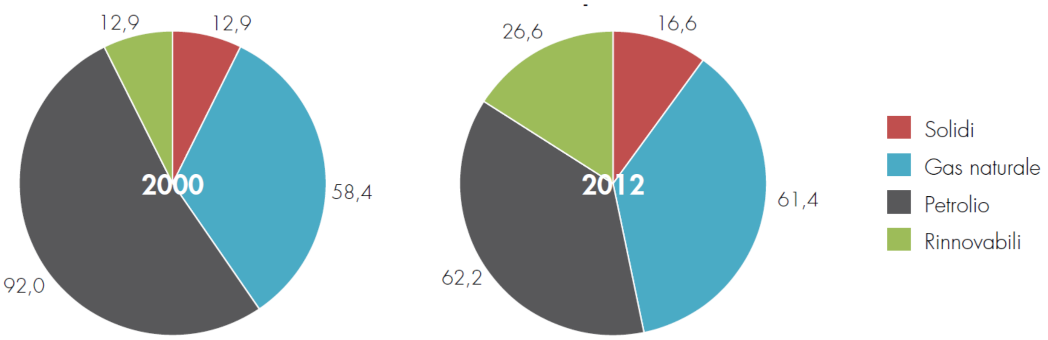


Figure 2.5 Energy consumption per source (Mtep) (Source: Legambiente, 2014)

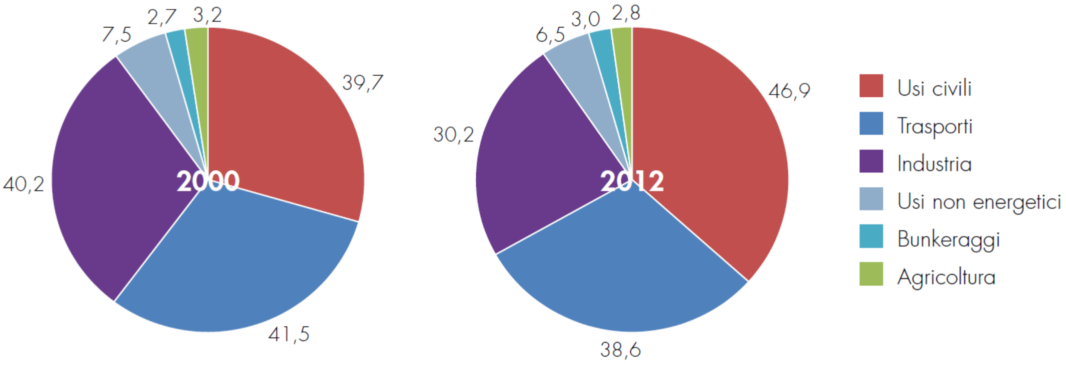


Figure 2.6 Final energy consumption per sector (Mtep) (Source: Legambiente, 2014)

2.3 Power demand variations

From an analysis based on the data given by ISTAT and Terna (Italian operator on the electrical network that manages 65’000 km of lines at high voltage) it is clear that in Italy the yearly total electric demand has not been constant during the last 50 years. We passed from an internal gross consumption around 130 Mtep (‘70s) with a constant growing rate until the edge of 200 Mtep in 2005. After that, it has been a reduction to the value of 175 Mtep, the same as the one registered in 1997. Obviously, the cause of this variation could be linked to the population growth, the economic variation (GDP), the industrial delocalization and many others factors. Without any doubts, also the attention paid to the global warming played a key role, in conjunction with the fluctuation of the oil cost. It is increased the energy demand with the population growth, but also the final efficiency increased. We could foresee an additional energy consumption decrease thanks to a slow but relentless direction change to a less pollutant and cheaper sustainable mobility. For sure, the latter aspect will change the electric power demand too. Nowadays, the electric load has a daily and monthly oscillatory behaviour (figure 2.7), with the adsorbed power that changes even of 50% inside the day-night period but also changing the season and during the weekend in spite of the working days. During the night and generally in the no working periods (holiday, weekend and so on), the electric request goes down drastically.

Figure 2.7 shows the hour load for the third Wednesday of every month, starting from January to December 2013. The productions are referred to different sources:

- W1 is for Hydro, wind and photovoltaic solar panel (PV);
- W2 is for thermal system that comprehends mainly turbo gas, but also biomass and others renewable (geothermic) and non-renewable sources.

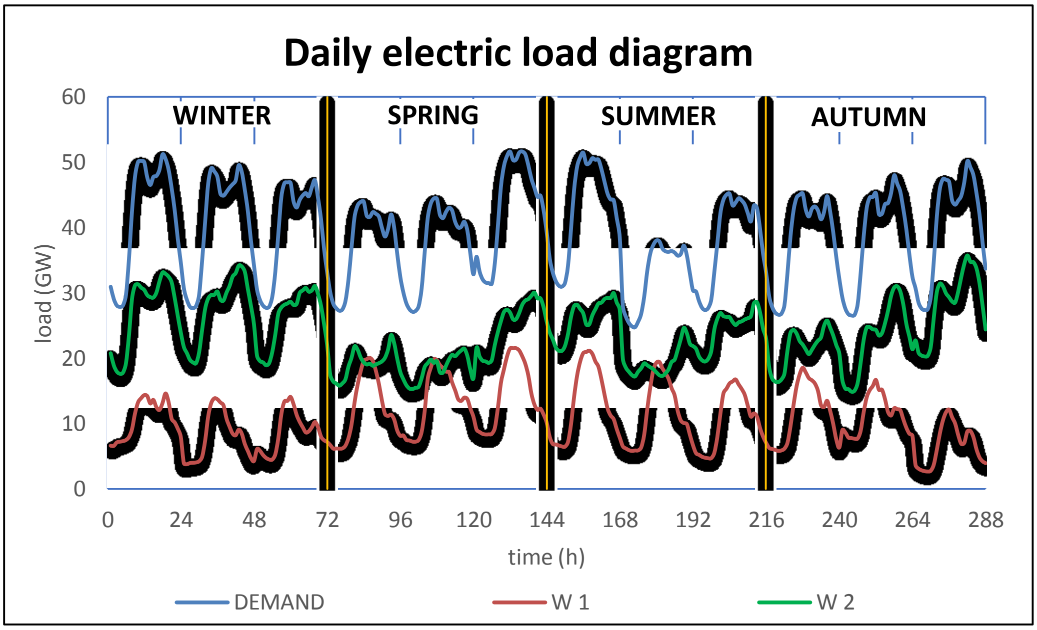


Figure 2.7 Daily oscillatory behaviour of the demand and the production of electric power. The data is referred to the third Wednesday of every month during 2013. Ideally, the vertical lines divide the seasons (Source: Terna, 2013).

It is immediately clear that the sources subdivision into two groups denotes a kind of classification for *flexibility* generation. Effectively, in the first group there are the photovoltaic and the wind sources, which have an inconstancy production very high (low capacity factor) and they still give doubts on a correct management of high power production into the grid (PV and wind parks). Nevertheless, the system becomes more manageable in case they are associated with hydropower generation and pumping system. On the other hand, the pattern of the second group it shows a higher average value, thanks to the great number of turbo gas plants that mainly use natural gas. The behaviour is slightly more *regular*, especially in the periods of high production from the first group sources. Natural gas system is the best available technology (BAT) for electric energy production that uses turbo gas machinery inside the Joule-Brighton cycle. By combining the last cycle with the Rankine cycle, it is possible to have an efficiency around 60% (the so-called combined cycle). Exactly, BAT in terms of electric efficiency but also in terms of *flexibility* of generation, because we are able to switch on and off the production in few minutes, following the demand fluctuation. Unfortunately, the raw material is not renewable and we have to buy it from other countries. By the way, the research development will take in future the electric efficiency of this kind of cycle powered by syngas (renewable gas from wood) close to the BAT, today stable at 40%. We hope that soon, we will feed our cars with electric energy, increasing the demand in the night time. Consequently, the demand fluctuation could be soften, but we will always have the problem to manage the production variability (caused by meteorological conditions) of renewable sources. A further development on systems able to store the extra energy produced and on the smart grid management it has to take the power demand as much as stable and foreseeable.

2.4 Yearly pro-capita electrical demand

During 2013, the yearly average pro-capita electrical demand it has been around 5’800 kWh (from ENEL website, very close to the value obtained from figure 2.7 of 5’560 kWh) that accounts for the request from: the industrial sector, the service sector (commercial areas, offices, etc.), the domestic demand (around 1’200 kWh per person), the grid leakage and so on. However, this value is averaged over all the Italian territory. Our country shows local situations very different from one place to another, due to geographic and climatic reasons and to the presence of industrial district. The influence from the thermal sources it is equal to about 3’500 kWh (60% of the demand), intended as before (annual average) and looking the data on the third Wednesday of every month (figure 2.7). Today the renewable sources at group one (hydro, PV and wind) they are able to satisfy on average around 25% of the request with 1’460 kWh year^{-1} p^{-1}. This last value will continue to rise, according to a scenario in which: the end use efficiency will increment, the renewable plants will continue growing, the leakage on the grid will decrement, and so on. Probably soon, the renewable sources will be able to cover even the 50% of the demand, supported also by an appropriate energetic policy. The mobility will play a fundamental role in an energy term. With the electric mobility, today it is possible to travel 160 km using an amount of 23 kWh. Using as a reference the value of 0.125 kWh km^{-1} and a travel length per capita of 12’000 km y^{-1}, it is possible to estimate that the annual per capita demand for the electric mobility will be around 1’700 kWh y^{-1} p^{-1}. In the analysis it is just taken into account the aspect linked to the individual mobility of every inhabitants. In the reality, a big part of the primary energy it is used for the transport of goods, from ships to trucks, which hardly could benefit from green electricity production caused by the heavy mass transported. In the future, it is easier that the use of bio-oil mixed with the traditional oil it will help this sector. We will be able to satisfy the energy demand for mobility by renewable sources, but a lot has to be done even individually rather than from a political aspect (in a scenario of better management of public transport). In the next case study, we will use a value of 3’000 kWh y^{-1} p^{-1} for the total electric demand (about 50% of the total demand for all the sectors) and 1’200 kWh y^{-1} p^{-1} as the household demand and the values will be respectively used for inhabitants and tourist.

2.4.1 Electric load composition

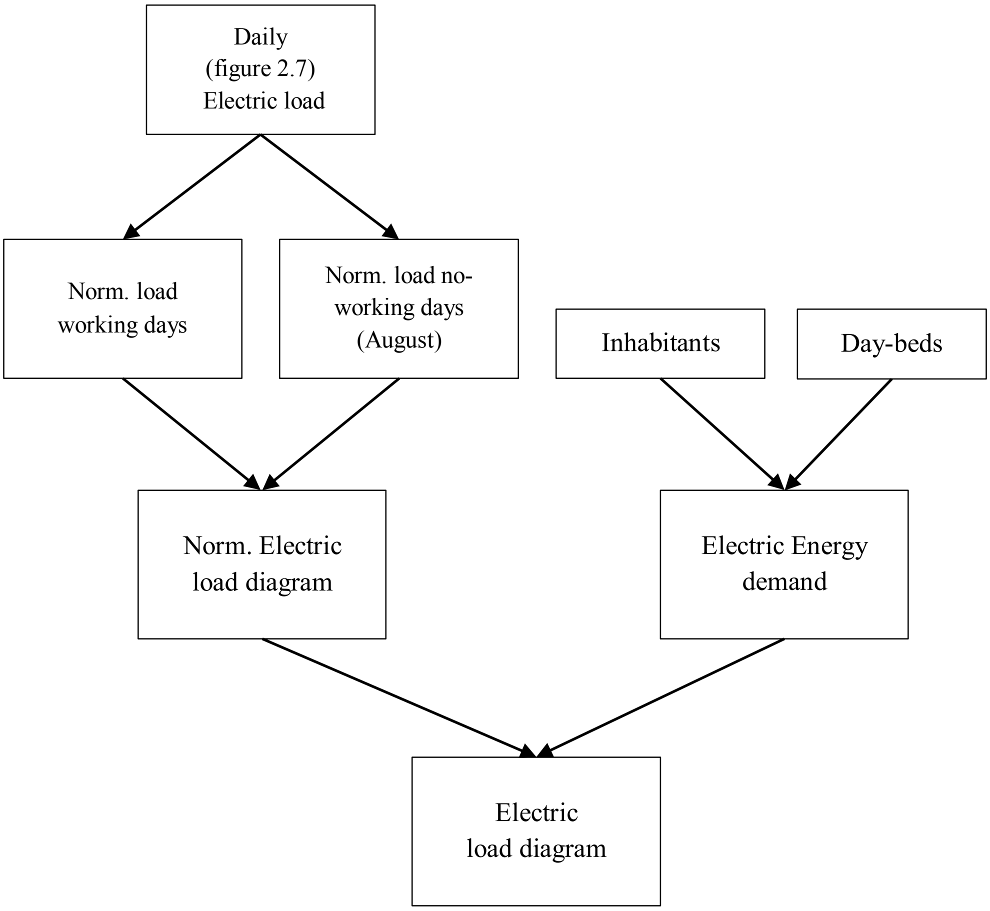


Figure 2.8 Sketch of the procedure adopted to obtain the Electric load diagram.

Figure 2.8 illustrates the procedure adopted to find the electric load diagram. On the left, there are the operations needed to build the yearly-normalized distribution curve of the electric energy demand. While on the right, it is illustrated the method used to define the amount of that specific demand in every potential location. The request is divided into two semesters: Summer and Winter. We start from the daily electric load showed in figure 2.8 and, for each day belonging the respective month, we extract 12 graphs (figure 2.9). We assume the august day as the load for the no-working days and following the table 2.2, it is possible to build the normalized electric load diagram in figure 2.10. In the next chapter, the information on the inhabitants and day beds are used to understand the total request of electric energy in every possible plant location. Then, this latter amount of energy it allows to define the final electric load diagram by imposing that the energy demand in two semesters (Summer and Winter) it has to follow the behaviour of the diagram.

	Working days	**No-working days**
January	22	9
February	21	7
March	21	10
April	20	10
May	22	9
June	20	10
July	23	8
August	21(0)	10(31)
September	22	8
October	23	8
November	20	10
December	19	12

Table 2.2 Working days in 2013. The months belonging to the Summer period are highlighted. Of course, during August, we assume no-working days at all.

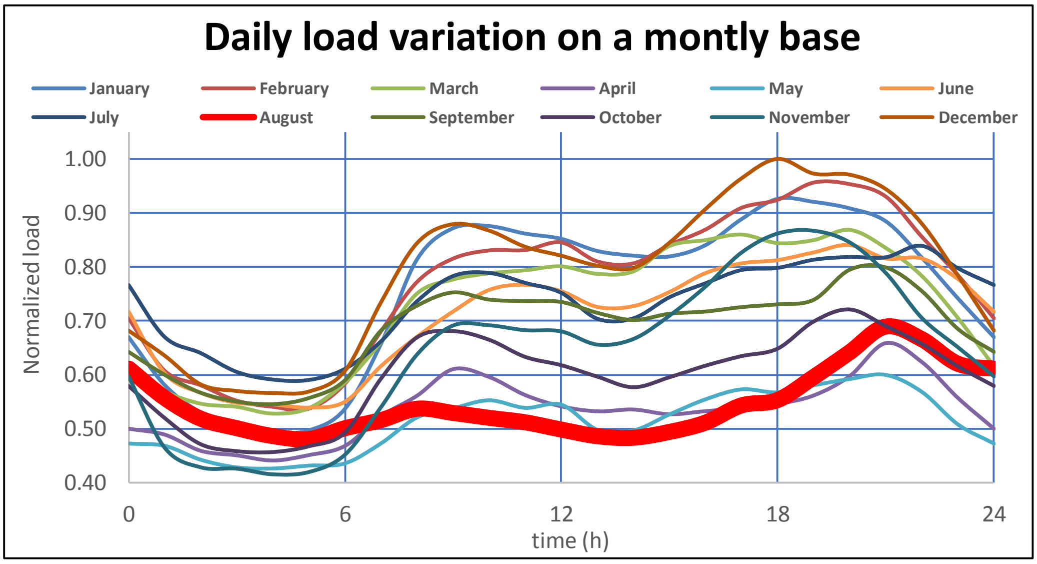


Figure 2.9 Daily load (third Wednesday) during 2013 (Source: Terna, 2013).

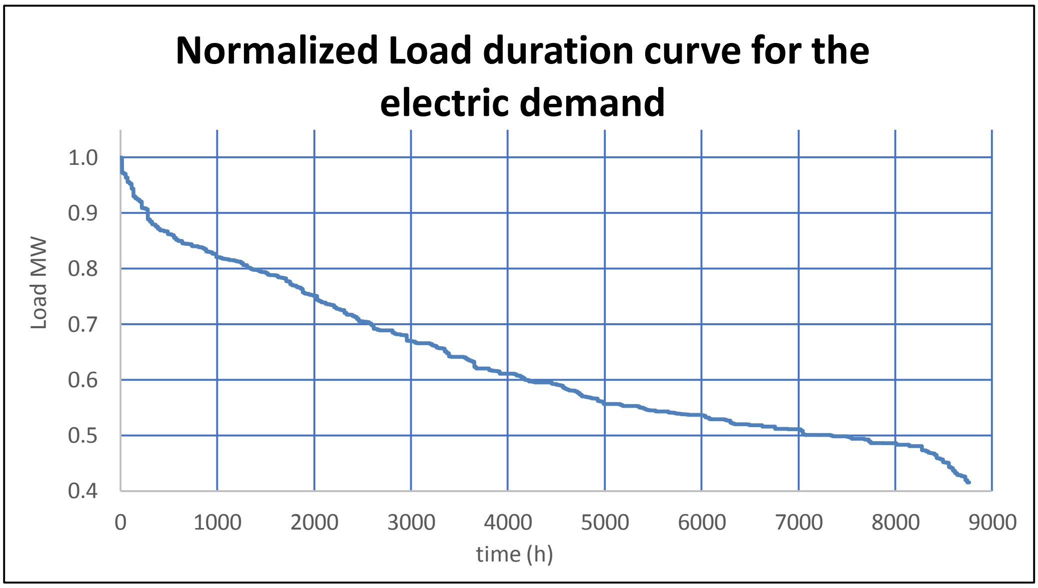


Figure 2.10 The normalized electric load duration curve (Source: Terna, 2013).

2.5 Thermal energy request

The Italian average demand of natural gas for household and heating purpose it is about 391.2 Nm^3 per inhabitant. The value in Como city it is grater, about 800 Nm^3 and mainly the difference is due to the climatic variation of the Italian territory. Taking into account the demand from the others economic sectors and the network leakages, the annual natural gas request is around 1'300 Nm^3 per person. Even in this case there is a high influence that an industrial district can have to the demand of the neighbouring territory. Thanks to the legislation on the energy certification of the buildings, it is possible to obtain a more precise information regarding the amount of thermal energy needed for a single building registered at CEER cadastre into Lombardy region. The energy performance certification is a procedure that evaluates and promotes the energy efficiency development for the buildings in terms of energy requested to maintain a good internal wellness through the APE (performance energy attestation) analysis. In this procedure is calculated the global energetic index (EPgl) that represents the annual amount of energy used by the building for the acclimatization (expressed in kWh per square meter per year for the residential buildings and kWh per cubic meter per year for the others facilities). The index takes into account: the heat amount for the winter acclimatization, the hot water production, the summer acclimatisation and the electric energy spent for the illumination. The last two indicators are not evaluated yet. Indeed following the legislation rules on the energy certification (DM 26-06-2009), the global index is equal to:

$$\mathbf{EP_{gl} = EP_{Heat} + EP_{Water} + EP_{e} + EP_{ill}}$$

These indicators represents:

- $\mathbf{EP_{Heat}}$ is the energy efficiency indicator for the winter acclimatization;
- $\mathbf{EP_{Water}}$ is the energy efficiency indicator for the hot water production;
- $\mathbf{Ep_{e}}$ is the energy efficiency indicator for the summer acclimatization (not mandatory for the residential buildings)
- $\mathbf{EP_{ill}}$ is the energy efficiency indicator for the artificial illumination (not mandatory for the residential buildings)

Actually, the formula is equal to:

$$\mathbf{EP_{gl} = EP_{Heat} + EP_{Water}}$$

Instead, the energetic index is a letter from A to G that indicates synthetically the energetic quality performance according to some parameters dependent on the climate characteristics such as GG (daily degrees) and on the building shape (surface to volume ratio). The energy efficiency indicator is a more precise value. The indicators are divided into residential use and non-residential use.

For residential buildings are intended:

- Hotel, boarding house and similar;
- Residential buildings with continuative occupation;
- Residential buildings with occasional occupation (second house).

For others use or non-residential buildings are intended:

- Pub, restaurant, disco;
- Cinema and theatre, congress facility;
- College, convent, prison and barracks;
- School;
- Church, exhibition, museum, library;
- Gym;
- Swimming pool and sauna;
- Support service at sport activities;
- Hospital , health care facility;
- Commercial centres and offices;
- Industrial and manufacturing facilities.

The average value of the indicator EP_{Heat} for residential facility in Como province it is around 215 kWh m^{-2} y^{-1}. The value is quite low compared to other provinces. It is referred to residential facility, which comprehends facilities for touristic accommodation purpose. It is clear that for a province like Como where there is a high touristic presence but concentrated during summer, the energetic performance index for the occasional facilities it is low because these typology of building it does not care about the energy consumption during the winter period. Unfortunately, the data series is not so long and not completely free. The CEER database does not cover the entire population because its compilation started few years ago and some information are hidden. Therefore, we could make just suppositions. The full database is a very important legislation instrument for planning and managing the territory. Thanks to the above-mentioned energetic performance index parameter, in the next chapter we will calculate the thermal energy demand for the residential and non-residential buildings in some locations of the Como Province, where it could be possible to locate some potential plant for energy production from wood biomass.

2.5.1 Thermal load composition

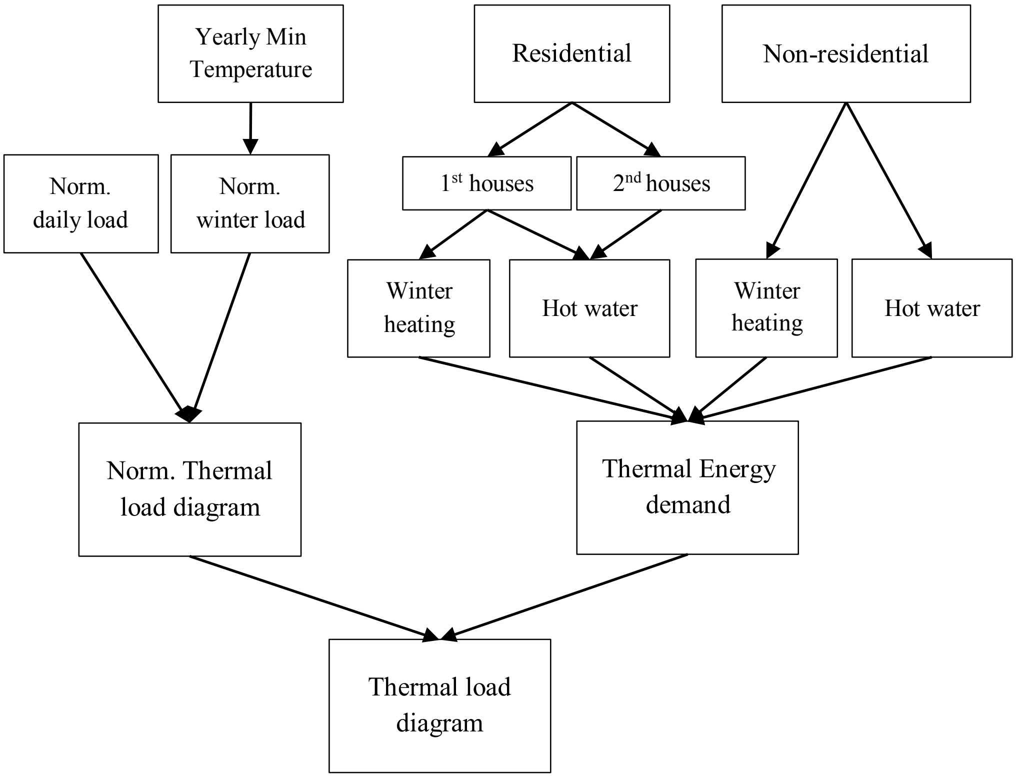


Figure 2.11 Sketch of the procedure adopted to obtain the thermal load diagram.

Figure 2.11 illustrates the procedure adopted to build the thermal load diagram. The procedure is similar to the previous one. On the left we have the method used to find the distribution of the demand while on the right, the total amount of the demand (for the two semesters). This last procedure is more accurate than before.

The distribution is done using a general daily behaviour (ENEA), which has two peaks: one around 1 pm and the second at 20 pm (figure 2.12, blue line). Then we analyse the yearly minimum temperature (figure 2.13) and we normalize it (figure 2.14) during the winter period (from November to April), namely when there is an energy request for heating purposes. The peak is in between January and February (figure 2.14). Using the normalized winter load and the normalized daily load it is possible to build the normalized thermal load diagram as done previously. Therefore, by imposing that the total energy amount needed in the two semesters it has to follow that distribution, we obtain the thermal load diagram. The thermal energy demand is composed by the request from the residential buildings and the non-residential ones. The firsts can be decomposed again between permanent inhabitants (1st house) and salutary inhabitants (2nd house). Indeed the demand is spread into two semester (winter and summer) to obtain the demand for the two periods depending on the kind of inhabitant. By linking the normalized thermal load to the total energy request, it is possible to define the thermal load diagram. It is very important, as we have saw for the electric production, to find the thermal yearly load. This diagram allows the estimation of the capacity factor of a possible plant according to the size we choose for it. The thermal energy demand characteristics is more important than the electric one because a possible district heating is a closed network and so an excess of thermal energy produced cannot be sold to others network. Instead electricity can be transformed in high voltage current and sent to a distance neither comparable with a district heating length. Unfortunately, the thermal daily load is not known as much as in the electric case. We use a general daily behaviour following the shape of a daily load coming from the literature, which has two peaks, one around 1 pm and the second at 20 pm (figure 2.12, blue line). Nevertheless we make another hypothesis on the minimum value that will be higher than the standard one (figure 2.11, red line). This decision is taken according to the heating system used in the newest buildings that uses radiant technology under the floor and a good isolation of the wall surroundings the rooms. In this way, it is possible to heat the rooms during the night, shifting the demand in a period that usually it sees a decrease. A good policy, for what concern a price reduction, it can increase the load during the night throughout the preheating of the rooms for those consumers that uses the building during the morning such as schools, offices, gyms and so on. For what concerns the yearly pattern, we use the monthly average minimum temperature of the environment, values which in turn are averaged on the year from 1981 to 2010, as shown in figure 2.12. By normalizing this last information and associating it with the daily behaviour, it is possible to find the normalized winter duration curve showed in figure 2.13. The real curve will be presented in the next chapter because we need to estimate first the total amount of energy needed in the two phases, which for simplicity will be called summer and winter but they correspond to a six months period. Exactly summer is from May to October and winter is composed by the remaining months.

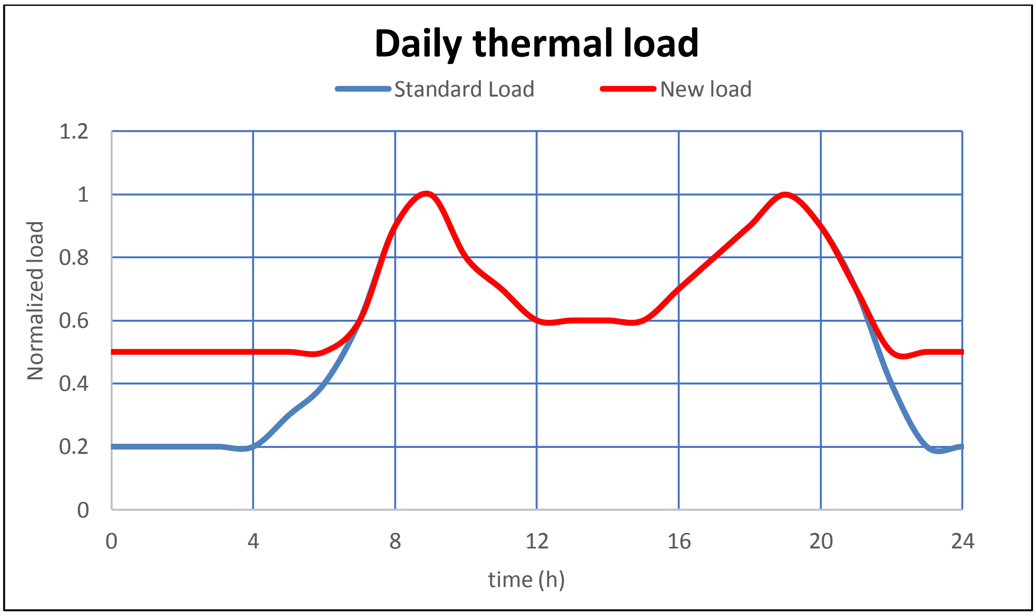


Figure 2.12 Daily normalized thermal load (Source ENEA, 2014).

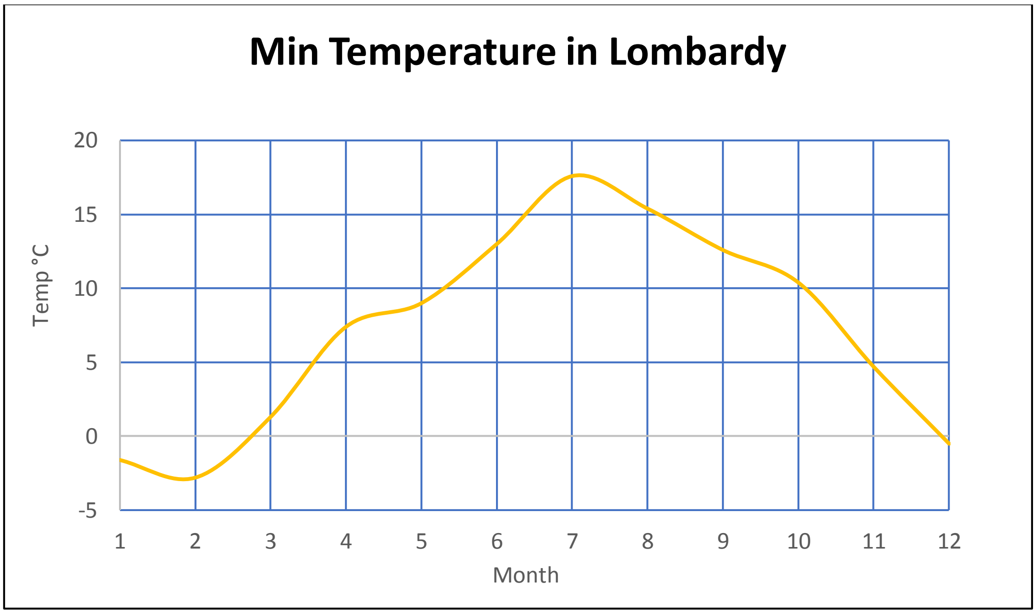


Figure 2.13 Minimum average temperature in Lombardy. (Source ISTAT, 2014).

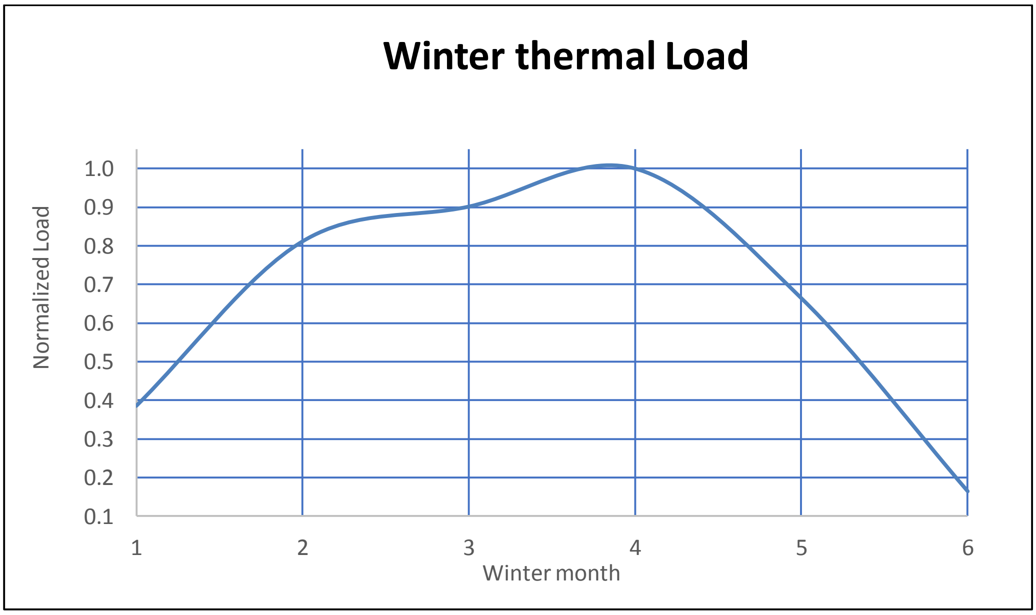


Figure 2.14 Winter energy request from November to April (Source: ISTAT, 2014).

Chapter 3

The case study

In this chapter, we focus our attention on the energy request from a study area. We want to produce this amount of energy as much as possible from a renewable source. Wood biomass is the available raw material entering in the energetic conversion process that is able to produce electric energy and thermal energy throw a district heating. Some potential plant locations are presented. These lasts are selected according to an indicator of urbanized area per square kilometre, which could ensure an economic realization of a district heating.

The study area encompasses the western part of Lake Como, going from the lakeshore to the border of Switzerland through the Como Pre-Alps. The zone is mountainous and today the tourism is the main contributor to the economy. As shown in figure 3.1, the management and the valorisation of the highland is committed to the Highland Community (Comunità Montana): “Lario Intelvese”, “Valli del Lario e del Ceresio”. The area involved is about 800 km^2. The value is obtained thanks to the information inside the Digital Terrain Model at 20m. Anyway, it is an approximated area. From an air quality point of view (section 3 of DL 13/08/10 155), this area is classified as highland (letter C) characterized by:

- a less significant amount of Particulate Matter emission (PM10), nitrogen dioxide and monoxide (NOx), anthropogenic volatile organic carbon (VOC) and ammonia (NH_3);
- important natural emission of VOC;
- mountain orography;
- meteorological condition more favourable to the pollutants dispersion;
- low population density.

Whereas, according to the classification related to the tropospheric ozone, the zone is categorized as C1 (Pre-Alps and Apennines), namely more exposed to the pollutant transport coming from the level ground (in particular the ozone precursor element, NOx).

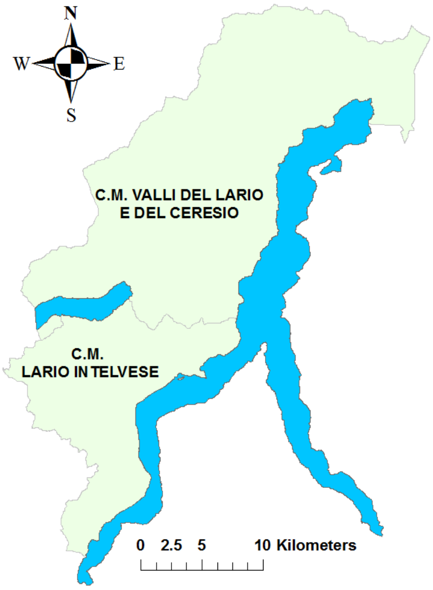


Figure 3.1 Highland Community (Source: Lombardy Region, 2014).

Taking into account a spatial analysis (figure 3.2), namely evaluating the indicators resulting from an examination of a spatial statistic of the variable “soil consumption” (intended as percentage of urbanized municipal area), we can divide the Como province territory into the following portions:

- “Urban areas” defines the municipalities with higher urbanization than the average and higher than the neighbouring;
- “Urban areas in rural context” defines the municipalities with higher urbanization than the average, but lesser than the neighbouring;
- “Rural areas in urban context” defines the municipalities with lower urbanization than the average, but higher than the neighbouring;
- “Rural areas” defines the municipalities with lower urbanization than the average and lesser than the neighbouring.

Furthermore, there is a secondary classification integrated with a significance statistic level of the indicator soil consumption of 5%. It is clear that the low population density is due to the high percentage of natural land (hardly accessible by the household sector). Anyway, it is possible to highlight some municipalities that are different from the surroundings for urbanization density ("Rurali", light green in figure 3.2). In these locations, there could be an amount of energy demand sufficient for the realization of a district heating. Therefore, thanks to the wood availability in the rural area we can suppose that in these zones could be feasible the biomass exploitation for energy production.

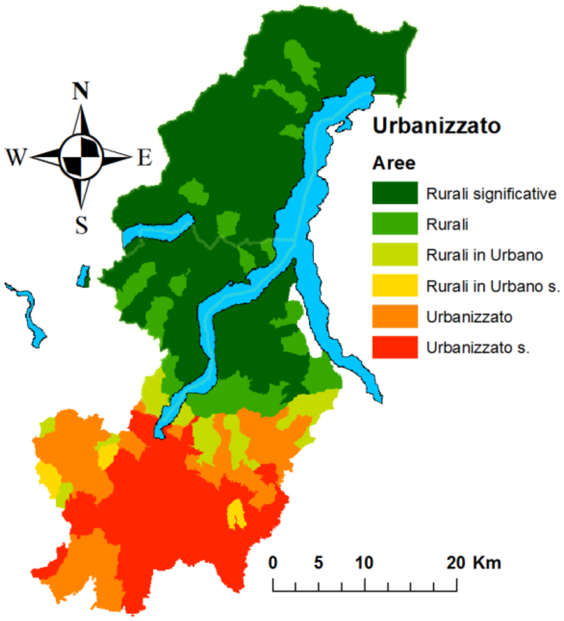


Figure 3.2 Soil consumption in the Como province (Source: Lombardy Region, 2007).

3.1 Plants localization

In 2010 the population of the two Highland Communities it was around 70'000 inhabitants (about 90 person per square kilometre). Of course, the population is more concentrated in some zones than others as shown in figure 3.3. However, the map does not identify the real geographic position of the inhabitants because the indicator is in the middle of the entire municipal territory and not in the urbanized zone. It is possible to improve the analysis, putting one layer over the others, specifically:

- "Consolidated urban zones", created at municipal level inside the Rules Plan;
- "Areas urbanized polygon", identifies all the urbanized areas, both residential and industrial, with a minimum surface of 4 hectare and with a minimum side of 100 meters;
- "Old historical centre", created at municipal level inside the Rules Plan;
- "Soil consumption in the urbanized areas", contained inside the database DUSAF (1999).

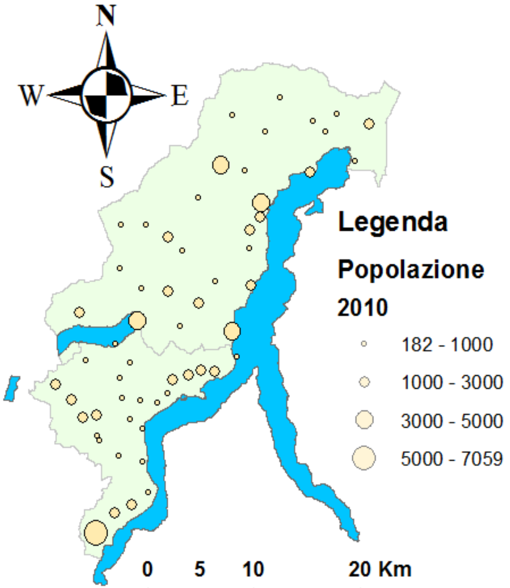


Figure 3.3 Centralized population position (Source: Lombardy Region, 2014).

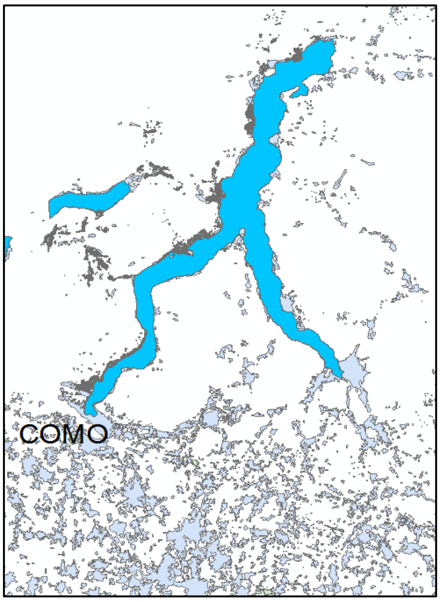


Figure 3.4 Urbanized area (Source: Lombardy Region, 2014).

By adding the information contained in all the layers we obtain the map showed in figure 3.4 that represents the urbanized surface. In this way, we can define a new population density indicator (inhabitants per urbanized square kilometre) that describes the territory. Finally, as shown in figure 3.5 with green circles, the inhabitants are located in the right position and spread in the urbanized land.

The study area has a tourism focus. Therefore, at the inhabitant's population we sum the numbers of day beds for every municipalities (data from ISTAT database ATECO, 2007). In this way, we obtain a value of the population present in the winter period and the one present in the summer period, comprehensive of the tourists. This information is very useful, combined to the thermal and electrical load to understand how the energy demand is spatially distributed on the territory. We can order all the locations according to a classification of the municipalities based on the urbanized population density and the total population. Therefore, it is possible to choose those municipalities where it is more feasible to create a district heating by selecting from all the dataset the ones that have a value of the two indicators higher than the median of the sample. With this approach, we take from 57 locations 14 municipalities (showed in figure 3.6) where we assume that is probably more convenient the realization of a biomass plant (high energy demand) and a district heating (high urbanization). In this way, we do not take into account those small villages where the realization of a district heating is economically less feasible, both for the low population and for the strewn distribution on the territory.

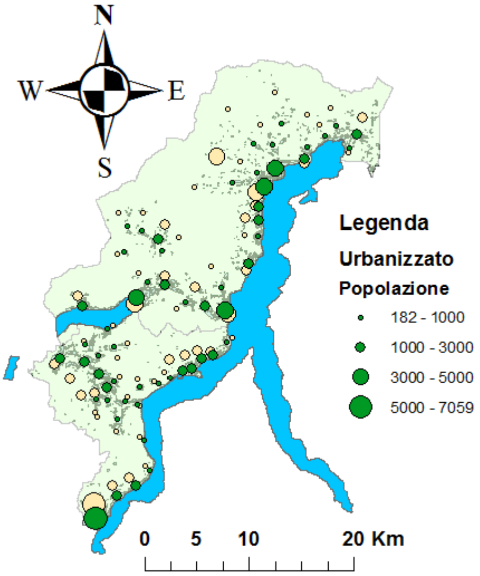


Figure 3.5 Urbanized position (green circle) (Source: Lombardy region, 2014).

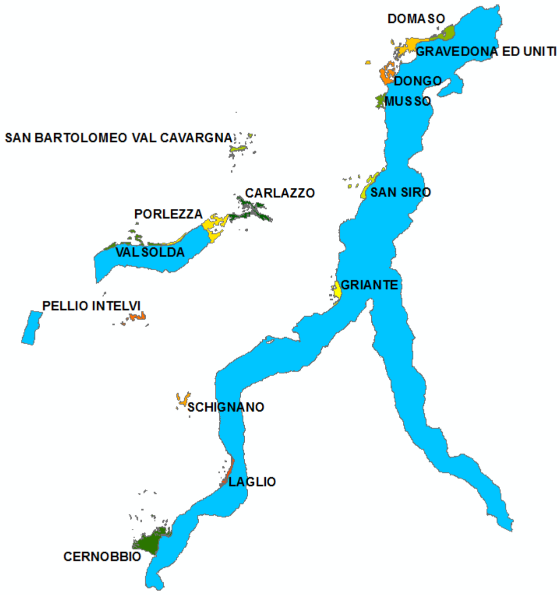


Figure 3.6 Locations involved in the project (Source: Lombardy Region 2014).

Municipality	Reference id
Domaso&Gravedona	**1**
Dongo&Musso	**2**
San Siro	**3**
Porlezza&Carlazzo	**4**
San Bartolomeo	**5**
Valsolda	**6**
Pellio Intelvi	**7**
Schignano	**8**
Griante	**9**
Laglio	**10**
Cernobbio	**11**

Table 3.1 Reference number used for the potential plants in the next tables.

Looking at the map in figure 3.6 it is clear that a single potential plant can satisfy the thermal demand of two villages (evaluating the distance between the sampled municipalities). This is the case of Domaso and Gravedona or Porlezza and Carlazzo, which have an urbanization connexion. Indeed, we define 11 points on the territory on which we could place the possible plants. The next step is to evaluate:

- The thermal demand through the analysis of the energy performance indicators;
- The electric demand, taking as a reference for the annual residential facility the value of 3’000 kWh y^{-1} p^{-1} and the tourists will account for 600 kWh y^{-1} p^{-1} in the summer period.

3.2 Energy request

The CEER (regional building cadastre) is a free database that contains the necessary information useful to calculate the thermal energy consumption for the winter heating and the production of hot water for sanitary purposes. The cadastre is divided into residential facility (house, restaurant, hotel, etc.) and non-residential one (industries, services, etc.). Concerning the first, we have some indicators such as:

- EpH-R is the average energy demand for the winter heating expressed as kWh m^{-2} y^{-1} at municipal level;
- EpW-R is the average energy demand for the hot water production expressed as kWh m^{-2} y^{-1} at provincial detail;
- A-R is the total net heated surface expressed as m^2 at municipal level.

For what concerns the facilities different from the residential one, we need to extrapolate the average building height from the ratio of the average net volume and the average net surface. Now it is possible to obtain the total volume, multiplying the average height and the total net surface. Then, for the non-residential facilities, the indicators are:

- V-NR is the net total heated volume expressed as m^3 at municipal level;
- EpH-NR is the average energy demand for the winter heating expressed as kWh m^{-3} y^{-1} at municipal level;
- EpW-NR is the average energy demand for the hot water production expressed as kWh m^{-3} y^{-1} at provincial detail.

We have to update the total net surface for the residential facilities related to San Bartolomeo and Schignano using the value of Pellio Intelvi that has a similar population and day-beds. This problem arises because the database does not cover the whole energy demand due to the recent (2009) law dispositions on buildings energy performance registration. In general, all the indicators could underestimate the total energy amount needed but this difference could be balanced in the next years thanks to the building energy efficiency improvement and thanks to a wider database. The ratio of the permanent facilities (the so called 1st houses) and the occasional ones (hotel, restaurant, 2nd houses, etc.) is not published by CEER. The latter do not consume energy during the winter because they are closed. Indeed, we decide to estimate the percentage of buildings that has a yearly request of thermal energy. This is done taking into account a possible relation between the number of day beds over the total population and a personal knowledge of the territory. The real data is inside the CEER cadastre but the database is not at completely free access. Anyway, now we have a thermal energy request over the year, spread into two semesters (winter semester and summer one). Explicitly, the energy needed for acclimatisation it is concentrated during the winter season. Instead, the salutary inhabitants and the hotels do not have a winter demand, neither for sanitary water production that is concentrated during the summer semester as shown in the sketch in figure 3.8. We spread the electrical demand in the same way, using the value of 3’000 kWh y^{-1} p^{-1} for the permanent population and a value of 600 kWh for a tourist in the summer period (1’200 kWh y^{-1} p^{-1}).

Table 3.2 shows the value of the parameters and the final energy demand for all the potential plants. Since 2009, the energetic performance is a mandatory procedure for all the commercial and accommodating facilities. Instead, for the household facilities it is mandatory just in case of new construction, property renovation and tenement. It is clear that today not all the buildings are present in the cadastre, both because several houses are inhabit but old and because often the tenant has not a regular lease. As said before, in an open database it could be interesting to evaluate the percentage of buildings that has the energy performance, but as showed in table 3.2 the results are in the foresee order of magnitude. The CEER’s data gathering is increasing thanks to the incentives for the property renovation (the amount could arrive at 65% of the total cost). It is curious the Freiburg example (Germany) situated in a worse position then Como, in terms of climatic condition, where a large portion of the urban centre has an energy performance indicator about 50 kWh m^{-2} y^{-1}, with a peak of 15 with several houses that produce more energy than needed (thanks to solar PV, geothermal, etc.). For sure, the energetic policy adopted by German has been more incisive than in Italy. As showed in figure 3.7, the average indicator EP_H in Como province is about 215 kWh m^{-2} y^{-1}.

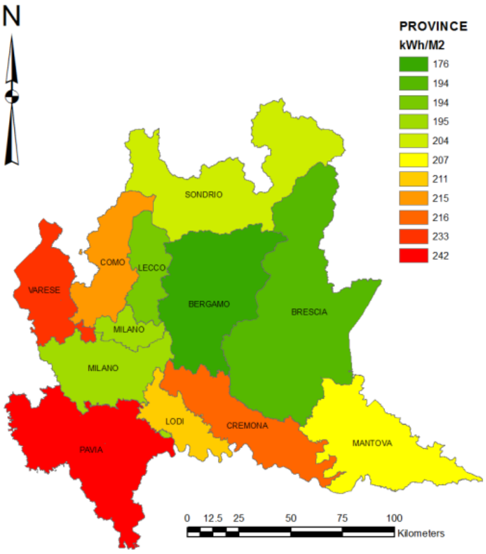


Figure 3.7 Mean EP_{Heat} for residential facilities (Source: CEER, 2014).

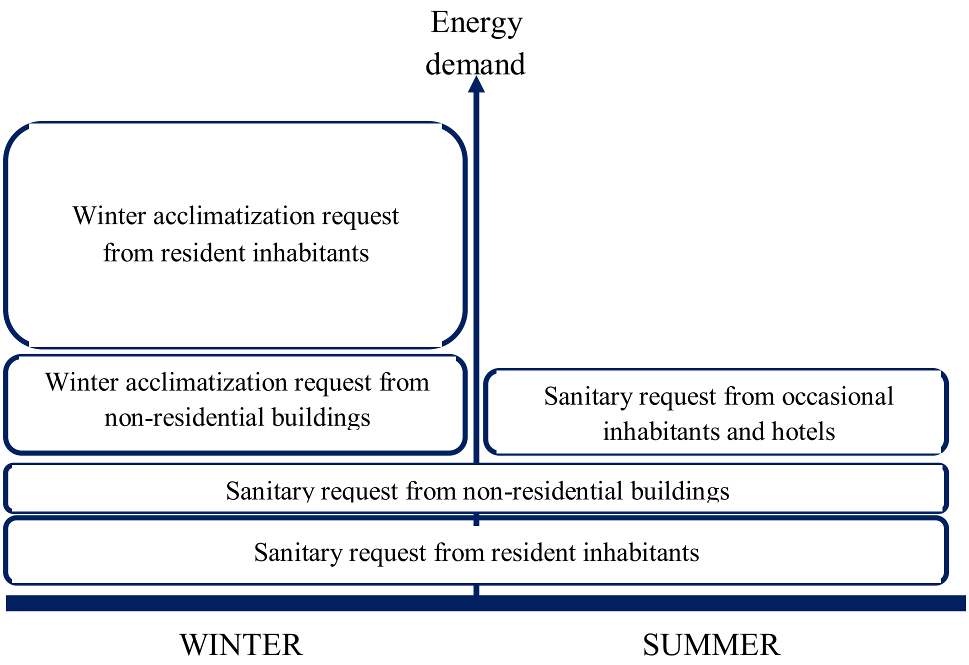


Figure 3.8 Conceptual sketch of the energetic demand spread into two semesters.

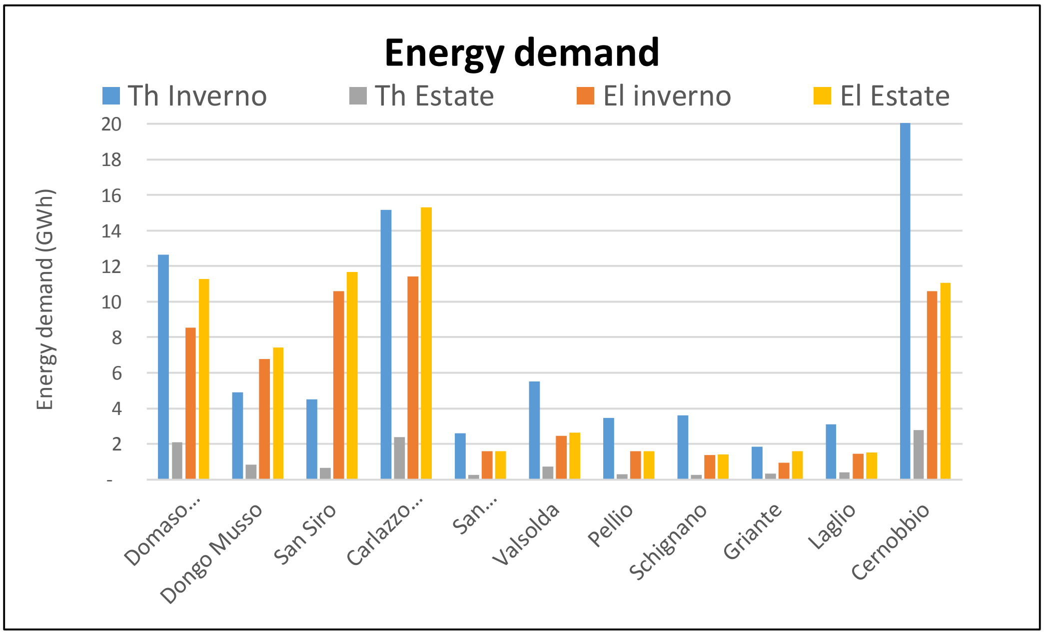


Figure 3.9 Electric and Thermal Energy demand for the summer and the winter period (Source: CEER, 2014).

POT PLANT	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
EpH-r (kWh/m^2)	202	240	219	222	261	247	300	344	226	235	233
EpW-r (kWh/m^2)	51	51	51	51	51	51	51	51	51	51	51
Surface (m^2)	58441	29793	25682	74811	10000	27658	10033	10000	12810	15876	95015
% S household	50%	50%	70%	50%	90%	70%	90%	90%	50%	70%	70%
S household (m^2)	29221	14897	17977	37406	9000	19361	9030	9000	6405	11113	66511
S occasional (m^2)	29221	14897	7705	37406	1000	8297	1003	1000	6405	4763	28505
Winter heat consumption R (MWh)	**5900**	**3570**	**3942**	**8307**	**2353**	**4779**	**2709**	**3100**	**1445**	**2606**	**15488**
Annual hot water consumption R (MWh)	**1484**	**757**	**913**	**1900**	**457**	**984**	**459**	**457**	**325**	**565**	**3379**
Summer hot water consumption R (MWh)	**1484**	**757**	**391**	**1900**	**51**	**422**	**51**	**51**	**325**	**242**	**1448**
EpH-nr (kWh/m^3)	66	79	73	82	45	108	106	207	124	115	86
EpW-nr (kWh/m^3)	14	14	14	14	14	14	14	14	14	14	14
Volume nr (m^3)	82210	11101	1428	66166	382	2202	4709	1273	1890	1681	52647
Winter heat consumption nr (MWh)	**5396**	**875**	**104**	**5423**	**17**	**237**	**501**	**263**	**234**	**193**	**4553**
Annual hot water consumption nr (MWh)	**1184**	**160**	**21**	**953**	**6**	**32**	**68**	**18**	**27**	**24**	**758**
Annual Inhabitants	5688	4508	7061	7614	1049	1639	1053	914	636	957	7059
Electrical annual consumption rate (MWh/p/y)	3	3	3	3	3	3	3	3	3	3	3
Electrical annual consumption (MWh)	**17064**	**13524**	**21183**	**22842**	**3147**	**4917**	**3159**	**2742**	**2742**	**1908**	**21177**
Tourists	4589	1089	1804	6460	41	282	43	53	1049	121	786
Tourist consumption rate (MWh/p/estate)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Tourist consumption (MWh)	**2753**	**653**	**1082**	**3876**	**25**	**170**	**26**	**32**	**630**	**73**	**472**

Table 3.2 Energy demand characteristics for every location (Source: CEER, 2014).

3.3 Load diagrams

In the second chapter, we have seen how to build the normalized thermal and electric load diagram, extracted from the winter minimum temperature and the Terna data respectively. In this section, we estimate the peak power thanks to the information obtained from the total amount of energy needed from every potential location. It is used an excel spreadsheet and the "solver" function, since we have to find what is the peak load value that can satisfy the constraint on the total energy needed in every areas served by the plant and following the diagram of the electric and the thermal normalized load (figure 2.10 and 2.15). At that point, depending on the peak load, it is possible to estimate the capacity factor. This parameter is the ratio between the amount of energy needed (that can be sold) and the total amount of energy that the plant could produce if it works all year long at the nominal power. It is important that the capacity factor is high as much as possible because for high value (the maximum is 100%) we have sized the plant to a power value that allows it to work at the maximum efficiency. Nevertheless, having a high capacity factor means that we are using a technology at its best potential of energy production. However, in our case to have a 100% capacity factor we must decrease the plant size. In this way, the system is not able to satisfy the peak power demand. It is possible to explain the problem looking at the load diagram in figure 3.10 and 3.11. Choosing a nominal plant size that is able to satisfy for example the 80% of the peak power value, it follows that the system is able to produce energy at its nominal power size just for a small period in a year. Concerning the heat demand for example, during Winter we need a high plant size to satisfy the request but in summer the plant is not used at its power size since the request is low. However, it is quite common having a situation like this for what concerns the thermal energy production at the Lombardy latitude and so with few months of thermal energy demand for heating purposes (6 months, from 10/15 to 4/15).

The overall feasibility of a project on energy production from renewable sources it could be improved in case we have a thermal energy request during summer too. This demand changes the load diagram, increasing the capacity factor of the technology adopted. For example, a solution could be the tri-generation that is the usage of heat during summer for fresh air-conditioning.

Now, we want to define the characteristics of our plants in terms of:

- power size;
- how much electric energy they are able to produce (Electric Capacity Factor);
- how much thermal energy they are able to sell (Thermal Capacity Factor);

For our calculations, we assume that all the electric energy produced can be sold. We have to define the plant size according to the peak load found in the load diagram (3.10 and 3.11). Then, the capacity is equal to the ratio between the area under the load diagram and the yearly energy produced with that plant size. It is for these reasons that we calculate three different cases:

- Case A, 100% of the peak load;
- Case B, 80% of the peak load;
- Case C, 60% of the peak load.

Since we have two energy demand types, the electric one and the thermal one, it is possible to define two scenarios of energetic satisfaction. Thus, depending on the kind of energy demand at which we focus our attention, we define two scenarios:

- Scenario 1, satisfaction of the thermal energy demand;
- Scenario 2, satisfaction of the electric energy demand.

In both the situations, for a complete fulfilment of a demand (thermal or electric) there is a partial or complete satisfaction of the other request. For example, if we size the plant for the complete satisfaction of the thermal energy demand, there will be a partial production of electric energy. Instead, in the second one we satisfy completely the electric energy demand while we are producing an amount of thermal energy that is usually higher than the request, so a huge percentage of it is wasted. This is due to the different efficiencies rate (thermal and electric) that characterize the technology used in the plant, explained in the next chapter. By looking at the table 3.3 and 3.4 it is easy to understand that by decreasing the nominal power of a plant it is possible to increase the capacity factor. For the second scenario, we have a more constant demand of electric energy during the year in spite of the thermal request as shown in figure 3.10 and 3.11. Indeed, the electric capacity factor is higher because the electric load diagram is flat compared to the thermal one. For this reason in the second scenario, we could choose the size and the capacity factor of the case C. Nevertheless, the amount of energy that is not produced by the plant can be made by others renewable sources during the higher demand period, that for electric energy is the summer semester coincident with the peak production of solar PV. While for the first scenario, sizing the plant according to the case C (60% of the peak) means that we need an extra device to supply the thermal energy, which could be another boiler. Indeed, we cannot go under the 80% of the peak load because a smaller percentage is for sure not able to satisfy the demand in the colder period of the year. Furthermore, the nominal power of a plant it is the size at which it has its maximum efficiency. Usually a boiler can produce more power than the nominal size (slightly less efficient than at the nominal power). We assume that the nominal power is 80% of the maximum power that a boiler can produce. After these considerations, we choose the case B for the first scenario as the best solution in case we focus our attention at the thermal energy satisfaction. The capability of the system to sell electric energy in the first scenario is possible just supposing that the two demands are in phase. Meaning that when a plant produce a quantity of thermal energy, if the technology is co-generative, the whole amount of electric energy produced can be sold.

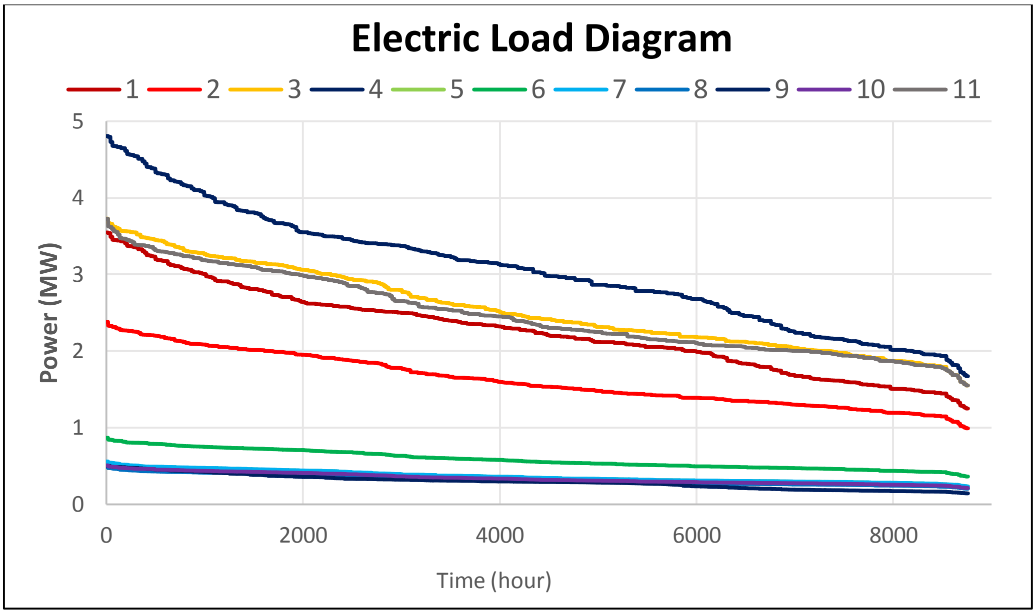


Figure 3.10 Electric load diagram for each possible plant (Source: ISTAT, Terna, CEER, 2014).

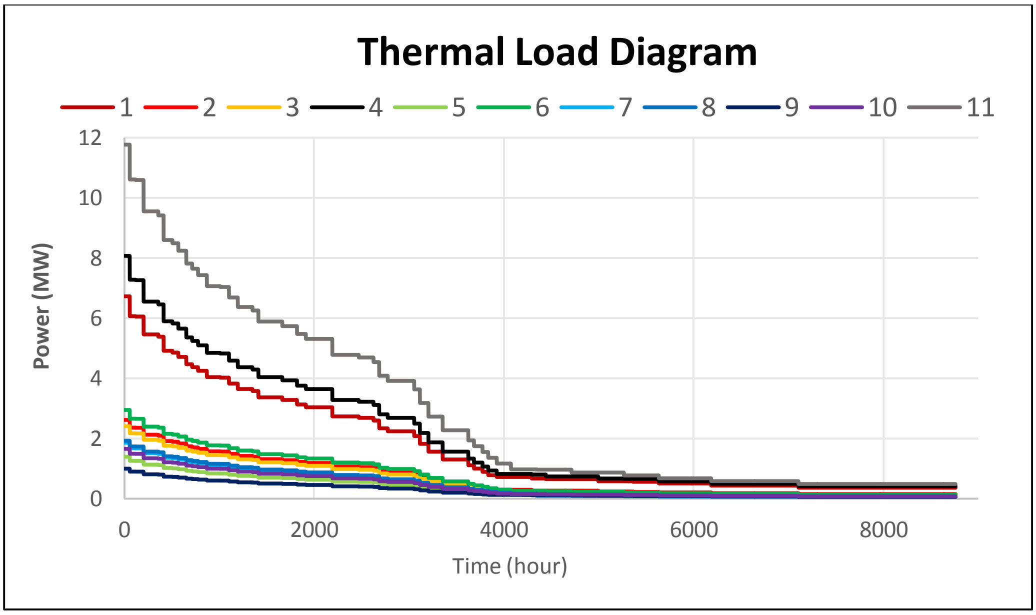


Figure 3.11 Thermal load diagram for each potential plant (Source: ISTAT, Terna, CEER, 2014).

SCENARIO 1 Thermal energy satisfaction						
Plant	A		B		C	
	Power MWth	Cap factor	Power MWth	Cap factor	Power MWth	Cap factor
1	6.7	0.25	5.4	0.31	4.0	0.39
2	2.6	0.25	2.1	0.31	1.6	0.39
3	2.4	0.25	1.9	0.30	1.4	0.38
4	8.1	0.25	6.5	0.31	4.8	0.39
5	1.4	0.24	1.1	0.29	0.8	0.36
6	2.9	0.24	2.4	0.30	1.8	0.38
7	1.8	0.23	1.5	0.29	1.1	0.37
8	1.9	0.23	1.5	0.28	1.2	0.36
9	1.0	0.25	0.8	0.31	0.6	0.39
10	1.6	0.24	1.3	0.30	1.0	0.38
11	11.8	0.24	9.4	0.30	7.1	0.37

Table 3.3 Thermal energy satisfaction (Source: ISTAT, Terna, CEER, 2014).

SCENARIO 2 Electric energy satisfaction						
Plant	A		B		C	
	Power MWel	Cap factor	Power MWel	Cap factor	Power MWel	Cap factor
1	4.2	0.54	3.4	0.67	2.5	0.85
2	2.8	0.58	2.2	0.73	1.7	0.90
3	4.4	0.58	3.5	0.73	2.6	0.90
4	5.7	0.53	4.6	0.67	3.4	0.84
5	0.6	0.61	0.5	0.75	0.4	1.00
6	1.0	0.59	0.8	0.74	0.6	0.90
7	0.6	0.61	0.5	0.75	0.4	0.92
8	0.5	0.60	0.4	0.84	0.3	0.97
9	0.6	0.49	0.5	0.61	0.4	0.77
10	0.6	0.60	0.5	0.74	0.3	0.91
11	4.1	0.60	3.3	0.74	2.5	0.91

Table 3.4 Electric energy satisfaction (Source: ISTAT, Terna, CEER, 2014).

Chapter 4

The economic feasibility

In this chapter, we examine different technology solutions for the conversion of wood biomass into useful energy. The economic aspect is very important, the payback period will be an economic evaluation parameter for our calculations. We are searching solutions with a payback period less than 10 years. Firstly, we compare the technologies using the Levelized Energy Cost and the data from a report done by Politecnico di Milano (Biomass Executive Energy Report, 2013). As showed in table 4.1, the main technology used can be classified according to different parameters (e.g. kind of energy produced, plant efficiency, etc.) and the quality of the raw material (humidity, LHV, lignin content, etc.). The values of the efficiencies in parenthesis they are referred to plants with power size equal to the maximum available in the BEER report. In our case, we do not take into account an increase of the efficiency by rising the plant size. Even the investment and the management costs they are not influenced by a scale factor. We use the small size values. The efficiency parameter has an uncertainty due to the data analysis. This last has been done throw a real plants data treatment. Therefore, we decide to use the average value. ORC plants are the most diffuse on the territory because they entered in the market when the price to sale the electric energy it was 0.36 € MWh^{-1}. Data available for this technology are for 0.25 and 2 MW of power size. Indeed, the possible range is in between these two values. While concerning gasification and pyrolysis, data are available just for 0.5 MW configuration. We decide to use a range between 0.25 MW and 0.75 MW even if the major producers of these systems they are pushing on the market small plant size configurations. Gasification and pyrolysis system needs a good material as input in the transformation process in terms of physical and chemical properties of the wood. Firstly, humidity is very important. Different harvest periods coincide with high or low water content into the porous matter of tree crops and grasses. After the harvest, it starts the drying period that could be more or less longer depending on the desired quality in terms of energetic content and density. Consequently the total harvest cost will rise. The tree's trunk without the treetop, it can be debarked and dehydrated, while the branches are chipped (reduced in chips of about 5÷10 cm) and dehydrated as well in stack. The wood is reduced in chips to enhance the natural dewatering thanks to a higher surface in contact with the air. The chips from the branches and the trunks have two differences:

- The chips from branches, being smaller and with the bark, has an ash content higher than a debarked trunk;
- The trunk has a high lignin content, because lignin grows in the internal part of the trunk. This parameter has a high influence on the gasification and pyrolysis syngas quality and as a consequence on the total plant efficiency.

Technology	**η electric**	**η thermal**	**Plant size MW el**	**Plant size MW th**	***Quality of the raw material***
Pellet System		0.86 ÷ 0.91 (0.88 ÷ 0.95)	0	0.02 0.1	*Very good*
Gasification plant	0.31 ÷ 0.36	0.50 ÷ 0.60	0.5 (0.25÷0.75)	≅ 0.8	*Good*
Pyrolysis plant	0.30 ÷ 0.40	0.45 ÷ 0.50	0.5 (0.25÷0.75)	≅ 0.6	*Good*
ORC plant	0.12 ÷ 0.18 (0.16 ÷ 0.20)	0.74 ÷ 0.80 (0.74 ÷ 0.78)	0.25 2	≅ 1 ≅ 8	*Bad*
Chips system only district heating		0.78 ÷ 0.85 (0.85 ÷ 0.90)	0	1 8	*Bad*

Table 4.1 Technology production characteristics. (Source: BEER, 2013).

Raw material with bad quality mainly corresponds to chips from small branches (less 5 cm). The water content does not have influence in the process for the ORC technology (≅ 40%) and in the normal boiler system for the district heating (without electric energy production). For a good wood quality is intended the wood having a significant lignin content, the ash presence is less important (for gasification) than the water content (has to be around 15%). In the end, pellet has the best quality because the wood needs many physical processes to reduce the size and to decrease the ash content and the water content (less than 10%).

Indeed, for each technology the total harvesting cost (harvest, collection and preparation) depends on the characteristics of the raw material. Analysing the information given by the Management department of the Politecnico di Milano, contained in the biomass Energy Executive Report (BEER) it is possible to give a numeric value to the harvesting cost based on three classes, specified in table 4.2.

Raw material quality	**Very good**	**Good**	**Bad**
Total harvesting cost	≅ 180 € Mg^{-1} dry matter	≅ 100 € Mg^{-1} dry matter	≅ 50 € Mg^{-1} dry matter

Table 4.2 Total harvesting cost of raw material. The values are expressed in € per Mg of dry matter (Source: BEER, 2013).

Now it is time to examine the different technologies from an economic point of view looking at the following indicators: the investment cost, the yearly management cost, the harvesting cost for a given capacity factor and the LEC indicator (Levelized energy cost). This last parameter is equal to the ratio between the annual cost and the total energy produced.

$$\mathrm{LEC} = \frac{crf\ C_{inv} + C_{M\&H}}{E_{net}}$$

Equation 4.1

crf = depreciation factor;
C_{inv} = invested capital;
$C_{M\&H}$ = management and harvesting annual cost;
E_{net} = yearly energy produced.

For all the technologies, the life cycle is equal to 25 years.

4.1 Economic analysis

Pellet technology characteristics are show in table 4.3. Pellet technology has an automated system for the wood load. In this way, thanks also to a programmable timer, the performance is similar to a traditional natural gas boiler. It has a nominal power from few kW to some hundreds and it would be possible using it for a small district heating. With a size of 20 kW it is possible to heat a flat of about 100-120 square meters and satisfy the demand of hot water too. This technology is economically profitable even with a small capacity factor, following the behaviour of the demand and without producing excess energy. Thanks to the high energy density of the pellet, the storage compartment and its cost is reduced significantly.

Chips boiler for a district heating technology is shown in table 4.4. It allows supplying heat (such as ORC and the others co-generative system) to a set of houses, commercial and public facilities, industries, which are nearby the plant. In this kind of plant, it is possible to use as raw material all the wasted matter from the wood supply chain, even with high moisture content and low LHV, allowing a high heterogeneity. The high cost for the realization of the grid, which allows the heat distribution, has a negative influence on the feasibility of the entire project.

The ORC technology (in picture 4.5) is based on a closed organic Rankine cycle and it uses an organic fluid instead of water. The main product of this kind of plant is electric energy, but it founds its best performance in co-generative plants (heat and electricity), in which the heat subtracted from the organic fluid is used for other purposes (civil or industrial). The fuel used to feed it can be domestic waste. Generally, these plants can be linked to boilers fed by any material that is able to produce sufficient heat for the Rankine cycle. The ORC technology has a size that typically is in a range from 250 kWel to 2 MWel. In the last years, these plants found a large diffusion thanks to the incentives on the electric energy produced from renewable sources.

Gasification and pyrolysis are thermochemical conversion processes of a fuel (in this case the wood biomass) into a gaseous fuel called synthesis gas or syngas. In the case of pyrolysis, we obtain also other sub product such as the pyrolytic oil and the char that could have another economic value, in a percentage that depends on the process parameter (pressure, temperature and residence time). This system is able to produce both electric energy and thermal energy and the range size is from 250 kWel to 2 MWel. A traditional combustion process is characterised by an oxidation of the fuel with an excess of oxygen and the release of heat in the environment. From a thermodynamically point of view it is a conversion process from the chemical energy into heat and the products are the combustion soot and the inert solid residual. Whereas the gasification consists in the partial combustion of a material with low air content and the main product is a gas enriched in carbon monoxide and hydrogen. The partial oxidation reactions produces a smaller amount of inert solids and liquids than gases (not such as the pyro-process) and the heat necessary for the reaction is given by the partial oxidation of the carbon until to get rid from an outside system. Therefore, in the pyrolysis is developed a process without oxygen and the heat needed to let the reaction start and maintain is usually given by a fraction of the gas or liquid produced.

kW$_{th}$	**ηth**	**Investment €/kW$_{th}$**	**Management €/kW$_{th}$**	**Harvesting cost €/kW$_{th}$ y^{-1}**	**Capacity factor**	**LEC €/kWh$_{th}$**
20	0.88	600	15	50	15%	≅ 0.09
100	0.93	400	10	48	15%	≅ 0.07

Table 4.3 Economic analysis for the pellet technology (Source: BEER, 2013)

MWth	**ηth**	**Investment €/kW$_{th}$**	**Management €/kW$_{th}$**	**Harvesting cost €/kW$_{th}$ y^{-1}**	**Capacity factor**	**LEC €/kWh$_{th}$**
1	0.83	1400	90	180	68%	≅ 0.07
8	0.88	1300	80	160	68%	≅ 0.06

Table 4.4 Economic analysis for the chips technology (Source: BEER, 2013).

kW$_{el}$	**ηel**	**ηth**	**Investment €/kW$_{el}$**	**Management €/kW$_{el}$**	**Harvesting cost €/kW$_{el}$ y^{-1}**	**Capacity factor**	**LEC €/kWh$_{el}$**
250	0.15	0.77	5000	250	550	100%	≅0.15
2000	0.18	0.76	4500	220	450	100%	≅0.13

Table 4.5 Economic analysis for the ORC technology (Source: BEER, 2013).

kWel 500	**ηel**	**ηth**	**Investment €/kW$_{el}$**	**Management €/kW$_{el}$**	**Harvesting cost €/kW$_{el}$ y^{-1}**	**Capacity factor**	**LEC €/kWh$_{el}$**
GASS	0.33	0.55	3500	450	420	57%	≅0.24
PIRO	0.35	0.47	3700	500	420	57%	≅0.25

Table 4.6 Economic analysis for the gasification and pyrolysis technology (Source: BEER, 2013).

4.2 Parameters influence on LEC

As we have seen in the previous section the Levelized Energy Cost (LEC) changes a lot for every technology presented. Indeed is not possible to define what is the best solution without knowing the parameters that characterise the system. In this section, we analyse the behaviour of the LEC changing the factors such as the capacity factor and the harvesting cost. We are trying to understand what is the best scenario to adopt. Sizing the plant to satisfy the electric energy demand or we have to focus on the thermal peak load? In figure 4.1, it is shown that for the pellet technology the cost of the raw material has a high influence on the LEC indicator because the line is very steep compared to the others. For what concern the systems that produce both electric energy and thermal energy it is possible to see that gasification and pyrolysis suffer more by harvesting cost than ORC. In figure 4.2 we have a look to the LEC variation by changing the capacity factor parameter. For what concern co-generative systems, it is possible to see that the hyperbolic curve is quite flat in the range from 70% to 100% of the capacity factor, and even in this case the ORC technology is the best solution. While for thermal energy technologies, after 20% of capacity factor for pellet and after 60% for chips boiler, an improvement does not change the LEC value so much. This is mainly due to the lower management cost for pellet technology than chips. The results in figure 4.1 and 4.2 show that the ORC technology looks like the best solution for electric and thermal energy production taking as selling price the values of 0.10 €/kWh$_{th}$ for the thermal energy and 0.16 €/kWh$_{el}$ for the electric energy. At this point is useful to highlight that all the indicators are referred to the electric energy unit. For the ORC technology and its efficiency rates, we have a higher production of thermal energy, specifically equal to 4 kWh of thermal energy per kWh of electric one. This value is obtained averaging the efficiency rates inside the BEER report and taking into account the energy lost for the district heating (around 5%). For the ORC technology, the revenue per unit energy is equal to 0.56 €/h. This value is intended as the revenue selling all the energy produced in one hour at the nominal power size but, after the thermal energy satisfaction, the profit will be equal to the only fraction of electric energy (0.16 €/kWh). It is simple to understand that for a LEC higher than 0.16 €/kWh el the system is not convenient and just selling as much as possible the thermal energy we can have an economic benefit. It is for this reason that we choose the first scenario as the reference to dimension the plant size. Indeed, we choose the values reported in table 3.3 (case B) as the upper limit size of the potential plants.

Moreover, the profit for the sale of thermal energy is equal to the corresponding capacity factor multiplied by the amount of hour in a year and the power size.

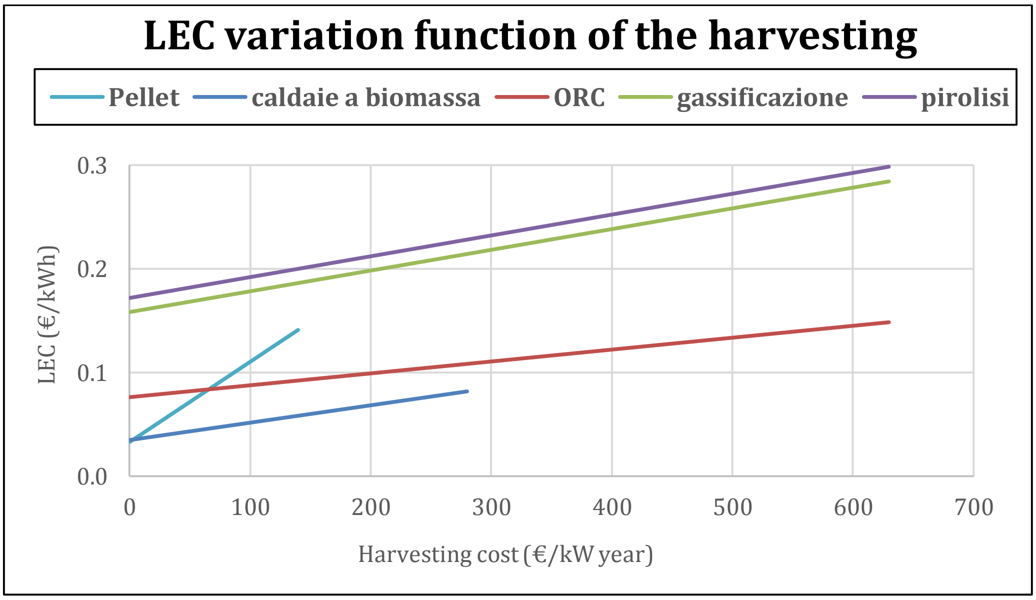


Figure 4.1 Variation of the LEC function of the harvesting cost (Source: BEER, 2013)

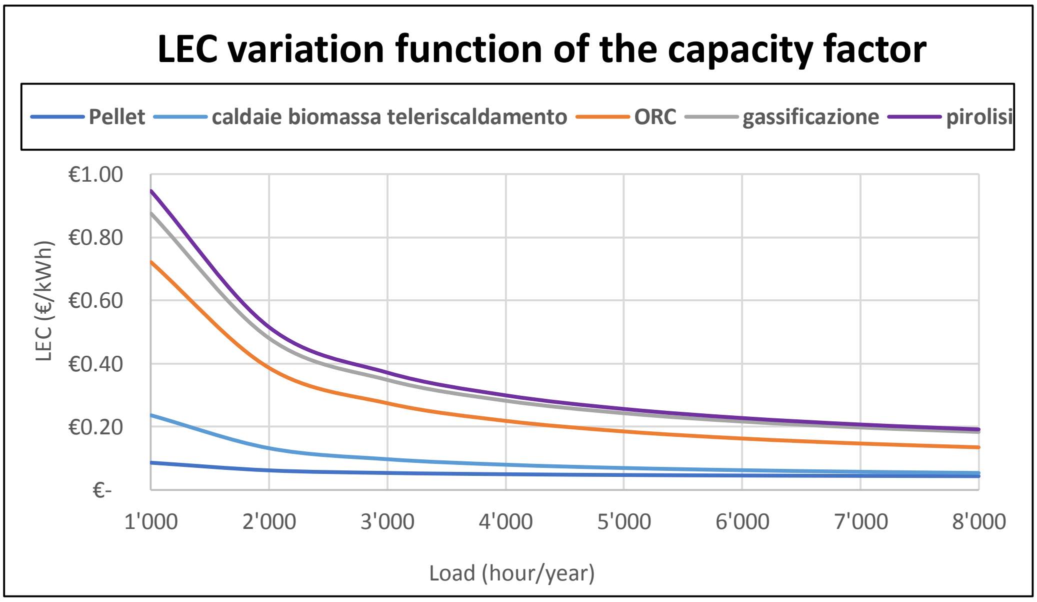


Figure 4.2 LEC variation function of the capacity factor (Source: BEER 2013).

4.3 Cost and Profit

We realize immediately (table 4.5 and 4.6) that the co-generative technologies do not take into account the cost of the realization of the district heating. The LEC indicator is useless for our calculations. The grid cost can be a huge fraction of the entire investment depending on the dimension of the grid, the slope of the territory and so on. From available information (Marchesi, 2008), it is possible to simplify that the cost of the grid realization it accounts for 40% of the total investment (plant installation account for 60%). Therefore, it is possible to update the information related to this aspect as shown in table 4.7.

Co-generative Technology	ηel	ηth	Investment 10^6 €/MWel	District heating cost 10^6 €/MWel
ORC	0.15	0.77	5	3.3
Gasification	0.33	0.55	3.5	2.3
Pyrolysis	0.35	0.47	3.7	2.4

Table 4.7 Cost definition for a district heating realization (Marchesi, 2008).

We want to determine the economic feasibility of the investment in a potential plant. Different aspects compose the economic balance (cash flows) of an enterprise, such as the sale of the energy and the investment costs (throw the depreciation factor). The first has a positive effect on the balance while the second has a negative influence. For example, the green certificates are economic incentives to help the installation of zero emission system for the production of energy. Namely, those renewable plants that avoid the emission in the atmosphere of CO_2 (compared to others fossil fuel technology) they receive a certain amount of certificates with the possibility to sell them in a special market. This amount of extra profit is dependent from the emission balance of the adopted solution. It is calculated throw 4 factors:

- C_{el} and C_{th} are the avoided emissions compared to Natural gas technology for the production of electric and thermal energy respectively;
- C_{tr} is the emission for the transport of wood from the parcels to the plants;
- C_{hr} is the emission for the harvest operation.

B_{el} is equal to 0.59 $Mg_{of}CO_2$ MWh^{-1} and it will be multiplied by the total electric energy produced and sold E_{el} (electric efficiency rate for methane system equal to 55% and 85% the thermal one). B_{th} is equal to 0.38 $Mg_{of}CO_2$ MWh^{-1} and it will be multiplied by the energy sold E_{th} (Perego, 2009). It is possible to obtain the avoided emission by multiplying the energy produced with these two parameters. While the harvest emission B_{hr} is equal to 5 10^{-4} $Mg_{of}CO_2$ Mg^{-1} and the transport emission B_{tr} is equivalent to 245 10^{-6} $Mg_{of}CO_2$ Mg^{-1} km^{-1}. They will be multiplied by the amount of wood harvested and transported (weight on dry matter). These data are obtained from a thesis done for Politecnico di Milano (Perego, 2009). The final avoided emission B_{tot} is equal to:

$$B_{tot} = (B_{th}\, E_{th} + B_{el}\, E_{el}) - M_k^i (B_{tr}\, d_k^i + B_{hr})$$

Equation 4.2

Where M is the mass of wood transported from the forest i to a plant k as well as d is the distance between them. The total amount of Extra profit E obtained throw the sale of the green certificates is equal to a sale price S (it can be around 10 € $Mg^{-1}{}_{of}CO_2$) multiplied by the carbon balance in equation 4.2. Indeed, E is equal to:

$$E = B_{tot}\, S$$

Equation 4.3

The payback period is obtained throw the Net Present Value calculated at the period t for a total number of periods N (the life cycle of the plant equal to 25 years) and i is the discount rate equal to 10%. Indeed, the NPV is equal to:

$$NPV\,(i, N) = \sum_{t=0}^{N} {R_t}/{(1+i)^t}$$

Equation 4.4

The cash flow R_t, is an economic balance in the period t. In our calculations, the cash flow is equal to:

$$R_t = P + E - M - H - T$$

Equation 4.5

Where P is the sum of the profit for the sale of thermal and electric energy, E accounts for the extra profit from the green certificates. H and T are respectively the harvest and the transportation costs. While M is equal to:

$$M = crf\ inv + man$$

Equation 4.6

Where crf is the depreciation factor (equal to 10%) on the investment *inv*. In addition, *man* corresponds to the management costs. At t equal to 0, namely at the plant realization, we buy the technology and we start building the district heating. At year 1, the plant working and the district heating is done. This is a simplification of the reality. We assume that the R_0 value is equal to the investment plus the grid realization (table 4.7). The grid cost will account for a lower percentage than the one in table 4.7. Specifically for 20%, taking into account that a district heating has a life cycle much higher than the installed technology.

4.4 Capacity factors definition

In this section, we use the load diagram for the energy demand presented in the previous chapter and we evaluate the capacity factors for every plant that produces electric energy. We need two parameters that indicate how much electric energy a plant can sell and the amount of the thermal one. We assume that the thermal capacity factor of a plant is equal to the thermal energy that a plant is able to sell and not equal to energy produced. In the example in figure 4.3, the amount of primary energy needed to follow the thermal load diagram corresponds to the thermal capacity factor multiplied by the size of the plant (using the primary power). This amount of energy represent also the amount of wood necessary throw a conversion factor (e.g 4 MWh/MG). This configuration is possible assuming a boiler technology for heat production able to guarantee the behaviour of the thermal load diagram. While for co-generative systems we assume that they can work just at their nominal power size. Without taking into account an operative range. Indeed, the electric capacity factor will be equal to the electric energy produced over the total electric energy that a plant can produce. In the case presented in figure 4.3, the plant can sell electric energy only for about 400 hours per year (4% capacity factor). For this capacity value, the installation of an ORC technology is not convenient. Indeed, we are presenting 2 cases:

- Case 1: electric capacity factor equal to 50% (figure 4.3). e.g. we produce electric energy only during the period of high demand of thermal energy (Winter);
- Case 2: electric capacity factor equal to 100% (figure 4.4). e.g. we produce electricity all year long, even if during summer the thermal production is wasted;

In figure 4.3, 4.4 and 4.5 the blue area represents the amount of thermal energy produced by an ORC plant while the red one according to the efficiency is the electric energy produced. As we said before, the amount of thermal energy that can be sold can be represented by the area under the thermal load diagram in figure 4.3. In the next chapter, we focus on the biomass availability while in the chapter six we implement the model able to determine the optimal size of the potential plants according to the biomass availability and the quantity of thermal and electric energy that we can sell.

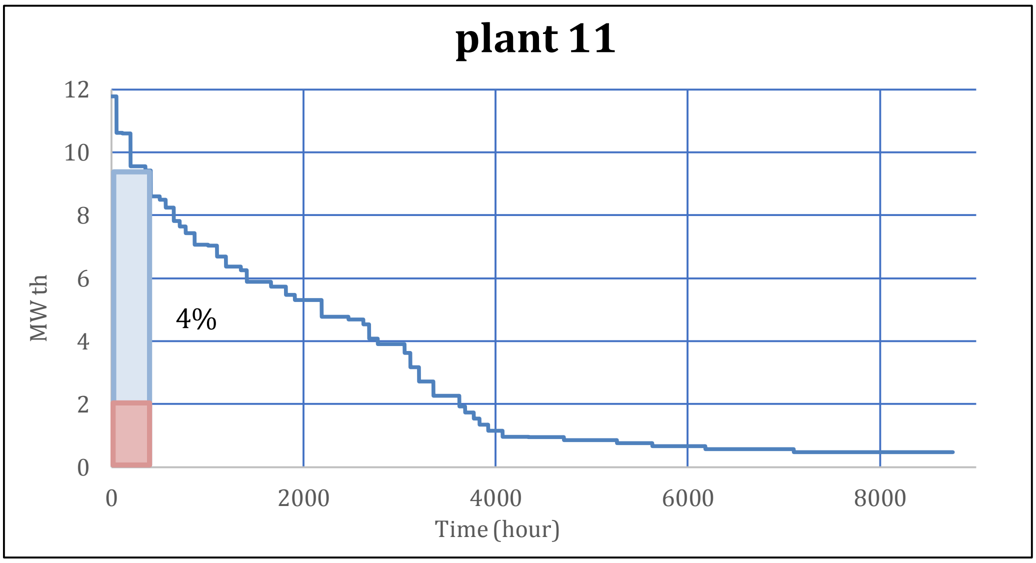


Figure 4.3 Representation of the total amount of thermal energy needed from an ORC system (blue area) for the production of a small amount of electric energy (red area).

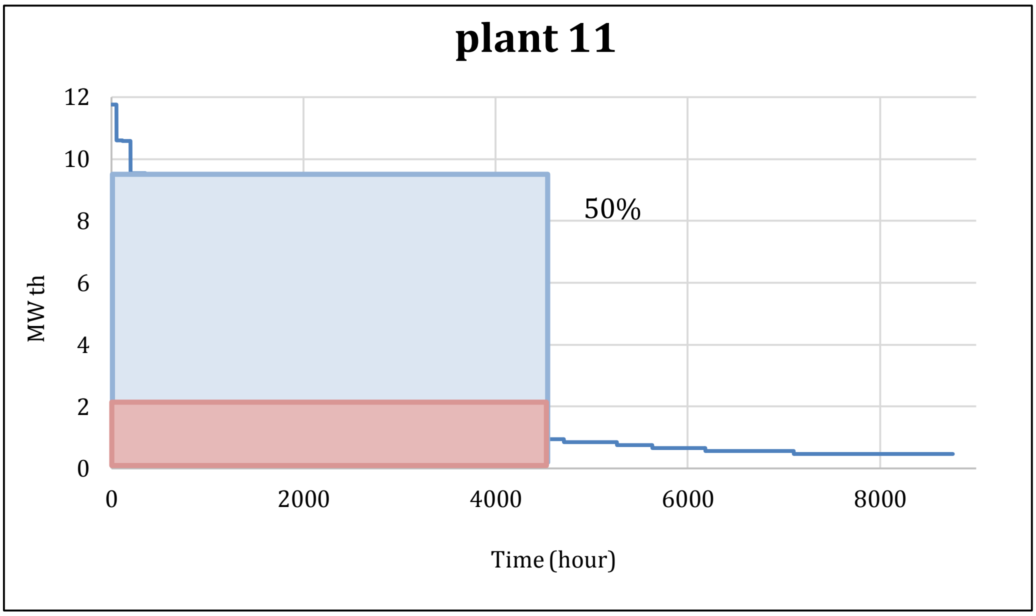


Figure 4.4 Representation of an utilization factor of 50%.

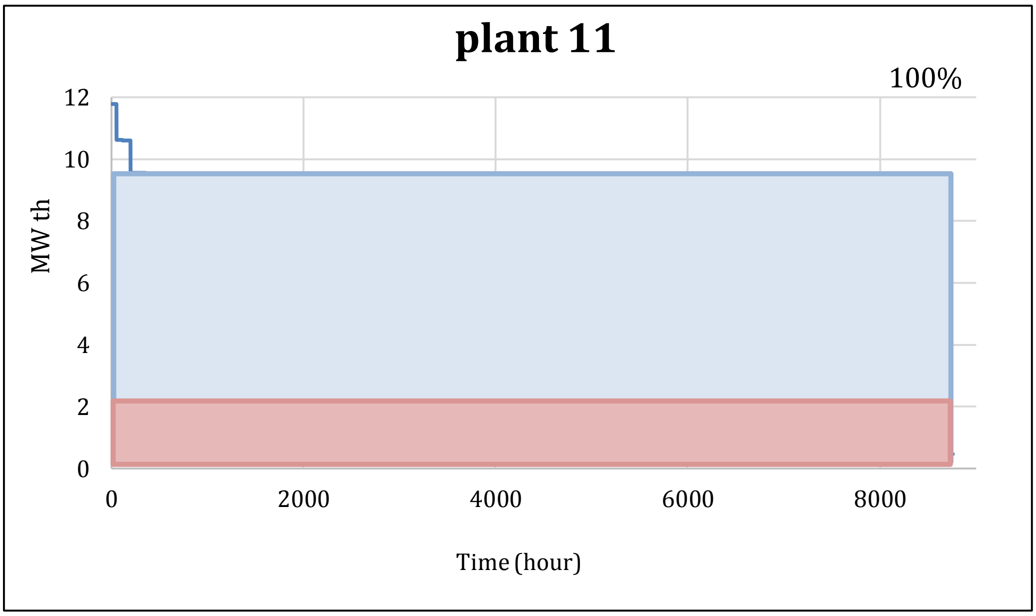


Figure 4.5 Representation of an utilization factor of 100%.

Chapter 5

Biomass availability

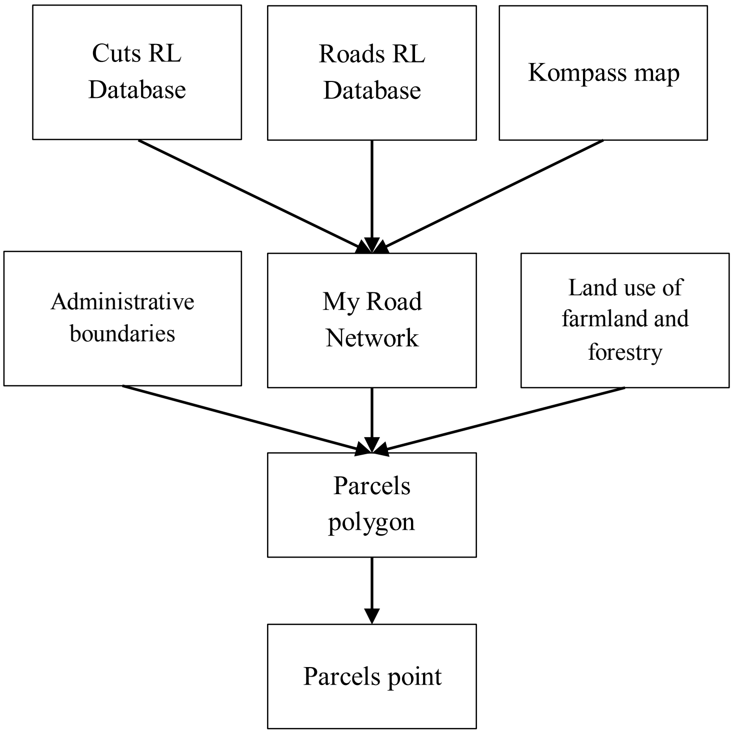


Figure 5.1 Sketch of the procedure adopted to obtain the parcels.

Figure 5.1 Illustrates adopted procedure to find where to harvest the biomass. We start defining the road network thanks to the information contained in the Lombardy Region database and in the hiking map (Kompass). Then, we make a buffer around the road network and we intersect the obtained polygon with the ones describing the type of tree species (Land use of farmland and forestry layer). The result is polygon layer that contains the information needed (such as the biomass availability, etc.). By transforming the polygon layer into a point layer, it is possible to calculate in a GIS software the distance between the parcels and every potential plant.

Until now, we did not analyse the biomass availability and the transportation costs. In the next paragraphs, we examine the problem of collecting the raw material from the forests, divided into parcels, which through a road network are linked to the possible plants location. All the calculations are done in a situation of sustainable management of the wood resource in terms of:

- low economic impacts for the harvesting and transportation costs;
- low environmental impacts for a sustainable biomass harvesting rate.

The meaning of locate the parcels is to identify the position of well-defined areas where the biomass is harvested and collected. Indeed, a parcel is represented by different information, such as:

- The distance from the plants (road length) suitable for the transportation cost;
- The accessibility (kind of road used), appropriate for the harvesting cost;
- The amount of biomass available for the harvest.

The Highland Communities in collaboration with the forest consortiums (owner private association) have the responsibility to define this information. Every ten years the Highland Community should have to present the forestry assessment plan (PAF) and the forestry orientation plan (PIF). The first has to locate the zones suitable to collect the biomass, while the second has to define the harvest procedures. Unfortunately, the above-mentioned plans are not available and so in this chapter we present a way to solve this problem.

5.1 Forestry management today and tomorrow

The forestry management adopted inside the study area is defined as the autopoiesis system approach namely those open system (the forest ecosystem), which is able to continuously define, sustain and reproduce itself. Indeed an autopoiethic system can be represented as a network of creation, transformation and destruction processes of components that interacting between each other they are able perpetually to sustain and regenerate the same system. Therefore, the system is self-defined or rather the existence domain of an autopoiethic system coincide with the topologic domain of its components. In substance, it should not be followed a purely economic management (maximize a harvest rate constant in time) but it should be evaluate individually on defined zones (few hectares) the procedure to follow for the harvest and especially the period between an operation and another one, called assessment. The economic forestry system and the autopoiethic one are showed briefly in table 5.1.

ECONOMIC FORESTRY SYSTEM	AUTOPOIETIC FORESTRY SYSTEM
Linear system, poor of alternatives.	Non-linear system, rich of alternatives.
Uniform and homogeneous system.	Mutable and irregular system.
MANAGEMENT	**MANAGEMENT**
The cultivation uniformity needs a centralized control in operation of the profit and the market.	The mutable cultivation needs a decentralized control and increase the value of the "local knowledge".
Forest rigidly structured into chronological or diametrical classes.	Forest unstructured, able to organize itself.
Products uniformity: principally wood.	Diversified products: wood among the others.
ECOLOGIC EVALUATION	**ECOLOGIC EVALUATION**
Stable and sustainable forestry system thanks to the introduction of energy, work and assets.	Autonomously stable, sustainable and renewable forestry system.
PRIMARY OBJECTIVE	**PRIMARY OBJECTIVE**
Economic productivity, return and value are independent from the ecosystem. Profit maximization with the commercial use of the forest.	Economic productivity, return and value are dependent from the ecosystem. The cultivation alternatives do not affect the forest equilibrium.

Table 5.1 Economic and autopoiethic system (Source: CRA, 2014)

Unfortunately, to this day the PIF and PAF are expired in the study zone and the newest are not ready yet. The Highland Community does the plan endorsement, but the authorities that can present a forest management plan can be, in addition to the HC for what concerns the state-owned land, the forestry consortiums formed by private citizens or farm enterprises. Anyway, the lack of this plan does not exclude the possibility to harvest the wood in the forest. The woodcutter has to present a declaration (done by an expert) on which it has to be specified:

- the dendrometric mass (in cubic meters);
- the interested surface (in hectares);

- the position;
- the tree type and age;
- the kind of forest management;
- who is harvesting;
- the land property;
- the end use of the wood;
- etc.

This declaration is registered in a geo-localized database and the information is available on Lombardy Region website. In the two HC, the cuts done in the last three years are about 3’000, for an interested surface of about 1’000 hectares and a volume of fresh wood of about 70’000 cubic meters. Using a specific volume of 0.6 Mg of dry matter over a cubic meter of fresh wood, we can estimate an amount of 40’000 Mg dm of wood harvested in the last three years (around 10 Mg dm ha^{-1} y^{-1}). The lack of information on the rotation of the cuts and the subsequently assessment let us make just an approximate analysis. Later, in case the interested surface is greater than 1 hectare, the declarant has to present an appropriate harvest project. In this latter situation, an ERSAF (forestry government authority) expert has the task of marking the three that has to be cut in a period of maximum five years. From an analysis of the previous cuts done in the area, it is possible to notice interesting information for the parcels definition:

- the surface interested by the harvest is correct with good approximation and it takes into account the slope of the ground, indeed it is a real surface and not projected on the horizontal reference plane;
- for sure, the forest analysis on the three characteristics (age, type) is more reliable than the data given by Lombardy Region from aero photo-interpretation;
- the harvest in those areas is possible and above all economically feasible, supposing that all the declarants have done a correct analysis on the harvesting costs assuming a wood market cost of 100 € Mg^{-1}dm.
- The irregularity of the harvest per hectare rate. We should obtain a constant value for every declaration at least in the same type of forest (broad-leaved, conifer, young, old, etc.) but it is not like this.

This last aspect probably is due both for the approximation of the dendrometric mass calculation and because there is no information about the rotation of the cuts (without an assessment plan PAF). The dataset covers the harvest done since 2011 until today. It is clear that either having a dataset covering for example 50 years (1-2 rotation for the high forest cuts and 3-4 rotation for the coppice ones) or having the PAF, it could give us more interesting information on the harvested biomass. Moreover, having a wider dataset should allow us to understand the maximum amount that could be cut, taking into account the assessment too. For sure we have information that not cover the whole cuts done in the area during the last three years and in some cases the harvesting rate is very high, supposing a massive exploitation. To understand how much wood per hectare it is possible to harvest, we use the results in table 5.2 of a previous thesis (Perego, 2009) on the forestry sustainable management in Lombardy Region that models the forest as an interaction between many subsystems (soil, litter, tree, etc.). The model takes into account different aspects such as the rotation, the induced mortality by the cuts operation, the average temperature, the precipitations, etc. The obtained results have to be intended in a scenario of maximization of two indicators:

- the captured CO_2 from the atmosphere and fixed to the soil;
- The avoided emission of CO_2 using the biomass as fuel for cogeneration plants as alternative to the use of natural gas.

TYPE OF TREE	**Harvest rate (m^3 dm y^{-1} ha^{-1})**	**Captured CO_2 (Mg CO_{2eq} $anno^{-1}$ ha^{-1})**
Broad-leaved	3.40	0.25
Conifer	5.52	0.07
Mixed	5.32	0.20
Short Rotation Forestry SRF	33.51	-0.11
Natural vegetation	3	0.17

Table 5.2 Sustainable management of the Lombardy forests (Source: Perego, 2009)

5.2 Parcels distance and its accessibility

To estimate the distance between two points (forest, possible plant) it is necessary that a road network connect them. Lombardy Region provides two layers, main road and secondary road, which are able to define partially the above-mentioned network. The first represents the major road that links the different villages, while the latter is the link between the village and that territory portion called in slang “to the mount”. The definition of this area has to be researched in the economic and social history of the study area. Until fifty years ago, the economy was primarily based on the stock rearing, fishing and commerce. In consideration of the territory structure, the zones most suitable for the pasture were represented by the extensive mountain areas over the actual villages. Indeed, often two living centres were present in every municipalities. The first relative to that portion of territory most suitable for the commerce, localized on the main road that run along the Como and Lugano lakes. The second one was that situated in between the mountain pasture and the commercial area mentioned before, avoiding a cold winter to the animals. These two layers are not enough to describe the whole road network. Therefore, we create a third road layer that complete the network called mountain road. It has been possible creating it using a hiking touristic map given by Kompass (a company that realize mainly touristic map) and digitalizing it on a software GIS to calculate the length (figure 5.3). The information on the digital terrain model at 20 meters (DTM-20m) has been used to approximate the length projected on the horizontal plane to the approximated one. Then, it is possible to extract the roads used for harvesting a large amount of wood evaluating the cuts position and dimension in terms of harvested area from Lombardy Region database. Indeed, we proceed dividing the layer mountain road into two subclasses defined by the availability to use tractors or small vehicles for the transportation of the raw material and the necessary equipment (figure 5.3). The roads suitable for tractor are the ones where in the last three years it has been harvested an area higher than 1 hectare and within a distance below 150 meters from the road. The roads suitable for small vehicles are the remaining part (in figure 5.2).

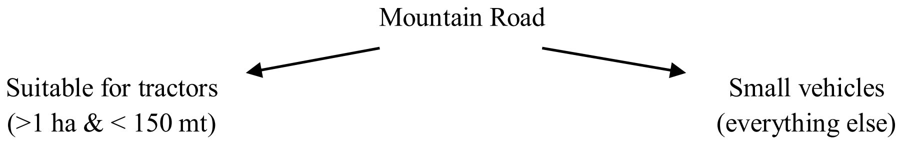


Figure 5.2 Conceptual division method of the Mountain road.

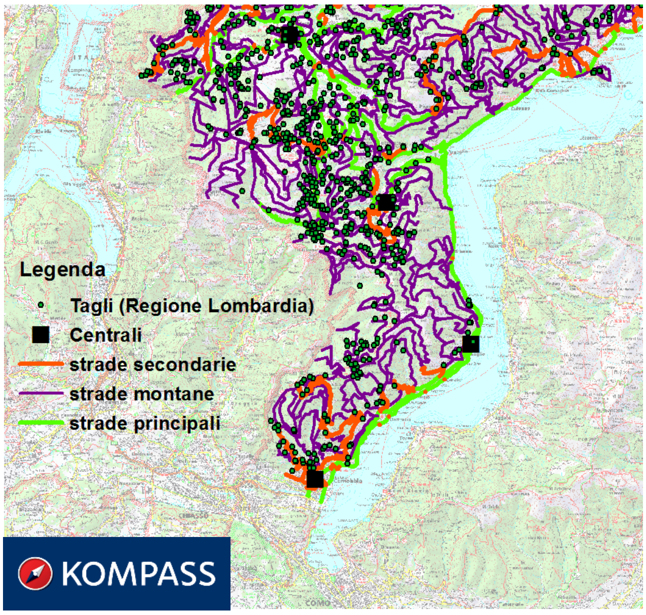


Figure 5.3 Mountain road creation (source: Kompass, 2014)

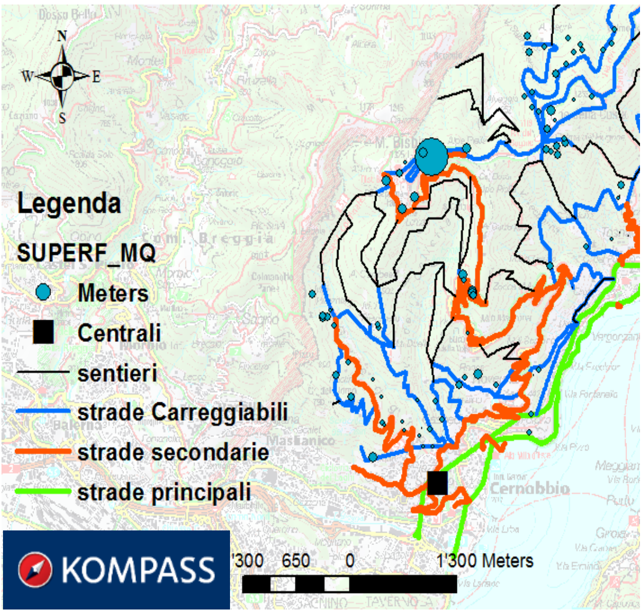


Figure 5.4 My road network (Source: Kompass, Lombardy Region, 2014).

After the four layers definition (main roads, secondary roads, tractors and suitable for small vehicles), Lombardy Region released in December 2014 another layer that defines the farm roads (Agro-Silvo-Pastorali, ASP). In this last road level, we have the information about the real position of the roads. Moreover, the layer contain the information about the size of the vehicles that can drive across it. Indeed, ASP is divided into wide roads suitable for tractor and narrow road suitable for small vehicle. Analysing the ASP with the tractors layer found implicitly, it is possible to say that:

- The method used in figure 5.2 it is right because with a good approximation the two layers coincide;
- Just few ASP are directly linked to the main and secondary roads, so there is a lack of information and they are useless without a connection to the main road network;
- The size of the vehicles that can drive across the ASP gives us an idea on the amount of wood that can be transported using that road and nevertheless, about the possibility to use the necessary equipment for the harvesting operations.

The final result is composed by just two road layers that characterize the entire network as shown in table 5.3.

Easy operation	**Hard operation**
Main road Secondary road Road suitable for tractors	Road suitable for small vehicles

Table 5.3 Final composition of the road network (Source: Kompass, Lombardy Region, 2014)

Now, we have to define the area where it is possible to harvest. We decide to create a buffer of 150 meters around the two layers. In this way, we obtain two defined areas classified by the difficulty to harvest the raw material and transport it to the plant (figure 5.6). The interested area for the easy operation is around 27’000 hectares and 9’000 for the hard one. The use of the adjective “easy” associated to the harvest in the study area does not mean that necessarily the operations is easy but it is just a way to define the actual distinction between the two classes reaching the parcel by wide vehicles.

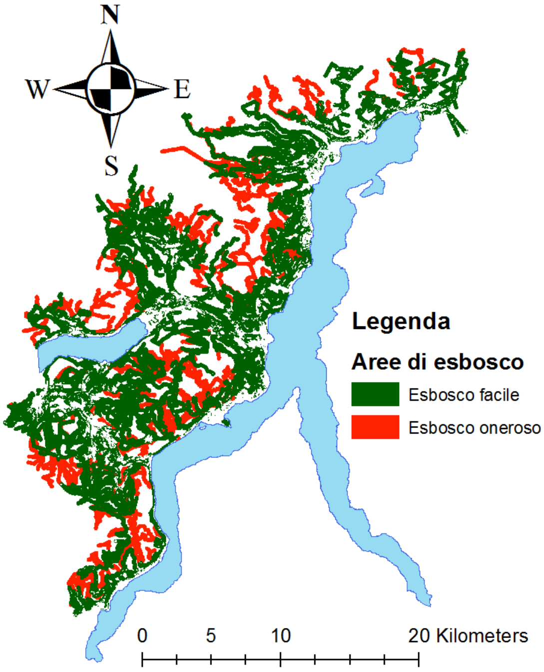


Figure 5.5 Definition of the two layers easy (green) and hard (red) operation (Source: Kompass, Lombardy Region, 2014)

Now it is time to define the costs of these operations: harvest and transportation. Thanks to literature data (Bernetti, 2003) it is possible to define the parameters (table 5.4) that describe the assumed linear function in figure 5.5 of the transportation cost over the distance referred to the two classes of vehicles used. Knowing the distance between the parcels and the plants it is possible to calculate the transportation costs. For what concern the harvest, finding the cost is a complex problem. The PIF should give some information about this aspect but even knowing it, we should make a deep analysis for every parcel taking into account: the slope of the ground, the possibility to use cableways, the time and the space needed for drying the wood, and so on. This aspect compete to an expert of forestry. We can just approximate that the different accessibility classes takes into account also a different harvest methods. For sure, we can say that reaching a parcel with a tractor it allows the woodcutter to use machineries with high efficiency in terms of high biomass harvested over the process cost. Nevertheless, using a price of 100 € Mg^{-1}dm that is the actual wood price in the study area for a good quality product, somehow takes into account all the cost for the harvesting operations because related to the cuts done in LR database even if they cover the 20% of the wood available in all the area. Indeed, we suppose that:

- for the easy operation we have a total harvest cost using the value reported in table 4.2 (100 € Mg^{-1}dm for a good quality wood, 180 € Mg^{-1}dm for pellet and 50 € Mg^{-1}dm for a bad quality wood)
- While for the hard operation, we have a charge of 20%.

Type of vehicle	**Accessibility to the parcel**	**Harvest price for good quality wood (€/Mg)**	**Transport parameter**	
			Slope €/(Mg km)	**Intercept (€/Mg)**
Tractor	Easy operation	100	0.17	0.83
Small vehicle	Hard operation	120	0.28	0.22

Table 5.4 Parameters used for the transport and harvest costs (Source: Bernetti, 2003).

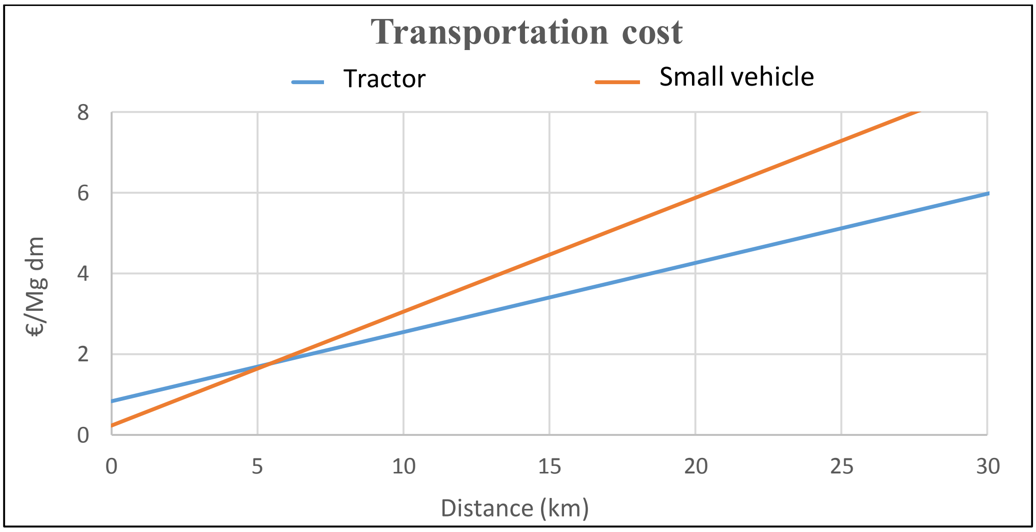


Figure 5.6 Linear function of the transportation charge for tractor and small vehicles (Source: Bernetti, 2003).

It is clear from figure 5.7 that the transportation cost has a low influence on the total harvest cost. For example we can see that for a distance of 5 km, the cost is around 2 € and it represents the 2% of an harvesting cost of 100 €/Mg dm. The highest distance from a parcel to a plant, it is around 70 km (the less probable situation), so the influence on the total operation cost by the transport is around 20% of the harvest charge. Below 5 km it looks like it is more convenient the usage of a small vehicle but since it is associated to a hard operation with an harvest cost of 120 €/Mg, in any case a small vehicle is less convenient than a tractor. Figure 5.8 shows the service area, namely the area that is possible to reach by covering a distance of 7 km.

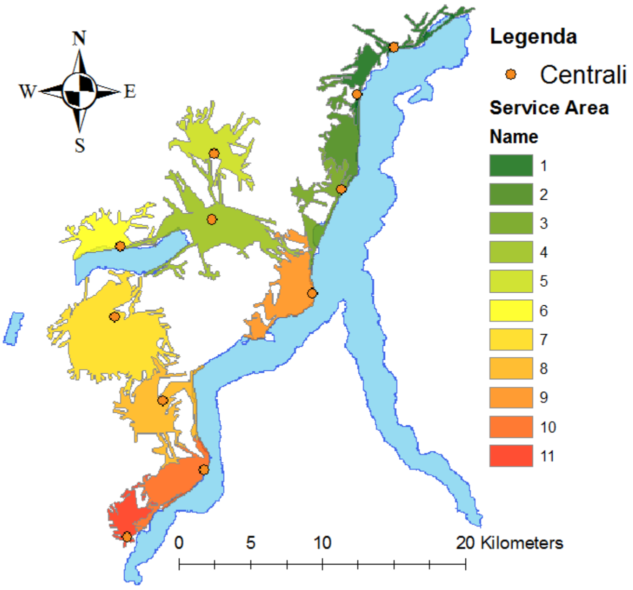


Figure 5.7 Service area of 7 km from the plants.

5.3 Biomass species

By monitoring the land use, Lombardy Region has started in 2001 the creation of a database called: "Land use of farmland and forestry" (DUSAF). This database is divided into five classes. From the first to the third, the classes are general: urbanized land, farmland, forest and natural environment. The fourth and the fifth level are local and its definition has been possible from other database, different from the photo interpretation. The information detail is coherent with the scale 1:10’000 and it is made by a polygonal component. To develop an exploitation model for the energy production from biomass, we have to determine those territory portions able to give the necessary biomass to the potential plants. For this reason, we extract the layers regarding the class 2 and 3, namely the farmland and the forest and natural environment. Nevertheless, we extract 4 subclasses from them, useful for our objective (showed in figure 5.9):

Conifer forest, Broad-leaved forest, Mixed forest and Natural vegetation.

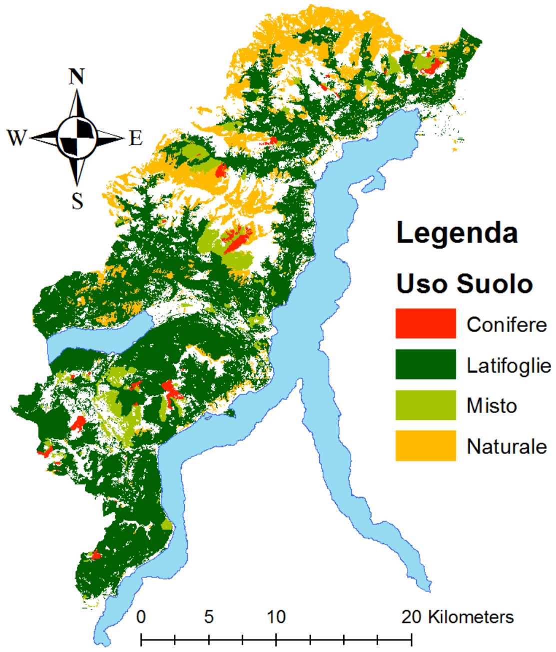


Figure 5.8 Areas defined by the forest species (Source: Lombardy Region, 2014)

It is possible to obtain (using the DTM20m) the total forest area divided by forest specie and consequently the amount of biomass that is possible to harvest in a sustainable way using the harvest rate in table 5.2. Thus, knowing the volumetric mass in table 5.5 it is possible to evaluate the total biomass that is present. The most distributed forest species is the broad-leaved one (figure 5.10), while the others species cover an area of few thousands of hectares.

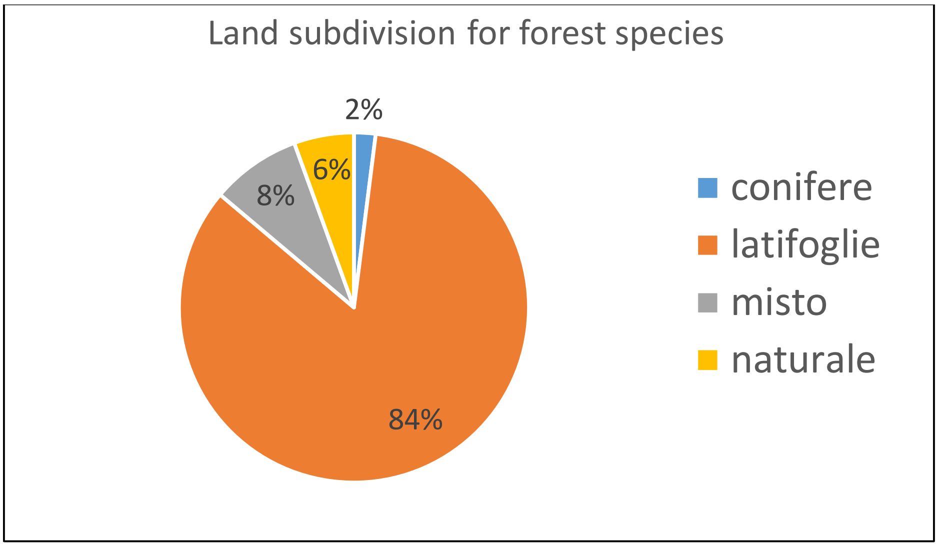


Figure 5.9 Land subdivision for forest species (Source: Lombardy Region, 2014).

5.4 The parcels

Finally, we have to define the parcels involved in the harvest. Thus, now we intersect the area defined by the roads and the one defined by the species of tree present. The first has a surface of about 36’000 hectares while the second has an area of about 50’000 ha. The intersected surface has an extension of about 27’000 ha. The surface has been intersected again with the 57 municipality boundaries. Indeed, we obtain a polygonal layer composed by 309 areas classified by: accessibility (easy and hard), surface (ha), the amount of wood to harvest in a sustainable manner and the municipality at which the parcel belong. It is possible to improve the analysis evaluating the average slope indicator. The value has been obtained from the knowledge of the DTM20m. A huge amount of the parcels (78% on the total surface) has an average slope between 40% and 80%. Thanks to the information used from the cuts (on Lombardy Region database), this high slope can be seen as an usual characteristics of the harvest condition in the study area. Indeed, extracting the worst situation that coincides with a slope higher than 80%, we obtain a layer of 200 polygons with an total surface of about 21’600 hectares (DTM procedure) .The total biomass available is around 53’000 Mg dm. Of course, some parcels are closer to some plants (figure 5.11). The final layer called “parcels” is simplified in 200 points classified by the amount of wood available, the accessibility and its position on the territory (in the middle of the original polygon). Transforming the layer from polygons to points it is possible to calculate the distance between every possible plants to the parcels using the GIS function “origins and destinations” that creates a matrix composed by 200 rows (the parcels) and 11 columns (the potential plants). In the next chapter, we see how to use this information to understand if the available biomass is economically suitable to feed the possible plants.

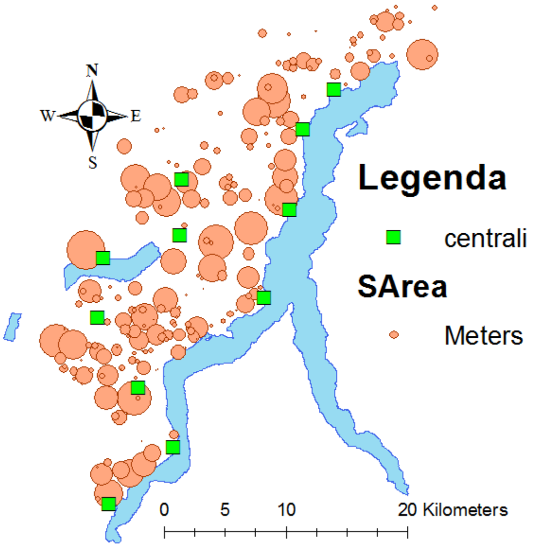


Figure 5.10 Spatial distribution of the parcels. The indicator is proportional to the surface (Source: Lombardy Region, 2014).

Forest species	Area (ha)	Harvest sustainable rate ($m^3 ha^{-1} y^{-1}$)	Dry volumetric mass ($Mg\ m^{-3}$)	Dry biomass ($Mg\ ha^{-1} y^{-1}$)	Total biomass ($Mg\ y^{-1}$)
Conifer	903	5.52	0.53	2.92	2’636
Broad-leaved	34’878	3.40	0.71	2.41	84’056
Mixed	3’600	5.32	0.62	3.30	11’880
Natural	10’419	3.00	0.59	1.77	18’440
	49’800				117’012
TOTAL	**21’000**				**53’000**

Table 5.5 Parameters used and the potential total biomass that could be harvested (Source: Perego, 2009; Lombardy Region, 2014).

Chapter 6

Decision support system model

A decision support system for forest biomass exploitation for energy production purposes is presented. In the proposed approach, geographic information system based techniques are integrated with mathematical programming methods to yield a comprehensive system that allows the formalization of the problem, decision taking, and evaluation of effects. The aim of this chapter is to assess the possibility of biomass exploitation for both thermal and electric energy production in the areas served by the plants, while relating this use to an efficient and sustainable management of the forests within the same territory. The decision support system allows for the locating of plants, it is realization and the computing of their optimal sizing. The sets are composed by:

- $i = 1...N$ parcels where it is possible harvest the biomass;
- $k = 1...K$ potential plants where it is possible to satisfy the thermal energy demand;
- $l = 1...M$ technologies that can be installed in every location.

The decisions variables necessary to describe the considered system and to define the objective function and the constraints are the following:

- ϕ_{ik} is the biomass quantity, in Mg y^{-1}, that is yearly sent to the *k*th plant from the *i*th parcel;
- u^l_k is a binary variable that is equal to 1 when the *k*th plant has the *l* technology (with l going from *1* to M types of technologies) and equal to 0 when no plants are economically suitable;
- CAP_k is the size of the plant expressed as primary power.

The M technologies that we are taking into account and the related parameters, they are the ones listed in chapter 4 (4.7). It is evaluated the situation of 50% and 100% of electric capacity factor.

6.1 Objective function

The objective function takes into account the costs and benefits of the decision throw the cash flows R_k in every possible kth plant. As we have seen before (equation 4.5) total harvest costs, transportation and plant costs are considered together with benefits from the sale of thermal and electrical energy and the green certificates. The objective function that has to be maximized is:

$$O = \sum_{k=1}^{K} R_k$$

Equation 6.1

Five components contribute to the definition of the cash flows R_k:

- P_k are the benefits deriving from the sale of the energy needed by kth possible plant;
- E_k is the extra profit on the sale of green certificates (Equation 4.3);
- M_k are the costs related to the plant installation and maintenance;
- H_k are the total harvesting costs;
- T_k are the transportation costs.

Thus, the overall objective to be maximized is:

$$O = \sum_{k=1}^{K} P_k + E_k - M_k - H_k - T_k$$

Equation 6.2

The energy production profits (for $k = 1 \ldots K$) can be determined as:

$$P_k = \sum_{l=1}^{M} u_k^l \left[C_{el} \left(CAP_k \, \eta_{el}^l \, CF_{el}^l \right) + C_{th} \left(CAP_k \, \eta_{th}^l \, CF_{th}^k \right) \right]$$

Equation 6.3

Where u^l_k is the binary variable for the technology option in the kth plant. l corresponds to:

- ORC, Gasification and Pyrolysis technology with 50% of capacity factor;
- ORC, Gasification and Pyrolysis with 100% of capacity factor;

C_{el} is the unit price of the sale of electric energy (0.16 €/kWh$_{el}$) and C_{th} is the unit price of the sale of thermal energy (0.10 €/kWh$_{th}$). CAP_k is the size of the kth plant ($k=1...K$) expressed as the primary power needed for the conversion process. Indeed, η^l_{el} is the electric efficiency whereas η^l_{th} is the thermal efficiency of the corresponding lth technology. For passing from the power to the energy and related cost, we need the capacity factor expressed as hours of working. So CF^l_{el} is the electric capacity factor of the lth technology and CF^k_{th} is the thermal capacity factor of the kth plant expressed as equivalent hour.

The extra profit E_k from the sale of the green certificates (for $k=1...K$) can be determined as:

$$E_k = B_{tot}\, S$$

Where S is the sale of the green certificates (10 € Mg$_{of}$CO$_2$) and B_{tot} is equal to:

$$B_{tot} = (B_{th}\, E_{th} + B_{el}\, E_{el}) - M^i_k\left(B_{tr}\, d^i_k + B_{hr}\right)$$

Thus, E_k (for $k=1...K$) can be rewritten as:

$$E_k = \sum_{i=1}^{N}\sum_{l=1}^{M} u^l_k\, S\left[B_{th}\left(CAP_k\, \eta^l_{el}\, CF^l_{el}\right) + B_{el}\left(CAP_k\, \eta^l_{th}\, CF^k_{th}\right) - \phi^k_i\left(B_{tr}\, d^k_i + B_{hr}\right)\right]$$

Equation 6.4

Where ϕ^k_i is the mass flux from the ith parcel to the kth plant and d^k_i is the distance from the ith parcel to the kth plant as well. The others parameters are referred to the equation 4.2.

The management and investment costs M_k (for $k=1...K$) can be defined as:

$$M_k = \sum_{l=1}^{M} u_k^l \left(\eta_{el}^l CAP_k(crf^l \, inv^l + man^l)\right)$$

Equation 6.5

crf^l is the depreciation factor for the lth technology. inv^l and man^l are respectively the investment and the management costs for the l technology expressed as electric energy (€/kWh$_{el}$).

The total harvesting costs (for $k = 1...K$) can be determined as:

$$H_k = \sum_{i=1}^{N} \sum_{l=1}^{M} u_k^l \left(CC_i^l \, \phi_i^k\right)$$

Equation 6.6

CC^l_i is the collection cost for the i parcel related to the lth technology utilization. Collection cost differs for easy or hard harvest operations and type of raw material needed for the technology option.

The transportation costs can be determined as:

$$T = \sum_{k=1}^{K} \sum_{i=1}^{N} \phi_i^k \left(m_i \, d_i^k + q_i\right)$$

Equation 6.7

Where m_i *and* q_i are respectively the slope and the intercept of the linear relationship between distance and the harvest cost in the ith parcel (accessibility).

6.2 Constraints

A constraint has to be set on the binary variable u to impose that only one or none technology it can be installed in the kth location:

$\sum_{l=1}^{M} u_k^l \leq 1 \qquad k = 1...K$

Equation 6.8

On the technology range size (BEER) in MW:

$$\sum_{l=1}^{M} u_k^l \left(\frac{CAP_{min}^l}{\eta_{el}^l}\right) \leq CAP_k \leq \sum_{l=1}^{M} u_k^l \left(\frac{CAP_{max}^l}{\eta_{el}^l}\right) \qquad k = 1 \ldots K$$

Equation 6.9

Every technology has a minimum size CAP^l_{min} and a maximum size CAP^l_{max} we use the values from the BEER report (table 4.1).

On the energy conservation in the *k*th plant:

$$\sum_{l=1}^{M} u_k^l \left(CAP_k\, CF_{el}^l\right) \leq \sum_{l=1}^{M} \sum_{i=1}^{N} u_k^l \left(\phi_i^k\, LHV^l\right) \qquad k = 1 \ldots K$$

Equation 6.10

With LHV^l different for every type of raw material entering in the technology. Depending on the raw material quality, we assume that LHV is equal to: bad quality as input 3.4 MWh/Mg dm and 4 MWh/Mg dm for a good quality wood.

On the mass conservation in the *i*th parcel (Mg):

$$\sum_{k=1}^{K} \phi_i^k \leq M_i \qquad i = 1 \ldots N$$

Equation 6.11

A constraint has to be imposed to avoid the overexploiting of a parcel. M_i is the total mass in the *i*th parcel.

On the thermal power produced in the plant (MW):

$$\sum_{l=1}^{M} u_k^l \left(CAP_k\, \eta_{th}^l\right) \leq D_{th}^k \qquad k = 1 \ldots K$$

Equation 6.12

Where D^k_{th} is the thermal energy demand, a percentage of that estimated for the *k*th location.

On the total electric energy produced in the area (MWh):

$$\sum_{k=1}^{K} u_k^l \left(CAP_k\, \eta_{el}^l\, CF_{el}^l\right) \geq E\, D_{el}$$

Equation 6.13

Where E is equal to 15% and it is the percentage of the electric energy produced over the total demand of electric energy expressed as D_{el} (MWh).

On the economic feasibility of the investment:

$$P_k \geq \sum_{l=1}^{M} u_k^l \left(CAP_k\, \eta_{el}^l\, inv^l\, p^l\right) \qquad k = 1 \ldots K$$

Equation 6.14

With this last constraint, we impose that the payback period has to be around 10 years. The profit in the *k*th location has to be higher than a fraction of the investment cost through the parameter p^l. This last percentage is equal to 16% for all the technologies (using a sale for the electric energy equal to 0.16 €/kWh). The value has been calibrated during a trial and error phase. It is not possible to have better result because the software used to implement the model does not allow the excel lookup function for an automatic search of the payback period.

6.3 Software implementation

The type of model we implement is called "Multi Integer Linear Programming" (MILP) because we have 66 integer variables and the relations between the others variables (the parcels and the capacity) are linear. The software in use is "What's*Best!*" given by Lingo system as student version with unlimited capacity (constraints, variables, etc.). It is and add-in for the Excel spreadsheet. The software allows setting a number of options controlling the function of the integer solver. To understand the operation of the integer options, it is useful to understand how integer problems are usually solved. What's*Best!* solves integer problems using the following steps:

- What's*Best!* begins by solving the *continuous relaxation* (i.e. the original solution with integer restrictions removed). This gives a theoretical limit on the objective to the true integer model, because the objective of the integer restricted model could never be better than the objective of the continuous approximation.

- After solving the continuous approximation, What's*Best!* uses a process called *branch-and-bound* to find the optimal integer solution. Branch-and-bound implicitly enumerates all possible integer solutions in an intelligent manner, minimizing the number of solutions that have to be explicitly examined. However, the number of potential solutions grows exponentially with the number of integer adjustable cells. Thus, a model with a large number of integers it may take a *very long time* to solve.

Branch and bound (BB) is an algorithm design paradigm for discrete and combinatorial optimization problems, as well as general real valued problems. A branch-and-bound algorithm consists of a systematic enumeration of candidate solutions by means of state space search: the set of candidate solutions is thought as forming a rooted tree with the full set at the root. The algorithm explores branches of this tree, which represent subsets of the solution set before enumerating the candidate solutions of a branch. The branch is checked against upper and lower estimated bounds on the optimal solution, and it is discarded if it cannot produce a better solution than the best one found so far by the algorithm. The method was first proposed by A. H. Land and A. G. Doig in 1960 for discrete programming, and has become the most commonly used tool for solving NP-hard optimization problems (Non-deterministic Polynomial-time hard). The name "branch and bound" first occurred in the traveling salesman problem.

Options such as the optimality tolerances set limits upon how exhaustively this branch-and-bound search will be carried out. *Optimality Tolerance* is particularly useful in some integer problems as a means of significantly decreasing the solution time. Using the *Direction* drop-down box in the *Branching* box allows to govern the preferred direction of branching. Branching occurs when the branch-and-bound manager forces an integer variable that is currently fractional to an integer value. When the branching direction is set to *Up*, the branch-and-bound manager will branch on a fractional integer variable by first forcing it to the next largest integer. The reverse is true when this option is set to *Down*. When the option is set to *Both*, the branch-and-bound manager makes an educated guess as to the best initial branching direction for each fractional variable. The default setting is *Both*.

Due to the potential for round-off error on digital computers, it is not always possible to find exact integer values for the integer variables. The two tolerances in the *Integrality* box, *Absolute* and *Relative*, control the amount of deviation from integrality that will be tolerated. Specifically, if *I* is the closest integer value to *X*, *X* will be considered an integer if:

- $|X - I| <=$ *Absolute Integrality Tolerance*.

The default value for this tolerance is .000001. Although one might be tempted to set this tolerance to 0, this may result in feasible models being reported as infeasible.

Concerning the relative integrality tolerance, if *I* is the closest integer value to *X*, *X* will be considered an integer if:

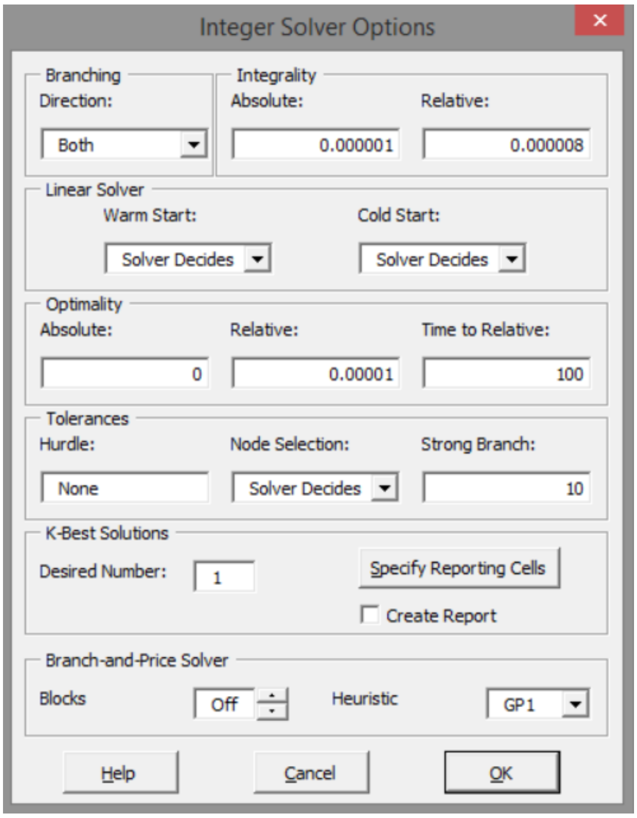
- $|X – I| / |X| <=$ *Relative Integrality Tolerance*.

The default value is .000008. Although one might be tempted to set this tolerance to 0, this may result in feasible models being reported as infeasible.

When solving a mixed linear integer programming model, the branch-and-bound solver solves a linear programming (LP) model at each node of the solution tree. The two options in the *LP Solver* box, *Warm Start* and *Cold Start*, control this choice of LP solver based on whether there is a starting basis (warm start) or no starting basis (cold start). It is possible to use the *Warm Start* option to control the linear solver that is used by the branch-and-bound solver at each node of the solution tree when a starting basis is present to use as an initial starting point. The *Cold Start* option, discussed below, determines the solver to use when a previous solution does not exist. The available options are:

- *Solver Decides* – What'sBest! chooses the most appropriate solver.
- *Barrier* – What'sBest! uses the barrier method.
- *Primal* – The primal solver will be used exclusively.
- *Dual* – The dual solver will be used exclusively.

In general, *Solver Decides* will yield the best results. The barrier solver can't make use of a pre-existing solution, so *Barrier* usually won't give the best results. In general, *Dual* will be faster than *Primal* for re-optimization during branch-and-bound.



Branching
Direction: Both

Integrality
Absolute: 0.000001
Relative: 0.000008

Linear Solver
Warm Start: Solver Decides
Cold Start: Solver Decides

Optimality
Absolute: 0
Relative: 0.00001
Time to Relative: 100

Tolerances
Hurdle: None
Node Selection: Solver Decides
Strong Branch: 10

K-Best Solutions
Desired Number: 1
☐ Create Report

Branch-and-Price Solver
Blocks: Off
Heuristic: GP1

Figure 6.1 Integer solver dialog box of the What's*Best!* Software (Source: Lindo, 2015)

It is possible to use the *Cold Start* option to control the linear solver that is used by the branch-and-bound solver at each node of the solution tree, when a previous solution is not present. In this way, we initialize the variables that will be used in the *Warm Start* option, discussed above.

Chapter 7

Results and conclusions

As we have seen in the last paragraph of the previous chapter, we need to initialize all the variables (cold start) to allow at the model to find a solution. We remove the constraint on the thermal energy produced D_{th} (equation 6.12). The others parameters of the Integer Solver Options dialog box (in figure 6.1) they are set to the default value. The result is in table 7.1. The system is composed by 2 ORC plants with 100% of electric capacity factor and they need as input in the transformation process the 93% of wood available. The electricity produced it covers the 21.6% of the whole demand E_{el}. These locations could be seen as:

- the ones with the best position regardless of the parcels;
- the plants with the best thermal demand configuration on the territory in spite of all the others potential locations.

The plants are located in: San Siro (3) and Porlezza&Carlazzo(4).

Plant	Technology	Thermal energy produced (%)	Size (MW_{el})	inhabitants	tourist	PBP	IRR
3	ORC	235%	0.88	7061	1804	10.0	5.4
4	ORC	159%	2	7614	6460	10.0	5.4
Electricity produced 21.6% of the demand							
Wood used 93%							

Table 7.1 Results of the cold start implementation.

The plant located in San Siro it produces more than two times the energy requested in that area. This result is not acceptable because for the model, the thermal energy is sold even if the production is higher than the request. It is interesting to notice that the selected plants have a high touristic vocation. The plants having a high thermal capacity factor they are in advantage in spite of the others. However, also the position of the plants in spite of the parcels it is important. In fact, the plants selected are those having a central position on the territory (figure 3.6). We save this configuration as initialization of the variables.

7.1 Warm start

After the cold start initialization, it is possible to perform the real optimization of our model. We add the constraint removed before on the thermal power needed (MW) in every potential locations and we set the value E (% request of electric energy) to 10%. The parameter S that accounts for the green certificates (equation 6.4) is equal to 10 €/MgCO_2. The results are shown in table 7.2.

Plant	Technology	Thermal power (%total request)	Size (MW_{el})	PBP	IRR
3	ORC	100%	0.37	9.4	5.9
4	ORC	100%	1.26	9.4	5.9
Objective function (10^6 €)			1.56		
Harvest/Transport Cost (10^6 €)			1.4/0.07		
Electricity produced			12.3%		
Wood used			53%		

Table 7.2 Model results of the warm start configuration.

The plants selected are still the n.3 and n.4. The electricity produced is equal to 12.3% of the total request and the wood used is equal to 53% of the availability. We do not obtain an extraordinary amount of electric energy but the biomass used is about half of the availability. This is a good result, because the uncertainty related to the estimation of the obtainable biomass it is very high as well as the cost of harvesting, equal to 1.4 million of euro. This last information is very important to understand, in collaboration with the Highland Community and the forestry consortium, if this amount of money it is enough to harvest that amount of wood. The methodology used to determine the biomass availability it is just an approximation of the real biomass accessible at that harvesting cost. For a better interpretation of the results, we should try to do not harvest all the biomass available. Moreover, we want to give to the environment a central position while determining the economic feasibility of this study. The transportation cost is equal to 70 thousands euro, a small amount compared to the objective function equal to 1.56 million of euro. This value is referred to the sum of the two cash flows of the plants. The payback period and the internal rate of investment it is equal for both the plants. Indeed, the two plants have the same economic performance. Figure 7.1 shows the biomass exploitation and the parcels that feed the plants.

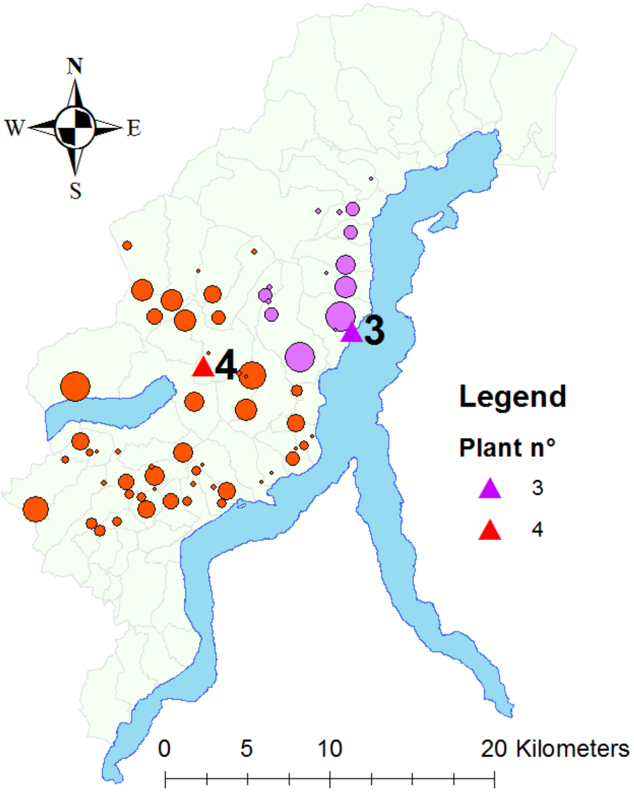


Figure 7.1 Biomass harvested for a production of 12.3% of electric energy. The symbol size is proportional to the amount of wood (Mg).

7.2 How the incentive affects the system

It is not possible to increase the electric energy produced over the 13% with the assumption done on the sale price of the electric energy (0.16 €/kWh_{el}) and on the value of the green certificate (10 €/$MgCO_2$). Regarding the first aspect, it is possible to evaluate a particular situation. In Italy, during the past years, we had an increase of the ORC installation thanks to the incentive on the sale of the electric energy. It was equal to about 0.28 €/kWh_{el} (0.36 € minus the conversion efficiency for plant of 1-2 MW_{el} size). Thus, we want to understand how our system changes if we take into account this value of sale. It is a way to understand how we could behave just five years ago, when on the market and at that range size, there was simply the ORC technology. So we perform another run of our model, taking into account only the ORC technology and the values of the green certificates they are equal to zero, while the price for the sale of electric energy it is equal to 0.28 €/kWh. The results are shown in table 7.3.

Plant	**Technology**	**Thermal power (%total request)**	**Size (MW_{el})**	**PBP**	**IRR**
2	ORC 100	100%	0.41	3.8	21
4	ORC 100	100%	1.26	3.8	21
6	ORC 50	100%	0.46	7.4	8.6
8	ORC 50	100%	0.30	8.6	6.9
10	ORC 50	100%	0.26	7.7	8.2
11	ORC 50	100%	1.83	7.7	8.2
Electricity produced 23.2% of the demand					
Wood used 100%					

Table 7.3 Results using a sale price of 0.28 €/kWh_{el} and only ORC technology.

Using a so high price for the sale of electric energy it allows to produce 10% more of the electric energy than the previous simulation (table 7.2) and the system harvests all the wood available. The ORC 50 becomes convenient and we are satisfying the thermal demand of 6 municipalities. The simulation gives an idea of the maximum amount of electric energy that is possible to produce by using all the available biomass and the ORC technology. In fact, if we try to perform the same analysis but adding also the gasification and pyrolysis system we obtain the results shown in table 7.4.

Plant	**Technology**	**Thermal power (%total request)**	**Size (MW_{el})**	**PBP**	**IRR**
1	GASS	23%	0.75	3.8	20.9%
2	GASS	60%	0.75	3.8	20.9%
3	GASS	65%	0.75	3.8	21.2%
4	GASS	19%	0.75	3.8	21.0%
5	PYRO	90%	0.74	4.5	16.8%
6	GASS	53%	0.75	3.7	21.3%
7	GASS	85%	0.75	3.9	20.5%
8	GASS	82%	0.75	3.9	20.4%
9	PYRO	100%	0.59	4.4	17.6%
10	GASS	95%	0.75	3.8	20.9%
11	GASS	13%	0.75	3.9	20.4%
Electricity produced 60.7% of the demand					
Wood used 100%					

Table 7.4 Results using a sale price of 0.28 €/kWh_{el} and all the technologies.

By using all the available wood, it is possible to produce 60% of the electric energy requested with this configuration. This is due to the high electric efficiency of the technology but also thanks to the high LHV of the wood used in the gasification and pyrolysis plants. We assumed that by increasing the harvesting costs, it is possible to increase the energetic content of the wood. Therefore, the harvest costs is very high but we give to the raw material a higher energetic value. We do not completely satisfy the demand in every plant, but we install 11-district heating. This aspect can be positive because we do not know how the thermal demand will be in future. For sure, the energetic performance of buildings will tend to rise. Consequently, the thermal load diagram could be more regular with a lower peak. We notice that the plant size is equal to 0.75 for many locations. The results are influenced by the constraint on the range size of the gasification and pyrolysis technology (equation 6.9). The data shown in table 7.4, it represents the utopia point because there is no more a sale of the electric energy equal to 0.28 €/kWh$_{el}$. Today, the green certificates have to help the overall feasibility of an investment on renewable energy.

7.3 Sensitivity analysis on the green certificates

The whole quantity of electric energy requested in the areas served by the potential plants, it has been calculated as half of the Italian demand (around 6000 kWh/y/p). Indeed, we used a request of electricity equal to 3000 kWh/y/p. Now, we are searching a solution able to reach the domestic demand (around 1200 kWh/y/p), meaning that E has to be around 40%.

Even the social aspect is important. The realization of a plant for the production of energy from wood, it is able to start and to close a hypothetic supply chain linked to the forest. A starting point could be the creation of farm enterprises able to harvest the biomass. Meaning new job opportunities, even for people with problems (social enterprises). A biomass plant can be the last chain when for example it can be fed by vegetable waste from gardener or from carpentry and others sectors such as the food chain. Others activities can start with the investment on energy from renewable sources. By the way, we need others incentives, throw the green certificates. Therefore, we perform a sensitivity analysis to understand how the parameter S it has to be to obtain an energy production equal to around 40%. The results are shown in table 7.5 and in figure 7.2.

** Sale of electric energy 0.028 €/kWh (only ORC)
*** Sale of electric energy 0.028 €/kWh

S Green certificate (€/MgCO2)	0 **	0***	10	20	30	40	50	60	70	80
Electric energy %	23.2	60.7	12.3	20.1	23.2	23.2	23.2	38.3	49.2	60.1
Number of plants	6	11	2	3	4	5	7	9	10	11
Obj. function(10^6 €)	6.08	10.4	1.56	2.77	2.62	3.64	5.85	5.73	5.54	6.15
Harvest %	100	100	53	87	100	100	100	100	100	100
Cost of harvest/ transport	2.7/ 0.17	5.47/ 0.12	1.4/ 0.07	2.3/ 0.15	2.7/ 0.18	2.7/ 0.19	2.7/ 0.15	3.8/ 0.14	4.6/ 0.15	5.4/ 0.12

Table 7.5 Sensitivity analysis on the parameter S

Starting from the simulation done before with S equal to 10 €/MgCO_2, we increase the incentives at 20 and 30 €/MGCO_2. In this range, we are approaching the maximum amount of electric energy that can be made by ORC technology (the 0** case). For S equal to 40 and 50 the model increases the number of ORC plants and therefore the thermal energy satisfaction. Nevertheless, since there is a wood availability limit, the electric energy does not change. From figure 7.2 it is possible to see that at S between 50 and 60 €/MgCO_2 there is a sudden change of behaviour. We reached the S value at which the extra economic profit obtained throw the green certificates it is enough to invest in high electric efficiency technology (Gasification and Pyrolysis). By increasing again the S value, we understand that we are approaching the result 0*** obtained in table 7.4, namely with a selling price of the electric energy equal to 0.28 €/kWh.

We want to focus on the production of an amount of energy equal to the domestic demand and so we represent the results of the simulation with S equal to 60 €/MgCO_2 (table 7.6) while in figure 7.3 is shown the biomass harvest.

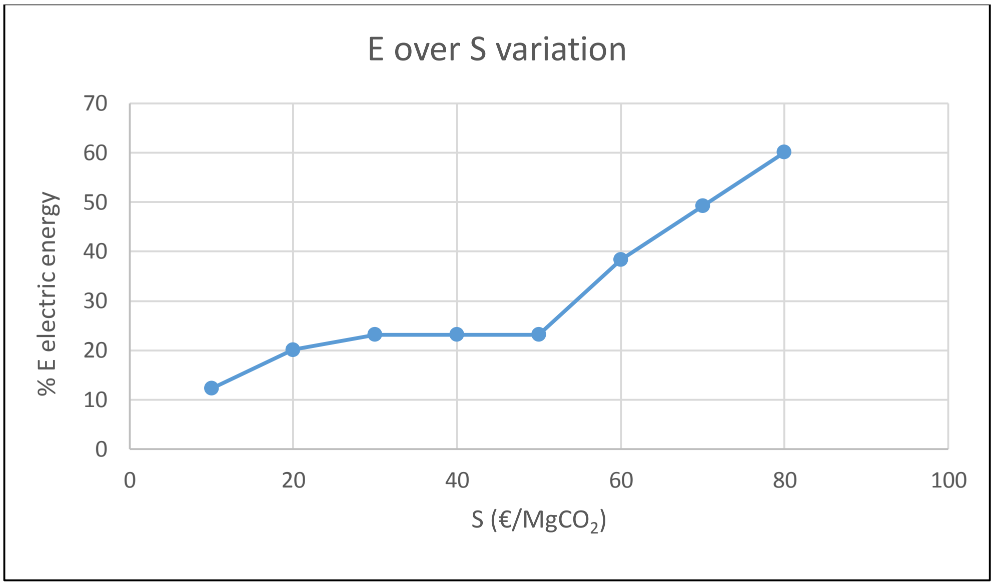


Figure 7.2 Graph of the Electric energy production (E) over the green certificates value (S).

Plant	Technology	Thermal power (%total request)	Size (MW_{el})	PBP	IRR
1	ORC 50	100%	1.05	8.5	7.0%
2	ORC 50	100%	0.41	8.8	6.6%
3	GASS	65%	0.75	9.3	6.1%
4	ORC 50	100%	1.26	8.8	6.7%
5	GASS	81%	0.54	9.8	5.6%
6	GASS	53%	0.75	9.7	5.7%
9	GASS	100%	0.47	9.0	6.4%
10	GASS	95%	0.75	9.6	5.7%
11	ORC 50	52%	0.95	9.4	5.9%
Electricity produced 38.3% of the demand					
Wood used 100%					

Table 7.6 Model results adopting the green certificates S equal to 60 €/MgCO$_2$

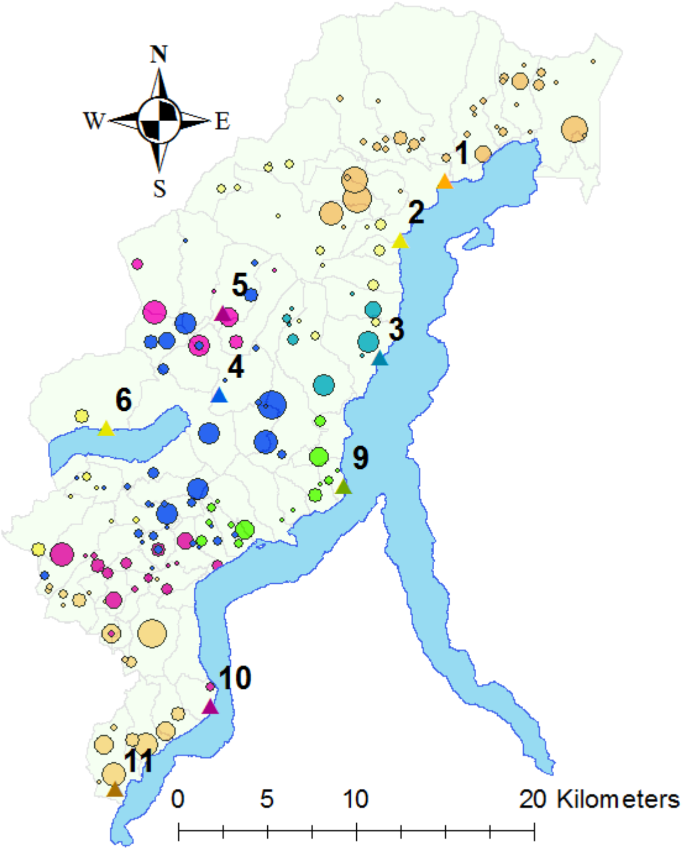


Figure 7.3 Distributed system for a production of 38.3% of electric energy. The symbol size is proportional to the amount of wood (Mg).

7.4 Conclusions

The final result of this project it is obtained with a production of electric energy equal to 12.3% of the demand, with a sale price equal to 0.16€/kWh$_{el}$ and 10 €/MgCO$_2$ for the green certificates. This is the lower bound of the model. Increasing the green certificate contribution, we understand that the value it has to be higher than a certain point to allow the installation of 2nd generation technology for energy production from wood, such as gasification and pyrolysis. The high efficiency and the need of more treatments of the raw material, it allows to use the available biomass in a more efficient way, reaching the domestic demand of electric energy from the population living in the 11 potential plants. In the case study, we are exploiting the forest resources belonging to 57

municipalities (around 70’000 inhabitants) to produce 12.3% of the electrical demand from 11 municipalities (38’178 inhabitants and 16’317 day-beds). It is easy to say that if we really want to do something for the climate change and upgrade our Italian energetic system, in terms of independency from the market oil price and from foreign countries, we have to invest resources in the efficient systems for the energy conversion and utilization. By the way, even the ORC technology can be a good starting point. The economic profitability of an ORC plant is a positive aspect. The high cost of a district heating can be repaid quickly by this solution.
Finally, we understand that we have to evaluate the size of the plant and the overall profitability of the investment considering:

- the thermal demand will tend to decrease by increasing the energy efficiency parameter of buildings;
- we should try to use the thermal energy as much as possible (e.g. tri-generation, food-chain, pellet production), looking for a flat load diagram;
- the forest resource needs maintenance, evaluating the assessment after the harvest and, if managed in the proper way, the short-rotation forestry can help the overall system to reach a significant electric production.

An implementation of a distributed system for the production of energy it creates job opportunities, such as for woodcutter, carpentry, farmers and so on. Meaning that funds in the Italian productive energetic sector, they are the starting point to let the economy be more independent from the market and self-sufficient.

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