Bioenergy resources from waste, energy crops and forest in Los Ríos Region (southern Chile) - A systemic approach based on sustainability on designing a bioenergy area

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Index

General Index

Index of Figures

Index of Tables

IN APPENDIX

1 Summary

As many countries today, Chile is facing the taking off of renewable energies. Los Ríos Region in south-central Chile shows one of the highest biomass productivity. Therefore, in the quest for a scientific analysis of sustainable solutions a research question was set, to look for *the best, most sustainable bioenergy production concept that could be developed in Los Ríos Region.* To answer the research question, systemic multiscale quantitative/qualitative multi- and inter-disciplinary processes of selection and elimination of alternatives are carried out. This process follows a classical discarding method to obtain the best bioenergy alternatives. Every step corresponds to a chapter in the text as follows:

Total possibilities: The limitations of strictly quantitative approaches are explored. In order to get solutions, these approaches have to be complemented with qualitative and transdisciplinary methods

General quantitative level: The results of the international research on sustainability and techno-economic performances of different biofuels are compiled. As particular methodologies result in different formats, the information is gathered and processed by a synthesis method. Relevant differences among different biofuels are found, but also differences among results of different authors regarding the same biofuels. The ranking of the studied biofuel according to their environmental performances give the following order from best to worst: biofuels from residues (liquids and gaseous, including all biofuels from lignocellulosic biomass), biogas, biodiesel and bioethanol. Specific crops and geographic conditions may change the ranking in specific cases. Correlations are found between greenhouse gas (GHG) reduction and cultivation systems, as well as GHG reduction and the output/input energy ratio.

Prioritized qualitative level: Components of a bioenergy system are selected according to local specifications. With such a set of selected components, a network analysis using Ucinet-Netdraw software is carried out (Borgatti, S.P., Everett, M.G. and Freeman, 2002), from which an index of network connectivity is developed for every energy carrier analysed. Among biofuels, biomethane has the best score, followed by syngas and alcohol in second place.

Regional quantitative level: The biomass and bioenergy potential of the Los Rios Region is estimated for energy crops, urban and industrial organic waste and slurry from cattle production. The program BioStar is successfully validated for the Region and then used for modelling the productivity of energy crops. The results suggest that about 332,400 hectares, equivalent to 18.1% of the region's surface area, currently covered dominantly by grasslands, could potentially be used to grow energy crops. This area could provide 2,96 million m^3 of biogas from wheat or 4,98 million m^3 from maize. In a region that consumes 553 GWh and produces 771 GWh of electricity, the potential production of electricity from cogeneration of biogas could be 6,809 GWh from wheat or 11,449 GWh from maize respectively. Therefore, the electricity that could be produced from maize in this region would account for over 20 times the consumption of the region, equivalent to 19% of the national electric production. Maximum yields of 22.1 t DM/ha for wheat and 33.9 t DM/ha for maize are calculated, which is similar to the empirical data in the region. Regarding cogeneration of other sources, the regional potentials are: Industrial and urban organic residues 71.5 GWh, slurry (theoretical maximum) 560 GWh.

Local qualitative level: The German bioenergy village concept is tested for Los Ríos Region. The heat from biogas of a heat and power cogeneration unit can be sold in Germany for a considerably higher price than in Chile. After a qualitative analysis, three alternatives for bioenergy village concepts are proposed: a) BEV1, a rural village with a (non-electric) biogas

network, b) BEV2, an urban area with a heat network, and c) BEV3, an urban community with cogeneration of power and heat from organic municipal solid waste (OMSW). BEV1 would allow each family to reduce their firewood demand by 62% by changing the type of stove and using green biomass (grass or crops silage) from 140 to 1,200 m^2 for completely energy self-sufficient cooking and drastically reducing air pollution at the same time. BEV2 would provide more energy efficiency and comfort, but needs urban settlements. BEV3 is presented in detail in the next level.

***Local quantitative level**:* A quantitative study of the biogas potential from the organic fraction of Valdivia's waste is performed with the goal to make the Isla Teja campus of the Universidad Austral de Chile in Valdivia (UACh) independent of external power sources. The sustainability performance of such a system is compared for three situations: S0) the current situation, S1) an energy crop based system, and S2) an OMSW based system. As was expected, the sustainability performance of the energy supplied by biogas from crops was positive in relation to the current situation, but the energy production from OMSW was much more sustainable concerning land use, noxious gases, transportation, water and soil pollution, as well as nutrient recycling. The greenhouse gas (GHG) reduction of the energy crop-fed campus is positive or negative depending on whether or not indirect land use changes are considered in the calculations. However, an outstanding GHG reduction of 940% is reached when using OMSW, since the release of methane gas from the landfill is avoided. Finally, an energy crop-fed campus would reduce its energy costs by 30%, whereas an OMSW-fed campus would increase them by 59%.

Epistemological considerations: This chapter explores the limitations of quantitative and disciplinary approaches in complex, inter or transdisciplinary problems, and suggests ways to overcome such limitation. Among the findings can be mentioned that the level of complexity of the problem analysed do not allow a strict scientific demonstration of the "best" performances obtained. In part that is so because of the multidisciplinary nature of the problem, in which disciplinary demonstrations are incomplete. Demonstration is commonly restricted to a final stage of the research exercise, whereas the problem definition and election of the research method are not subjected to demonstration, being simply defined from consensual criteria. As the main problem involves applied sciences, design is involved in the process. By definition, the design of a solution give always the "best" solution, as is at the core of the solving process. However, as a cognition is also a historical/evolutionary process, every design process give the "best" solution in relation to its context regarding cultural, economic, scientific, etc. Under this perspective, the use of a model of network analysis allowed to process qualitative and transdisciplinary, as well as quantitative and disciplinary information, resulting in a useful tool for dealing with such complex topic.

2 Abbreviations

BEV: Bioenergy Village
BtL: Biomass to Liquid (Fischer-Tropsch reaction)
CHP: Heat and power cogeneration unit
CO_2eq: Carbon dioxide equivalent
DM: dry matter
dm: decimetre (10 centimeters)
GHG: Greenhouse gases
GWh: Gigawatt hours
GWP: Global warming potential
LCA: Life Cycle Analysis
LPG: Liquefied Propane Gas
LUC: Land Use Change
OMSW: Organic Municipal Solid Waste
SIC: Central Interconnected Electrical System of Chile
UACh: Universidad Austral de Chile

3 Introduction

Population growth and human overtake of the planet have caused an unprecedented global change. The resulting environmental alterations have deeply modified the physical and biological boundaries (atmosphere, hydrosphere, pedosphere and biosphere) of the planet. Manmade changes are so significant that for the most recent epoch the term Anthropocene was chosen by a growing group of scientists (Waters et al., 2016).
Climate change is only one characteristic of global change, but according to the United Nations, without a massive change of human behaviour regarding energy and land use, catastrophic feedback loops of the global climatic drivers will be triggered, with dramatic consequences for humanity and life as a whole (IPCC, 2011a). The Los Ríos Region, in southern Chile, has already perceived the effects of climate change, as is shown in Figure 1.

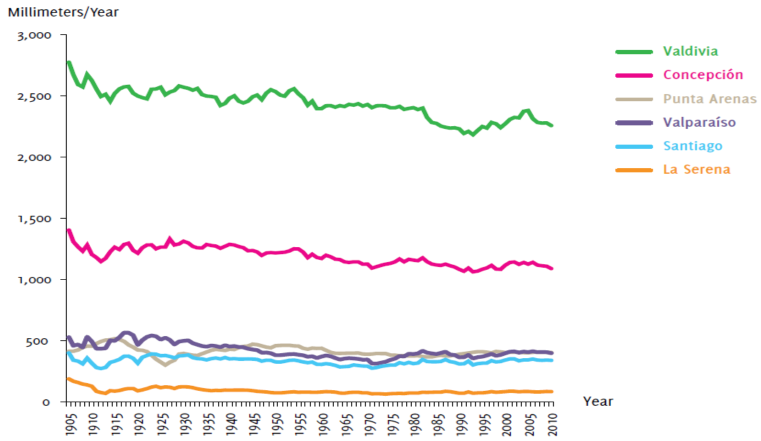

Figure 1: Rainfall of main Chilean cites for the last 100 years. Valdivia, the capital of Los Ríos Region, has shown the highest absolute reduction in the amount of rainfall.

If the emissions of GHG continue, it is expected that the rates of some changes will increase, according to the non-linearity of climate dynamics (IPCC, 2012). Recent studies suggest for 2100 an eventual rise of temperature to 2.5 to 3.5 degrees Celsius as well as a reduction of 15 to 30% in rainfall. For a schematic forecast of climate change in central-southern Chile during this century see Figure 2.

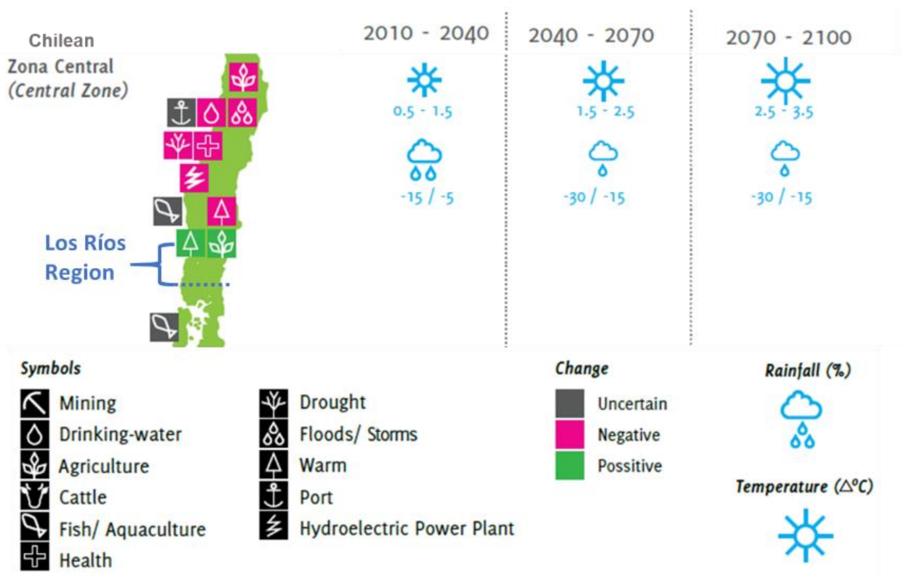

Figure 2: Schematic representation of impacts on climate change and their relation to future climate projections (MMA, 2012). Rainfall numbers are given in %.

Although Chile is only responsible for 0.26 percent of the total world-wide GHG emissions, it is ranked as 44 out of 186 countries. Also, Chile obtains its energy mostly from fossil fuels, as shown in Figures 3 to 5. However, renewable energy contributes almost 30% to the energy supply, which is especially relevant for the residential sector.

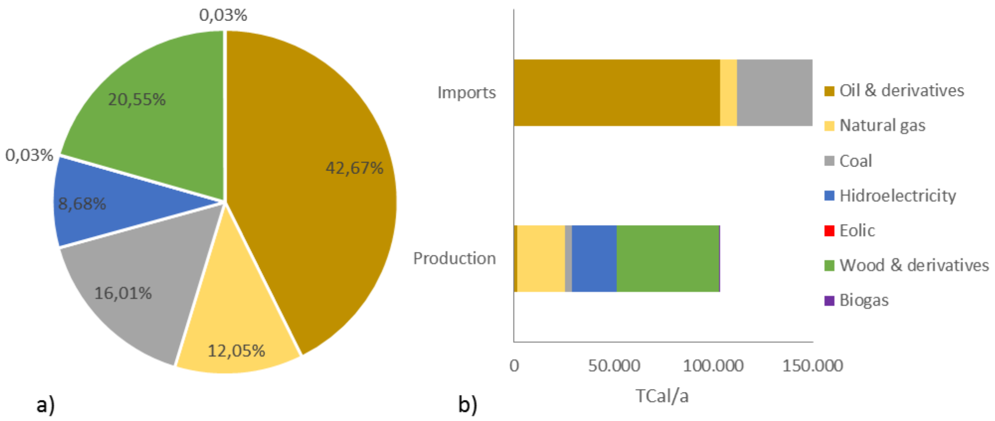

Figure 3: Chilean consumption of primary energy in 2009 (MinErg, 2010). a) Percent of contribution from different sources. b) Energy imports and local production.

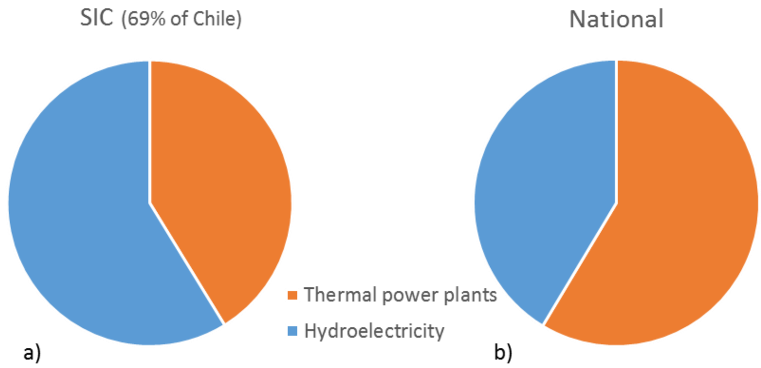

Figure 4: Origin of Chilean electric power in 2009 (MinErg, 2010). a) The SIC (Central Interconnected System) corresponds to 69% of the national electricity, and supplies electricity to 92% of the population, including Los Ríos Region. b) Origin of total national power.

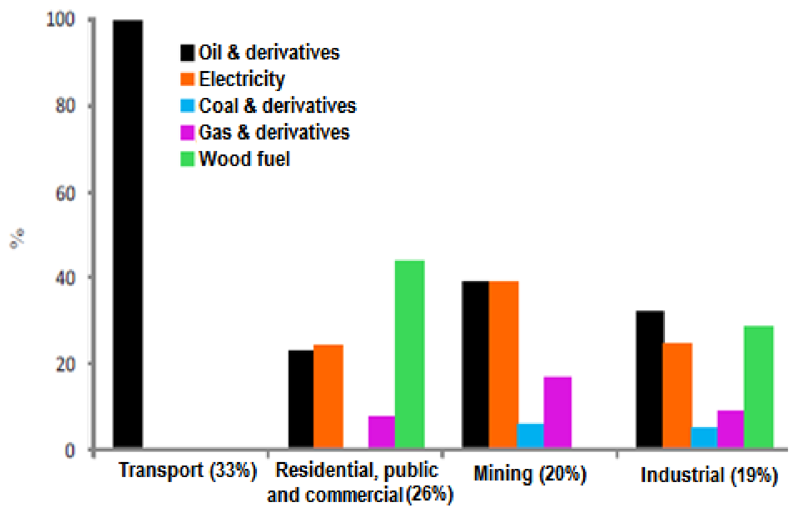

Figure 5: Chilean consumption of secondary energy by sector in 2010 (Reyes and Neira, 2012).

Most of the fossil fuels are imported. The future economic development of Chile is uncertain, as the country depends on external supply and prices. Under this scenario, Chile presented an INDC[1] during the United Nations Frame Convention of Climate Change in Paris (December 2015), committing to the reduction of its CO_2 emissions per unit of GDP by 30% by 2030 relative to the 2007 level. Chile has also committed to the restauration of 100,000 hectares of native forests and the reforestation of another 100,000 hectares with native species (Chilean Government, 2015). However, regardless of the international political promises made by the Chilean government, there is currently a persistent increase in the national GHG emissions. Emissions increased by more than 6 times in less than 2 decades, since energy consumption almost doubled each decade (Figure 6).

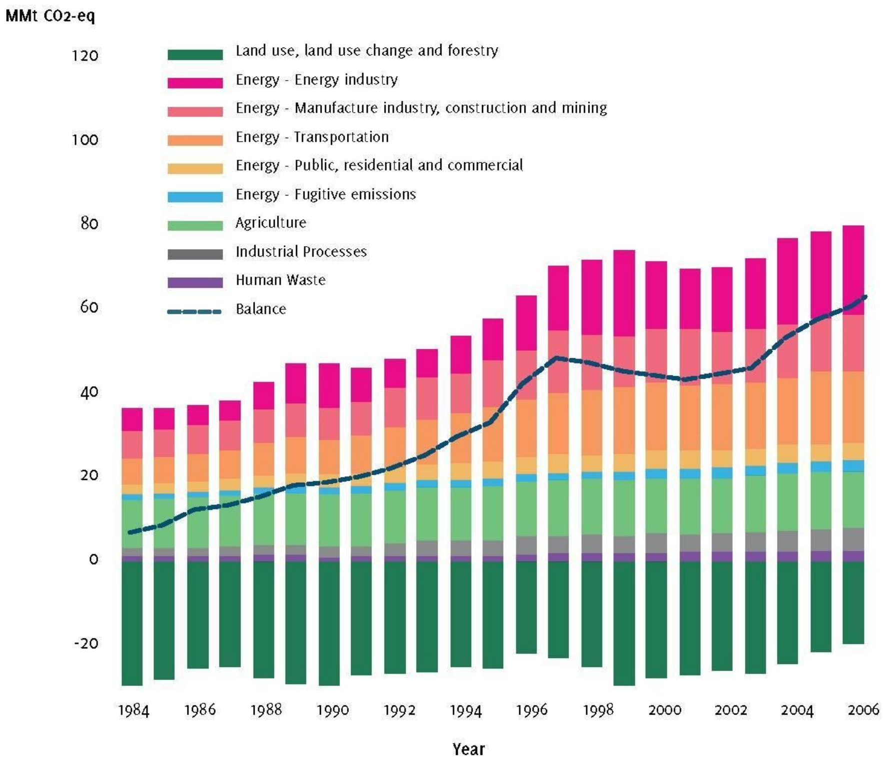

Figure 6: Net Chilean GHG emissions by sector, 1984-2006 (MMA, 2012).

The main cause of global warming is the use of fossil fuels. Therefore, one key aspect of mitigation is the replacement of fossil fuels by renewable energy sources. An impressive renewable technology revolution has already started. Replacing current energy sources is one way. In addition, the use of energy should be much more efficient and the question also arises, must our energy needs be so high or could it be limited them towards real needs (self-sufficiency). Such changes demand a deep cultural reflexion that can take decades, while urgent actions are needed now. In this respect, renewable energies have been considered as the main mitigation mechanism against climate change. If so, they should grow tremendously. Since the Earth's system is a complex interconnected entity where evolution has resulted in the colonization of all available niches, the global irruption of a new set of artificial devices that harvest accessible energy, such as renewable energies, will necessarily cause new environmental impacts in an already stressed human and not human world. Therefore, it is of high priority to accurately identify and assess the positive and negative effects of this new technological revolution of renewable energies, in order to ensure a safe transition towards a sustainable society.

[1] Intended National Determined Contribution

Among renewables, bioenergy may play an important role, given its advantages and differences in regards to other renewable energies analysed in this document. However, it can also become a key driver of land use change in the next decades, putting more pressure on already degraded ecosystem components like biodiversity or soils.
Regarding Los Ríos Region, bioenergy is a very important sector, as almost 2/3 of the region is covered by trees, either native or fast-growing plantations. Also, firewood is the main source of domestic energy in the region, accounting for over 90% of the thermal energy (used for heating and cooking). About 1/3 of the available land is covered by grasslands and less than 3% of the region is used for agriculture, but experiments and models (including the results obtained with BioStar) suggest that most of the grasslands have potentials for crop production (Cazangas et al., 2010). Regarding the forecast of the expected climate change, Los Ríos Region shows a major potential for bioenergy in the national context, and may play a decisive role for the implementation of this renewable energy form on a nation-wide scale. For that reason, the bioenergy role is analysed in this work in order to clarify the possibilities and drawbacks of bioenergy in the context of the renewable energy supply for Chile and especially for Los Ríos Region.
One main hypothesis of this research is that biogas outstands among biofuels, based on its biological nature and the fact that it comes from a natural degradation process, thus allowing the use of residues to complete the cycle of organic matter. Such recycling is at the core of nature´s resource efficiency. In an attempt to answer this and other related hypotheses the analysis of the sustainability performance and suitability of biogas for Los Ríos Region is thoroughly addressed in various Chapters of this research. As a parallel practical experience, a small biodigestor was designed and built to test this knowledge in practice, and let the questions arise (for pictures of the biodigestor see Section 9.5 in the Appendix).
One source of knowledge and inspiration for this research has been the German biogas experience. On many fronts Germany has led the environmental revolution, implementing long-term solutions and prioritizing quality and human ethics over a currently globalized neo-classical economic worldview, which works on value-free economics driven by short-term profit and fossil fuels. As is characteristic of its culture, Germany had quickly mobilized its academic, industrial and political power towards a completely renewable future with unprecedented results, although that situation slowed down in the last years. Amidst such transformation, biogas has stood out as a technology greatly advanced by German developments. In the last 13 years, the number of biogas plants in Germany has increased by 700% while its generating capacity has risen by 350%. However, new subsidy regulations will put an end to biogas financing, because bioenergy in the classical form is considered the most expensive renewable energy form (German Ministry of Economy and Energy, 2016).
In any case, such a rapid change of infrastructure is worth studying as another research subject. Studying the German example makes two things clear: First, a renewable revolution is possible. Second, Chile is not Germany. This is not superficial, but dramatically relevant for a successful technological exchange. This research has to look for success factors in order to adopt a technology from a country with such a different cultural and economic situation. Latin America, and Chile in particular, have not few episodes of bad implementation of good ideas brought from overseas. How it can be known if German technical solutions are applicable in Los Ríos? The idea of transferring experiences from one culture to another is explored in this research through the study of the cognitive (epistemological) aspects involved.
Another question is not just how to follow the German model, but to what extent. For example, the dominant activity in Germany's biogas area is the use of large areas of land for cultivation of maize. In 2011, Germany was using 2.2 million hectares of the total arable land area of 17 Mio. ha for either energy crop production or renewable primary products. Of this area, 800,000 hectares were being used for biogas crops, mainly maize, while 900,000 hectares were being used for oil (rapeseed) for the country's bio-diesel production, and 250,000 hectares for starch and bio-ethanol production (FNR, 2014). However, Germany uses millions

of ha areas outside Germany especially in South America. Replicating this situation in other countries and continents is complex, especially when the world population is still growing while the availability of fossil fuels is depleting, and the reduction of fossil inputs in agriculture may result in a reduction of land productivity, increasing the demand for more land. An increased expansion of land use, in a global context of poverty, habitat reduction and biodiversity extinction, could reduce ecosystems' resilience, implying to trespass some of the Earth's tipping points, rendering its resilience out of control (Gao et al., 2016; Steffen et al., 2015). How much, where, how and why land will be used must be carefully questioned. The answers should give fundamental information for decision makers. The impacts on the environment and society will depend on a good bioenergetic management and planning (Paneque, 2011). Land use planning based on scientific criteria is a technical tool that can allow us to face these questions and find ways to implement integrated land development, which can make different uses compatible and even synergic. This research is intended to contribute with systemic arguments and validated scientific information to the discussion and planning of the bioenergy development in Los Rios Region in the context of regional sustainable land use.

3.1 Research Questions

General question:
What bioenergy system(s) is (are) the best choice to be developed in Los Ríos Region?

Specific question:
I Interactions
1. What different bioenergy technological approaches are currently available in the Chilean and international markets?
2. What bioenergy concepts would be a good fit for the region?
3. What combinations of technology or biomass resources are possible?
4. What combinations fit the best and are most convenient for Los Ríos Region in terms of technical suitability (determined also by culture), cost effectiveness, energy efficiency, and socioenvironmental sustainability?
5. What indicators/criteria are preferable for the evaluation of such combinations?
6. What indicators/criteria are better for a deeper understanding of southern Chile´s reality?

II Potentials
7. In terms of different biomass alternatives, what potential does the Los Ríos Region have to produce bioenergy? Alternatives:
    a. biomass from crops
    b. biomass from forest resources
    c. wastes:
        i. Cattle production
        ii. Agroindustry
        iii. Urban organic
        iv. Water treatment sludge
8. What land use changes would occur during a transition to bioenergy? Regarding:
    a. potential land use changes
    b. bioenergy expansion's impact on agricultural and other natural resources
    c. logistical limitations

III Bioenergy area (case study)
9. How should a bioenergy area in southern Chile be developed?
10. What aspects of the German Bioenergy Village model can be used or applied in southern Chile? How must the German concept be modified?

11. When establishing a bioenergy system in a specific area:
    a. How much of the CO_2 footprint can be reduced?
    b. To what extent can energy costs be reduced?
    c. What are the main steps in order to establish a carbon neutral system in the region?

3.2 Research Hypotheses

FIRST HYPOTHESIS: Cycling systems
There is a pattern of combinations of resource use (land use, production practices and technologies) that maximizes energy efficiency and minimizes environmental and social impacts, as well as gaining a system´s autonomy through cycling the matter and energy flows in a land unit. This pattern of combinations is discrete, replicable and mathematically formalizable.

SECOND HYPOTHESIS: Advantages of biogas
Given that the typical attributes of biogas are decentralised/local, biological product (therefore energy efficient, with no extreme parameters of temperature, pressure, or toxic chemicals), simple, secure and safe, it is assumed that biogas is the biofuel with the best score in terms of its sustainable multidimensional energy-economy-social-environmental performance.

THIRD HYPOTHESIS: A systemic epistemological view
For a new/future scenario the following is assumed:

- There are no previous observations to use as a base.
- If these previous observations could be obtained, the quantity of all the information involved would be theoretically infinite.
- If all of this theoretically infinite information could be obtained, it would be impossible to process it.

A new epistemological model, based on holistic scientific principles (including ecosystems, complexity, systems and cognition theories) could improve the decision making process since it would allow to deal with many dimensions/ scientific disciplines.

4 General Methodology for this Work

According to the previous discussion, a structure for answering the given hypotheses is proposed. The general research question "What bioenergy system(s) is(are) the best choice to be developed in Los Ríos Region?" must be answered understanding "best choice" as the one with the best sustainability performance, and conceiving sustainability as the integration of technical, ecological, economic and social performance (for more details about the concept of sustainability, see Section 6.5). The general methodology can be considered as a discard process, going from a general to a particular focus through the elimination of irrelevant information or subjects.
To answer the general research question with a scientific outlook, a demonstration of the best solution would be possible by comparing the "best" bioenergy system to its alternatives. Therefore, it would be necessary to:

- Firstly, list all of the alternative systems that should to be compared.
- Secondly, to have access to the specific information of parameters for every alternative system that is used in the comparisons.

However, it is impossible to proceed in such way, as both:

- The number of alternatives may be enormously high.
- The number of parameters to be used in the comparison may be even higher.

In other words, in research it is possible to manage a limited amount of information, given the available time and the processing capacities (intellectual and computing capacities), which are both limited. Therefore, with such limited capacities the researcher is commonly obliged to choose between dealing with many factors (or a large scale) in a broad way or dealing with few factors (or a small scale) in a more detailed manner. This is intimately related to the problem of “the one and the many”, a dilemma which is frequently discussed in philosophy (Bortoft, 1996; Gastó et al., 2012; Röling, 2000). In graphical terms, one has to choose between a generalistic or reductionistic approach, or using different terminology, as seen in Figure 7.

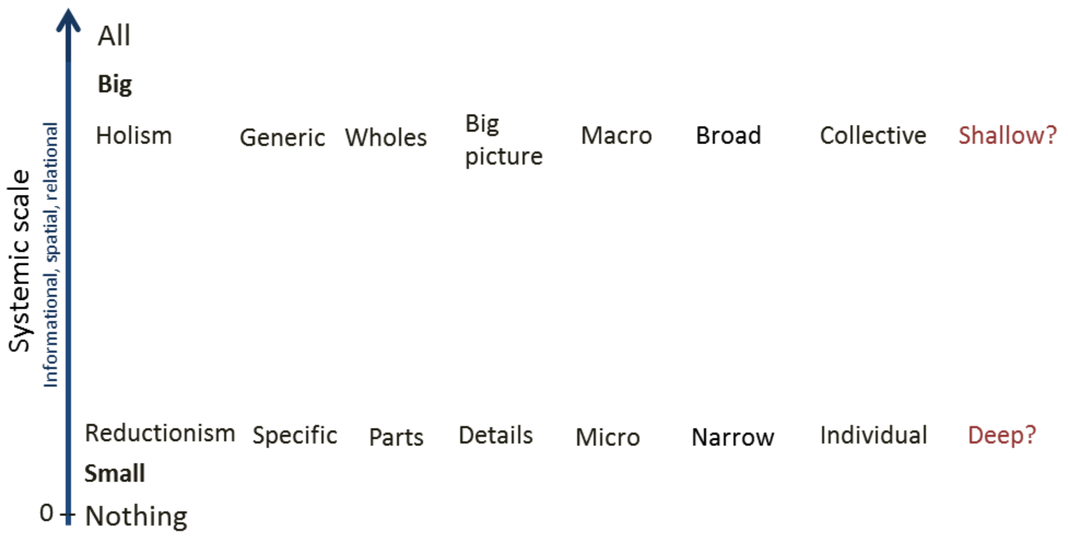

Figure 7: Reductionist and holistic approaches, seen in a dualistic manner (as opposed).

It is important to note that a holistic approach tends to be considered shallow in terms of the level of details of the involved components compared to a reductionist approach and vice versa. However, an analysis can be deep or shallow in both reductionist and holistic levels, depending on the level of information managed in the analysis. A deep holistic approach goes deep in the relational dimension of the phenomenon studied (network of relations between the phenomenon and its interacting parts or environment), whereas a shallow reductionist approach would not address even the relevant information even at small scale or in terms of specific subjects. Therefore, smaller does not necessarily mean deeper. From a cognitive point of view, information is potentially infinite (see Sections 6.1.1 on complexity and 6.4 on cognition), implying that either reductionist or holistic approaches can be deep or shallow depending on the background used in the analysis.

How then should be proceed when faced with such a multidimensional problem? To address the research question, a conventional process of discard (similar to Cartesian method: narrowing through elimination) will be used in this study.

In the next Figure (see Figure 8) a mathematical model is presented to approach the problem based on the information processing theory. According to Shannon (1948), when transmitting a message there is a trade-off between the amount of information transmitted and the probability that the message will be well received. That trade-off follows a logarithmic curve.

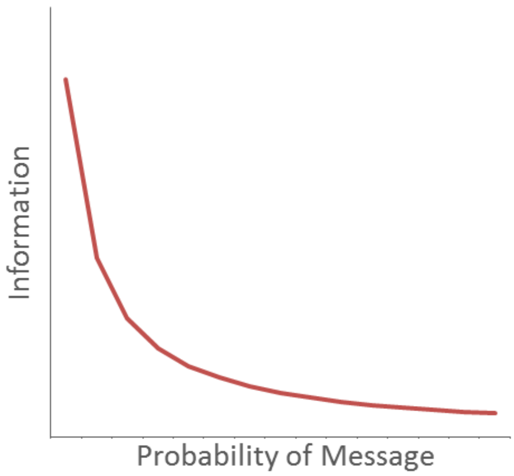

Figure 8: Relation between the amount of information of a message and the probability of a successful transfer and understanding of such message, according to Shannon´s Information Theory (Shannon, 1948).

The decrease in the probability of message comprehension is produced by the saturation of the receptor with information. Such saturation tends to increase as the level of information or choices increases, as expressed in the Hick Law (Hick, 1952) (Figure 9):

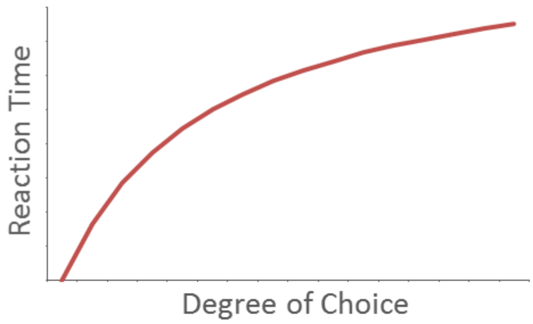

Figure 9: Hick´s Law; the time to make a decision increases if more choices are available (Hick, 1952).

For the purpose of this thesis, let´s assume that from the universe of variables, factors are aspects or subjects that are desired to be analysed, and parameters are specific information about them that can be quantified. Under this prospect, assuming that the information is determined by the number of factors analysed and by the number of parameters for every factor analysed, the discrete amount of manageable information able to be considered is a product of the following formula:

I=F*P

where

I: discrete amount of information

F: number of factors analysed

P: number of parameters analysed

Given certain area A, where:

A=X*Y

The discrete area, when variables are changed, would describe the curve of points that set equal surface, or an iso-surface curve given the following equation:
Y=A/X

The curve of iso-information can be specified by the equation:
P=I/F

The discrete amount of iso-information can be represented as a discrete area on a graph showing a non-linear shape. Every point of the curve implies the same amount of information (Figure 10).

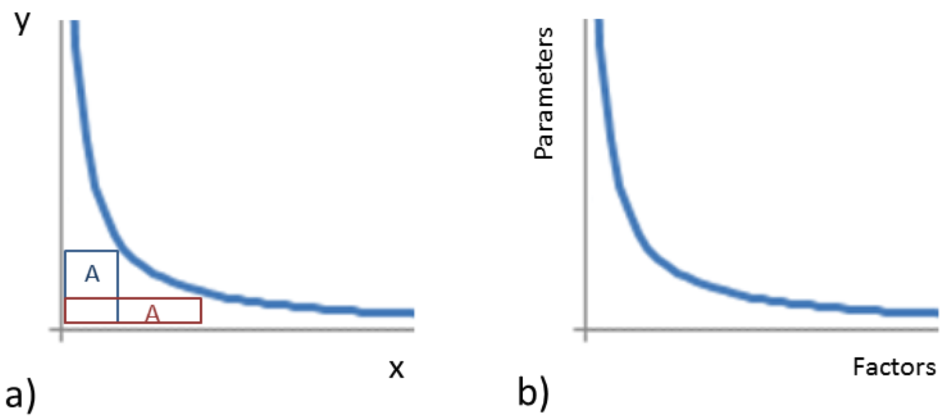

Figure 10: Curves of iso-surface (a) and iso-information (b).

Again, with a limited capacity to manage information, a researcher can choose between analysing many factors with few parameters each, few factors with many parameters each, or an intermediate situation. In other words, within a system with a limited capacity, the more factors involved in the system, the fewer parameters involved.
Therefore, one way to answer the research question is to move from a general level to a specific scale of analysis, reducing the factors and increasing the specific parameters to cope with the complexity, similar to a traditional discarding (Cartesian) method that goes from a general to a particular level. This process must be limited to discrete steps, because not all intermediate scales or levels can be studied, otherwise the process would be endless. Therefore, a discrete number of steps in the analysis would be like the ones shown in Figure 11a. In practice it is a multidimensional domain. When simplified into a two dimensional problem, it could go from a general scale (or generalist) to a smaller one (specific), moving through a curve of iso-information (see Figure 11b).

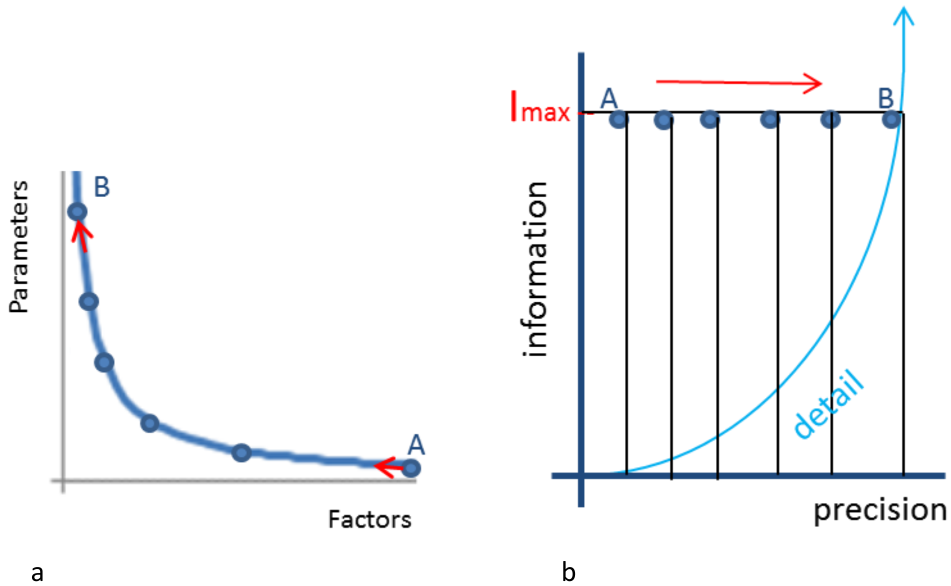

Figure 11: Steps in research from a generalist focus (point A) to a specific focus (point B) through discrete steps along the iso-information curve showed in two formats. a) An iso-information curve like in Figure 10. b) The same amount of information but of a different quality can be achieved by increasing the level of detail (or precision) and reducing the scale of analysis. At I_{max} the greatest amount of manageable information is reached.

As previously discussed, it is not possible to deal with complex information only in quantitative terms. In many cases, qualitative information can be effective in selecting variables. Therefore, it is proposed to alternate quantitative and qualitative analysis steps, enhancing the scoping process. This way, the discrete steps in the analysis can be conceptualized as in Figure 12a. In the same manner, a series of steps for the research is proposed, from a generalist view to a specific level of analysis as shown in Figure 12b. The steps are compiled in Table 1.

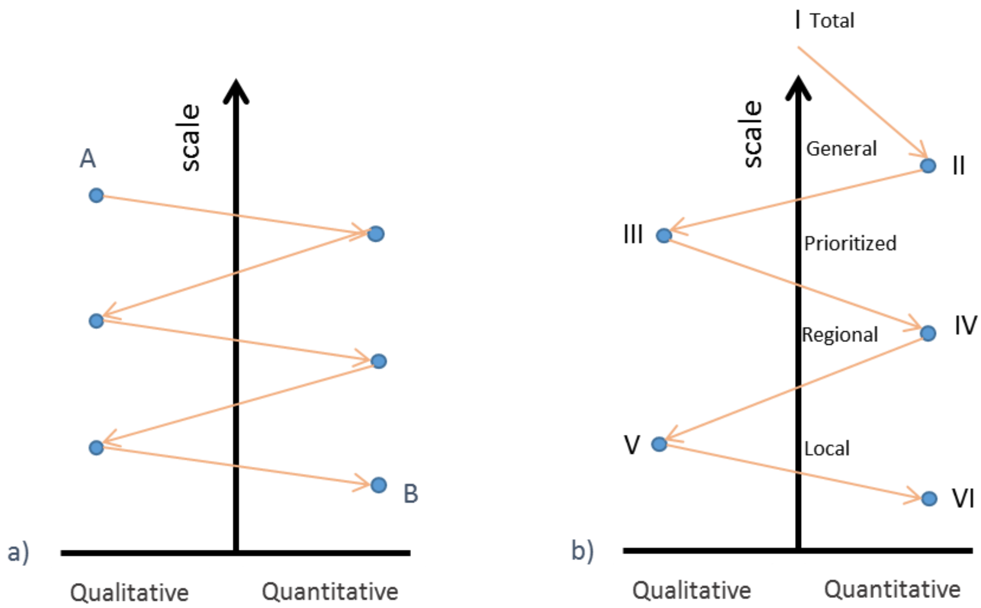

Figure 12: Steps in the research process, from a general to a specific level of detail and scale alternating between a quantitative and a qualitative approach. a) general example, b) steps for bioenergy alternatives (interactions) for Los Ríos Region.

Table 1: Steps proposed for this research, from a generalist view to a specific level of analysis.

Item	Steps of interactions' analysis	Bioenergy interactions considered
General interactions	I Theoretical total quantitative	Total combinations of bioenergy possibilities
	II General quantitative	State of the art bioenergy options
	III Prioritized qualitative	Potential bioenergy options for the region
Regional potentials	IV Regional quantitative	Regional land use
Local unit	V Local qualitative	Alternatives to bioenergy villages
	VI Local quantitative	Case study: Bioenergy Campus

5 Results

5.1 Total Quantitative Interactions

"*Not everything that can be counted counts,*
and not everything that counts can be counted"
Albert Einstein

As is discussed more deeply in Chapter 6 (epistemological considerations), reality cannot be divided into discrete numbers as was assumed in the corpuscular view of classical science. The number of variables is determined by the distinctions chosen by the observers' (researchers) needs, preferences and priorities. Nevertheless, once a criterion for discrete information is chosen, the complexity of the managed information can still be a limitation for research, given the complexity of the system itself. In a complex system like a whole region with a theoretically limitless degree of detail and number of external interactions, a fully quantitative account seems to be impossible to obtain and is therefore not resolvable in pure mathematical terms.

5.2 General Quantitative Interactions

Considering the already mentioned limitations of a strictly quantitative approach in the search for the best bioenergy options among all of the possibilities in Los Ríos Region, a quantitative selection process is developed. This second step in the search for suitable bioenergy alternatives is to gather international experiences evaluating the sustainability performance (provided by environmental and economic dimensions) of biofuels in order to guide the search towards fewer alternatives and more precision and specification of variables. Sustainability parameters for biofuels taken from numerous studies are compiled in Table 2, focusing on the environmental and economical performances of different biofuels. Many of these studies are reviews and recompilations of numerous publications. It is important to consider that these studies were carried out in places very different from Los Ríos Region, but many studies contain data for areas in temperate humid climates, similar to that in Los Rios Region. Such information is very relevant to the selection process, where repetitively low performance alternatives can be eliminated. It is also important to notice that Table 2 shows the original data from the authors, so parameters are not yet transformed.

Table 2: Summary of results of different studies on the environmental and economic performances of different biofuels

Parameter	GHG reductions					Fossil Energy Ratio (output/input)		Plants energetic efficiency			Land use intensity (Energy/area)					Biofuel production costs		Ecological footprint	Cultivation systems[2]	Water footprint agriculture
Specific variables	GHG reductions with indirect Land Use Change per unit of raw biomass.	GHG emissions	GHG reduction	GHG reduction	Contribution to Global Warming	Fossil Energy Ratio[3]	EROI[4] (Energy return on investment)	Energetic efficiency for biofuel production plants	Life Cycle Energy Efficiency[5]	Technical analysis[6]	Energy/ha/y[7]	Land Use Intensity[8]	Land Use Intensity	Area efficiencies of fuel production	Carbon Stock Change Emissions due LUC[9]	Biofuel production costs	Biofuel production costs			
Unit	t CO2-eq/TJ	kg CO2eq/GJ	%	%	kg CO2-eq/MJ	without dimension	Energy output/fossil energy input.	%	(dimensionless)	Energy efficiency [%]	(Km/ha yr)	m^2 yr /MJ	l Diesel eq/ hectare (Germany)	(W m^{-2}) (year's average)	kg CO2-eq/MJ	Eur/GJ	$/GJ	m2 yr/KWh	Overall assessment	lt/MJ
Source	WBGU, 2008	Müller-Langer et al., 2014	FNR, 2014	Samaniego and Antonissen, 2008	Mata et al., 2013	Mata et al., 2013	Anton and Steinicke, 2012	Müller-Langer et al., 2014	Mata et al., 2013	WBGU, 2008	FNR, 2014	Mata et al., 2013	Kleinschmidt, 2010	Anton and Steinicke, 2012	Mata et al., 2013	Müller-Langer et al., 2014	van Eijck et al., 2014	Stoeglehner and Narodoslawsky, 2009	WBGU, 2008	Samaniego and Antonissen, 2008
BTL /FT (lignocelluloses)	51	8	93					58		16	64400		3880			45	21		1	
Bioethanol (lignocellulose)		10		20			5.4	57						0.2		30	18			
Ethanol from wheat straw	32		85							11							21.5		1	
Biomethane/biogas (residues)	85	27	83					53		20						22			1	
Biomethane / biogas (silage)	28	35					4.8	60		27.4	67600		4984	1.1		37		7	3	
Biodiesel from waste	80		83							25								10	1	
Biodiesel-Vegetable oil (rape)	29	50	48		0.04	1.15	2	83	2.9	43	23300	0.31	1413	0.2	0.78	23		79	3	140
Sunflower biodiesel			52		0.05	1.04			1.04			0.28			0.7					300
Biodiesel (soya)		50	31		0.13	0.41		88	0.41			0.46			1.66	22	13			400
Biodiesel (palm)	-25.75	50	18		0.04	1.28		52	1.28	16.75		0.05			0.08	18	14		2.5	95
Bioethanol (corn)	-10	42		85	0.06	1.84	1.5	53	1.53	11		0.11	1690	0.3	0.29	25		30	3	105
Bioethanol (wheat, rye, triticale)	-45	56	35	70				66		11	22400					35		65	3	
Bioethanol (sugar beet)		39	52	60			3.5	62						0.4		24			3	
Bioethanol (sugar cane)	22	26	71	15	0.06	7.63	8	46	7.63	8.5		0.03		0.5	0.07	18	23		2	100
Jatropha biodiesel	63.25									25							28		2	
Firewood							10							0.2						
Biodiesel from algae					0.14	0.56	1		1.84			0.01			0.01					
Photovoltaic (electricity)							7							5						
Fossil comparator		90	100		0.09	1	1	58	5.715									110		

[2] WBGU (2008) qualitative overall assessment, which qualifies the ecological friendliness of a cultivation system. The higher the value the best ecological friendliness. More details next in this section.

[3] Ratio between the energy content of the final fuel product (fuel energy output) and the amount of fossil energy input (non-renewable energy) required for the fuel production through the supply chain.

[4] EROI denotes the amount of energy that is returned (energy output) per unit of fossil energy invested (energy input) during biomass production and conversion to, for example, liquid biofuels or electricity. Fossil energy input includes fuels required for land management, for the synthesis of fertilizers and pesticides, for sawing and harvesting as well as for the conversion of the biomass to biofuels.

[5] Ratio of the total energy output, consisting of the energy content of the biofuel, plus that of byproducts only if they are used to supply energy to the biofuel production system, to the amount of energy expended to obtain the biofuel (dimensionless). LCEE can be considered an efficiency indicator, as it is a measure of the maximum energy obtained from the fuel and byproducts (total energy output) per unit of energy used to make it available through its life cycle.

[6] Energy efficiency aggregated from different processes involved in biofuel production.

[7] Bioenergy productivity expressed as equivalent kilometers of a middle class car that can be driven with biofuel from a crop area of 1 ha.

[8] Measures the area of land used per unit energy of fuel product, focusing on the land needed for the biofuels feedstocks cultivation, which affects biodiversity and life support functions.

[9] The annualized emissions from carbon stock changes caused by land use change can be calculated by dividing total emissions equally over 20 years.

An important output of this analysis is that the systems are not easily comparable. As every research has its own purposes, most of the different studies reviewed do not include all parameters and biofuels available for analysis, so that certain comparisons cannot be realized. In some cases, certain parameters are analysed in different studies, but the results are uncertain because differences in methodologies, places, or variables measured render the results incomparable. In an attempt to analyse and compare results of different studies, parameters are first transformed into units of positive impact, which means that the higher the number the better the performance is. For example, for the parameter of global warming impact, variables of reduction of GHG were used, but variables of GHG emissions are inversed (1/x) so that the higher value corresponds to the lowest emission or the biggest reduction. A similar procedure is applied for production costs (€/energy unit), which is inversed in "cost efficiency" (energy/€), and for the parameter of Land Use Intensity (land surface/energy yield), which is inversed to "Land Use Efficiency" (energy yield/land surface). Afterwards, when the units for certain parameters are not transferable or too complex to be transformed (because of different methodologies), the data from the different studies are normalized, with the value 1,0 set for the highest/best performance in order to create a scale of general comparison. In the specific case of the information given by the German Advisory Council for Global Change (WBGU, 2008), a very detailed performance of different biofuels is carried out, which include combinations of several specific biomasses (Maize, Jatropha, slurry, palm oil, straw, etc.) with different technological processes (biodigestion, methanation, incineration, fuel cells, pelletization, etc.) and several final uses (engine cogeneration, gas turbine, steam turbine, diesel car, electrical car, etc.). Unfortunately, the performance at the level of energy carrier (biogas, biodiesel, etc.) is not explicitly given. Also, the WBGU include a land use factor in their calculations, so that the same energy carrier can reflect relevant differences according to the origin of the biomass (for example from degraded land, agricultural land or natural forest land). Accordingly, a selection process of specific pathways is either averaged or selected, in order to extract the most representative number for each energy carrier. For example, the GHG reduction of palm oil for use in car engines is 149% in the case of degraded land (as a part of restoration management) and -257% in the case of rainforest land. If the same biodiesel is used for a small scale CHP (engine heat and power cogeneration) values are 190% and -185% in GHG reduction, respectively. In that case the value taken was -26%. The same pattern occurs with other crops that compete with rainforests, like Jatropha or sugar cane.

Figures 13 through 17 show the results of comparable parameters from different studies, in order to check for matches and differences. Some additional publications with qualitative comparisons of biofuels in environmental terms, as well as some of the original graphs of the studies used in these Figures, can be found in the appendix 9.1 and 9.2.

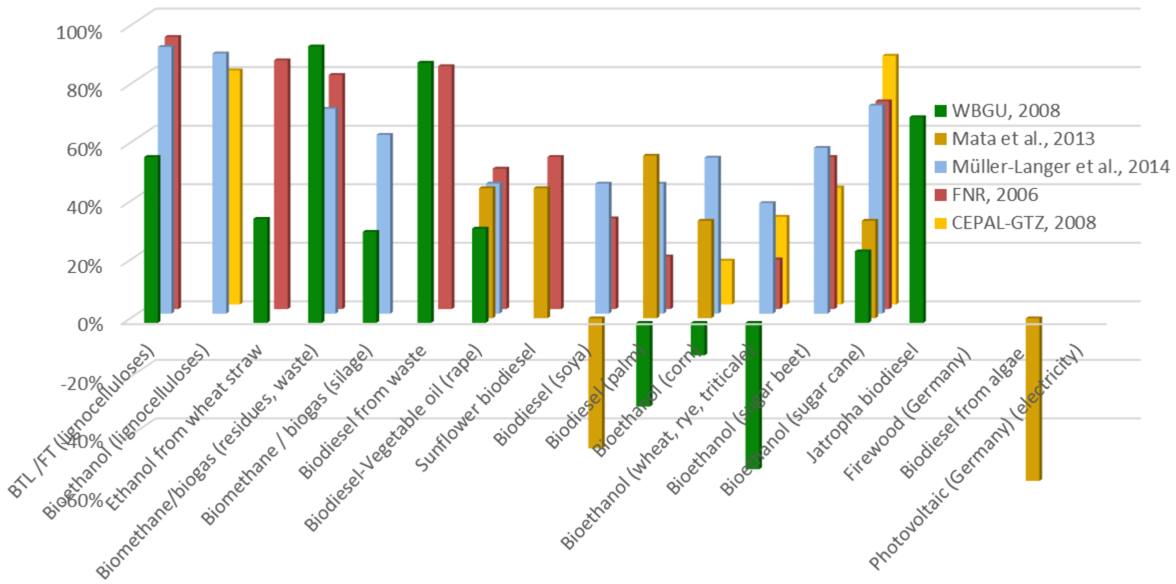

Figure 13: GHG Reduction (% respect to fossil fuel emissions) for different biofuels in the studies considered. Data from WBGU (2008) include the effect of indirect land use change.

It is important to note that the negative values for GHG reduction result from the consideration of the indirect impact of land use change in the calculation, which is very relevant in the performance of biofuels associated with energy crops that demand agricultural land.

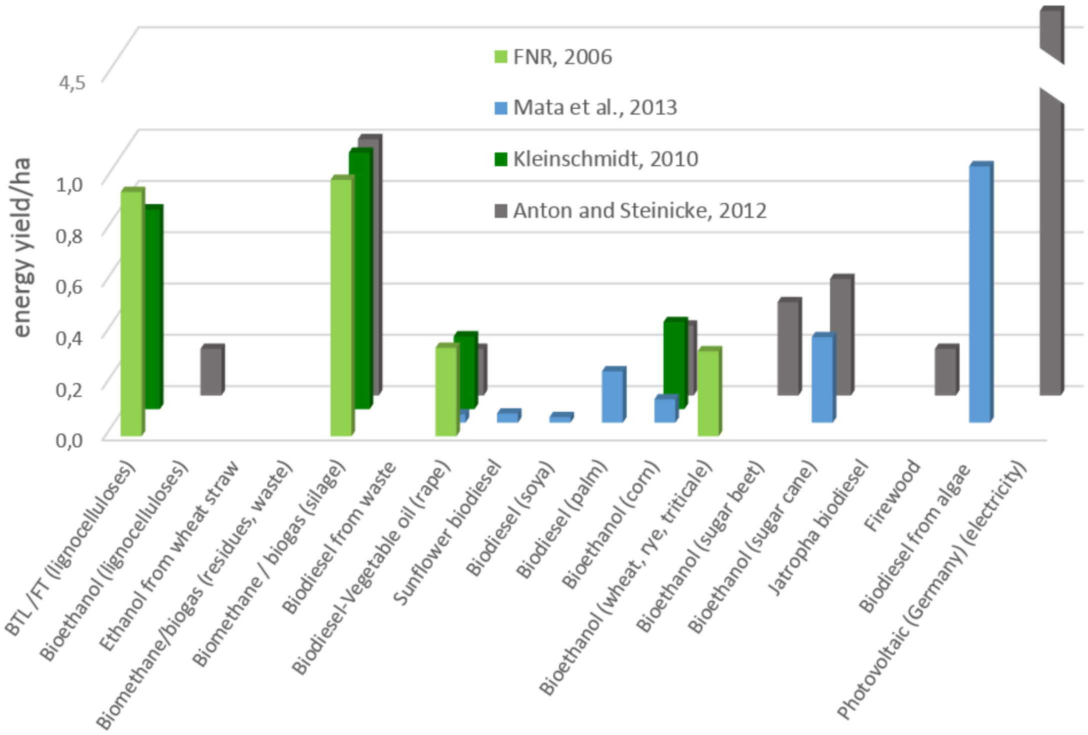

Figure 14: Relative land use efficiency of different biofuels in the studies considered, expressed in terms of land productivity. The higher the value, the less surface area is needed for the same amount of energy harvested. In order to compare different units, values are normalized: value 1.0 is given to the best performance of every study (except photovoltaic, which has a value of 4.55 and may serve as a reference).

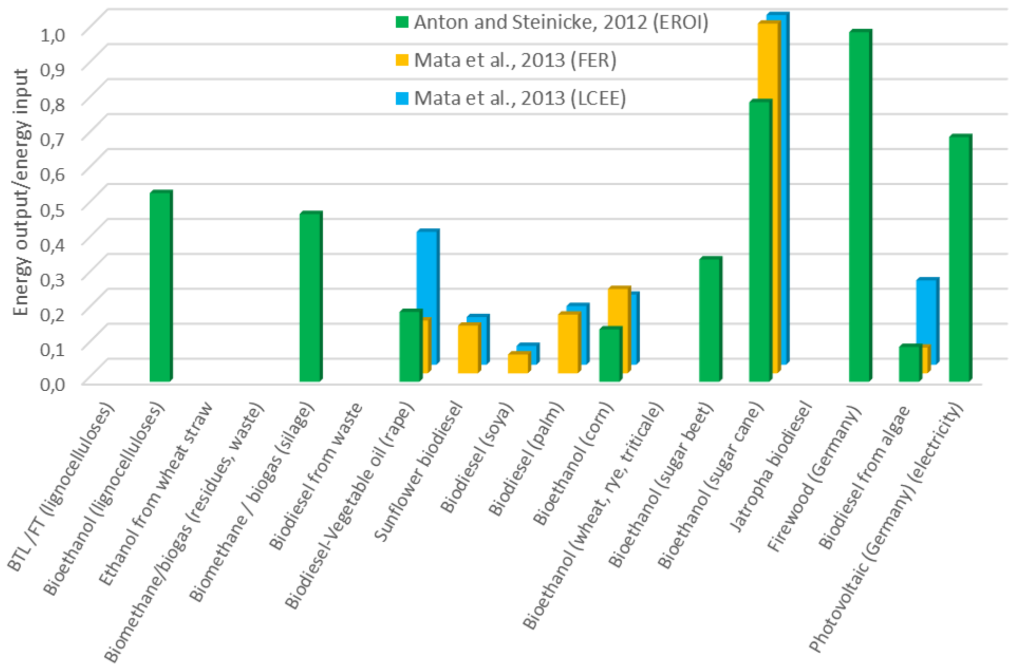

Figure 15: Output/Input energy ratio of biofuel production. Values are normalized as in Figure 14. Different approaches are considered: Energy Return On Investment (EROI) and Fossil Energy Ratio (FER) refer to fuel energy output and fossil energy input, whereas Life Cycle Energy Efficiency (LCEE) consider the total outputs and inputs of the process (including non-fossil energy inputs, and non-fuel energy output, i.e. by-products of the process).

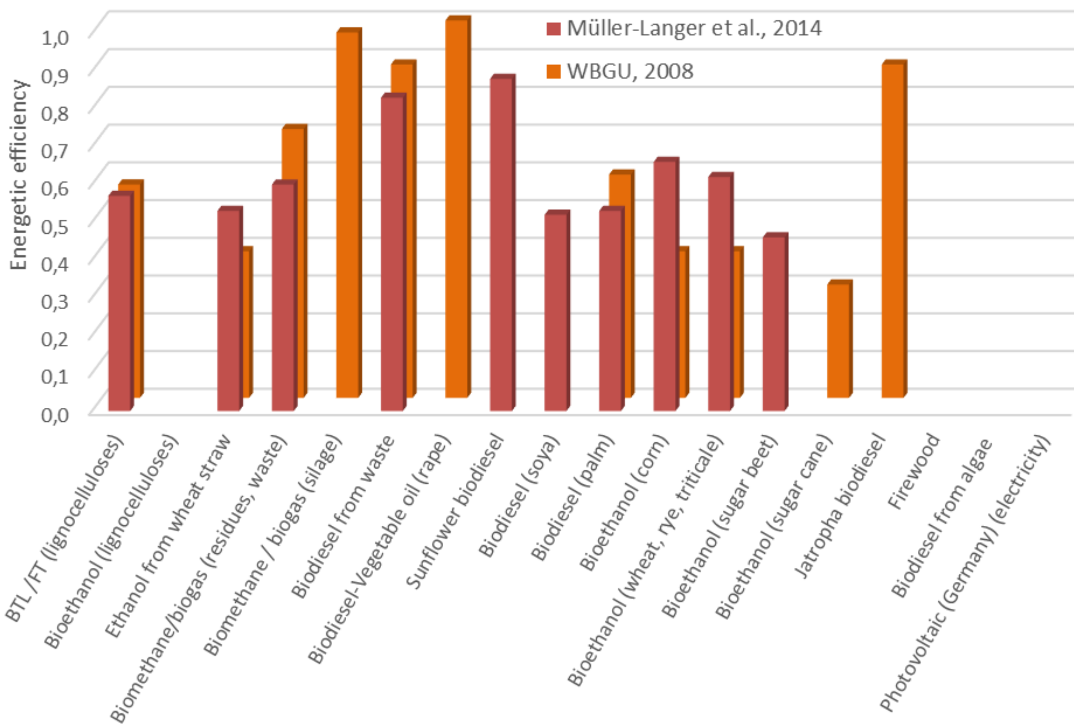

Figure 16: Energetic efficiency of the biofuel production process. Values are normalized as in Figure 14. Different approaches are considered: Exergetic/energetic efficiencies of the bioenergy pathways from the production of biomass to the final electric/mechanical/thermal energy result (WBGU, 2008) and the energetic efficiency of different biofuel production factories (Müller-Langer et al., 2014).

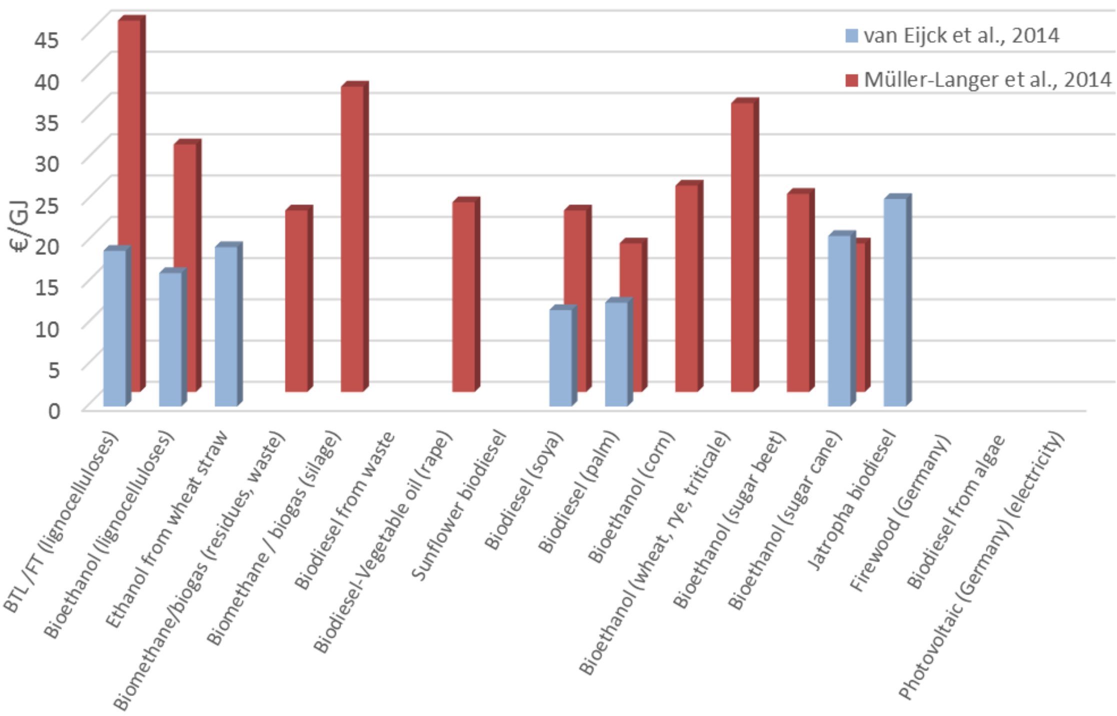

Figure 17: Energy production costs, in Euros per gigajoule of biofuel.

As can be seen in the last figures, different studies give similar results for the same biofuels, as in the case of land use efficiency and output/input energy ratio. This is repeated to some extent in GHG reduction[10], but a weak relation is found in the case of production costs. As discussed, differences among studies in their methodologies, but also in their resources and production processes, as well as the local agro-climatic, ecological, and economic situations may be the reasons for large differences. In any case, taking into account this fact, and the fact that at the same time the information processed does suggest significance through results coherence, an average of the different results for every biofuel was calculated. This procedure may be justified as a contribution in the search for references to compare different biofuels and to answer the research questions of this thesis. Some parameters are not available for every biofuel. In order to realize a graphic comparison (Figures 18 and 19), such parameters are estimated based on the values of biofuels with similar characteristics and their performance in the other parameters analysed. The ecological and water footprint parameters are not used in the analysis, as they are not considered in most of the studies. The WBGU (2008) qualitative overall assessment is included, which qualifies the ecological friendliness of a cultivation system. This parameter is named “Cultivation assessment”. At the same time, although firewood is the only solid fuel which cannot be directly used for combustion engines, it is included for referential purposes, because forests are the most abundant bioenergy resource in the region. The results, including assumptions in red, are shown in Table 3.

[10] Data from the WBGU (2008) show more differences, probably because it is the only study that includes the effect of indirect land use change. In the case of the source of land for Jatropha and sugar cane, an average between cropland and degraded land is used. For palm oil land sources, an average between rainforest land and degraded land is used).

Table 3: Average of normalized values for 6 parameters studied. Red values are estimated, as they are not available in the studies analysed.

	GHG Reduction	Output/input energy ratio	Energetic efficiency	Land Use Intensity	Cost efficiency	Cultivation assessment
BTL /FT (lignocelluloses)	0.80	0.45	0.57	0.57	0.48	1.00
Bioethanol (lignocelluloses)	0.84	0.54	0.29	0.12	0.66	1.00
Ethanol from wheat straw	0.60	0.45	0.19	1.00	0.79	1.00
Biomethane/biogas (residues, waste)	0.81	0.50	0.62	1.00	0.69	1.00
Biomethane / biogas (silage)	0.46	0.48	0.78	0.66	0.41	0.33
Biodiesel from waste	0.86	0.50	0.44	1.00	0.80	1.00
Biodiesel-Vegetable oil (rape)	0.29	0.18	0.92	0.12	0.66	0.33
Sunflower biodiesel	0.48	0.14	0.50	0.04	0.50	0.33
Biodiesel (soya)	0.10	0.05	0.44	0.02	0.91	0.33
Biodiesel (palm)	0.22	0.17	0.56	0.35	1.00	0.40
Bioethanol (corn)	0.23	0.20	0.46	0.16	0.61	0.33
Bioethanol (wheat, rye, triticale)	0.09	0.25	0.52	0.22	0.44	0.33
Bioethanol (sugar beet)	0.50	0.35	0.31	0.24	0.64	0.33
Bioethanol (sugar cane)	0.57	0.90	0.38	0.39	0.79	0.50
Jatropha biodiesel	0.70	0.60	0.44	**0.35**	0.61	0.50
Firewood	**0.90**	1.00	0.90	0.13	1.00	1.00

It is important to note that the numbers presented are set as a ranking, not in absolute values, because of the normalization process. Based on Table 3, the results are transformed in graphical terms, separating them into environmental (figure 18) and techno-economic dimensions (figure 19).

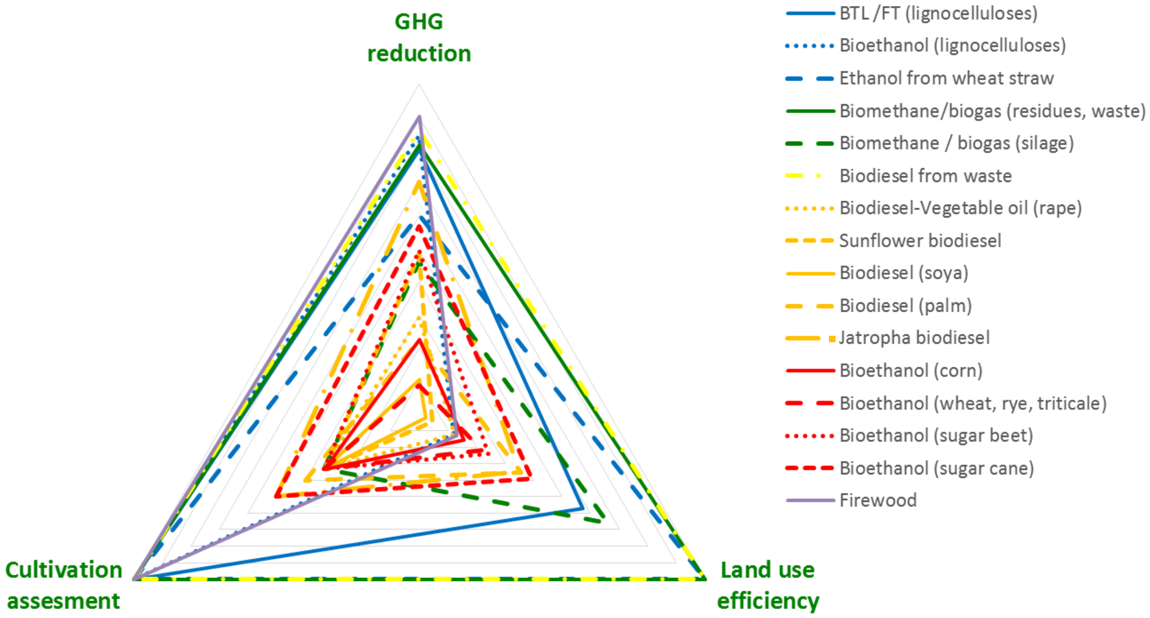

Figure 18: Environmental performance of different biofuels, implying three environmental parameters studied. Blue: biofuels from lignocellulosic sources; green: biomethane/biogas; yellow: biodiesel; red: bioethanol.

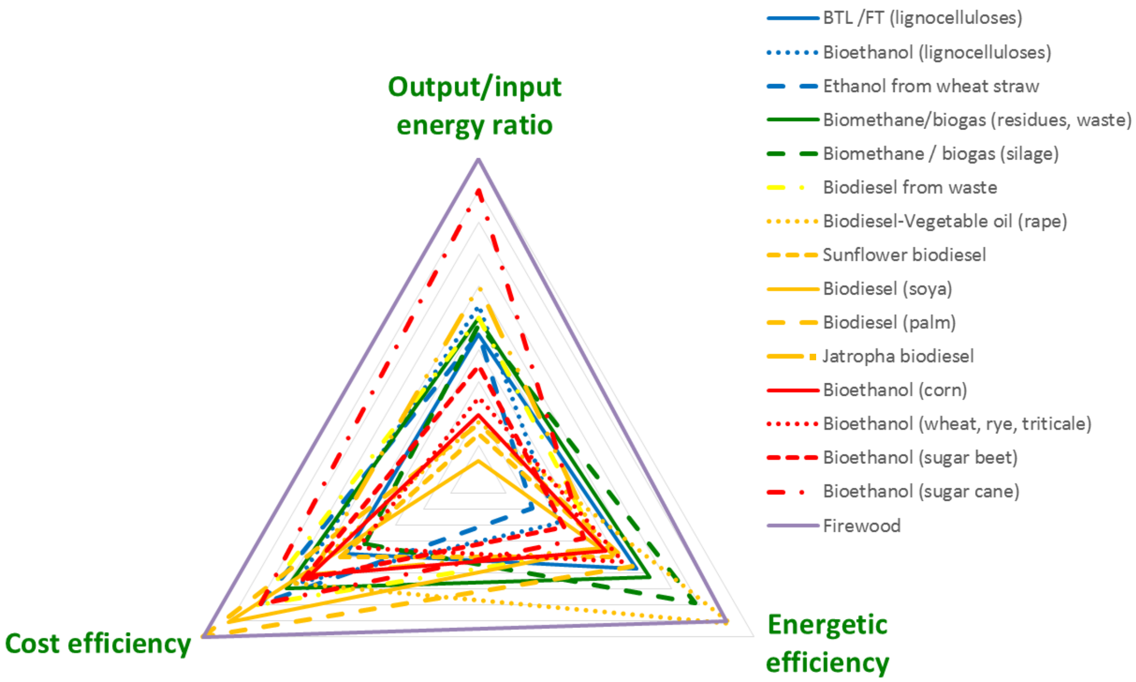

Figure 19: Techno-economic performance for different biofuels, given the three parameters studied.

As can be seen in Figure 18, in general terms residues have the best environmental performance (for example lignocellulosic BTL, biomethane or biodiesel produced from organic remains), as they do not require land, cultivation systems, nor high fossil inputs in their production, which is dissimilar to the cultivation process in energy crops. Also biofuels derived from lignocellulosic sources (in blue in Figure 18) demonstrate high environmental performance because those sources mostly represent residual material like straw. In the case of firewood, a forest does not need much input for its wood production. It has a good output/input balance and therefore a high rate of GHG reduction. The cultivation assessment used for firewood was 1.0, according to the WBGU methodology. This makes sense since in firewood production there is no tillage and the chemical input in production tends to be low in comparison to energy crops. However, it must be noted that there is a great difference in terms of the ecological impacts of firewood depending if it comes from a non-managed native forest, a managed native forest, or from a fast growing tree plantation (exotic species). In that case the worst performance will probably be the non-managed native forest, and the best situation will be the managed native forest, considering that the fast growing plantations in the region generate a reduction in various ecological services like biodiversity, water production, or landscape quality.

Lower environmental performance than that of residues and lignocellulosic biomass is seen for high-productive crops, like sugar cane bioethanol, maize silage biogas, or Jatropha biodiesel. The reason is that higher biomass production implies less land use for the same amount of energy, and a higher output/input ratio when compared to other crops that need similar amounts of input per land surface unit. Also, crops that can grow in marginal lands, like Jatropha, avoid competition for agriculture land for food and can be grown with less artificial inputs, which is ecologically desirable.

Biogas from maize silage shows higher land use efficiency than from the sugar beet. It is expected that it would also show higher GHG reduction than the sugar beet, as it has higher productivity, needs less inputs, and avoids underground harvest or distillation. However, that is not the case, probably because the sugar beet was not considered in the WBGU study

(2008), which includes indirect land use change in the GHG calculations. This study shows an approximate 30% GHG reduction for maize silage when including indirect land use change, but a 90% GHG reduction when it is not included. This dramatic drop in GHG reduction did not affect the sugar beet, so that the average calculation pushed the sugar beet higher in the ranking. Therefore, the methodology used in this comparison, which uses the averages of several studies, has the critical problem of misrepresentation of some data.
Lower in the ranking are seen bioethanol and biodiesel from crops, with the lowest environmental performance for cereal-based bioethanol and soy biodiesel.
As a rough generalization it can be concluded that the ranking of biofuel environmental performance decreases as follows: residue sources, lignocellulosic sources, crop biomethane/biogas, crop biodiesel and crop bioethanol.
It is important to note that in the considered studies the comparison of crop biogas with other crop biofuels is based on maize silage, which is a very intensive management crop. However, the numbers for grassland silage biogas (WBGU, 2008, not included in the comparison) show significantly higher environmental performance. In fact, unlike other biofuels, crops raised for biogas production can include many environmentally-friendly possibilities that certainly help to improve its environmental performance. Among those possibilities are (Ruppert et al., 2008):

- use of the whole plant[11]
- multiple cropping
- wide range of different crops, or even a mix of them, or perennial grass
- more than one harvest a year[12]
- direct sowing (no bare soil)
- toleration of weeds
- reduced herbicides or pesticide treatments
- almost total nutrient recycling by bringing the biogas residues back to the fields
- overall low fossil inputs

Such possibilities can imply, as in environmental performance:

- high productivity in land use
- higher agricultural and biological diversity
- low import of fertilizers
- minimal soil erosion
- low leaching of nitrate to underground water and rivers
- overall lower GHG emissions

For a deeper analysis of the sustainability of bioenergy production see Section 6.3.1.

Figure 19 gives the result of techno-economic performance. Regarding production costs, although residues show very high environmental performances, their management or transformation process toward fuels can be expensive so that biofuels made from them may be less cost-efficient. The contrary happens with soy or palm oil biodiesel, which show very low environmental performances, but the highest cost efficiencies. This interesting trade-off between environmental and economic services may explain the large growth of soy plantations in South America and palm oil plantations in Southeast Asia, but also explains the strong opposition against them from environmentalist groups. Highly productive crops like

[11] Not just a fractional part, like only oil in biodiesel or starch in bioethanol. This allows for the growth of many species.
[12] As biogas is produced from immature crops (green biomass), shorter growing periods are possible, allowing more harvesting cycles per year in adequate climates.

sugar cane or palm oil show a very high cost-efficiency, probably due to the high output/input ratio, which means less external inputs (that imply costs) per unit of energy.

Over all, some relations between the parameters studied are found. The coefficients of determination (R^2) between parameters are shown in Table 4. Figure 20 shows graphics for the couples with the highest R^2 found.

Table 4: Coefficients of determination (R^2) between parameters studied in the biofuels comparison.

	Output/input energy ratio	Energetic efficiency	Land use efficiency	Cost efficiency	Cultivation assessment
GHG reduction	0.5329	0.0528	0.2096	0.0076	0.7027
Output/input energy ratio		0.0470	0.0639	0.0511	0.3065
Energetic efficiency			0.0034	0.0708	0.0944
Land use efficiency				0.0001	0.3249
Cost efficiency					0.0644

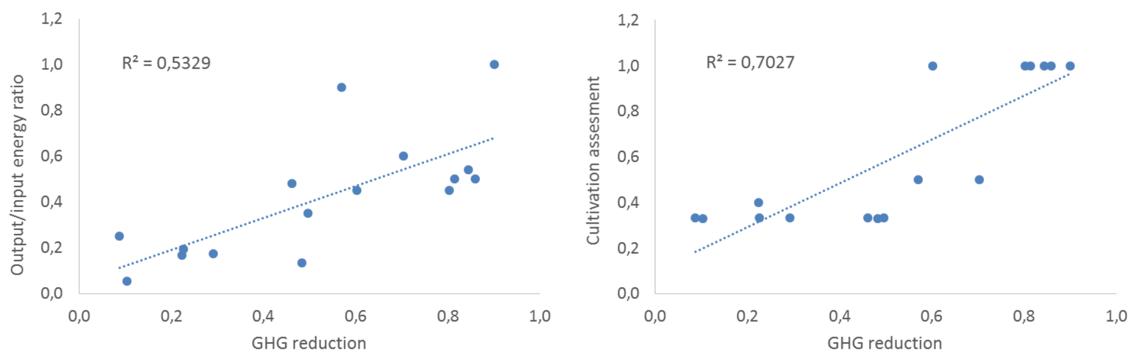

Figure 20: Best correlations between the parameters studied.

By the correlations shown in Figure 20 it is demonstrated that the information processed does has a certain degree of coherence. The correlation between GHG reduction and output/input energy ratio, is expected to be positive, as a bigger output/input energy ratio means less emissions of GHG per unit of biofuel energy produced, and therefore, a higher potential for GHG reduction. However, the positive correlation between GHG reduction and cultivation assessment is not so clearly expected, although it make sense, as environmental impacts are directly related to fossil inputs, like fuel for agriculture machinery or energy, and organic compounds to produce agrochemicals. It is interesting to note that the level of environmental impacts of a cultivation system are found inversely proportional to its capacity for GHG reduction, or in other terms, directly proportional to its carbon footprint. That raises the question of whether biofuels based on highly productive crops grown with a lot of chemical and technical input are an efficient technological solution against climate change.

It is important to note that the values of the parameters shown here are imprecise and not resilient due to the differences between the studies and the fact that some numbers, like cultivation assessment, come from qualitative analysis. In any case, the purpose of this chapter is to explore previous research in which biofuels are compared in order to establish references that can guide the selection process of bioenergy alternatives for Los Ríos Region. According to the findings of this chapter, the second research hypothesis seems to be correct that biogas, especially produced from waste resources, has environmental and techno-economic advantages in comparison to other biofuels. This fact is particularly relevant in regions with temperate climatic conditions like in Los Ríos, where biofuels with higher productivity, like sugar cane, palm oil, or Jatropha cannot be grown successfully. The other biofuels that can compete with biogas are the ones produced from lignocellulosic residues from the forestry sector, which in the region could be extremely abundant as almost half of the region´s used land is native forest (see Figure 4 in Paper 1, Section 5.4.1.1). In this way, a rational level of production in the lignocellulosic industry could facilitate the conservation of native forests through sustainable management. However, it is still possible that other biofuels generated from lignocellulosic biomass through gasification (raw gas/clean gas/syngas/biomethane or BtL), might have advantages in the region or high compatibility with biogas, but since data are not yet available in the comparative studies, that question remains unanswered[13]. For an understanding of the production pathway of potential lignocellulosic products in regards to different biofuels see Figure 21. It is very interesting that lignocellulosic biomass can end up producing biomethane, just as biogas, consolidating biomethane as a highly promising energy carrier (WBGU, 2008). However, the lignocellulosic gasification alternative may be an equally as positive option as biogas for the region, given its abundancy and high environmental performance. Probably the combination of both (lignocellulosic gasification and biogas) is an even better option, taking into consideration the opportunities presented by each and the compatibilities between them. In order to analyse deeper the pros and cons of biogas and lignocellulosic biofuels, a specific comparison between them is done in Table 5.

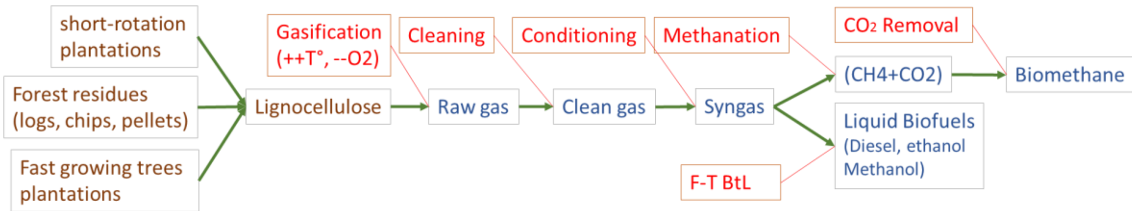

Figure 21: Main production pathway of lignocellulosic products towards syngas and different biofuels (based on WBGU, 2008).

Table 5: Comparison of fermentable and cellulosic organic matter as energy sources in terms of advantages and disadvantages based on different criteria

Criterion	Biogas/biomethane	Lignocellulosic biofuels
Might compete with food production	Yes	No (excepting Short Rotation Plantations)
Might use organic residues	Yes	Yes
Might use high moisture source	Yes	No
Highly available resources	No	Yes
Complexity	Middle	Firewood: very low, Raw gas: middle, BtL: very high

[13] WBGU (2008) presents some results for those resources. However, it is not enough information to compare with all parameters studied because only this source includes raw gas and lignocellulosic biomethane. Also those results are expressed in final energy (electric, mechanical and thermic), and not at the biofuel level.

Criterion	Biogas/biomethane	Lignocellulosic biofuels
Available at small scale for cogeneration or fuel production	Yes	No, only for thermic energy. Small electric generation is very inefficient and expensive. In electric generation becomes economic from 10 MW up (CNE-GTZ, 2008), which is consider small size worldwide (Ahrenfeldt et al., 2011).
Fuel thermal efficiency	>90%	Firewood: 68% double chamber woodstove (average 32% moisture, Torres-Álvarez &Peña-Cortés, 2011). Firewood in boilers 90%, liquid and gas fuels >90%
Electrical efficiency	40%	25% (CCA, 2008)
Electrical production costs (€-Cent/KWh$_{el}$, WBGU, 2008)	CHP[14]: 8 (manure), 13 (maize silage), 25 (organic waste)	Raw gas turbine: 22 (residues), 28 (short rotation plantations). Chips CHP steam turbine: 15 (residues pellet), 14 (SRP) Raw gas CHP steam turbine: 23 (residues pellet), 27 (SRP) Biomethane: 25 (residues) BtL: N.D.
Fuel production efficiency (from original carbon)	50%	10%
Fuel transformation efficiency (from energy input)	Biomethane cleaning process: less than 10% energy loss	BtL transformation process: 50% energy loss Raw gas wood gasification: 10-70% (depending on the size and technology)
Fuel production costs (€-Cent/vehicle km, WBGU, 2008)	Biomethane: 6 (manure), 7 (maize silage)	BtL Diesel: 4.5 (residues), 6 (short rotation plantations).[15]
Conservation of nutrients	Almost complete (99%), conservation of the biological medium.	Partial (loss of volatilizable nutrients: N, K, S). Change in the chemical composition due to incineration.
Conservation of biology	High (residues), Low (crops)	High (native forest), Low (exotic plantations)
Proportion of carbon used (reduction to carbon dioxide)	75% (Deublein and Steinhauser, 2011)	> 95%
Production of waste water	Yes (liquid fertilizer)	No

[14] Also for biogas, biomethane and lignocellulosic raw gas is the process with fuel cells, that have better efficiency, but much higher costs.
[15] According to Guo et al. (2015) syngas from gasification of woody biomass is not cost-competitive. Best projection: lignocellulosic bioethanol, and biogas sectors.

Criterion	Biogas/biomethane	Lignocellulosic biofuels
Emission of gas contaminants[16]: Particulate matter Generation of toxics	 PM <1 mg/MJ CO: 133 mg/MJ SO2: 60 mg/MJ	Firewood combustion: PM 100-240 mg/MJ, depending on the technology CO: 600-3000 mg/MJ SO2: 2-20 mg/MJ Gasification (potential): CO, PAH[17], furans, dioxins, tars, sulphur, halogen and nitrogen compounds (Seidel et al., 2013; WBGU, 2008)[18]
Fuel type	Biogas, biomethane	Firewood. Raw gas, Syngas, biomethane, BtL biodiesel, ethanol, methanol.
Potential fuel uses	High (high versatility in household use: cooking, lighting, heating, cooling, conventional engines/ electric generators)	Limited (Raw gas toxic for humans). Firewood restricted to heat production.

In this Chapter, biofuels are compared in generic terms. However, using those biofuels for different specific energy production pathways can mark important differences in terms of final environmental performance. Such technological pathways are compared in Table A6 according to the technical specifications given in Tables A7 and A8 of the Appendix.

5.3 Prioritized Qualitative Interactions

5.3.1 Searching for bioenergy alternatives

As a next step in the bioenergy selection process, a qualitative method is developed. In order to achieve this, a conceptual model with a new scale of interaction analysis is developed in order to provide structure and define limits, as well as to systematically synthesize the information. This new step includes land use interactions, as well as human needs in the system analyzed. As a basic structure, the process of energy delivery involved is used. The alternative processes are many, as well as the ways in which to represent or visualize the process of transformation of biomass into different fuel types and other energy uses. As a reference, a good example is given in Figure 22, which is a systematic generalization of the transformation to energy process common for most biomass (other alternatives are shown in Section 9.3 of the Appendix).

[16] For a detailed comparison, see table 3 in the paper "Sustainability of implementing a biogas cogeneration unit on a university campus in Valdivia, southern Chile", in chapter 6.6.
[17] Polycyclic Aromatic Hydrocarbons.
[18] Cogeneration plants restricted in Europe by environmental regulations

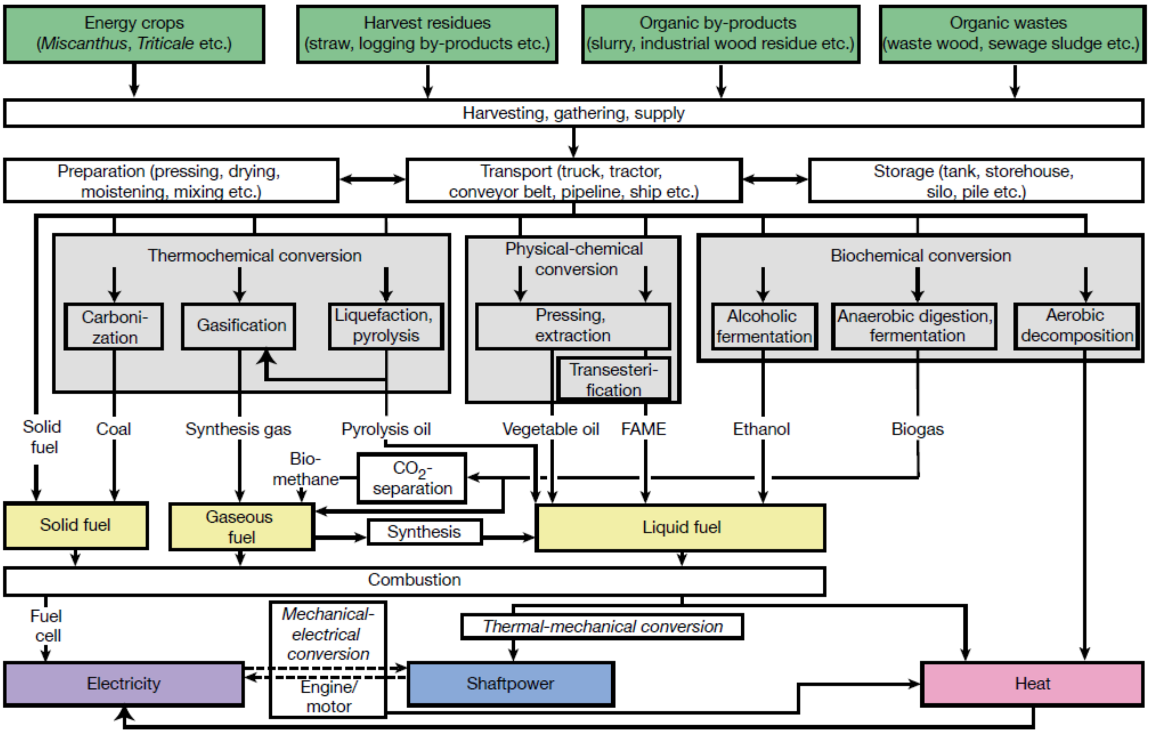

Figure 22: Simplified representation of typical biomass feedstock life cycles for final or useful energy provision (WBGU, 2008; adapted from Kaltschmitt & Hartmann, 2003).

As the core of this research is the study of interactions between land use and bioenergy potentials, the conceptual model (or system analysed) is rooted in a land-use approach because ecosystem productivity is the basis for resources and bioenergy supply. Therefore, land use is also the main driver for achieving land self-sufficiency as a desirable condition for sustainability (Erlwein, 2002). As in the conceptual model of Florin et al. (2014) for a sustainable biofuel production, the model presented here relates biophysical and socio-economic drivers that are assessed through sustainability indicators[19]. The model configures particular combinations of biomass resources and technology under the restrictions of land availability and human needs. Human needs are simplified as energy needs (in their different energy forms), food, and materials[20]; the three categories can be translated into land use requirements. Each particular bioenergy alternative can be compared to others in terms of its (overall) sustainability performance. However the system considers one type of bioenergy at a time, so that the multiple combinations of more than one bioenergy alternative are not studied in this model. Although a region should not be restricted to a single concept or model, as the combination of multiple alternatives may deliver synergies and better sustainability performance, the search for the "one best solution" is important as a reference for the potentialities of the region and therefore as valuable information in regional bioenergy development. The conceptual model proposed for this stage of the research is shown in Figure 23.

[19] For a full quantification of sustainability indicators see Chapter 6.6.

[20] Water is not considered since in Los Ríos Region there is generally a big surplus of water for human consumption.

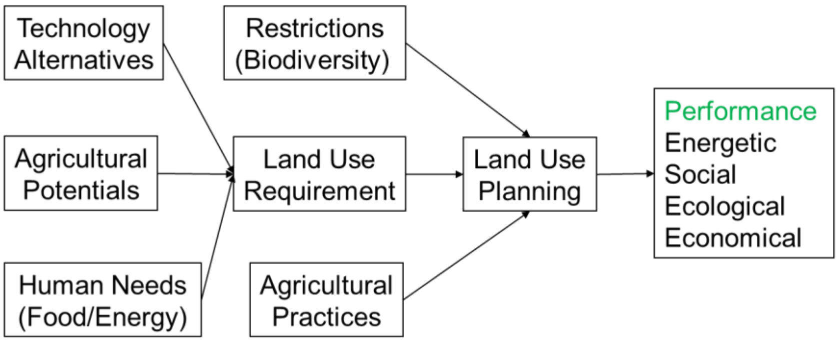

Figure 23: Conceptual model for analysing the interactions involved in choosing a sustainable bioenergy system for Los Ríos Region, southern Chile.

After establishing the conceptual model, a selection/discard (elimination) process of alternatives towards a more precise specification of factors is carried out. In order to achieve this, information from the comparison of biofuels in the last Section is used in combination with qualitative information of comparisons among biofuels. Table A1 in the appendix shows a comprehensive qualitative comparison of the advantages and disadvantages of different biofuels. Table A2 in the appendix shows a summary of the qualitative environmental rating for different cultivation systems of biomass stock for bioenergy. For the new selection process of bioenergy alternatives, basic requirements are used as general criteria. These general criteria are related to the sustainability of the conceptual model and are developed by matching several perspectives of bioenergy sustainability with regards to the specific reality of Los Ríos Region. The general criteria used in the selection process are listed here:

- Biomass
    - Sources available in Los Ríos Region
    - Crops that can be grown in the region
    - High biomass production
    - Lower environmental impacts of production practices
        - Low competition with food production or land use
        - Low tillage
        - Low chemical inputs (pesticides, fertilizers)
        - Maximum nutrient recycling
        - Diversity of species and crops
        - Preference for endemic or naturalized species
        - Compatibility with management of abundant native forests
- Technological process
    - Possibility of importation and commercially availability
    - Financially affordable – low cost investment and operation
    - Low environmental impacts of facility construction and operation
    - Operation complexity according to local expertise/education level
    - Low security risk operation
    - High diversity of biomass sources
    - High energy efficiency
    - Low carbon footprint
- Social and individual aspects
    - Diversity of energy formats (heat, power, shaft)
    - Diversity of possible uses (cocking, lighting, engine fuel, heating)
    - Simplicity of use
    - Supply amounts related to local needs
    - Decentralized & local-scale system
    - Participative system

Selection of local alternatives and structure of the analysis

Based on the previous criteria, the new, more specific selection of bioenergy alternatives for Los Ríos Region is conducted in order to narrow the number of factors and variables to be assessed in the search for the best bioenergy options for the region. For exploration, a network analysis is carried out in order to find a clear structure which allows to distinguish different concepts and information involved in bioenergy systems. In Figures 24 to 27 part of the information for the structuring process is shown. In these Figures the steps for setting the structure of the system studied in Section 6.2. in terms of variables and their connections are shown. A previous requirement for system analysis is to set its limits. Firstly, some concepts and variables relevant for Los Ríos Region are selected and collected in an information cloud (Figure 24).

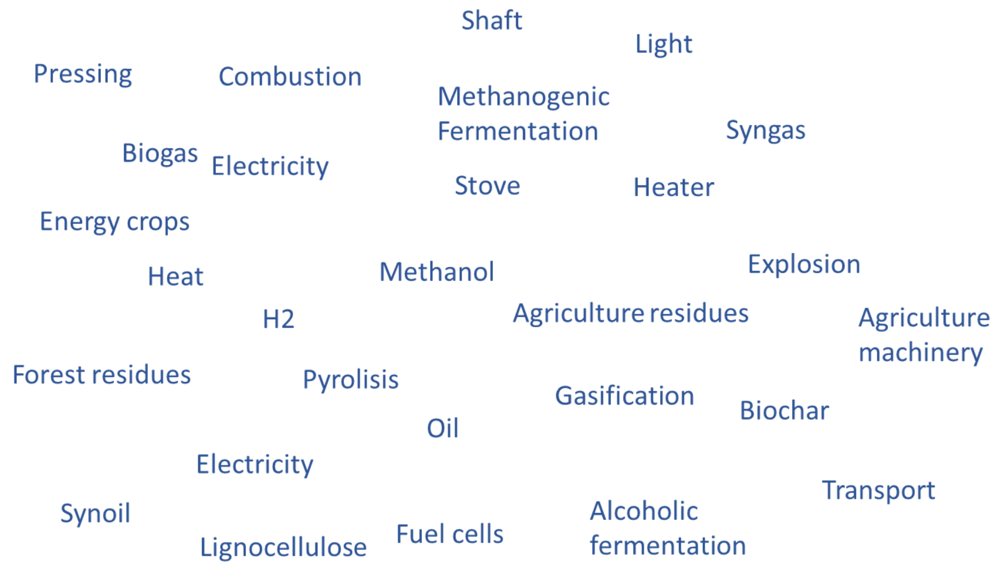

Figure 24: Structuring the analysis, Step 1: Gathering relevant variables in the search for a structure of analysis.

Afterwards, a network analysis is carried out in order to reveal interactions (causal relations) that define the dynamics, steps, and routes of energy transformation among the different resources (Figure 25).

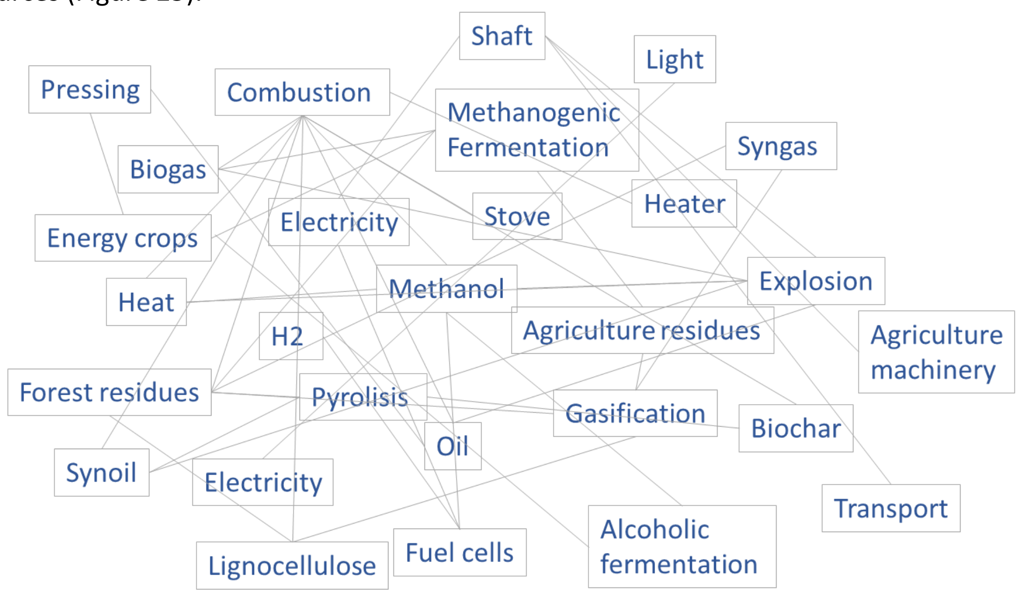

Figure 25: Structuring the analysis, Step 2: Draft of network connections with direct interactions between variables.

After studying the different combination of interactions in the system, a categorization is carried out according to the results and following the approach presented in Figure 22. Therefore, the variables analysed are classified into 6 categories (the results of the categorization process are shown in Figures 26 and 27):

Categories

- Biomass
- Transformation process of biomass
- Fuel-energy carrier (Product of transformation)
- Energy form
- Energy transformation
- Final Use

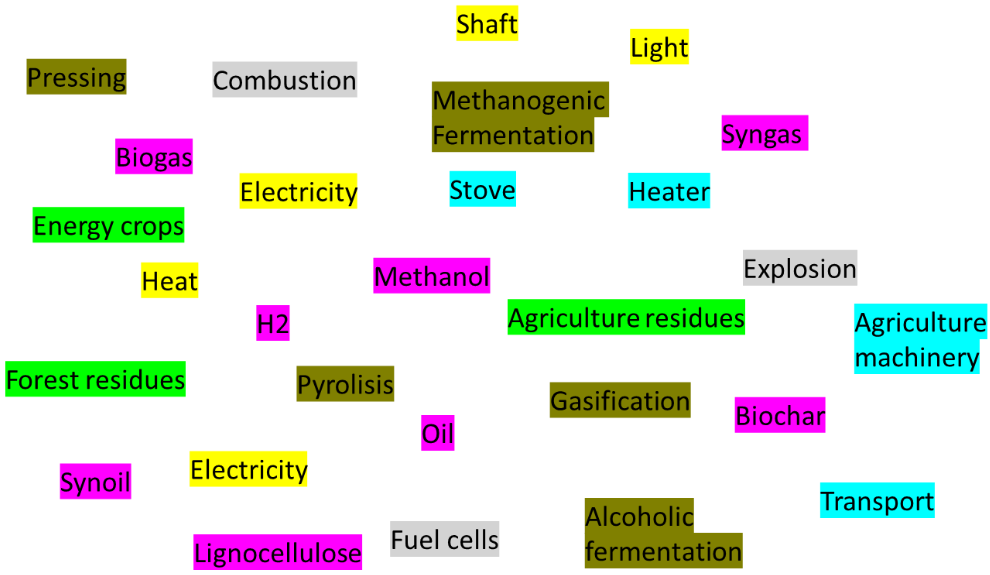

Figure 26: Structuring the analysis, Step 3: Variables of the system considered after categorization in the search for a structure of analysis.

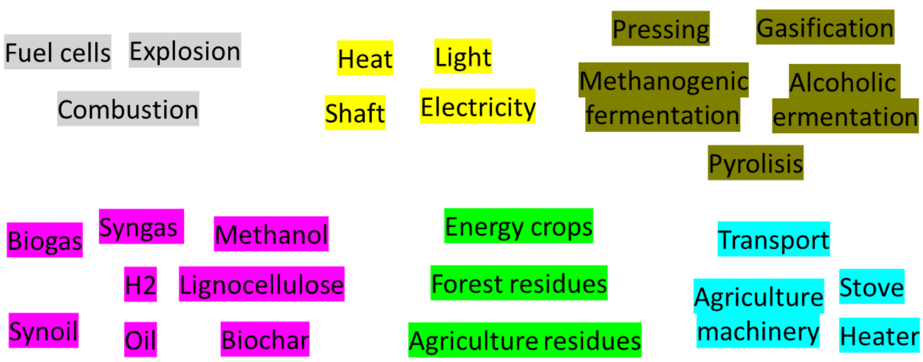

Figure 27: Structuring the analysis, Step 4: Different variables grouped by categories.

According to this structuring process, specific alternatives are selected and classified in stages from the production to the consumption of the bioenergy. These alternatives are resources and processes available for implementation in Los Ríos Region. For the selection of biomass resources, a summary of different sources (Cazangas et al., 2010; CATA, 2007; INE, 2007) in combination with the author´s personal experience in rural areas of the region are used. The selected alternatives are shown in Table 6.

Table 6: Specific component alternatives for a bioenergy system in Los Ríos Region according to process stages (pathways) from production to consumption of the bioenergy.

Biomass sources	Energy Carrier obtaining process	Energy Carrier	Energy Carrier transformation process	Energy forms	Final use
N=26	N=6	N=7	N=6	N=3	N=7
Forests, fast growing trees plantations • Wood ○ Firewood ○ Chips ○ Pellets *Fresh organic matter* • Crops & fruits ○ Maize ○ Wheat ○ Grass ○ Canola ○ Sunflower ○ Cabbage ○ Barley ○ Triticale ○ Potatoes ○ Apples • Grasslands • Organic wastes ○ Agricultural ○ Animal ○ Industry ○ Urban *Carbohydrates plants* • Starch ○ Maize ○ Wheat ○ Barley ○ Triticale ○ Potatoes • Sugar ○ Sugar beet ○ Fruit trees • Oil plants ○ Canola ○ Sunflower	• Gasification • Fischer-Tropsch reaction • Pyrolysis • Methanogenic fermentation • Alcoholic fermentation (hydrolysis) • Pressing-esterification	• Lignocellulose (also wood) • Syngas • Biogas • Alcohol • Biochar • Bio-oil/ Biodiesel • Biomass	• Simple combustion • Engine combustion • Steam turbine • Fuel cell • Cogeneration ○ Engine ○ Fuel cell ○ Turbine • Incineration	• Heat • Electricity • Physical work	• Light • Cooking • Heating • Hot water • Electronic devices • Agriculture machinery and transport • Industrial processes

5.3.2 Modelling feasibility of bioenergy alternatives

After this last prioritization process, in which the reduction and setting of new limits to the system is conducted, the next step is to search for the best combination of the selected resources and technologies, implied as an optimization process. Searching for models of potential methods for the comparison of biofuel alternatives, a survey among worldwide researchers on bioenergy is carried out through the web page RESEARCH GATE (from the beginning of March 2012 to end of July 2013). The question published on the researchers' website is as follows:

Does anyone know a method or software for modelling a set of different renewable energies in order to get the best combination of them?
I am working on the most adequate combination of sources of renewable energies for the needs of rural communities in the south of Chile. I am using variables of economic, energy efficiency and environmental performance of such combination of sources. Thanks!

The quest results are as follows: 170 answers and 36 software programs were suggested that differ greatly from each other in type and characteristics; for example, Multi Criterial Decision Analysis (MCDA), multi-objective optimization, linear programing, systems dynamics approach, or Life Cycle Analysis (LCA). The list of software programs is given in Table 7 (the answers to my question can be found in Section 9.4 of the appendix).

Table 7: List of software programs as suggested by participants of the survey in RESEARCH GATE:

#	Software	Characteristics	Webpage
1	AHP	MCDA+fuzzy logic	https://en.wikipedia.org/wiki/Analytic_hierarchy_process Use AHP: http://makeitrational.com/ http://sajidsiraj.com/priest/
2	ANSYS CFX	High-performance, general purpose fluid dynamics program used to optimized electro thermal systems as well as fluids	http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+CFX
3	DER-CAM	Optimize for min cost of operating on-site generation and combined heat and power (CHP) systems, either for individual customer sites or a µGrid (biogas also)	https://building-microgrid.lbl.gov/projects/der-cam
4	Energy Costing Tool	Estimates the amounts and types of energy investments required to meet Millennium Development Goals (MDGs)	http://www.undp.org/content/undp/en/home/librarypage/environment-energy/sustainable_energy/mdg_support_services-energycostingtool.html
5	Energy Plan	Simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors	http://www.energyplan.eu/
6	Energy Plus	Buildings energy simulation program to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings	https://energyplus.net/
7	GAMS	Multi-objective optimization. General Algebraic Modeling System (mathematical programming and optimization)	http://www.gams.com/

#	Software	Characteristics	Webpage
8	GE Smart Grid	Optimization of smart grids (generation, transmission and distribution)	http://www.gegridsolutions.com/UOS/EMS.htm
9	Greenius	Performance and economic calculations of Concentrating Solar Power (CSP) and other solar energy systems	http://freegreenius.dlr.de/
10	HOGA	Multi-objective optimization developed in C++ for Hybrid Renewable Systems for generation of electrical energy	http://hoga-renewable.es.tl/
11	HOMER	Optimization of electricity production. Design of off- and on-grid electrification options	https://analysis.nrel.gov/homer/
12	Hybrid2	Probabilistic/time series computer model, perform detailed long term performance and economic analysis on a wide variety of hybrid wind-solar power systems	http://www.umass.edu/windenergy/research/topics/tools/software/hybrid2
13	HYSYS	Process simulation and optimization in design and operations, developed for oil and gas producers, refineries, and engineering companies	http://www.aspentech.com/products/aspen-hysys.aspx
14	IES	Optimization of emissions, energy, costs, etc. Buildings and cities	www.iesve.com
15	LEAP	Integrated Energy/Environment Analysis	http://www.energycommunity.org/default.asp?action=47
16	MARKAL	Linear programing. Cost and emissions optimization	http://www.iea-etsap.org/web/MARKAL.asp
17	Matlab/ Simulink	Model for parameters numerical optimization. Applications for wind and solar	http://www.mathworks.com/products/?s_tid=gn_ps
18	MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	http://webarchive.iiasa.ac.at/Research/ENE/model/message.html
19	META	Model for Electricity Technology Assessment (World Bank). Levelled costs for generation, transmission, and distribution of each electricity supply/ technology option.	https://www.esmap.org/node/3051
21	MIPOWER	Electric optimization. Power systems design and analysis	http://www.prdcinfotech.com/business/software-products/mipower/
22	Modelica	Systems dynamics approach	https://modelica.org/ https://www.openmodelica.org/
23	ModerGIS/IntiGIS	MCDA+LEAP+GIS (CEPAL)	http://www2.unalmed.edu.co/~modergis/#sthash.XfFMBKcg.dpuf http://www.cepal.org/ilpes/noticias/paginas/8/40548/Rquijano_Modergis_Cepal_Cartagena_08_10.pdf
24	NAVITAS	Techno-financial software for marine renewable energy.	http://www.ucc.ie/en/hmrc/projects/navitas/

#	Software	Characteristics	Webpage
25	NREL	System dynamics simulation (not optimization) to model dynamic interactions across the supply chain of domestic biofuels. BSM explicitly focuses on policy issues, their feasibility, and potential side effects.	http://www.nrel.gov/analysis/bsm/
26	PSCAD/ EMTDC	Power system transient simulation package	https://hvdc.ca/pscad/
27	PSS E	Electric transmission system analysis and planning. Used worldwide	http://w3.siemens.com/smartgrid/global/en/products-systems-solutions/software-solutions/planning-data-management-software/planning-simulation/pages/pss-e.aspx
28	RetScreen	Energy production, life-cycle costs and GHG emission reductions for various energy efficient and renewable energy technologies	http://www.retscreen.net/
29	SAM	Set of various performance models. Optimization of performance and financial metrics of electric power generation systems from the U.S. Department of Energy and National Renewable Energy Laboratory. Land potentials	https://sam.nrel.gov/
30	SimaPro/GaBi	LCA software	https://simapro.com/ www.gabi-software.com
31	StudioPress/ Vensim PLE	Systems dynamics approach	www.powersim.com www.vensim.com
32	T*SOL	Optimization in design solar thermal systems	http://www.valentin-software.com/en/products/solar-thermal/14/tsol
33	TIMES	Linear programing. Cost and emissions optimization	http://www.iea-etsap.org/web/TIMES.asp
34	TOPSIS/ ELECTRE	MCDA+fuzzy logic	http://www.stat-design.com/Software/TOPSIS.html https://en.wikipedia.org/wiki/ELECTRE
35	TRNSYS	Optimization of finances, MCDA	http://www.trnsys.com/ http://sel.me.wisc.edu/trnsys/index.html
36	WASP/IPP	Computational Fluid Dynamics (CFD) wind model for wind resource and energy yield assessments	http://www.wasp.dk/

After systematically compiling the answers of the survey according to the preferences of software alternatives among participants, a ranking of software programs is prepared, which is shown in Figure 28.

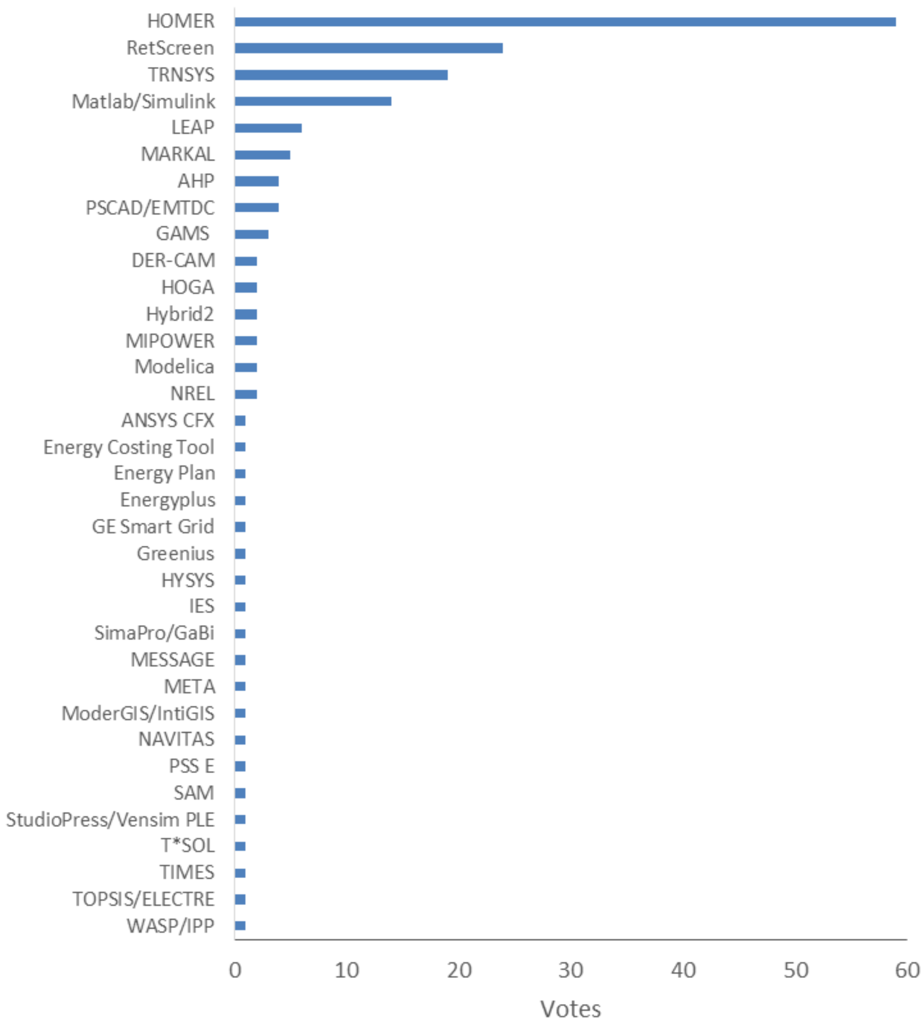

Figure 28: Preferences of software alternatives "*for modelling a set of different renewable energies in order to get the best combination of them*" suggested by participants of a survey in the researchers´ network RESEARCH GATE.

As it can be appreciated from the high diversity of software types mentioned in the survey, there are many alternatives for the optimization processes of renewable sources. The problem of modelling can in fact increase the complexity of the research, as there are more variables to cope with, an aspect which is discussed in more detail in Chapter 6. In any case, most of the models listed are quantitative and specific for electrical grids, but this research is not focussed in grid optimization rather in sustainability performance. Therefore such software programs are not optimal for the research process in this work. The given list of software programs can be useful in the fine optimization of specific features of a specific bioenergy system in the region after having the main structure and components of the bioenergy system already defined. This is possible only after a reduction in the level of disciplinary interactions involved, which will be done in the next selection process of this research, as follows.

5.3.2.1 Network analysis

In consideration of the problematic previously exposed, a software program from the family of network analysis, based on qualitative information model is explored. Qualitative models are common in system sciences, but also in social sciences, as these sciences work with problems with a high level of complexity, as well as with qualitative or "subjective" information.

Network analysing programs allows the researcher to work with a broad range of complex phenomena, especially exceling in social network analysis (see details of network analysis in section 6.1.3.4). Optimizing given time and technical restrictions of this research, the software programs Ucinet and Netdraw are selected for modelling. These include a temporary free network visualization package, designed as an Organizational Network Analysis project mainly for social relations analysis, but also likely to be used in many other subjects including rural development studies (Clark, 2006). For setting the model, the previously selected alternatives are structured according to the defined conceptual model and network structure. In other words, the software fills in a matrix of components and interactions. Every component interacts with the components of contiguous pathways through connectors, specifying a relational configuration, as usually done in network maps. The interactions can have different strength. The criteria for establishing interaction strength (figured as the width of connectors; i.e. the thicker the connector line, the higher the interaction strength) is based on an overall value of feasibility, resource availability, overall efficiency, and the simplicity of the inclusion. A network map with the interactions involved is shown in Figure 29:

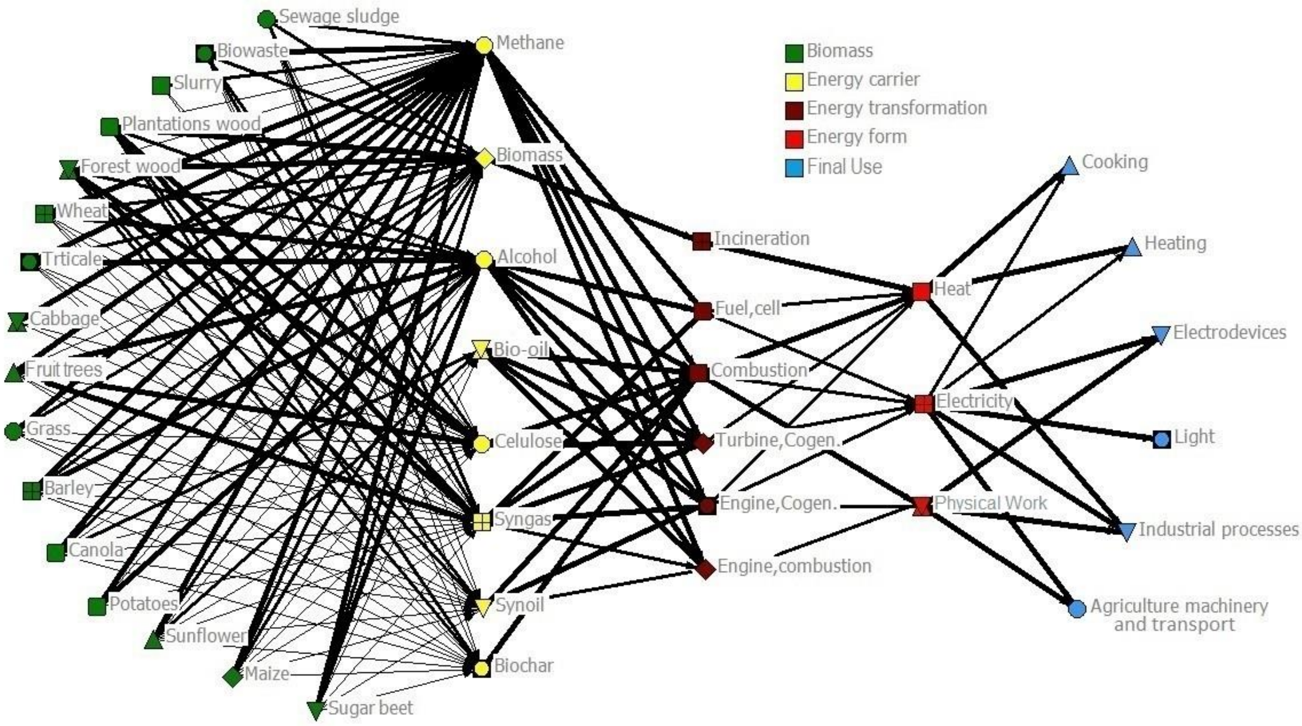

Figure 29: Network map (UCINET-NETDRAW) for potential pathways of bioenergy production, transformation, and consumption in Los Ríos Region according to its resource availability. The thickness of a connector line indicates the overall strength of the interaction.

After running the model, it can be graphically appreciated that the bioenergy carrier methane (biogas) shows the strongest connectivity in comparison to the other options. For a mathematical evaluation of such connectivity, an indicator was developed, which compiles all the interactions and their strengths for each energy carrier. The indicator formula is shown as follows and the results are presented in Figure 30:

$$I_F = \sum I_{FB} * \sum (I_{FT} * \sum (I_{FTE} * \sum I_{FTEU}))$$

Where:

I_F: Total interaction strength of each specific biofuel (energy carrier)

I_{FB}: Interaction strength between biomass type and the specific biofuel

I_{FT}: Interaction strength between the specific biofuel and energy transformation technology
I_{FTE}: Interaction strength between technologies and energy forms
I_{FTEU}: Interaction strength between energy forms and final uses

The I_F score is a parameter of the quantity and quality of feasibility interactions for different biofuels, therefore it can be considered as a reference of the use potential of every studied biofuel in the region. The higher the value of I_F, the greater the potential use. As can be observed in Figure 30, methane (biogas) shows the highest relational richness among energy carriers, due to its high versatility (of biomass sources, potential transformation processes, forms of energy and uses), in combination with a high technical performance (resource/energy efficiency and practical feasibility).

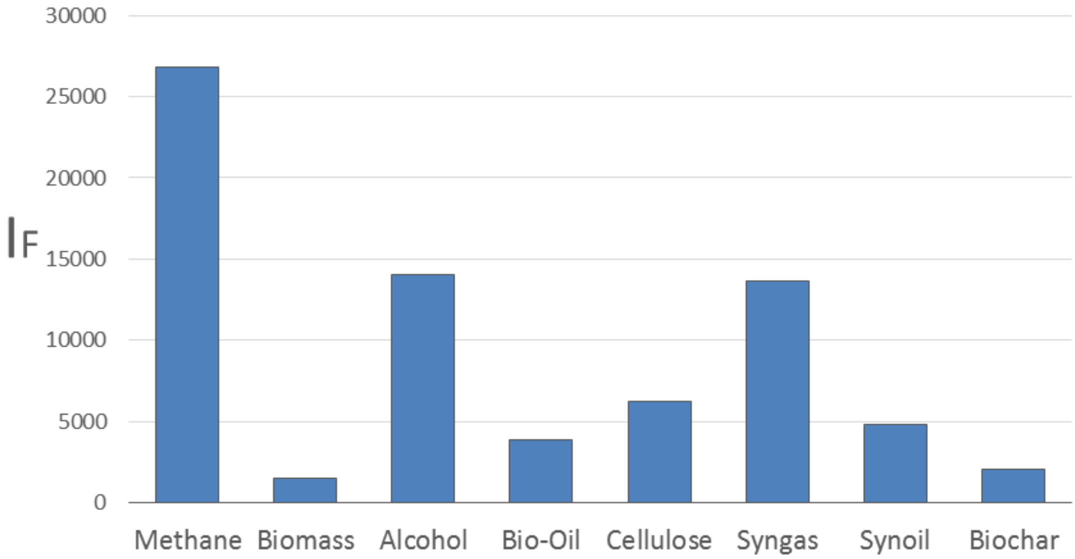

Figure 30: Values of I_F (total interactions strength) for each energy carrier analysed.

It is important to consider that I_F does not take into account specific information about biomasses[21], including the sustainability performance of each biomass or the potential availability of each biomass resource in the region. For example, in Los Ríos Region the availability of lignocellulosic resources (wood) is high compared to other biomass resources so that cellulose and syngas might be underestimated in terms of feasibility in this model. However, the sustainability performance of different biofuels, including the accountability of the source of biomass was already studied in Section 5.2, so that the two sources of information are complementary. In fact, results from last analysis are similar to the ones in Section 5.2 in terms of best performance reached by biofuels biogas, lignocellulosic fuels and their derivatives. This fact suggests again a confirmation of the second research hypothesis of this thesis. In addition, I_F has been conducted using secondary information, and does not consider local empiric (primary) economic or cultural aspects that can ultimately determine preferences and feasibilities in the execution of biofuel production. For improving in this way the biofuel performance estimation, further research in this line is needed.

Finally, the last modelling process can be considered an antecedent for considering the acceptance of the first research hypothesis as:

[21] Biomass in terms of organic matter resource (crops, wastes, etc.), and not as fuel for incineration.

- The probability of configuration of circular processes of matter and energy flows (recycling) should increase with growing connectivity within a specific system
- The connectivity can be represented as a mathematical formalization

5.4 Regional Quantitative Interactions: Bioenergy Potentials

5.4.1 Bioenergy from crops

As an previous exercise of modelling bioenergy potentials from energy crops with BioStar (next Section), a Bachelor thesis was realized, offered to Mr. Mario Alejandro Celedón Martínez, tutored by me. The thesis investigated the biogas potential of current wheat and maize production in Los Rios Region. The original title is "*Estimación del potencial de generación de biogás a partir de ensilajes de cultivos de trigo (Triticum aestivum L.) y maíz (Zea mays) en base a sus superficies y productividades para la Región de Los Ríos.*" (Estimation of the potential biogas generation from energetic crops of wheat (Triticum aestivum L.) and maize (Zea mays) based on their current surfaces and productivities in Los Ríos Region). The abstract of the thesis, accepted by the Faculty of Agrarian Science, Universidad Austral de Chile, is attached to this document in the Section 9.5 of the Appendix. The thesis was approved with a grade of 6.0, on a scale with 7.0 as the maximum (optimum) and 1.0 as the minimum.
Another thesis containing a case study of electricity and heat production by biogas produced from maize, which is similar to concept common in Germany, was also co-tutored. The original title of the Bachelor thesis by Mr. Rodrigo Schnettler Sabugo is "*Análisis técnico económico de una planta productora de biogás a base de maíz (Zea mays) para la cogeneración eléctrica y térmica*." (Technical and economic analysis of a plant producing biogas from maize (Zea mays) for combined heat and power). The abstract of the thesis, accepted by the Faculty of Agrarian Science and approved with distinction, is attached to this document in the Section 9.6 of the Appendix.

5.4.1.1 Paper 1: Modelling site-specific biomass and bioenergy potentials in Southern Chile using BioSTAR

The draft of my paper "*Modelling site-specific biomass and bioenergy potentials in Southern Chile using BioSTAR,"* is shown on the next pages.

Modelling site-specific biomass and bioenergy potentials in Southern Chile using BioSTAR

Key words: Bioenergy modelling; BioSTAR; biomass potential, energy crop, biofuel

Alfredo Erlwein-Vicuña[22][23], Martin Kappas[22][24]

ABSTRACT

The ability to predict biomass potentials would be strategic for regional planning and development. Modelling site-specific biomass potentials could be an effective, resource-saving way to achieve this. BioSTAR modelling software has demonstrated accuracy in predicting biomass potentials in Lower Saxony, Germany, where it was developed. The model was applied to Los Ríos region, a temperate area in southern Chile, for the evaluation of its performance. For model operation, a GIS-based database that includes the soils and climate districts of the region was developed. The results of the model were compared with available local field data and with the regional average yields provided by the national agricultural census based on the data of more than 2000 farmers in the region. Compared to BioSTAR results, the maximum yield potentials (trials) were 50% higher and the farmers regional averages were 25% lower. Results suggest that there is a significant correlation between the model and reality, although more site-specific validation is needed. Considering only the soils with agricultural use capacity, and excluding the areas with native forests, a potential surface of 332,400 hectares, equivalent to 18.1% of the region, was identified and used in the calculations. From that area, a total regional biomass potential of 5.9 million tons of dry matter biomass (whole plant) and 2.8 million of dry matter grain was calculated with BioSTAR for wheat, whereas for maize 10 million tons of dry matter biomass was calculated. From these results, a potential biogas production of 2,960 million m^3 for wheat and 4,978 million m^3 for maize was reached, with a total bioenergy potential of 17.8 and 29.9 TWh respectively.

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Contents

1 ABBREVIATIONS

AD: Anaerobic digestion
BioSTAR: **Bio**mass **S**imulation **T**ool for **A**gricultural **R**esources; a model to estimate biomass potential (developed in the Department of Cartography, GIS and Remote Sensing; University of Göttingen, Germany)
CHP: Cogeneration of Heat and Power
DM: Dry Matter
GIS: Geographical Information System
IIAS: Institute of Agriculture Engineering and Soil Science, Faculty of Agrarian Sciences, UACh
IZNE: Interdisciplinary Center for Sustainable Development, University of Göttingen
LRR: Los Ríos Region
LUC: Land Use Change
SRES: Santa Rosa Experimental Station, UACh
UACh: Universidad Austral de Chile, Valdivia

2 INTRODUCTION

2.1 Climate change and bioenergy

Climate change is possibly the most challenging environmental problem that faces the current development of our civilization (IPCC, 2011b). Bioenergy is a renewable source of energy that can contribute to the mitigation of climate change, especially in the period of transition out of the fossil fuel energy structure (WBGU, 2008).

Among bioenergy sources, biogas presents a series of advantages that makes it suitable as a rural energy supply, especially in underdeveloped countries (USDA 2014; WBGU 2008; Deublein D, Steinhauser 2008; Vögeli et al. 2014):

- It is a renewable energy source available in rural areas, for example in Los Ríos region (LRR) (Paneque et al., 2011)
- It fits especially well in small scale human settlements, like rural communities and villages
- It allows decentralized energy autonomy, especially in isolated areas (Ruppert, 2013)
- It can be a rather simple technology (Guardado-Chacón 2006; Martín Herrero and Martí-Herrero 2008), allowing populations without high-technical skills to operate it.
- As a biological process that does not require high temperatures, pressures, nor toxic chemicals, it is a safe and environmentally innocuous technology
- It allows for the use of different plant species, or a combination of them, diversifying options and avoiding monocultures (Karpenstein-Machan, 2013)
- It allows for very high nutrient recycling (Ruppert, 2013)
- It can be a solution for the recycling of organic waste (Varnero 2011; StMUGV 2004)
- It is a technology with high energy and carbon efficiency and low environmental impact compared to other biofuels (Stoeglehner and Narodoslawsky 2009; Hennig and Gawor 2012; FNR 2014)
- Biogas is a highly flexible energy carrier that can be used to produce different energy formats as mechanical work (fuel for engines and machinery), electricity (fuel cells or combustion engines), thermal energy like cooking and heating (combustion or CHP systems), or as light (Hilbert, 2010).

In rural areas there are abundant of resources for feeding biogas systems, including all sources of biomass waste like animal excrements, rotten harvest or left-over plant material, agricultural residues, and residential organic waste. Additionally, agriculture products can be directly used for biogas production (Deublein and Steinhauser, 2011). However, this direct use has been greatly debated, as bioenergy crops can compete with food production (Boddiger, 2007), imply deforestation risks to natural forests (Patz et al., 2007), become an accelerator of the loss of biodiversity and/or soil (Anton and Steinicke 2012; Giampietro M, Mayumi 2009), and can potentially promote desertification and social inequity with respect to energy and resource access (FAO, 2008).
In 2011 Germany had 2.2 million hectares from the total agricultural area (17 Mio. ha) already in use for either energy crop production or renewable primary products. Of this area, 800,000 hectares were in use for bio gas crops, mainly as maize, while 900,000 hectares were used for oil (rapeseed) for the country's bio-diesel production, and the smallest share, 250.000 ha. were in use for starch and bio-ethanol production (Baubock, 2012). Replicating this situation in other countries and continents could be complex. Information on regional biomass potentials can inform us on the scale of potential land use change involved with respect to specific crops and energy production, especially dimensioning the expansion of crops under current and/or future economic scenarios.
In order to face the highly unsustainable structure of the current global energy system and its environmental and social implications, the first priority is to analyze and understand the trade-off between staying where we are and fully implementing the existing alternatives, as well as exploring the complexity of the options in between.
From a certain perspective, energy crops can be an alternative not only for energy purposes, but as an opportunity for better agricultural management (like rotations), diversification of activities, new sources of rural income, optimization of land use, and a chance for collective organization and social development (WBGU, 2008).
Even some prominent authors from the ecologist movement have justified the use of 5 to 10 % of available farm land for energy production (Mollison and Mia, 1991).
It is important to note that this work and research is being conducted in the midst of the international query for sustainable ways to transition towards a renewable and sustainable energy system.

2.2 BioSTAR, crop modelling software of biomass potentials

2.2.1 Modelling biomass potentials

Changes to land cover and land use are among the most significant impacts of human society on the environment (WBGU, 2008). Kappas (2013) states that the discussion on the future role of bioenergy is currently dominated by three issues that strongly affect decisions on energy development priorities: the security and the sustainability of both the energy and food supply, as well as climate change. The same authors point out the security trade-offs between water supply, energy, and food. Energy and food production, as well as carbon sequestration or water supply can all be considered environmental services (Costanza et al., 1998). There is a direct correlation between land use and ecosystem services (Lara et al. 2009; WBGU 2008). Together with energy, food, or material resources, land can provide other ecosystem services traditionally not traded in markets, like carbon sequestration, water supply, biodiversity, or depuration of toxic substances, to mention just a few. Based on this information and the IPAT equation of Paul Ehrlich (Chertow, 2000), a triangle of trade-offs between land use ecosystem services can be configured by the interplay of 3 main systemic drivers as shown in Figure 1 below. The final configuration and its sustainability are determined by how the main drivers (center of triangle) perform. Global change: degree and type of impacts of climate change; Population: current stage and demographic dynamics; Consumption practices: resource demand dictated by cultural determination of life standard and preferences, including resource efficiency and sufficiency; Production practices: sustainability and diversification of local production. The economy is modelled by producers and consumers. The traditionally non-monetized (not traded, ecological) services are related to commons with the function of ecosystem resilience, like air and water production and cleaning, biodiversity, landscape, waste and toxic depuration, nutrient recycling, pollination, pest control, etc. (UKNEA 2011; Daw et al. 2011). Some of them, like carbon sequestration, are now in transition to be traded.

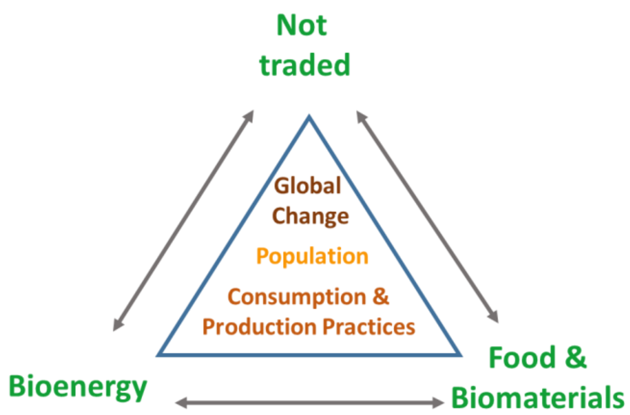

Figure 1: Trade-off between ecosystem services associated with land use (in green).

Therefore, it is of high priority to quantify the balance between the demands and offers of land resources for understanding the current and potential state of food and energy security as well as sustainability of the land use configuration. It is a way to know where we stand and where to go in terms of sustainable land use.

By estimating the agricultural and bioenergy potential for different crops in different sites, supported by GIS, it is possible to have a broad view of a regional potential, which in turns allows assess to several strategic local and regional parameters, as such (Bauböck 2012, 2013b, 2014; Tum et al. 2013; WBGU 2008):

-The total maximum food production
-The local availability of renewable energy sources by means of biomass
-The potential carbon sequestration
-The information basis for economic feasibility of bioenergy projects
-To theoretically test different alternatives in the planning processes
-To estimate the effects of climate change on yields
-To optimize production models (i.e. rotation, crop diversity, crop site-fitness)
-To predict land use conflicts and a way to manage them
-To identify exclusion areas and reduce the environmental impacts of land use change
-To analyze options of land use optimization by integrating different alternatives under a systemic/synergic view.

2.2.2 BioSTAR

The crop model "Biomass Simulation Tool for Agricultural Resources" (BioSTAR) was developed as part of the research project "Sustainable use of Bioenergy – bridging climate protection, nature conservation and society", by scientists at the Interdisciplinary Centre for Sustainable Development (IZNE) of the University of Göttingen and the Lower Saxony state office of mining, energy and geology (LBEG) in Hanover. It is a carbon-based crop model which assesses site-specific and larger area biomass potentials (R Bauböck, 2013). It was specifically developed to simulate climate and soil-dependent biomass yields for bioenergy crops, but it can also be used to predict yields for food crops of the same species as bioenergy crops (wheat, maize, rye, triticale, barley, sunflower, grass, sorghum, miscanthus, sugar beet, canola, willow, poplar, silphium, rice and oats), and is able to specify winter and spring varieties. The model's software is built in such a way that, depending on the resolution of the input data, small-scale (single plots or farms) or large-scale (larger areas with many input datasets) yield predictions can be generated very easily (Bauböck, 2014).

BioSTAR uses a carbon based growth engine to calculate an initial light and temperature dependent carbon accumulation rate from which photo-respiration (maintenance and growth) is deducted. The remaining fraction of CO2 is then used to calculate a photosynthesis-dependent transpiration rate. This is done by using the gradients of water vapor pressure and of the CO2- concentration inside the leaf to the corresponding pressures of the atmosphere (Bauböck, 2012).

The results are the potential yields for total biomass as well as food production (grains, beet, etc.). It is important to note that these are potential yields and do not reflect average yields of local farmland. Thus, the potentials represented here are neither theoretical (which consider all variables at best) nor practical, but technical potential (Roland Bauböck, 2013), which is the coverage of priority nutritional needs and takes into account the natural cycles, sustainability criteria (ecological), and technical constraints in energy.

As stated by Bauböck (2013b), the driving input variables of the crop model and the structure they are imbedded in are the climate components and the soil compartments. Plant specific parameters influence the processes of photosynthesis; assimilate distribution, transpiration and development speed. Plant physiological processes as well as fluxes are reduced to the availability of resources needed by the plants: (water, temperature and solar radiation). The flow chart is shown in Figure 2.

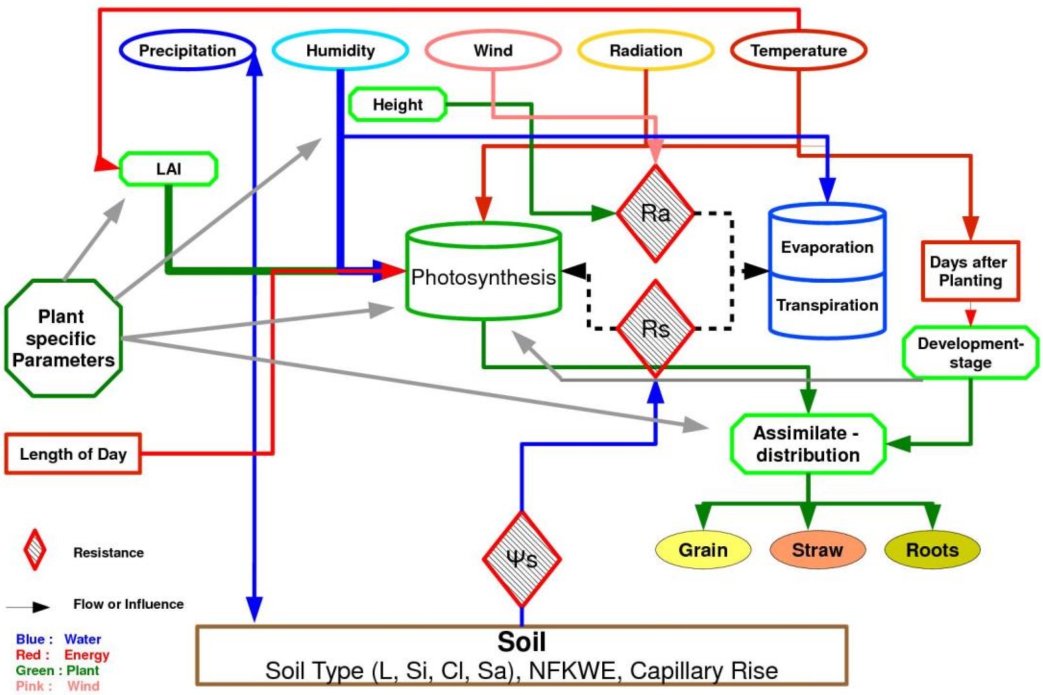

Figure 2: Flow chart with the main components of the model BioSTAR (R Bauböck, 2013). Abbreviations: L = loam ; Si = silt ; Cl = Clay ; Sa = Sand ; Ra and Rs = aerodynamic and stomata resistances; Ψs = matrix potential of the soil ; NFKWE = usable field capacity in the rooted zone ; LAI = leaf area index.

For running the model, series of data on climate and soil from the studied area are required. More details about the input information are given in the chapter "Materials and Methods".
BioSTAR has demonstrated significantly high accuracy on predicting crop yields. Regression analysis of validation trials in Lower Saxony, Germany (R Bauböck, 2013) that compare modeled vs real field yields for different crops have given the following correlation coefficient (R^2) : 0.8844 for maize (n=22), 0.8271 for winter wheat (n=51) and 0.7231 for sugar beet (n=30).

2.2.3 BioSTAR in Los Ríos Region

In this research, the model BioSTAR was used for Los Ríos Region in southern Chile, firstly for its calibration-validation against site specific field trials of wheat and maize, and then for estimating the regional potential for biomass and bioenergy (biogas).

3 MATERIALS AND METHODS

BioSTAR was run mainly at two levels of analysis:

A) Calibration of BioSTAR and validation of its results. The specific site at SRES was used because the station has the soil information, a complete weather record for the site, and field trials with which to compare the results of the model for such soil and weather conditions. Additionally, modeled results of SRES were compared with average yields in the region. After comparing the results of the model (yields of total dry matter biomass and total grains per hectare) with the available local field information, some parameters of the model were calibrated for fitness with the field trials in the search for the best predicting set of parameters.

B) Calculation of the regional biomass potentials (whole region). Once BioSTAR was calibrated, the biomass potential of all the agricultural soils in the region was calculated. Then, the information of the modeled regional potentials was analyzed in order to assess the robustness of these results.

3.1 Information for running the model

Although all the crops available in the software were modeled, this research is focused only on wheat and maize as there was available field trial information, specific studies, and a regional survey on these crops. The information on wheat is far more abundant as wheat is the most important crop in the region and the surface area of it in the region is significantly bigger than that of maize. Therefore, the calibration of the model was based mainly on wheat.

For running BioSTAR, a specific data-base of several parameters for the specific sites of the whole region was gathered and standardized according to the format required by the model. In this model, a site is considered a local place with a unique combination of soil and climate information. BioSTAR requires this information for every site that is going to be modeled. As the configuration of the sites is a result of a spatial interaction of soil and climate, the method of intercrossing them is described in the section 3.1.4 on Geographical Information Systems (GIS).

3.1.1 Climate

According to the two levels of analysis mentioned, two types of climate information were used:

A) As part of the calibration-validation process, real data from the SRES meteorological facility was used.

B) For the whole region biomass potential, the 15 Agroclimatic Districts defined for the region by CIREN (1990) were used.

BioSTAR can be run with daily or monthly data. In this research, monthly values were used. The variables needed by the model and their units are:

1. Julian-based calendar day (date)
2. Radiation, total per month average (Joules/cm2)
3. Precipitation, total per month (millimeters)
4. Temperature, monthly average (Celsius degrees, 2 meters high)
5. Air humidity, monthly average (%)
6. Wind (m/s), monthly average

The climate information used for calibration-validation was taken from the meteorological facility of the SRES and is displayed in Figure 3. The climate information used for estimating the regional biomass potential was taken from the zoning of agro-climatic districts (CIREN, 1990), available at the IIAS database. Agro-climatic districts are areas with representative climate values that have homogeneous agro-climatic conditions and have been defined and characterized by relevant variables for agriculture, summarizing thermal and water conditions for winter and summer. Each district is characterized by 27 climatic variables. The basic information is based on data sets of temperature, air humidity, solar radiation and precipitation, among others, which are recorded by weather stations. Through the analysis of this statistical and spatial information, basic mapping information is prepared and variable values of agricultural interest are established. Climate districts are shown in Figure 4c.

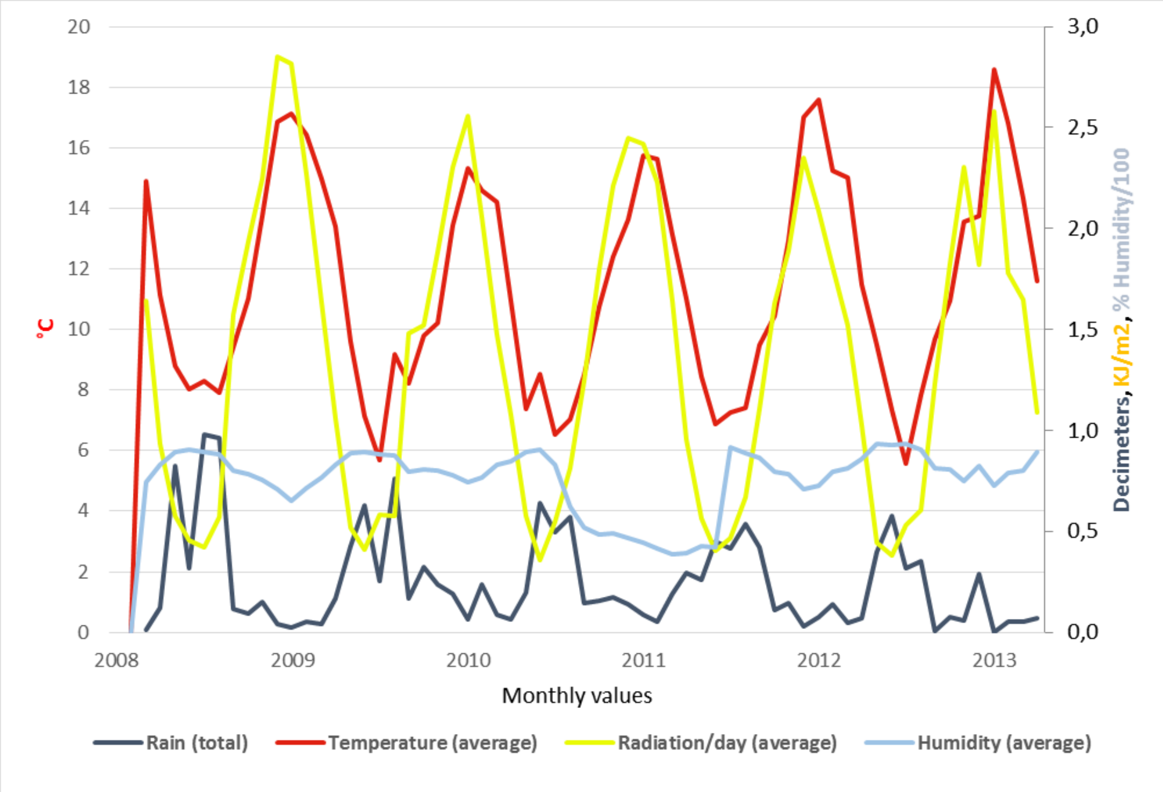

Figure 3: Climate information (precipitation, mean temperature, radiation and air humidity, monthly values) from the meteorological facility of the SRES for the five year period from March 2008 to April 2013.

As information on regional wind was not available, an average speed of 2 m/s was used. Figure 3 shows that the parameter of air humidity experienced a decrease in expected values in the period between August 2010 and June 2011. That anomaly is probably due to a temporal defect in measurement at the SRSE meteorological facility. A series of correlations for testing the accuracy of the weather information are shown in section 4.2, Figure 11.

3.1.2 Soils

In Los Ríos region a total of 44 soil type series were identified from a database developed by the national soil survey (CIREN 2003), through the GIS information database of IIAS. Of these, 5 classifications are not soil series (miscellaneous, no-soil and 3 types of alluvial terraces). As a reference, the identified soils were categorized following the work of Salazar et al. (2005), within two relevant international, soil classification systems: the FAO (1998) World Reference Base for Soil Resources (WRB), adopted by the International Union of Soil Science (IUSS) as the official system for soil correlation, and the US Soil Taxonomy (USSSS, 1999). The soil series and their correspondence with the US and FAO classification systems are shown in Table A1 in the appendix. The map of regional soils can be seen in Figure 4b.
In terms of soil characteristics, BioSTAR uses two parameters: texture and depth.

<u>Soil texture</u>
For homologation with the input database format of the model, correspondence of textures with the aforementioned taxonomical systems was analyzed. BioSTAR uses the soil texture format of FAO (2006) and the Chilean soil classification system (CIREN) is based on the US Soil Taxonomy classification system. In the case of the WRB, the textural classes are based on the triangle of textural soil classes of the USDA particle-size classification (USSSS, 2003) just like in

the Chilean system. Therefore, there is a correspondence between both textural classes, as shown in the following Table 1:

Table 1. Correspondence between textural classes of FAO and CIREN

USDA (FAO, 2006)				CIREN (2003)	
Symbol	Texture	Symbol	Texture	Symbol	
S	Sand (unspecified)	VFS	Very fine sand	a	amf
		FS	Fine sand		a_f
		MS	Medium sand		amf
		CS	Coarse sand		a_g
		US	Sand, unsorted		a
LS	Loamy sand	LVFS	Loamy very fine sand	aF	aF_{mf}
		LFS	Loamy fine sand		aF_f
		LCS	Loamy coarse sand		aF_g
SL	Sandy loam	FSL	Fine sandy loam	Fa	Fa_f, Fa_{mf}
		CSL	Coarse sandy loam		Fag
SCL	Sandy clay loam			FAa	
SiL	Silt loam			FL	
SiCL	Silty clay loam			FAL	
CL	Clay loam			FA	
L	Loam			F	
Si	Silt			L	
SC	Sandy clay			Aa	
SiC	Silty clay			AL	
C	Clay			A	
HC	Heavy clay			A(Arcillosa densa)	

The level of fineness as criterion for the definition of textural classes can be seen in Figure A1 in the Appendix.

The model recognized certain previously specified textures. For running the model, these were the textures usually found in the regional soils: impermeable (rock), sand, loamy-sand, sandy-loam, silt, silty-clay, silt-loam, sandy-clay-loam, clay-loam, silty-clay-loam, clay, sandy-clay, and water. Additionally, the category “imperm” was added, which was used for horizon C, layers of rock, or impermeable material. Organic matter or chemical properties are not considered by the model.

Soil depth

BioSTAR works by simulating a profile for each soil type in a matrix of 10 cm layers, from 0 (surface) to 1.5 meter depth. A particular texture is assigned to each decimeter (layer) to complete the whole profile. This was done for every soil series according to the original profile of textures described in the Chilean Soil Taxonomy of CIREN. An example for the series Piedras Negras is shown in the following Table 2:

Table 2. Transformation of a soil textural profile description into a simulated profile data base. Example for "Piedras Negras" soil series.

Profile for the "Piedras Negras" soil series (CIREN, 2003)

Horizont	Depth (cm)	Layer depth (cm)	Texture
a	23	23	F
	40	17	FA
b	60	20	AL
	110	50	FAL
	130	20	A
c	150+		

Profile in BioSTAR

Layer depth	Texture
dm 1 (0-10 cm)	Loam
dm 2	Loam
dm 3	clay-loam
dm 4	clay-loam
dm 5	silty-clay
dm 6	silty-clay
dm 7	silty-clay-loam
dm 8	silty-clay-loam
dm 9	silty-clay-loam
dm 1	silty-clay-loam
dm 11	silty-clay-loam
dm 12	clay
dm 13	clay
dm 14	imperm
dm 15	imperm

3.1.3 Sowing and harvesting dates

Key information for running the model is to specify if the crop variety is of a short or long growing period, and the sowing and harvesting dates, as the growth curves for the crops are determined by those variables. In the case of wheat, winter wheat has a longer growing period, and higher yield potential than spring wheat. Sowing and harvesting dates commonly seen in the region, as well as the dates used in modelling, are shown in Table 3:

Table 3; Sowing and harvesting dates commonly seen in Los Ríos region. In brackets, dates actually used for running the model.

Dates	Wheat		Maize	
	Winter Variety	Spring Variety	Early variety	Late variety
Sow	May 1st to June 30th (1st July)	June to September 1st (15th August)	Middle October (15th October)	Middle November (15th November)
Grain Harvest	Late February, early March (1st March)	Late February, early March (1st March)	No grain production in the region	No grain production in the region
Silage harvest (whole plant)	(1st March)	(1st March)	Beginning of April (April 1st)	End of April (April 30th)

It is important to note that specifying the harvest date in the model does not determine the growth potential of the crop, but it is useful when harvesting before maturity is desired. If not, the harvesting date is determined by the crop characteristics. If in the model the plants follow the path to maturity, the crop ends its growing at a specific date, and the grains are accumulated until that date.

Following the classification of soil use capacity (CIREN, 2003), only the soils with agricultural capacity from I to IV use capacity were considered for running the model, as soils from categories V to VII have limitations, whether in a sense of their chemistry, physics (like low depth or the presence of water or stones), or geomorphology (as in slope or parental material), making agriculture impossible in them.

3.1.4 Geographical Information Systems (GIS)

Finally, the soil and climate information were combined in a GIS data base using ArcGIS© to obtain spatial polygons. The polygons with similar combinations of climate and soil were grouped in specific, main categories of soil and climate. BioSTAR was run for each of these categories, giving a specific yield for each. After intersecting soil types with agro-climate districts, the GIS end up with 6564 polygons which were gathered into 547 soil-climate categories for running BioSTAR. The resulting map is shown in Figure 4.

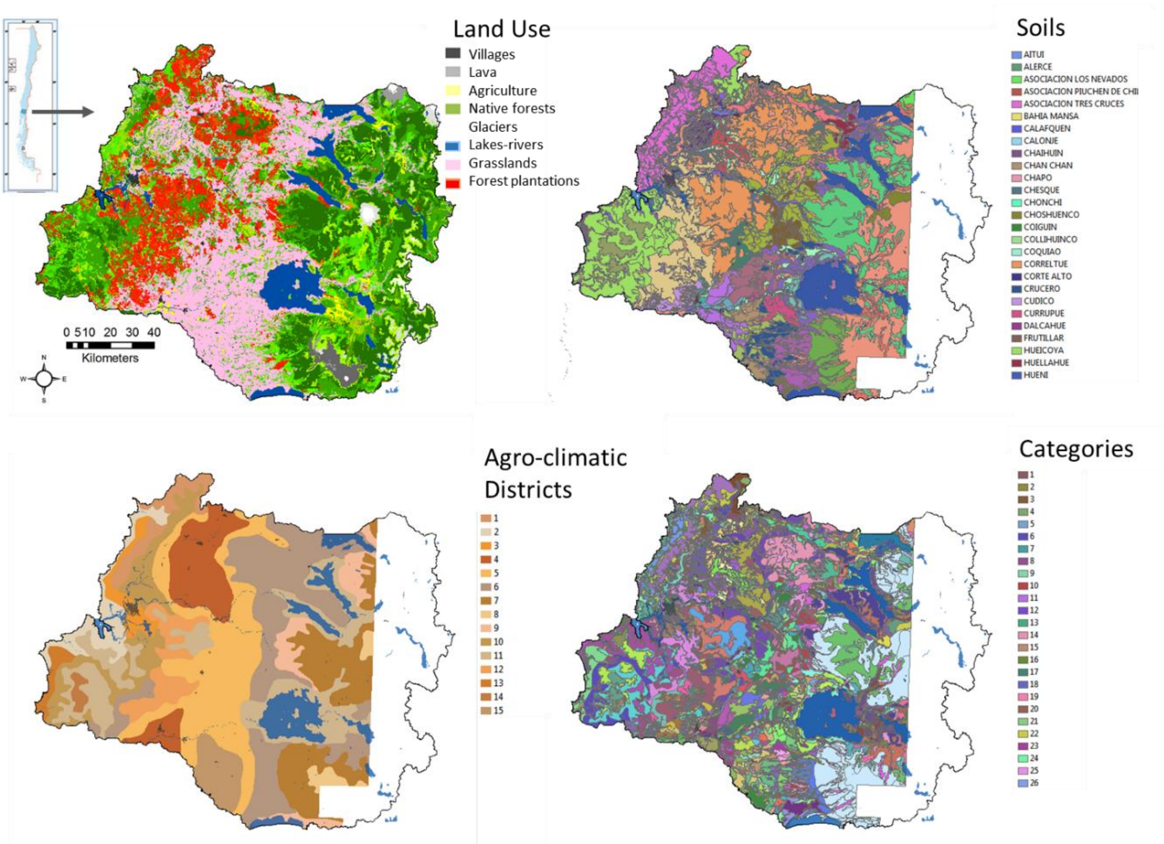

Figure 4: GIS information for configuring BioSTAR database with Los Ríos Region. a) Current land use. b) Soil Series. c) Agro-climate districts with climate isoclines. d) Intersection matrix of soil series and climate. Images b to d do not cover the whole region because no soil database information was available towards the Andean mountains.

3.2 Calibration and validation with data from Santa Rosa Experimental Station

For the calibration of BioSTAR on site-specific conditions, the model was run with site-specific information from SRES, as it was the only location with empiric data of yields, soil, and local climate, available for a period of time of more than one year.

The comparison of model results was realized against two sources of empiric information: local trials at SRES and regional averages. SRES has information available on trials conducted for maximum potential yields together with specific climate information, which is not available elsewhere in the region. However, those different trials were executed by different researchers in different years and with different crop varieties so that conditions are not uniform.
Additionally, as there is no long-term trial at SRES, it was not possible to compare the behavior of the model through different years. For that reason it was decided to compare a long-run of BioSTAR with SRES information against the records of the Ministry of Agriculture for the whole region, involving yields over many years and with very representative numbers from thousands of farmers so that the variation of yields through the years could be compared.
Finally, a comparison with a two-year long trial at SRES was realized, so that local, temporal changes and quantities could been studied simultaneously. A summary of the calibration process is shown in Table 4.

Table 4: Criteria used for calibration of the model results[25].

Criterion	Calibration against:	Source of information
Accuracy of yield amounts	SRES trials for wheat and maize	Pinochet et al. (2011) Mosaico (2008) Sandaña and Pinochet (2011)
Accuracy of yield variation over time (5 years)	National census of wheat yields for the Region	National Agricultural Census, regional average for wheat (INE, 2013)
Accuracy of yield amounts and variations over time (2 years)	SRES trial on wheat	Hasan (2010)

3.2.1 BioSTAR against one year trials for wheat and maize at SRES

Once BioSTAR was run using agro-climate districts (CIREN, 2003) for SRES, the first check was to compare the resulting yields given for the polygons that matched with SRES against specific trials of wheat and maize carried out at the station. This check has the disadvantage that climate, sowing dates, varieties, and probably the culture methods are not the same as in the comparison, but it gives a sense of accuracy in the calculations of BioSTAR as all were controlled field trials that reflect maximum, reachable yields. The trials, their year and yields are shown in Table 5.

[25] Different versions of BioSTAR itself were also calibrated in the process. See Figure A2 in the Appendix.

Table 5: Comparison between BioSTAR results and different trials for wheat and maize at SRES.

Source of information	BioSTAR with Agro-climatic District		(Dante Pinochet et al., 2011)		Mosaico 2008[26]		(Sandaña and Pinochet, 2011)	
Repetitions	2		6		13		3	
	Kg DM/ha	SD	Kg DM/ha	SD	Kg DM/ha	SD	Kg DM/ha	SD
Maize whole plant	27878	252	36353	2995				
Wheat whole plant	16863	66			15953	1418	22142	4796
Wheat Grain	8040	101					8691	2253

Maize does not reach grain maturity in the region, being used mainly for silage. Regarding the trial on maize, it is important to consider that it was realized under irrigation. For large farmers in Los Rios Region, the maximum yield for silage is 26,780 kg DM/ha and an average yield of 23,277 kg DM/ha is reached (Celedón, 2014). According to a study by Rojas and Manríquez (1998), in Los Ríos Region a yield of 12,990 kg/ha obtained from 95,000 plants/ha for resource-poor farmers was obtained at state toothed grain, 90% hard grain, and 8118.8 kg DM/ha with 62.5% DM silage. In the case of wheat, the model reached a yield in between the maximum yields reached by the analyzed trials. From the comparison shown in the last table it can be appreciated that model results roughly fit with what was obtained from field trials.

3.2.2 BioSTAR five years run against averages of regional farmers

As before stated, a long-term run of BioSTAR with recorded weather information from SRES was done for wheat and compared to the regional averages. The 5 year period was from 2008 to 2013. In this way, the sensibility and behavior of BioSTAR for spring wheat through weather of different years was tested. The disadvantage of this test is that different scales were used in the comparison: BioSTAR results from SRES against regional averages. This is because empiric weather information is not available at site level for the rest of the region, so that the BioSTAR results could not be compared for the rest of the region.

The wheat yield amounts used for testing are the average of the National Agricultural Census developed by the National Institute of Statistics for the region (INE, 2013). The survey gives results from a universe of 2,145 wheat farmers in the region. Although the variability of per hectare yield in the region is considerably high for small farmers (see Figure 5a), the number of farmers and the consistency of the data (see Figure 5b) make the average regional yield a robust value.

[26] Pinochet, D. Report of trials on nitrogen and zinc fertilization for Mosaic. Personal communication.

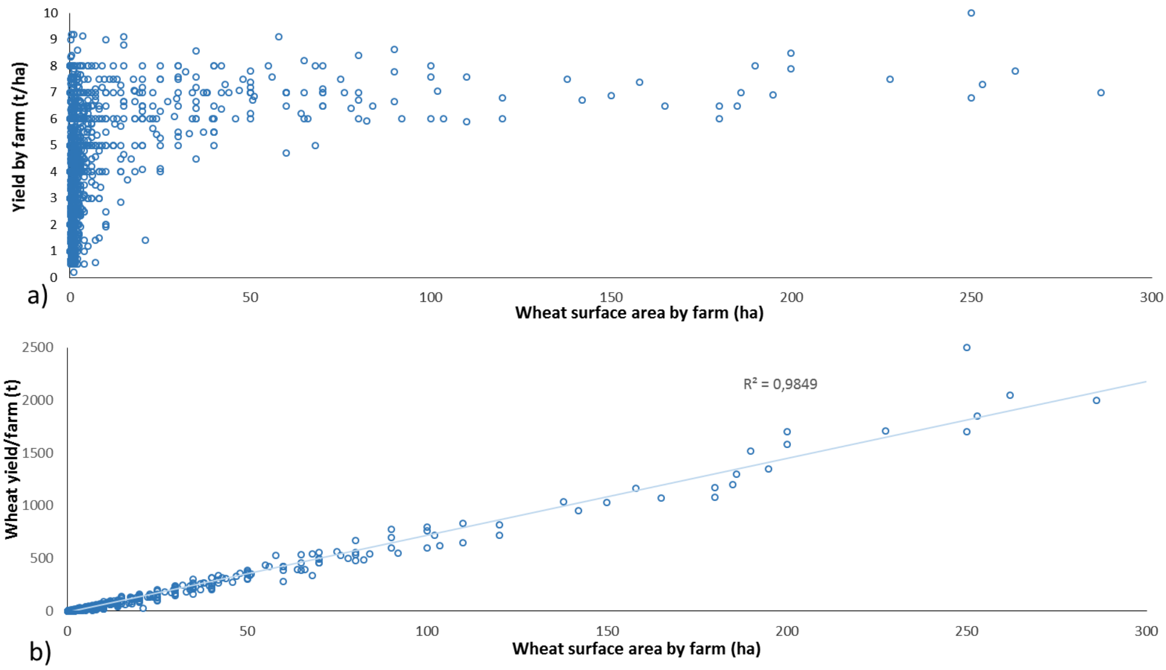

Figure 5: Correlation between surface area (ha) of wheat cultivated by farms in Los Ríos region in Census 2007 (INE, 2007), and grain yield obtained. Yields in a) farm average (ton/ha), b) total per farm (ton/farm).

As it can be appreciated from Figure 5a, the variability in land productivity tends to be higher as smaller the farm, being especially higher among small farmers which are also the most abundant in numbers, but less representative in total surface area and likewise in regional average yield.

The model was run with the original parameters set for Lower Saxony in Germany (R Bauböck, 2013). Afterwards, a calibration process with several variables was done in the search for the highest fitness between BioSTAR results and the recorded regional average yields. A graphic of the comparison, including original and final results of the calibration process is shown in Figure 6.

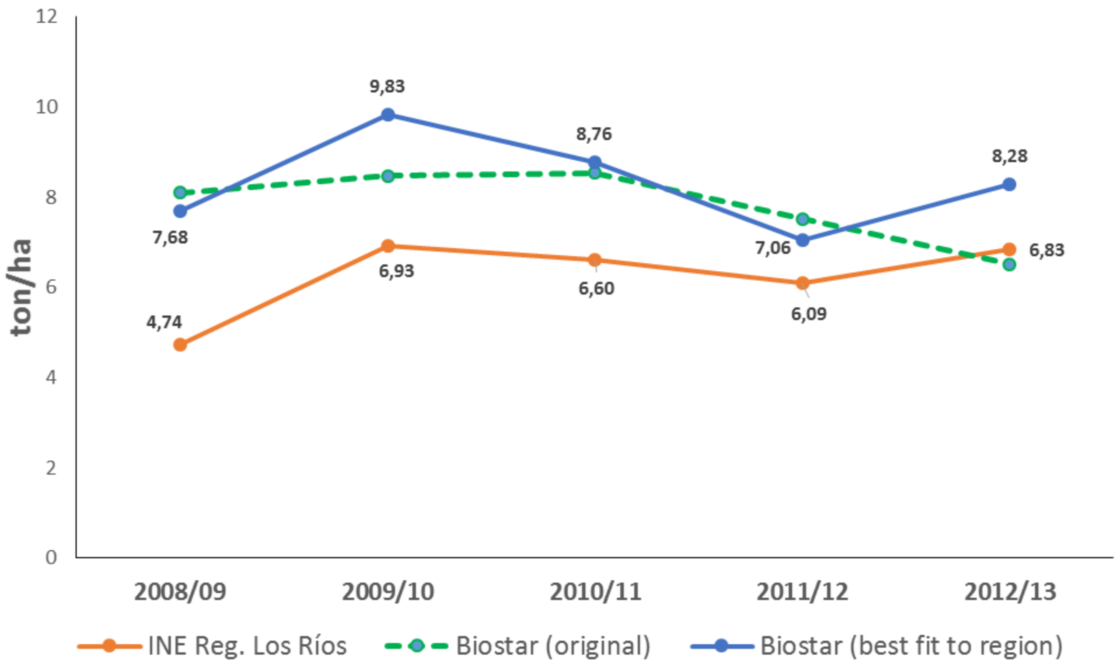

Figure 6: Five years comparison of wheat yield (grain) between regional registered average (INE, 2013) and BioSTAR results before and after calibration.

Model adjustment was obtained mainly through changes in the two coefficients of *leaf maximum photosynthetic genotype-specific rate*: PMAX1 (maximum carbon-dioxide exchange rate before flowering) and PMAX2 (maximum carbon-dioxide exchange rate after flowering), both in mmol $CO2/m^2s$. Originally those parameters were PMAX1=0.032 and PMAX2=0.016. It can be noted that the effect of the calibration on matching the regional tendency is significant, as with the corrected parameters (PMAX1=0.02 and PMAX2=0.14) the model shows a tendency to follow the regional average yields, with a $R^2 = 0.375$.
Commonly for wheat in Chile, average yields for farmers are around half the maximum yield potential, but with modelling the results were between 14 and 38%, with an average of 25% lower than the calculated potential with the model. Therefore, BioSTAR results seems to be rather low, perhaps because spring wheat was used, which has a short growing period. Setting up other parameters or using a winter wheat crop, which was not the case of this research, might improve the fitness of the model.

3.2.3 BioSTAR against a biannual trial on wheat at SRES

Finally, as a way to check the accuracy of the model on specific soil and measured local weather for more than a one year period, a comparison of BioSTAR results with a two year trial carried out by Hasan (2010) in SRES was done. Information on local soil, recorded two year weather variables, as well as the same dates of sowing and harvest as the original trial (Table 6) were used in running the model. The spring wheat option of the model was used. The result of the calibration process is shown in Figure 7.

Table 6: Actual sowing and harvesting dates of the wheat trial by Hasan (2010) and subsequently used for running BioSTAR in the calibration-validation process.

Season	Sowing	Harvest
2008-9	22-08-2008	31-01-2009
2009-10	05-09-2009	05-02-2010

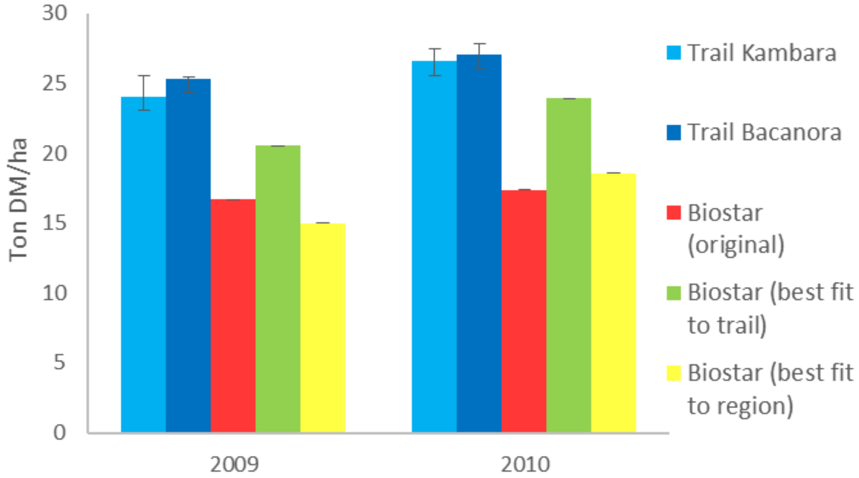

Figure 7: Comparison of wheat yield (whole plant, dry matter) for two year period between the trial of Hassan (2010, with two varieties of spring wheat: Kambara and Bacanora) and BioSTAR (before and after calibration, and with the values of best fitness to regional averages).

As it can be observed, the effect of the calibration on the fitness of the results against the field trials is relevant. The best fit for the trial was found with values PMAX1=0.08 and PMAX2=0.016. However, as the values obtained from the calibration of this last trial produced very low fitness when used against regional averages (long run), it was decided that the best values to be used in the model for estimating the regional potential would be the ones obtained in the test against regional average. When the best values of parameters found for regional averages (previous section, PMAX1=0.02 and PMAX2=0.14) were used, the results are an average of 35 % lower than what was found in the trial by Hassan (2010). If it is assumed that yields found by Hassan are actually the maximum potential, BioSTAR results would be 35% less than that maximum field potential. In other words, maximum potential for the region would correspond to BioSTAR results plus an additional 53.8% (roughly 50%). That is coherent with what was obtained in the previous validation, where regional average was 25% lower than BioSTAR, as it is expected that field yields should be around 50% of maximum potential.

When the results with the calibrated model were compared with the original values for these parameters (Lower Saxony calibration), relevant differences, but also non-linear coherences can be found (Figure 8). Additionally relevant differences, but linear coherences can be found between the crops analyzed (Figure 9).

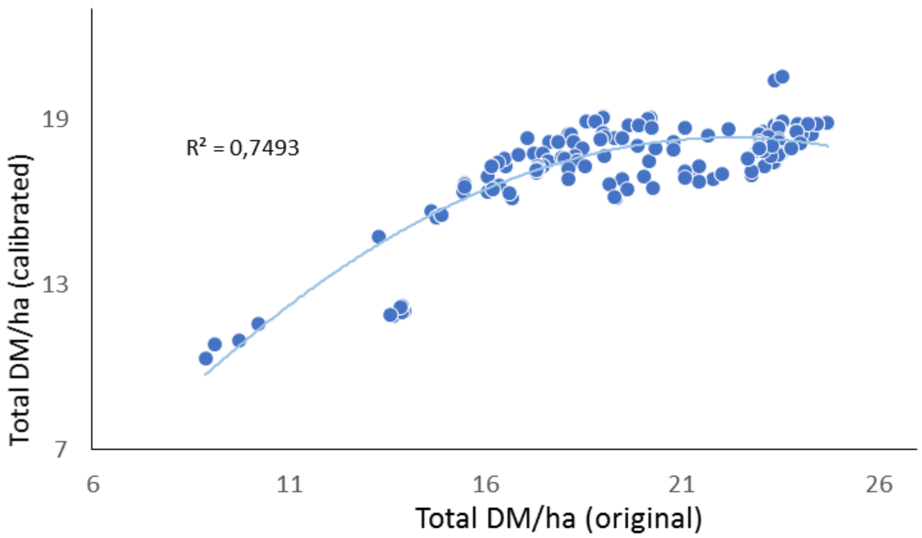

Figure 8: Correlation between original and calibrated results of BioSTAR for spring wheat.

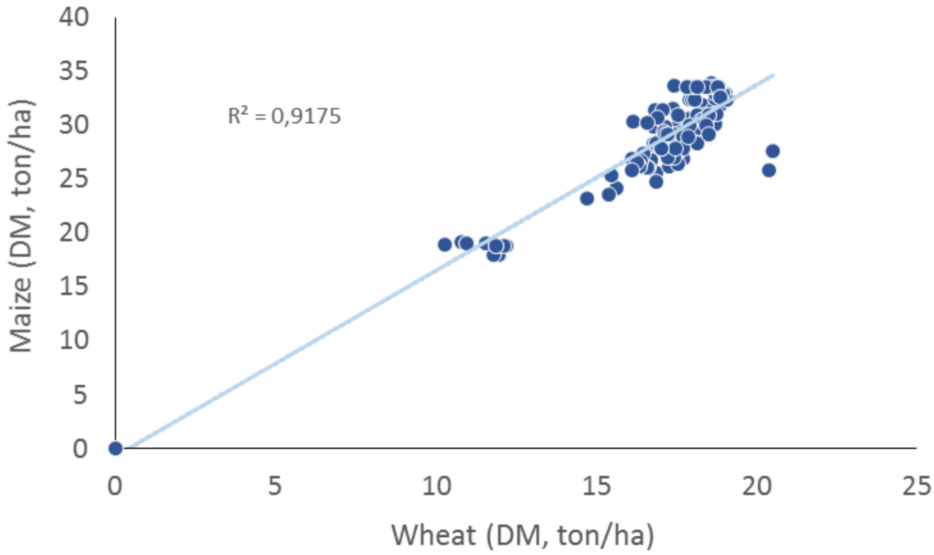

Figure 9: Correlation between wheat and maize results of BioSTAR for same soil and climate.

4 RESULTS AND DISCUSSION

4.1 Regional Potentials

After the calibration process, the parameters used for running the modelling of regional potentials are shown in Table 7 and described in the Table A2 of the Appendix. The resulting harvesting dates for spring wheat given by BioSTAR were between the 6th of January and the 12th of March.

Table 7, Values of parameters for the calibrated run of BioSTAR for spring wheat.

Name	S-Wheat	FACTOR_BTR	4	HARVINDEX	0.55	MCR	0.015
PATHWAY	3	INTEXT	0.8	STUBBLE	0.95	MCL	0.016
STRESS_1	30	MAXHIGHT	0.7	CRD_MAX	130	MCS	0.01
STRESS_2	60	K	0.45	MAXROOT	65	YGR	0.69
STRESS_3	75	DEGMIN	0	CULTTYPE	2	YGL	0.686
S_REACT	2	DEGMAX	35	DSPEED1	2.00	YGS	0.66
PMAX1	0.02	DEGOPT	15	DSPEED2	1.19	YGF	0.7
PMAX2	0.14	DEVMIN	0	DSPEED3	0.7	NMINIMUM	0.008
FACTOR_RUE	2.5	DEVMAX	25	DSPEED4	0.80	NCRITICAL	0.65
FACTOR_WP	15	DEVOPT	25	DSPEED5	0.80		
FACTOR_SD	0.9	FACTLAI	4.5	DSPEED6	0.60		

4.1.1 Total biomass

As the model runs only on soil and climate parameters, the results do not consider current land use. The land use of the modelled area currently includes large extensions of prairies, a few agricultural areas (less than 5 % of the surface of the region), forestry plantations with exotic species, and some extension of native forests. That is so, because some of these land uses are located on soils with a use capacity for agriculture. For the calculation of whole region biomass potential from the analysis with GIS, the theoretical available surface for crops, for food and/or bioenergy was calculated. It is theoretical and not practical, as local slope and other factors already mentioned were not considered. Although most of the soils with use capacity below V do not present high slopes, it might be possible that some local variations could have slopes over 15%. In Figure 10 a map of the modelled regional potentials for maize is shown.

With the potential production of each specific site calculated by their total specific area, the total regional potential biomass was obtained. From the regional area considered for the modelling (soil use capacity I to IV) only the areas with native forest were taken out of the calculations, as they are fortunately protected against land use change by Chilean regulations. Also the fields that presented no production in the Biostar modelling were left out. Finally, the average regional yield per hectare was calculated. As BioSTAR gives a potential yield per hectare, considering that the validation process gives a gap of +50% and -25% between the BioSTAR result and farmer yields (field) and maximum potential (trials) respectively, both potential yields were calculated. The total potential of the region is summarized in Table 8.

Table 8. Regional potentials for wheat and maize.

Regional total surface (ha)	1,839,965		
Regional theoretical available surface for crops (ha)	332,405		
(DM, ton)	Wheat- biomass	Wheat- grain	Maize- biomass
Total regional	5,920,524	2,823,723	9,955,307
BioSTAR yield potential /ha (regional average)	17.8	8,5	29.9
Maximum yield potential /ha (BioSTAR average + 50%)	26,6	12,7	Not calculated
Field yield potential/ha (BioSTAR average -25%)	13.3	6.4	Not calculated

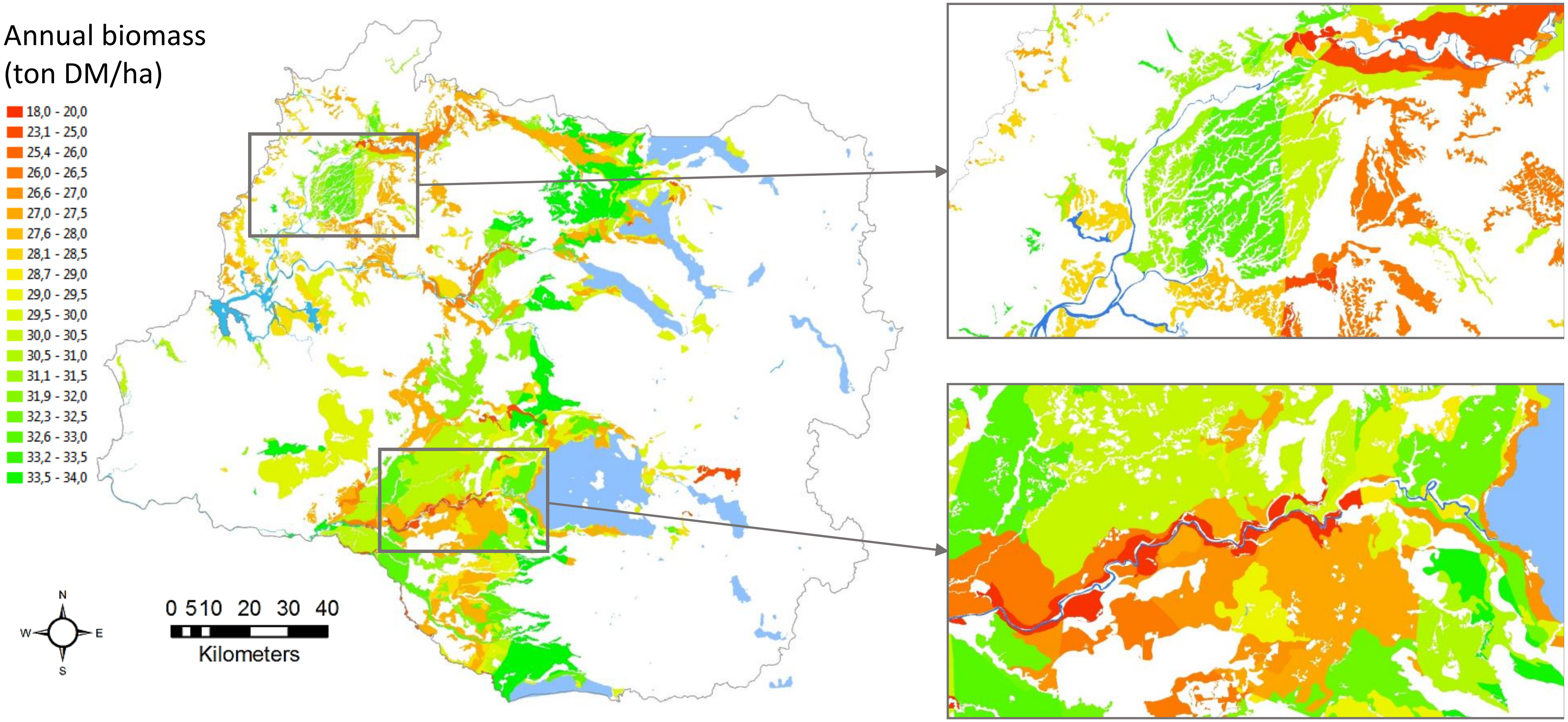

Figure 10: BioSTAR modelling result: total biomass potential for maize in Los Ríos Region, Chile (ton DM/ha). In blue lakes and rivers.

4.1.2 Total bioenergy

Considering that the farmers developing bioenergy would tend to be big and highly-technical, their yields should be in between regional average yield and maximum potential, similar to BioSTAR results. Therefore, for the calculations of bioenergy from biogas, the value of BioSTAR potential was used. A conversion from silage of 500 m3 of biogas per DM ton for wheat and maize was considered (Rincón et al., 2010; FNR 2013; Eder and Krieg 2012; StMUGV 2004). For the conversion from biogas to energy, 6 kWh/m3 was used (FNR, 2014), and from this, 2.3 kWh/m3 of biogas for electricity and 2.8 kWh/m3 of biogas for heat was used (FNR, 2013). The potential power was calculated assuming a whole year of constant generation. The results are shown in Table 9.

Table 9. Theoretical total bioenergy from crops silage in Los Ríos region (BioSTAR results).

	Wheat-biomass	Maize-biomass
Total Biogas (Million M3)	2,960	4,978
Total Energy (GWh)	17,762	29,866
Total Heat (GWh)	8,289	13,937
Total Electricity (GWh)	6,809	11,449
Electric Power (MW)	777	1,307

4.2 Testing the results

As explained previously, the available data for the validation of model results is rather few. A way to check the quality of the results is to test them against general figures that could show that the model works sufficiently accurately. Therefore, several correlations were tried for this purpose. No correlation was found between soil use capacity and soil depth or biomass productivity for wheat and maize. Some correlations are shown in Figure 11.

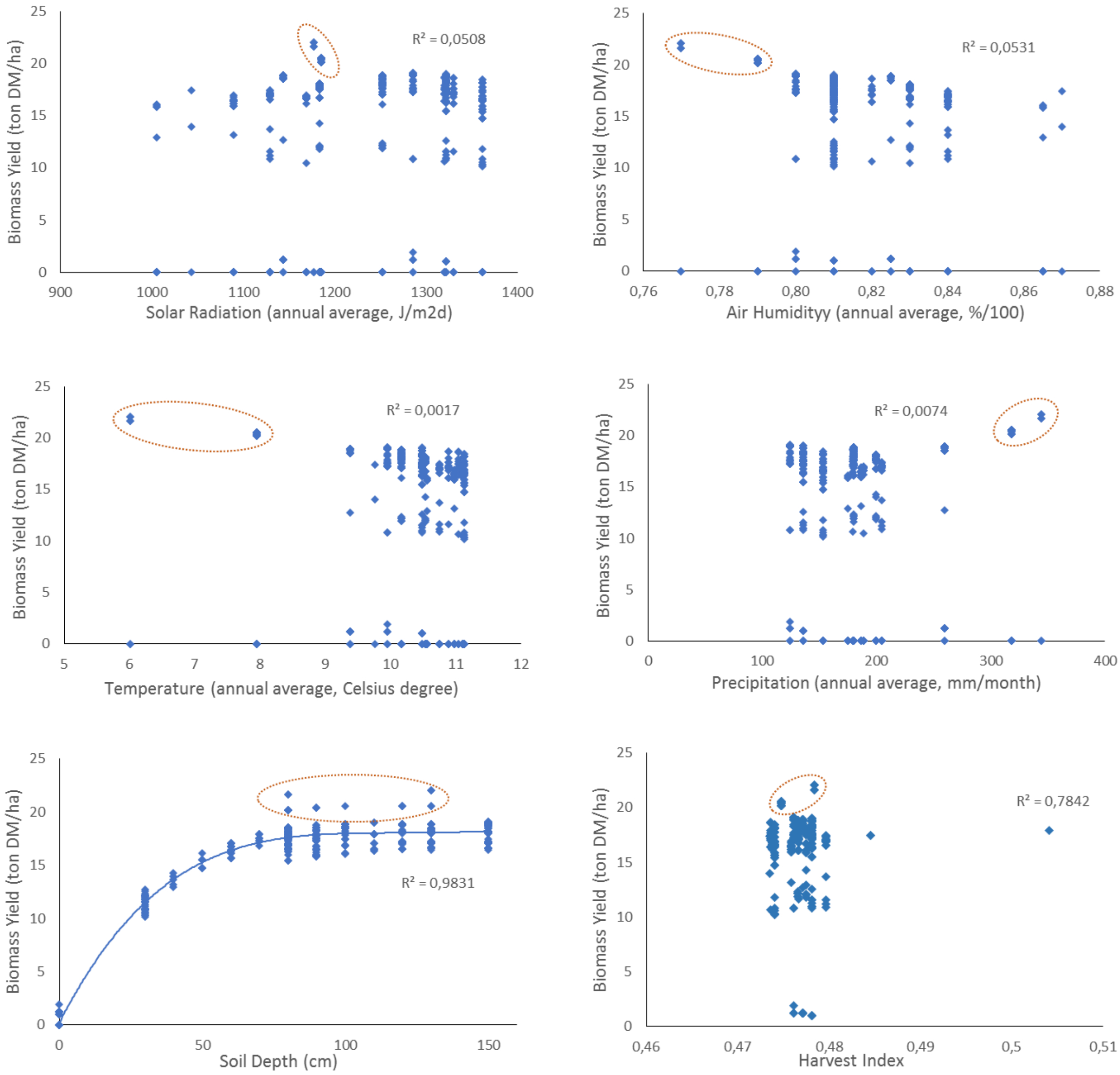

Figure 11: Correlations between wheat biomass productivity and annual average values of climate variables, soil depth and harvest index. Results for all regional soils.

As it can be seen in Figure 11, there was no correlation between biomass productivity and harvest index or climate average values. Nevertheless, exceptionally high yields were reached in the areas of simultaneously lower temperature and humidity and higher precipitation (in red circle). On the other hand, there was a strong correlation of yields with soil depth, which strongly determines the yields given by the model. Also it can be noted that the effect of soil depth is very relevant until 80 cm deep, where the curve of productivity tends to flatten. When selecting only soils with agricultural use capacity, and splitting the results in different climates, a relevant effect of the Agro-climatic Districts in yields is found, which follows a tendency independent from that of soil depth (Figure 12).

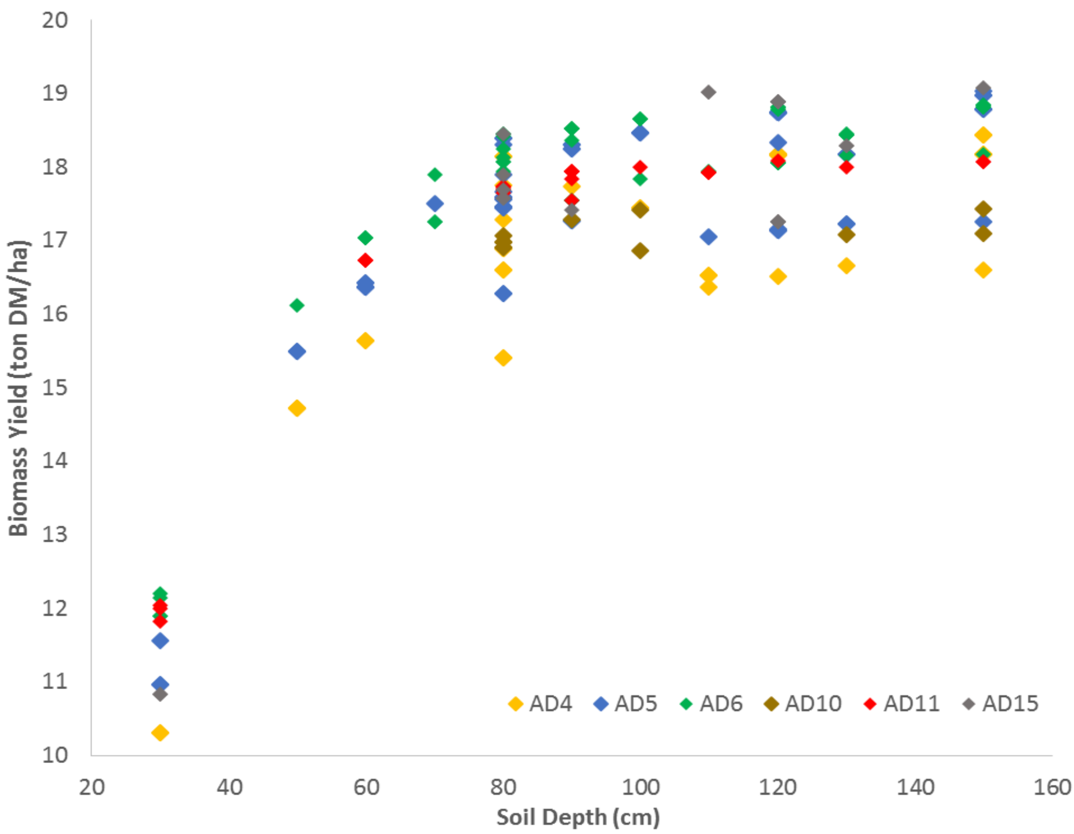

Figure 12: Correlation between soil depth and BioSTAR wheat yield (total biomass) for different climates (Agro-climatic Districts, AD) of Los Ríos region. Only the six most relevant Agro-climatic Districts are shown to facilitate the visualization.

As over 80 cm depth is not critical for productivity, the soils with more than that depth were compared in terms of climate given by Agro-climatic Districts. The average productivity of each Agro-climatic District was scored and correlated with all the other Agro-climatic Districts. The result is shown in Figure 13:

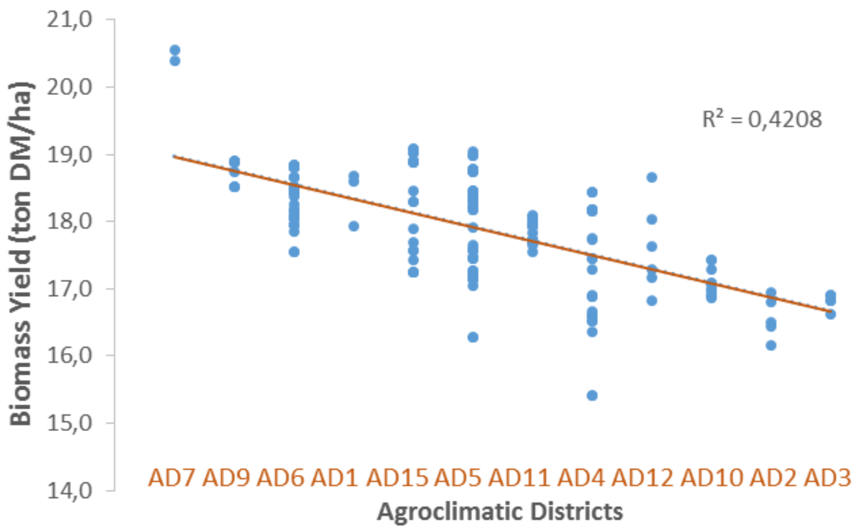

Figure 13: BioSTAR biomass wheat yields for every Agro-climatic District, ranked from higher to lower productivity.

This ranking was applied in GIS in order to see if there was any coherence between the results modeled and what actually exists in the region. The Agro-climatic Districts were colored according to the ranking of productivity already done. The result is shown in Figure 14.

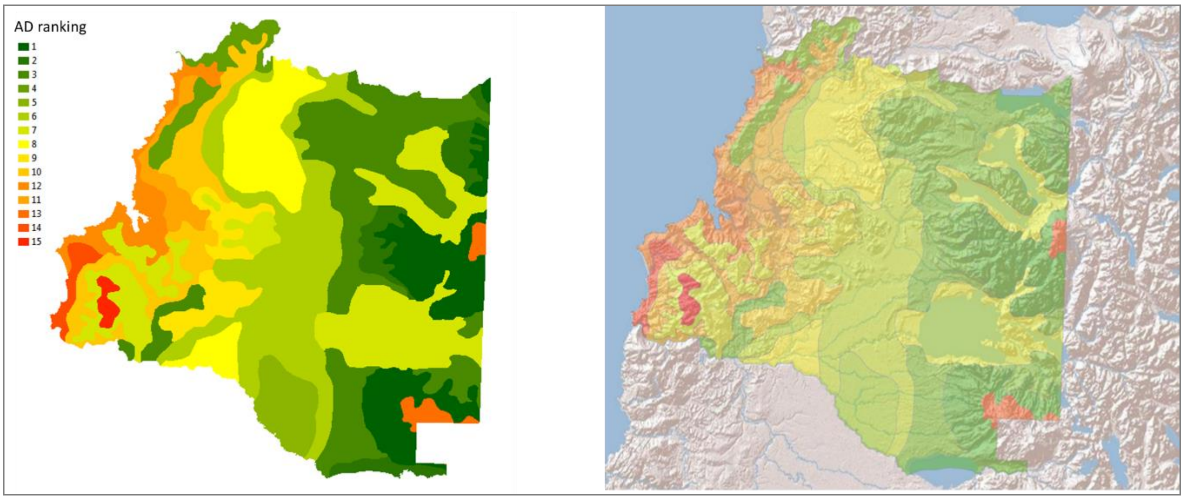

Figure 14: Productivity ranking for the Agro-climatic Districts (AD) of Los Ríos region. Green: high; Red: low. a) AD ranking map b) AD ranking map intersected with geomorphology.

In general terms, three main north-south transversal structures can be found in a classical Chilean geomorphologic profile: the coastal ranges (Cordillera de la Costa), intermediate depression (flatlands) and Los Andes Mountains. When the productivities given by the model are compared with geomorphology of the region (Figure 14b), it is possible to find coherences. The higher values were found in some summits of the costal ranges and mostly at the foothills of Los Andes. Although the model uses climate alone and does not consider geomorphology (slope or height), there is an interesting relationship of it with productivity. The high yields of Agro-climatic Districts on higher altitudes (9 and 7 in the Andes foothills and 1 in the western, coastal "cordillera") can be understood by the configuration of climate variables. At higher altitudes lower air humidity and temperature, together with higher precipitation is found. This corresponds precisely with what was found for the higher yields in the region (Figure 11, in circles). A reason for this behavior might be on the temperature effect, given by the incidence of plant growth inhibition at high temperatures through the respiration-related parameters in the equations of the model; the temperature-dependent maintenance respiration coefficient (R Bauböck, 2013), probably related with Rm(T). Among the variables in the model related to it are MCR, MCL, MCS, YGR, YGL, YGS and YGF, and the temperature-related variables DEGMAX, DEGOPT, DEVMAX and DEVOPT. To find an accurate value for such parameters or others involved, more research is needed.

Finally, considering that the model works with few and simple input variables, it is important to notice that given the current conditions, the model has not been validated for:
-Other regional soils than those studied at SRES (Valdivia series)
-Other local conditions of climate than those at SRES
-Other variables not include in the model (topography, chemistry, etc.)

Notwithstanding, the information from the database of biomass potential for the whole region elaborated with BioSTAR might be helpful in the study of land use change, especially considering that today there are not many bioenergy initiatives yet developed, but according to the trajectory of energy prices, there exists a very positive economic projection of incentives for such initiatives.

5 CONCLUSIONS

The existence of a well-tested model of biomass potentials can provide strategic information for the agricultural and local energy sectors, including total biomass potential of the region for food and energy, yield impacts of climate change, or tools for regional land use planning.
Tested for wheat and maize in Los Ríos region, the BioSTAR model gives results in the range of feasibility, with yields fairly close to what was found in the empirical record, both for SRES and farmers´ regional averages.
As no other relevant trials were found in the region for the validation of model, for now it is not possible to check the sensibility of it to other local conditions of soil and climate in the region. Although the tendency of the regional average is followed by the results of the model, with the exception of the case of SRES, the model is "blind" for the site-specific variations of the rest of the soils and local climate in the region, so that the performance in these areas need to be further researched.

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8 APPENDIX

Table A1. Soil series of Los Ríos region and their correspondence with the US and FAO classification systems.

	Soil Series	WRB (FAO et al. 1998),	Soil Taxonomy - US Soil Taxonomy (USSSS 2003)
1	Calafquén	Andosol Silandic-Acroxic (Hiperdistric)	Acrudoxic Fulvudands
2	Chaihuín	Umbrisol Haplic	Andic Durudepts
3	Chan Chan	Andosol Silandic-Histic (Endogleyic y Petroduric)	Histic Duraquands
4	Chesque	Andosol (Acroxic e Hiperdistric)	Acrudoxic Fulvudands
5	Choshuenco	Umbrisol Haplic	Andic Dystrudepts
6	Correltúe	Acrisol Umbri-Vetic (Hiperdistric y Rodic)	Andic Parehumults
7	Crucero	Andosol Silandic-Vetic (Hiperdistric)	Acrudoxic Hydric Hapludands
8	Cudico	Acrisol Umbri-Vetic (Hiperdistric y Cromic)	Typic Hapludults
9	Currupúe	Andosol Silandic-Fulvic (Acroxic e Hiperdistric)	Acrudoxic Fulvudands
10	Hueicoya	Acrisol Umbri-Vetic (Hiperdistric y Cromic)	Typic Haplohumults
11	Huellahue	Andosol Silandic-Acroxic (Hiperdistric)	Acrudoxic Hapludands
12	Huiti	Andosol Silandic-Epigleyic (Petroduric y Acroxic)	Acraquoxic Duraquands
13	Itropulli	Andosol Silandic-Petroduric (Vetic e Hiperdistric)	Typic Durudands
14	La Pelada	Cambisol Hiperdistric	Oxic Dystrudepts
15	La Unión	Umbrisol Haplic	Andic Dystrudepts
16	Lanco	Andosol Silandic-Petroduric (Acroxic e Hiperdistric)	Typic Durudands
17	Liquifie	Andosol Vitri-Acroxic (Hiperdistric)	Acrudoxic Hapludands
18	Llastuco	Andosol Silandic-Acroxic (Hiperdistric)	Acrudoxic Hapiudands
19	Loncoche	Andosol Silandic-Acroxic (Hiperdistric)	Acrudoxic Hapludands
20	Los Lagos	Andosol Silandic-Petroduric (Vetic e Hiperdistric)	Typic Durudands
21	Los Ulmos	Acrisol Umbri-Vetic (Hiperdistric y Crornic)	Typic Paleudults
22	Malihue	Andosol Silandic-Acroxic (Hiperdistric)	Acrudoxic Fulvudands
23	Muticao	Andosol Silandic-Fulvic (Endogleyic y Acroxic)	Acrudoxic Fulvudands
24	Osomo	Andosol Silandic-Vetic (Hiperdistric)	Typic Hapludands
25	Paillaco	Andosol Silandic-Vetic (Hiperdistric)	Typic Hapiudands
26	Panguipulli	Andosol Silandic-Endogleyic (Vetic e Hiperdistric)	Aquic Hapludands
27	Pelchuquín	Andosol Silandic-Vetic (Hiperdistric)	Eutric Fulvudands
28	Perquillán	Umbrisol Haplic	Typic Dystrudepts
29	Piedras Negras	Andosol Silandic-Melanic (Acroxic e Hiperdistric)	Acrudoxic Hydric Melanudands
30	Puerto Fonk	Andosol Silandic-Melanic (Ortidistric)	Pachic Melanudands
31	Ranco	Andosol Silandic-Fulvic (Vetic e Hiperdistric)	Eutric Fulvudands
32	Río Bueno	Andosol Silandic-Petroduric (Vetic e Hiperciistric)	Typic Durudands
33	Rucatayo	Andosol Vitri-Acroxic (Hiperdistric)	Acrudoxic Hapludands
34	Rupanquito	Andosol Silandic-Endogleyic (Vetic e Hiperdistric)	Aquic Hapludands
35	San José	Andosof Silandic-Endogleyic (Acroxic e Hiperdistric)	Aquic Hapludands
36	SAN PEDRO		

37	Valdivia	Andosol Silandic-Petroduric (Vetic e Hiperdistric)	Duric Hapludands
38	ASOCIACION LOS NEVADOS	Vitric reciente	
39	ASOCIACION TRES CRUCES	Metamorfic	
40	MISCELANEOS		
41	NO SUELOS		
42	TERRAZAS ALUVIALES		
43	TERRAZAS ALUVIALES CENIZAS VOL		
44	TERRAZAS ALUVIALES RIOS PRECOR		

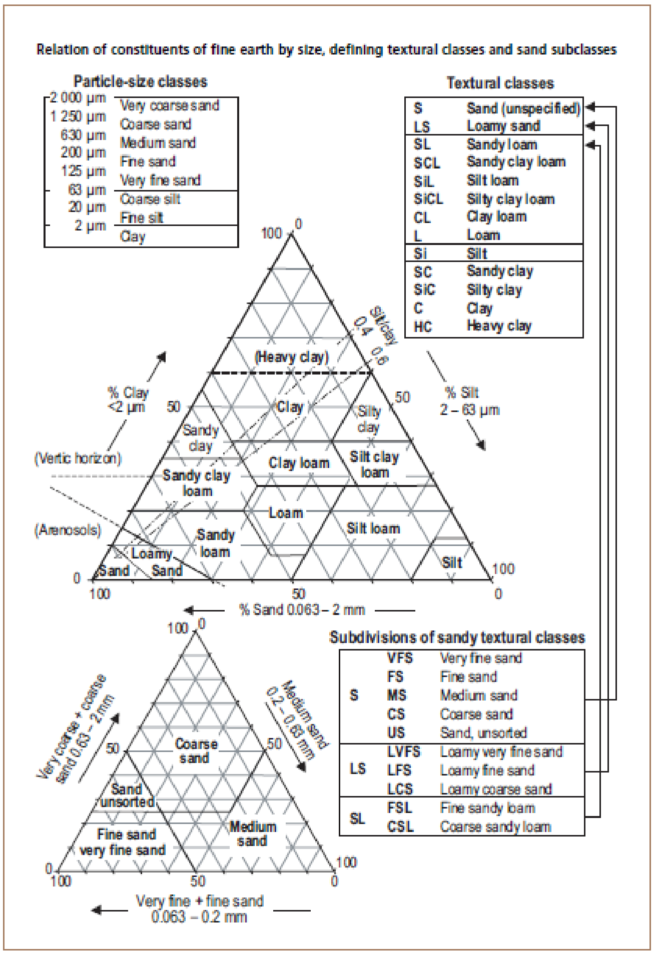

Figure A1. Soil fineness as criterion for definition of textural classes (FAO, 2006)

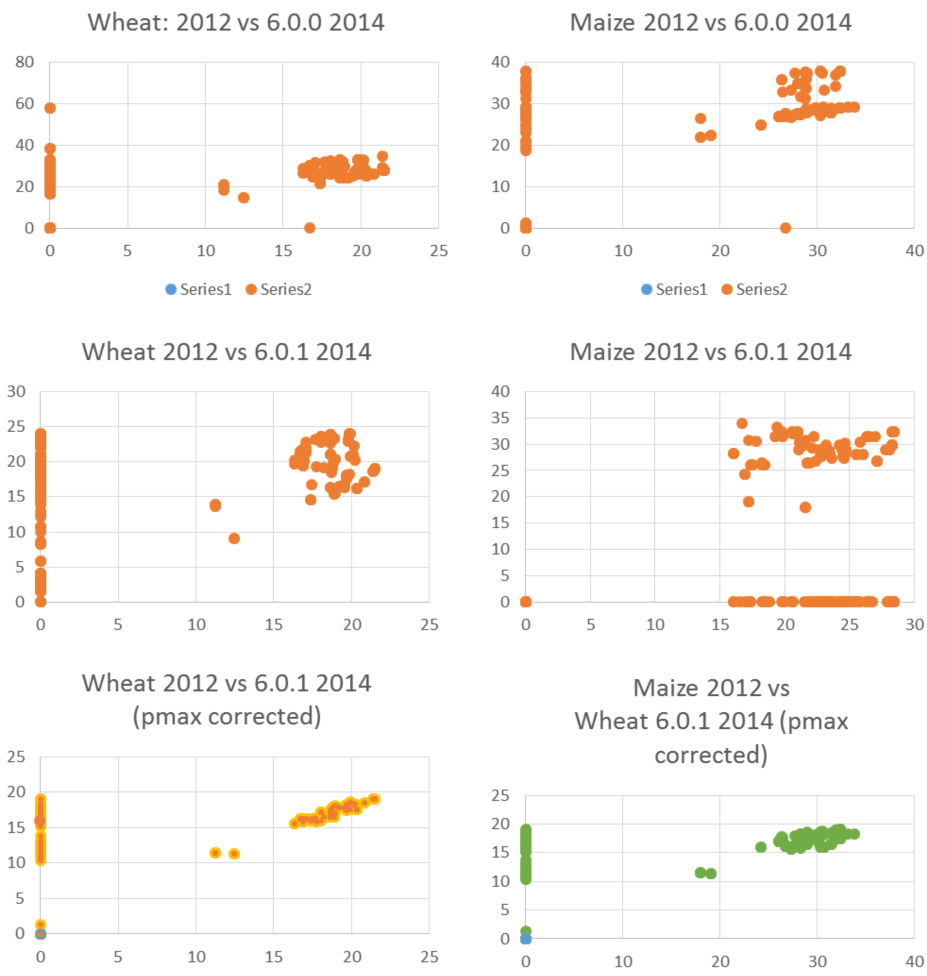

Figure A2. Calibration of different versions of Biostar between 2012 and 2014.

Table A2: Parameters of BioStar, values used in the modelling and their description.

Used value	Parameter description (Bauböck and Revilla, 2013)
S-Wheat	Name: Culture name
3	Pathway: C3 or C4 pathway (enter 3 or 4 here).
0.02	PMAX1: Maximum carbon-dioxide exchange rate before flowering in mmol CO2 * m^{-2} * s-1. Typical range: 0.02 - 0.07
0.14	PMAX2: Maximum carbon-dioxide exchange rate after flowering in mmol CO2 * m^{-2} * s-1. Typical range: 0.02 - 0.07
2.5	FACTOR_RUE: Radiation use efficiency in grams dry mass per MJ of global radiation. Typical range is from 1.5 to 5.
15	FACTOR_WP: Water productivity expressed in grams biomass per square meter per day. Typical values for C3 and C4 crops are 15-20 and 30-35 respectively.
0.9	FACTOR_SD: Exponent in the equation defining the reaction of the biomass transpiration ratio to the saturation deficit. Typical pre-calibrated values are 0.95 for C4 and 0.75 for C3 crops.
4	FACTOR_BTR: Biomass to transpiration ratio expressed in kg * m^{-2} * kPa-1 * m-1. Depending on climate region and average saturation deficits of the air values can range from 1 - 10.
0.8	INTEXT: Fraction of leaf internal to atmospheric CO2 content. Values for C3 crops are

	typically higher than for C4 crops (0.8 vs. 0.55).
0.7	MAXHIGHT: Typical maximum height for this crop in meters.
0.45	K: Extinction (light attenuation) coefficient (dimensionless). Typical range: 0.40 - 0.90
0	DEGMIN: Minimum degree centigrade value for photosynthesis to happen.
35	DEGMAX: Cut-off temperature (centigrade) for photosynthesis.
15	DEGOPT: Optimum temperature (centigrade) for photosynthesis
0	DEVMIN: Minimum degree centigrade value for crop development to happen.
25	DEVMAX: Temperature (centigrade) beyond which no further increase in crop development is achieved.
25	DEVOPT: Optimum temperature (centigrade) for crop development.
4.5	FACTLAI: Typical maximum value for the leaf area index in m² leaf area per m² ground area
0.55	HARVINDEX: Harvest index or crop yield fraction in the case of cereals, oil crops or beet (grain. cob and. beet).
0.95	
130	CRD_MAX: Typical maximum crop root depth in centimeters
65	MAXROOT: Point in crop development (BBCH-scale) where maximum root expansion is reached (typically this happens after flowering (65-70).
2	CULTTYPE: Culture type (1 = spring/summer culture. 2 = winter culture. 3 = perennial culture)
2.00	DSPEED_1: Factor for development speed from sowing to emergence (0-9)
1.19	DSPEED_2: Dormancy (winter crops) or emergence till 3-leaf stage(summer crops) (10-13)
0.7	DSPEED_3: 3-leaf stage till flowering (14-63)
0.80	DSPEED_4: Flowering till lactic ripeness (64-74)
0.80	DSPEED_5: Lactic ripeness till maturity (75-90)
0.60	DSPEED_6
0.015	MCR: Maintenance respiration coefficient (roots), expressed in grams CO2 per gram biomass per day.
0.016	MCL: Maintenance respiration coefficient (leaves).
0.01	MCS: Maintenance respiration coefficient (stems).
0.69	YGR: Growth respiration coefficient (roots)
0.686	YGL: Growth respiration coefficient (leaves)
0.66	YGS: Growth respiration coefficient (stems)
0.7	YGF: Growth respiration coefficient (storage)
0.008	NMINIMUM: Minimum plant nitrogen content for crop growth. Typical value range: 0.4 - 0.8% content of total biomass, with the lower value for C4-crops and the higher value for C3-crops.
0.65	NCRITICAL: Threshold plant nitrogen value (percent of total) for photosynthesis to function at optimum. Typical value range is from 35 - 65% with the lower value for C4-crops and the higher value for C3-crops.

5.4.2 Bioenergy from urban and industrial organic residues

Additionally, for the exploration of the regional biogas potential from urban and industrial organic residues, a Master thesis was offered and tutored. The thesis by Mr. Martín Vermehren "*Estimación del potencial de producción de biogas en la región de Los Ríos a partir de residuos biodegradables*" (Estimation of potential biogas generation from biodegradable residues in Los Ríos Region) was accepted by the Faculty of Agrarian Science and approved with distinction, and the abstract of it is attached to this document in the Section 9.7 of the Appendix.

5.4.2.1 Paper 2: Estimated biogas potential in XIV region based urban and agro-biodegradable waste

Based on this thesis, the paper "Potencial estimado de biogás en XIV Región a base de residuos urbanos y agroindustriales" (Estimated biogas potential in XIV region based urban and agro-biodegradable waste) has been submitted to the journal *Agrosur* and is attached next.

Potencial estimado de biogás en XIV Región a base de residuos urbanos y agroindustriales

Estimated biogas potential in XIV region based on urban and agro-industrial organic waste

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Titulo corto: Potencial de biogás en región de Los Ríos

Encabezado izquierdo:

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ABSTRACT

Key words: biogas, renewable energy, waste management

The lack of fossil fuels, high rates of growth in the national energy consumption, and environmental problems makes it necessary to find new sources for clean and safe energy.

For this reason the potential of biogas production from urban and agro-biodegradable waste and its economic assessment is estimated for Los Rios Region in south central Chile. To do this, we quantified dairy waste, slaughterhouse sludge, water treatment sludge and household waste performing a compilation, standardization and processing of available information. Then, using factors found in different databases, generated biogas, methane, electricity, heat and power load for the main plants of the region was estimated. The dairy industry, using cheese whey, has the highest bioenergy potential of all investigated waste sources, the slaughter industry had the lowest one. The total potential for the region reached 7,500,000 m^3 of biogas from cogeneration and could bring an electrical output of 9.1 MW. This energy could supply the electricity requirements of more than 170,000 people. An economic evaluation indicated feasibility for most of the projects evaluated. The economically feasible potential for the region reached 6.2 MWe.

RESUMEN

Palabras clave: biogás, energía renovable, residuos

La falta de combustibles fósiles, las altas tasas de crecimiento en el consumo energético nacional y los problemas ambientales, hacen necesario buscar nuevas fuentes limpias y seguras para la matriz energética nacional.

En este trabajo se estimó en forma preliminar el potencial de producción de biogás y su evaluación económica, a partir de residuos biodegradables urbanos y agroindustriales de la Región de los Ríos. Para esto, se cuantificaron los residuos de industria láctea, matadero, lodos residuales líquidos y residuos domiciliarios (RSU) realizándose una recopilación, estandarización y procesamiento de la información disponible. Luego, utilizando factores encontrados en distintas bases de datos se estimó la generación de biogás, metano, energía eléctrica, térmica y potencia instalada para las principales plantas de la región, encontrándose que el mayor potencial se encuentra en la industria láctea, utilizando el suero del queso. La industria de mataderos tuvo el potencial más bajo. El potencial total para la región alcanzó los 7.500.000 m^3 y surtiría mediante cogeneración una potencia eléctrica de 9,1 MW. Con esta energía se podría abastecer los requerimientos de electricidad de más de 170.000 personas.

La evaluación económica indicó viabilidad para gran parte de los proyectos evaluados. El potencial económicamente viable para la región alcanzó los 6,2 MWe.

INTRODUCCION

Mercado energético en Chile: Actualmente, el país importa casi las tres cuartas partes de la energía que consume. Entre los años 1990 y 2007 se evidenció un fuerte aumento en las importaciones de energía y un estancamiento de la producción de ésta, lo que lo hace vulnerable al país a condiciones externas. Es por ello que Chile hoy en día busca nuevas formas de aprovechar los recursos que posee para satisfacer la demanda creciente de energía (Soto y Werner, 2009).

Por otra parte, en los últimos 20 años, el consumo global de energía en Chile se ha expandido a una tasa anual en torno al 5,6%. En el mismo período, el aumento anual promedio del consumo de electricidad ha sido cerca de un 7,5%. De acuerdo a estas cifras, el país ha debido duplicar su capacidad de suministro eléctrico aproximadamente cada 10 años (Zanelli *et al.*, 2008).

Según CNE y GTZ (2009) la generación eléctrica total para el año 2007 fue de 55.914 GWh y provenía en un 38% de plantas hidroeléctricas, 10% de gas natural, 26% de carbón, 22% de petróleo combustible y un 3,1% de fuentes renovables no convencionales como pequeña hidráulica, biomasa y eólica.

Mercado eléctrico chileno: Según la Comisión Nacional de Energía, el mercado eléctrico en Chile se compone de 3 grandes áreas: generación, transmisión y distribución. Asimismo, el mercado eléctrico chileno se organiza en cuatro grandes sistemas eléctricos, éstos son: sistema interconectado del norte grande (SING), sistema interconectado central (SIC), sistema eléctrico de Aysén y sistema eléctrico de Magallanes (Hall *et al*., 2009).

La Región de Los Ríos se abastece de energía proveniente del sistema interconectado central, el cual abarca desde Tal-Tal, en la IV región, hasta Chiloé, en la X región.

El año 2010 la región de Los Ríos tuvo una generación de energía eléctrica de 771 GWh, representando tan solo un 1,28% del total nacional (Chile, Instituto Nacional de Estadística (INE), 2011). El consumo eléctrico en la región para el mismo año fue del orden de los 552,77 GWh (INE, 2012), siendo éste inferior a la generación total en la región.

Por otra parte, el sistema eléctrico en Chile se encuentra altamente concentrado, es así como al año 2006 participaban un total de 70 empresas, de las cuales 28 eran generadoras, 5 transmisoras y 37 eran distribuidoras. De éstas, tres (y sus filiales) poseían más del 89% de la potencia instalada en el SIC (51% ENDESA, 20% Colbún y 19% AES Gener), otras doce empresas poseían el 10% restante (CNE y GTZ, 2009).

Potencial energético: Las tecnologías disponibles en la actualidad permitirían a la Región de Los Ríos aprovechar una gran variedad de fuentes energéticas, destacando un alto potencial hidroeléctrico seguido de un importante potencial en biomasa, y en menor medida energía geotérmica, eólica y mini-hidráulica (Hall *et al*., 2009), además de los anteriores se suman algunas fuentes de combustible fósil, como el carbón próximo a ser explotado mediante un proyecto ya aprobado de gasificación de carbón en la localidad de Mulpún (Chile, Servicio de evaluación de impacto ambiental (SEIA), 2012).

Biogás: Dentro de las energías provenientes de biomasa, el biogás se presenta como una alternativa para la región (Hall *et al*., 2009). Flotats *et al.,* (1997) lo definen como un biocombustible gaseoso que se produce por la descomposición anaerobia (en ausencia total de oxigeno o nitratos) de la materia orgánica, resultando una mezcla de gases de proporción variable. Eltawil y Belal (2009) indican que biogás producido a partir de residuos agrícolas presenta entre un 54 a 75% de CH_4 (metano, gas que le otorga las propiedades combustibles a la mezcla), de un 33 a un 38% de CO_2, menos de un 2% corresponde a O_2 y N_2 y hasta 2622 ppm pueden corresponder a H_2S. En cuanto a la potencia calorífica, para el mismo tipo de residuos señalan que se encuentra entre los

7.476 y 6.658 kcal m^{-3}. Las instalaciones especialmente diseñadas para optimizar este proceso se designan como “digestores de metano”, “plantas de biogás”, “biodigestores” o simplemente “reactores anaerobios” (Flotats *et al*., 1997).
Por otra parte, la utilización de residuos orgánicos para la producción de energía supone muchas ventajas económicas, ambientales y sociales. El proceso fermentativo reduce la carga patógena de los residuos, especialmente los de producción animal o centros urbanos, constituyendo una alternativa para el tratamiento de ellos. Según Martin (2007) la fermentación reduce los niveles de patógenos tales como *Salmonella spp. Escherichia coli* (Migula) Castellani & Chalmers, virus enteríticos y huevos fértiles de Helmintos.

En vista de la problemática presentada y la oportunidad existente, el presente trabajo tiene como objetivo estimar en forma preliminar el volumen de biogás posible de producir en la Región de los Ríos y su evaluación económica a partir de los principales residuos orgánicos biofermentables urbanos y agroindustriales

MATERIAL Y MÉTODO

Material

Se utilizaron bases de datos científicas Science Direct y Web of Science (ISI), como también otras disponibles en el sistema de biblioteca electrónica que dispone la Universidad Austral de Chile. También se recurrió a plataformas gubernamentales nacionales como Instituto Nacional de Estadística (INE), Oficina de Estudios de Políticas Agrarias (ODEPA), Comisión Nacional de Energía (CNE), Superintendencia de Servicios Sanitarios (SISS), Servicio de Evaluación de Impacto Ambiental (SEIA) y Ministerio de Energía.
Para desarrollar los cálculos, gráficos y cuadros se utilizó el programa computacional Microsoft Excel 2010®.

Método

El método para cuantificar residuos y producción total de biogás y metano varió según la fuente de ellos y se realizó en forma separada. La evaluación económica se realizó una vez obtenidos los valores anteriores, tal como se indica a continuación:

Residuos orgánicos domiciliarios y municipales

Se cuantificaron a nivel de vertedero o relleno sanitario por comuna, a excepción del vertedero de la comuna de Valdivia, que funciona como lugar de acopio final para otras comunas. Según lo informado por Asociación de Municipalidades de los Ríos para el año 2011 se obtuvo el total de residuos generados en la región y la cantidad de materia orgánica presente en éstos. Utilizando los factores que mencionan CNE y GTZ (2009), se calculó el potencial total de biogás y metano.

Residuos orgánicos industriales

Se consideraron los residuos de la industria láctea e industria de matadero.

Industria láctea

De la totalidad de los productos lácteos que se elaboran en la región de los Ríos, Zaror (2000) indica que la producción de queso es la única que genera un residuo (o subproducto, según el uso que se le dé) de alta carga orgánica. Por tanto, en este trabajo se asumió que la mayor parte de éstos corresponden a lacto suero, despreciando los residuos provenientes del lavado de estanques, derrames y otros. De esta forma, según el promedio de la producción regional de queso entre los años 2011 y 2012 con datos de ODEPA y la cantidad de suero generado por unidad de queso producido, se estimó la generación anual de lacto suero para la región de los Ríos según lo señalado por Prazeres *et al.,* (2012). Luego, con los valores que muestran Comino *et al.,* (2012) se estimó el volumen de biogás y metano posible de producir en la región.

El cálculo anterior se complementará considerando producción regional de cada producto por año, con datos de ODEPA y generación media de solidos suspendidos por unidad de producto producido, según lo expresado por Zaror (2000).

Industria de matadero

Se evaluaron los 2 mataderos autorizados para la región: Frigorífico Valdivia y Frigorífico Balmaceda (en adelante FRIVAL y FRIGOBAL respectivamente). Para estimar los residuos de ambos se utilizó como base lo expuesto en la declaración de impacto ambiental de la planta FRIVAL presentado en el servicio de evaluación ambiental (SEIA, 2005) en donde se caracterizan sus RILES. El volumen de éstos se obtuvo del trabajo presentado por Altaner (2009) en donde indica el flujo diario de residuos líquidos generados en la planta FRIVAL, obteniéndose de esa forma la cantidad total de residuos sólidos generados en 1 año, asumiendo un funcionamiento de la planta durante los 365 días del año. El flujo de residuos anuales para la planta FRIGOBAL se encuentra disponible en superintendencia de Servicios Sanitarios (SSIS) y se utilizó como base la misma información utilizada para la planta FRIVAL.

Puesto que según lo señalado en la declaración de impacto ambiental (SEIA, 2005), las grasas son separadas de los RILES, para el cálculo total de biogás y metano se analizaron por separado el potencial de las grasas y el potencial del resto del RIL, utilizando para las grasas los factores señalados por Institut für Energetik und Umwelt (IEU) (2006) y para el RIL los señalados por Iglinski *et al.,* (2012).

Lodos residuales líquidos

Se consideraron a partir de plantas de tratamiento de aguas servidas (PTAS). La información sobre lodo deshidratado en base seca generado por planta para el año 2012 se obtuvo a través de la Superintendencia de servicios sanitarios (SSIS). Antes del año 2012 sólo se registraba el volumen de lodo generado por planta, sin tener información del contenido de humedad ni la densidad. A partir del año 2012 se comenzó a registrar el lodo generado en base seca, por lo tanto, se utilizó esta última información para los cálculos. Al comparar los volúmenes del año 2012 con los anteriores existía similitud, lo que fortalece el valor, considerando que se utilizó sólo un año para los cálculos. Para estimar el biogás y metano generado se utilizó la información presentada por Scievano *et al.,* (2009).

Transformaciones energéticas

Una vez obtenido el potencial de biogás y metano para cada residuo, se calculó la cantidad de energía eléctrica considerando que 1 m^3 de metano tiene 9.464 kcal m^{-3}. Una vez obtenido el contenido calórico del biogás, se transformó a energía eléctrica (kWh) considerando que 1 kcal = 0,001163 kWh (Quesada *et al*., 2007).

Se consideró para la transformación la cogeneración con un motor CAT 3520C con una eficiencia eléctrica de un 38% y térmica de un 40% (CNE y GTZ, 2007). La potencia eléctrica se calculó suponiendo un funcionamiento del motor de 7.784 horas (CNE y GIZ, 2012).

Evaluación económica

Para el cálculo económico se elaboró un cuadro en donde se estima una inversión inicial según potencia y costos de mantención y operación para cada planta, considerando datos de CNE y GTZ (2007) y Gamma Ingenieros (2011). Con esta información se asignó una inversión para cada proyecto en particular, los cuales se definieron considerando las plantas que en la actualidad generan residuos.

Los ingresos se cuantificaron considerando la venta de energía eléctrica, potencia eléctrica y energía térmica producida. No se consideraron ingresos por concepto de bonos de carbono, biofertilizante y otros beneficios ambientales. Para la energía eléctrica, el precio del kWh eléctrico a utilizar corresponde al precio nudo medio de mercado para el sistema interconectado central en el período correspondiente septiembre 2012 a diciembre 2012 (CNE, 2013) fijado en octubre del 2012 según la Comisión nacional de Energía, valor que alcanzó en ese período los $54.488. La potencia eléctrica se valorizó en US$ 8.784 de acuerdo a lo expresado por el Ministerio de Energía publicado en el diario oficial el día 12 de febrero del 2013. Para cuantificar los ingresos por venta de energía térmica se consideró la energía térmica generada (MWh) por planta y a ésta se le asignó un valor de 0,8 UF por MWh térmico, equivalente a lo que cuesta generar esa cantidad de energía a partir de chips de madera según lo señalado por Pavez (2013). este valor, según el mismo autor, está muy por debajo de lo que cuesta generar la misma cantidad de energía a partir de fuentes como el petróleo diésel, por tanto, se consideró correcto para ser utilizado en esta evaluación sin sobre estimar estos ingresos. El valor de UF utilizado fue el alcanzado al día 18 de junio del 2013, de $22.852,67.

RESULTADOS Y DISCUSIÓN

Residuos orgánicos domiciliarios y municipales

Las comunas de Valdivia, Panguipulli, Lanco, San José, Máfil, Los Lagos y Corral envían sus residuos al vertedero Morrompulli, ubicado en la comuna de Valdivia, por lo tanto, por ser lugar de acopio final se consideró este vertedero y los de las restantes comunas de la región (Futrono, La Unión, Rio Bueno, Lago Ranco y Paillaco), según la información entregada por la Asociación de Municipalidades de Los Ríos, tal como lo indica el cuadro 1.

CUADRO 1

Según la asociación de Municipalidades de Los Ríos, la proporción de materia orgánica presente en los residuos recibidos en el vertedero Morrompulli promedia el 55% del total de éstos, en peso húmedo, asumiéndose el mismo valor para los otros vertederos. Para el cálculo de biogás y metano generado al año, se utilizaron valores de 60 m^3 ton^{-1} MOH con un 50% de metano, considerándose la generación de biogás por tonelada de materia orgánica húmeda contenida en el residuo. Con estos datos, se calculó el potencial de biogás y metano para la Región de los Ríos, mostrándose los resultados en el cuadro 1. Como se observa en éste, el mayor potencial se encuentra en el vertedero Morrompulli, lo que se explica principalmente por la mayor población que cubre, y por consiguiente, el mayor tamaño de éste.

Es importante señalar que para estimar este potencial, se consideraron los residuos tal como llegan a vertedero, esto es, materia orgánica de composición y humedad variable, mezclada con metales, plásticos, vidrio, pilas, entre varios otros componentes de los RSU. Además, la mayor parte de los residuos envuelto por bolsas de polietileno u otro polímero de lenta degradación. El potencial podría ser considerablemente mayor si se separase lo orgánico del resto de residuos. De esta forma, IEU (2006) señala que por tonelada de materia húmeda de restos de comida, se pueden producir hasta 480 m^3 de biogás y hasta 200 m^3 a partir de residuos verdes. En este trabajo, se estimaron para la región 75.332 ton de materia orgánica húmeda. Lo que podría generar, en el caso que se encuentren separados del resto de los residuos, entre 15.066.400 y 36.159.360 m^3 de biogás al año, lo que equivale a entre 4 y 9 veces lo estimado en este trabajo.

Cabe destacar también, que sólo se consideraron residuos de áreas cubiertas por el servicio de recolección de basura, esto es cercano al 100% de la población urbana pero sólo cerca de un 50% de la rural, según estimaciones del Gobierno Regional para el año 2012. Por lo tanto, un aproximado de 60.000 personas (de un total de 360.000) no fueron consideradas en el cálculo del potencial regional.

Industria láctea

Se consideró la producción anual de queso para las 5 mayores plantas de este producto en la región (ODEPA, 2013). Segmento que es denominado por este organismo como industria láctea mayor. Estas plantas son:

- Planta Colún, comuna de La Unión
- Planta Soprole, comuna de Los Lagos
- Planta Lácteos las Parcelas, comuna de Valdivia.
- Planta Lácteos del Sur S.A., comuna de Rio Bueno
- Planta Quillayes – Peteroa, comuna de Futrono

Además, se consideró el total de la producción de quesos en la región (INE, 2013), a menor escala, denominada por INE como “láctea menor”.

De la elaboración de queso se genera suero de alta carga orgánica (Zaror, 2000) compuesto principalmente por agua, proteínas y lactosa (Santos, 1983). Los valores utilizados fueron: 6% de materia seca (Santos, 1983), 80% de MO (Comino et al., 2012) y 9 kg de suero húmedo por kg de queso producido (Prazeres *et al*., 2012). Para los cálculos se promediaron valores de industria láctea mayor y menor. Resultados en el cuadro 2.

CUADRO 2

Estos valores dan cuenta del gran potencial de la industria láctea mayor, principalmente de las plantas Colun y Soprole, las que debido a su elevada producción serían responsables de cerca del 75% del biogás que se podría producir en la Región.

Industria de matadero

En la región actualmente existen 2 mataderos autorizados: FRIVAL y FRIGOBAL, por lo tanto, para aprovechar el agrupamiento de éstos residuos y facilitar la cuantificación de éstos, sólo se consideraron ambas plantas, dejando de lado otras fuentes posibles, tales como mataderos clandestinos o faenamientos realizados en sectores rurales.

Para obtener la información correspondiente a la planta FRIVAL se consideró la caracterización de los RILes presentada en el SEIA (2005) por representante de la planta. El volumen de RILes diario generado en la planta lo indica Altaner (2009) en 650 m^3, obteniéndose de ésta forma los datos presentados en el cuadro 3.

CUADRO 3

Cabe destacar que los valores de sólidos suspendidos sumados a los de aceites y grasas, son significativamente inferiores a los de la DBO_5, sin embargo, no se encontraron indicadores adecuados para transformar esta última variable en biogás, por lo tanto, se utilizaron los sólidos suspendidos y las grasas para esto, de modo que es posible una subestimación del potencial para esta industria.

Para estimar los residuos generados en la planta FRIGOBAL se consideró el volumen de RILes generados, según lo señalado por la Superintendencia de Servicios Sanitarios, información que entregó a este organismo la planta de tratamiento de aguas residuales de la empresa Essal para el año 2011, en la comuna de La Unión. Esta empresa sanitaria mantiene contrato con FRIGOBAL para tratar sus RILes. Por este motivo, el frigorífico no fue considerado en el potencial regional de biogás, puesto que está incluida en esa planta de tratamiento de aguas servidas. Sin embargo, se estimó el potencial de este frigorífico para obtener una estimación del potencial regional de la industria de matadero. A continuación, se muestra el potencial regional de la industria de matadero.

CUADRO 4

En comparación a la industria láctea, el potencial de la industria de mataderos es significativamente inferior, representando menos del 2% del potencial regional de residuos industriales. Esto probablemente se debe a que los residuos que se consideraron para la producción de biogás, a diferencia del lacto suero, son de menor contenido energético, puesto que los RILes utilizados son una mezcla de 2 tipos de RILes: aguas rojas y aguas verdes. Las primeras corresponden al agua-sangre proveniente de la planta de faena; aguas de lavado de los equipos, productos y pisos, lavado de los equipos de la sala de procesamiento de vísceras rojas, zona limpia de procesamiento de guatitas y tripas, decomisos y desposte. Las segundas corresponden a aguas provenientes del lavado de camiones, corrales y salas de vísceras verdes, salas de procesamiento de vísceras verdes y pisos de las salas de zona sucia del procesamiento de vísceras verdes, aguas del lavado de equipos. Extracción del contenido ruminal de estómagos, vómito. Por lo tanto, no se considera en el cálculo el grueso de las grasas, restos cárnicos, sangre o huesos, puesto que actualmente son separados y comercializados en el mercado. En eventualidad que el precio de la energía aumenta, podrían considerarse estos residuos para producción de biogás y de ésa forma, aumentar la generación eléctrica y el potencial instalado total.

Lodos residuales líquidos

Se evaluaron las 11 plantas de tratamiento de aguas servidas (PTAS) que tratan las aguas residuales de las principales ciudades de la región. Las comunas de La Unión y Río Bueno comparten una sola planta, ubicada en esta última. Con la generación mensual de lodo (en toneladas de lodo deshidratado, como también la generación mensual en volumen durante los años 2010 y 2011 para cada planta, usando esta última información a modo de comparación, para fortalecer la información) presentada por Superintendencia de servicios Sanitarios (2013) y utilizando valores de MS de 19,3%, rendimiento de biogás de 240 m^3 ton^{-1} MS y un 65% de metano (Scievano *et al.,* 2009) se obtuvieron los resultados que muestra el cuadro 5.

CUADRO 5

El potencial de biogás de estos residuos es considerablemente inferior al de los residuos urbanos domiciliarios, lo que se puede explicar, entre otras cosas, a que el residuo considerado para el cálculo corresponde al lodo obtenido luego de un tratamiento aerobio, siendo el de lodos activados el sistema utilizado en casi la totalidad de las plantas de la región, exceptuando la planta Valdivia de la empresa Aguas Décima, que sólo realiza un tratamiento primario; por lo tanto, parte importante de la energía contenida en este residuo ya ha sido liberada.

Actualmente no se han desarrollado proyectos en la región para tratar las aguas residuales con una digestión anaerobia. Según CNE y GTZ (2007), es posible realizar un pre tratamiento anaerobio con obtención de biogás aprovechando cerca de un 30% de la energía presente en el residuo, además de reducir el consumo energético requerido en el tratamiento aerobio. De esta forma, el potencial de biogás a partir de residuos de plantas de tratamiento de aguas servidas podría aumentar de 986.773 m^3 a un mínimo cercano a 1.990.000 m^3 a un máximo de 3.970.000 m^3.

Por otra parte, las diferencias encontradas entre las plantas de la empresa Essal y la planta Valdivia perteneciente a la empresa Aguas Décima se explican porque esta última, como se mencionó anteriormente, además de cubrir una mayor población, sólo realiza tratamiento primario con desinfección, generando mayor cantidad de lodos que plantas de Essal, en donde se realiza tratamiento completo de lodos activados.

Generación eléctrica, térmica y capacidad instalada

Como era de esperar, el mayor potencial, con valores muy superiores, lo presentan los residuos industriales, particularmente la industria láctea con un uso potencial del suero para fines energéticos.

Como se aprecia en el cuadro 6, la potencia instalada eléctrica en la región alcanzaría los 9,1 MW.

CUADRO 6

Evaluación económica

La evaluación se realizó únicamente a plantas donde actualmente existen residuos agrupados, no considerando costos de transporte y dejando fuera fuentes menores de generación de residuos tales como industria láctea menor y otras fuentes de generación de residuos no consideradas en este trabajo. En cuanto a las plantas de tratamiento de aguas servidas de la región, se consideraron únicamente las que poseen una potencia instalada estimada superior a 10 kW.

Para estimar la inversión inicial y los costos de operación se basó en lo señalado por GTZ y CNE (2007) para proyectos con una potencia instalada superior a 0,3 MW, y para proyectos con potencia instalada entre 0,05 y 0,2 MW se consideró la información presentada por Gamma Ingenieros (2009). La razón de la diferencia en la inversión señalada por estos dos autores es justificada por el menor costo de los materiales para la construcción en proyectos de menores escalas.

A continuación se presentan los resultados del análisis económico de tipo VABN para los proyectos de potencias instaladas superiores a 10 kW.

Residuos domiciliarios y municipales: En estos residuos, por estar actualmente los rellenos sanitarios o vertederos autorizados en lugares alejados de centros productivos, condición que dificulta la venta de energía térmica, se evaluaron 2 escenarios; uno considerando la venta de esta energía y la otra sin considerarla, no habiendo cambios en la rentabilidad de cada proyecto entre uno y otro escenario. A continuación, en el cuadro 9 se presentan los resultados del VABN.

El relleno sanitario Morrompulli, a pesar de ser el que maneja mayores volúmenes de residuos, no logró un valor positivo en el análisis. Esto puede explicarse por la alta inversión relativa (US$ kWe instalado^{-1}) que se mostró en el cuadro 7. Se lograron índices positivos tan solo en los vertederos de las comunas de La Unión y Rio Bueno.

CUADRO 7

Evaluación económica para industria láctea: Los resultados del análisis de Valor actual de beneficios netos para las plantas de la industria láctea mayor se presenta en el cuadro 8.

CUADRO 8

Como era esperable, las 2 más grandes plantas lácteas de la región mostraron índices económicos positivos. Sin embargo, lácteos Las Parcelas y lácteos del Sur arrojaron indicadores negativos, posiblemente por su menor tamaño. La planta Quillayes – Peteroa arrojó indicadores positivos. Lo anterior se puede explicar por qué según Gamma Ingenieros (2011) proyectos con potencia similar o menor a 500 kW requieren alta inversión relativa (US$ kW^{-1} instalado) haciendo inviable dicha tecnología en el país. Sin embargo, plantas con potencias cercanas o menores a 100 kW instalados pueden abaratar los costos de inversión al reducir costos de materiales y tecnologías como piscinas cubiertas o estanques de fibra de vidrio enterrados, sin agitación ni control de temperatura. Con dichos cambios se disminuye la eficiencia en la obtención de biogás, sin embargo, se produce un importante ahorro en la inversión.

Evaluación económica para industria de matadero

Como se señaló anteriormente, se evaluó solo la planta FRIVAL, excluyendo la planta FRIGOBAL por tener una potencia instalada menor a 10 kW.

CUADRO 9

Como se aprecia en el cuadro 9, la evaluación de esta planta arrojó indicadores positivos, resultando viable económicamente según lo evaluado en este trabajo. Lo que se explicaría también por su bajo costo de inversión, como lo señala Gamma Ingenieros (2011).

Evaluación económica para lodos residuales

De las 11 plantas existentes en la región, se evaluaron únicamente los 4 proyectos con potencia instalada superior a 10 kW, mostrándose los resultados en el cuadro 10:

CUADRO 10

El análisis arrojó inviabilidad económica para los 3 proyectos de menor potencia instalada: Panguipulli, Rio Bueno y Lanco. Sin embargo, el proyecto Valdivia, de la planta del mismo nombre, perteneciente a la empresa Aguas Décima, mostró indicadores positivos.

Cabe destacar que la evaluación económica realizada es preliminar, a escala regional, sin profundizar mayormente en las condiciones específicas de cada proyecto, por lo que se requieren más estudios para profundizar lo visto en este trabajo. Por otra parte, corresponde a una evaluación económica tradicional, en donde solo se consideran variables que tienen un valor monetario transable en el mercado, no considerando otros como los impactos ambientales involucrados. El aprovechamiento de residuos para obtención de biogás permite una reducción de éstos, con un bajo costo energético (contrariamente a lo que ocurre por ejemplo con las plantas de tratamiento aerobio de aguas servidas, las que requieren de energía para agitadores y otros procesos), efectivo tratamiento natural contra varios agentes patógenos y además se evita la liberación de metano a la atmosfera, muy importante considerando un contexto de cambio climático. En esa misma línea, el obtener electricidad a partir de estos residuos reduce la utilización de otros combustibles de mayor impacto ambiental, como los combustibles fósiles o la leña, mejorando la calidad del aire, reduciendo presión por uso del bosque y mitigando los efectos del cambio climático al reducir el metano que se libera a la atmosfera. En cuanto a los impactos sociales, un aumento del desarrollo de proyectos de este tipo podría aumentar la tasa de ocupación al tener una empleabilidad asociada a cada proyecto. Por lo tanto, un análisis completo debiera considerar los factores anteriormente considerados.

El potencial total de la región alcanzaría casi los 7.500.000 m^3, lo que representaría un 21,4% del total de biogás que era aprovechado a nivel nacional para el 2010 (Gamma

Ingenieros y CNE, 2010), e instalaría una potencia eléctrica cercana a un 9,1 MW. Potencia superior a lo que se construía a nivel nacional en proyectos solares el año 2012 (Chile, Centro de Energías Renovables (CER), 2012). De esta forma, el potencial estimado en este trabajo puede aumentar en un 1,09 % la potencia instalada total nacional a partir de energías renovables no convencionales.

En cuanto a proyectos de biogás a nivel nacional, según Gamma Ingenieros y CNE (2010), para el año 2012 existían un total de 20 plantas funcionando, que sumadas producían cerca de 200 millones de m^3 de biogás, sin embargo, solo aproximadamente 35 millones (17,5%) eran aprovechados, el resto se quemaban en antorchas. Esta tendencia ha comenzado a cambiar y actualmente ya hay más de 10 proyectos a nivel nacional que contemplan el aprovechamiento energético mediante transformación a energía eléctrica, térmica o ambas.

En cuanto a la generación eléctrica, con el biogás producido a partir de los residuos considerados en este trabajo, se podrían generar 71.536 MWh al año, lo que corresponde a un 9,3 % del total generado en la región el año 2011. Además, a nivel de consumo por habitante, según INE (2008), para ese año, el consumo promedio de electricidad entre las VIII y XII regiones bordeaba los 416 kWh anual. La generación total eléctrica por año, estimada en este trabajo, alcanza los 71.536 MWh, por tanto, únicamente a partir del biogás obtenido de residuos actualmente generados por actividades urbanas e industriales a gran escala se podría abastecer la demanda eléctrica de al menos 170.000 personas, población superior a la reportada para la ciudad de Valdivia en el censo 2012.

CONCLUSIONES

En la Región de los Ríos actualmente se generan en promedio 136.967 ton año^{-1} de residuos domiciliarios, de las cuales 75.332 ton año^{-1} son orgánicas.

Los lodos de plantas de tratamiento de aguas servidas generados a nivel regional alcanzan en promedio las 2.990 ton MS año^{-1}.

Los principales grupos de residuos industriales orgánicos generados en la región corresponden a los de la industria láctea e industria de matadero, generando 26.250 y 584 ton MS año^{-1} respectivamente, y considerando en la primera únicamente residuos de la producción de quesos.

El volumen de biogás total que se podría generar en la región alcanzaría los 25.865.919 m^3.

La cogeneración eléctrica alcanzaría los 71.537 MWh por año. Asimismo, la generación térmica alcanzaría los 75.301 MWh al año.

En cuanto a la potencia eléctrica, ésta alcanzaría los 9,1 MW de capacidad instalada, provenientes en su mayor parte de la industria láctea.

La evaluación económica arrojó un potencial económicamente viable para la región de los Ríos de 6,2 MW. Las plantas Colun y Soprole resultaron un VABN positivo, como también frigorífico Valdivia (FRIVAL) y planta Valdivia de la empresa Aguas Décima. No resultó con un VABN positivo el vertedero Morrompulli.

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Captions

Cuadro 1. Generación anual de residuos y volumen anual de biogás y metano posible de producir por vertedero en la Región de Los Ríos a partir de residuos domiciliarios y municipales

Table 1. Annual waste generation rate and annual biogás and methane volume possible to generate per landfill in Los Rios region from household and municipal waste

Cuadro 2. Generación anual de suero seco, materia orgánica y producción estimada de biogás y metano para las industrias lácteas de la región de los Ríos

Table 2. Annual generation rate of dried whey, organic matter and estimate biogas and methane production from dairy industry in Los Rios region

Cuadro 3. Tasa anual de generación de materia orgánica, biogás y metano en la planta FRIVAL

Table 3. Annual generation rate of organic matter, biogas and methane in FRIVAL industry.

Cuadro 4. Tasa de generación anual de residuos orgánicos, biogás y metano para la industria de matadero

Table 4. Annual generation rate of organic waste, biogas and methane for slaughterhouse industry

Cuadro 5. Tasa de generación anual de lodo deshidratado generado (ton año^{-1}), volumen de biogás y metano posible de producir en la región de los ríos por año para cada planta

Table 5. Annual generation rate of dewatered ludge (ton year^{-1}), biogas and methane volumen possible to produce in Los Rios region for each plant

Cuadro 6. Potencial energético, eléctrico, térmico y potencia instalada eléctrica para las distintas fuentes, y el total de la región de los Ríos

Table 6. Energetic, electrical and thermal potential, and electrical installed power for different sources, and the total of Los Rios region

Cuadro 7. VABN para cada proyecto de vertederos en la región. La columna 1 considera la venta de energía térmica y la 2 no lo considera para la evaluación
Table 7. NPV for each landfill project in the region. Column 1 considers sale of thermal energy and column 2 is not considered for evaluation

Cuadro 8. VABN para cada planta de industria láctea mayor en la región
Table 8. NPV for each dairy plant in the region

Cuadro 9. VABN para planta FRIVAL de industria de matadero en la región.
Table 9. NPV for FRIVAL plant from slaughterhouse industry

Cuadro 10. VABN para las plantas de tratamiento de aguas servidas de la región con potencias instaladas superiores a 10 kW.
Table 10. NPV for each plant of wastewater treatment in the region with installed power greater than 10 kW.

Cuadro 1.

Vertedero	Residuos recibidos* (ton año^{-1})	Biogás (m^3 año^{-1})	Metano (m^3 año^{-1})
Morrompulli (Valdivia)	111.167	3.668.524	1.834.262
Futrono	2.300	75.900	37.950
La Unión	12.000	396.000	198.000
Lago Ranco	1.800	59.400	29.700
Paillaco	3.200	105.600	52.800
Rio Bueno	6.500	214.500	107.250
Total	136.967	4.519.924	2.259.962

*Fuente Asociación de Municipalidades de los Ríos

Cuadro 2.

Industria	Suero seco (kg)	Materia orgánica (ton MS)	Biogás (m^3)	Metano (m^3)
Láctea mayor	26.129.210	22.863	20.005.176	14.003.623
Colún	12.710.821	11.122	9.731.722	6.812.206
Soprole	8.351.214	7.307	6.393.898	4.475.729
Lácteos Las Parcelas	2.474.893	2.166	1.894.840	1.326.388
Lácteos del Sur	1.854.595	1.623	1.419.924	993.947
Quillayes - Peteroa	737.687	646	564.792	395.354
Láctea menor	241.344	211	184.771	129.340
TOTAL REGION	**26.370.544**	**23.074**	**20.189.947**	**14.132.963**

Cuadro 3.

Parámetro	Materia orgánica (ton año^{-1})	Biogás (m^3 año^{-1})	Metano (m^3 año^{-1})
Sólidos Suspendidos	370	174.331	108.957
Aceites y Grasas	125	87.329	54.581
TOTAL	495	261.660	163.538

Cuadro 4.

Planta	Materia orgánica (ton año^{-1})	Biogás (m^3 año^{-1})	Metano (m^3 año^{-1})
FRIVAL	495	261.660	163.538
FRIGOBAL	25	13.269	8.448
TOTAL	520	274.929	171.986

Cuadro 5.

Planta tratamiento aguas servidas	Lodo deshidratado (ton año^{-1})	Biogás (m^3 año^{-1})	Metano (m^3 año^{-1})
Corral	3,1	1.008	625
Futrono	56	18.478	11.457
Lago Ranco	3,0	981	608
Lanco	99,3	3.780	20.324
Los Lagos	86,3	28.469	17.651
Máfil	47,9	15.814	9.805
Paillaco	70,1	23.148	14.352
Panguipulli	98,1	3.359	20.063
Rio Bueno	660,9	218.085	132.213
S. J. de la Mariquina	39,6	13.057	8.095
Valdivia	1.826,0	602.593	373.608
TOTAL GENERAL	2.990,2	986.773	611.800

Cuadro 6.

Tipo residuo	**Energía Total**	**Energía eléctrica**	**Energía térmica**	**Potencia**
	Mcal año^{-1}	**MWh año^{-1}**		**MWe**
Industriales[1]	134.690.047	59.525	62.658	7,6
Láctea	133.142.327	58.841	61.938	7,5
Matadero[1]	1.547.720	684	720	0,1
Municipales	21.388.278	9.452	9.950	1,2
Lodos residuales	5.790.071	2.559	2.694	0,3
TOTAL	161.868.396	71.536	75.301	9,1

[1] Para el cálculo del potencial regional total de matadero no se consideró la industria FRIGOBAL, puesto que deposita sus RILES a la planta de tratamiento La Unión, de la empresa Essal.

Cuadro 7.

Vertedero	Potencia eléctrica (MW)	VABN1	VABN2
Morrompulli	0,97	-538162	-1123496252
Futrono	0,02	-44609306	-67842772
La Unión	0,11	363029458	241811371
Lago Ranco	0,02	-65621613	-83804326
Paillaco	0,03	-6787152	-39111975
Rio Bueno	0,06	131894076	66234280
Total Región	1,2		

Cuadro 8.

Planta	Potencia (MW)	VABN
Colun	3,6	$8.187.078.899
Soprole	2,4	$4.870.682.997
Las parcelas	0,7	-$1.294.065.626
Lácteos del Sur	0,5	-$824.055.920
Quillayes – Peteroa	0,2	$865.680.171
TOTAL	7,4	

Cuadro 9.

Planta	Potencia (MW)	VABN
FRIVAL	0,087	$275.255.602

Cuadro 10.

Planta	Potencia (MW)	VABN
Lanco	0,011	-$124.696.635
Panguipulli	0,011	-$124.909.145
Rio Bueno	0,072	-$31.030.210
Valdivia	0,198	$163.327.483
Total Regional	0,325	

5.4.3 Bioenergy from slurry

As can be seen from Figure 34, a high percentage of land use in Los Ríos Region is devoted to grasslands for cattle production (regional land use map in Figure 4, Paper 1, Section 5.4.1.1). Therefore, the main agricultural residue is slurry. Consequently a Bachelor thesis was offered and tutored exploring the biogas potential from the slurry produced in the region. The thesis of Mr. Manuel Antonio Ríos Gutiérrez with the title "*Estimación De La Producción Potencial De Biogás A Partir De Purines Bovinos En La Región De Los Ríos (Chile*)" (Estimation of Biogas Potential Production from Cattle Manure in Los Rios Region (Chile)) was successfully approved by the Faculty of Veterinary Science, Universidad Austral de Chile and the abstract of the thesis is attached to this document in the Section 9.8 of the Appendix. According to the results of it a theoretical maximum of 8.240.850m3 of biogas can be generated from cattle manure per year, which implies 1,457 GW of total energy or 560 GWh of power from cogeneration.

5.4.4 Bioenergy from forests

For modelling with BioStar, only soils suitable for agriculture are used (use capacity), meaning that native forests are taken out of the calculations. Due to this omission and considering that native forests cover almost 50% of the region's land surface, the model "Explorador de Biomasa Forestal" (Forest Biomass Explorer; UACh, 2013) was downloaded and combined with a GIS system to extract regional potentials of energy from forests. The "explorador" was created by the Faculty of Forest Sciences of the Universidad Austral de Chile, and considers biomass that fulfil certain environmental and technical restrictions, such as:

- Parts of the tree that could be used for wood production; only residual parts considered
- Forests that present endangered species
- Forests related to national parks or conservation uses
- RAMSAR wetlands and their protection zones
- Water borders protection zones
- Glacier borders protection zones
- Zones with soils that have erosion
- Slopes over 30%
- Soils with less than 20 cms depth

Figure 31 shows the region's forest potential derived from this model.

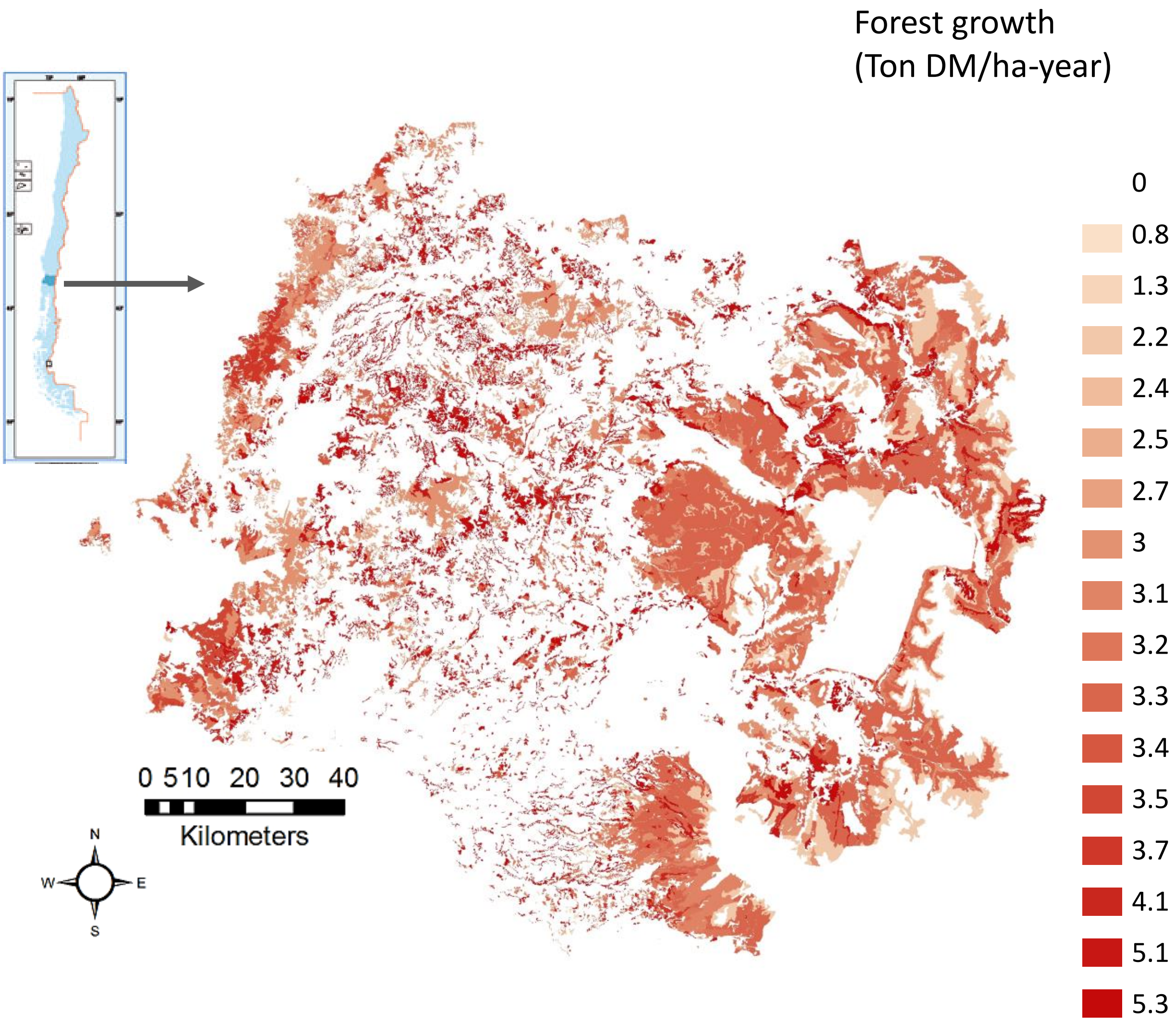

Figure 31: Manageable biomass annual growth of regional native forests by the model *Forest Biomass Explorer* developed by Universidad Austral (UACh, 2013a).

With the data from this model it is possible, in combination with the results of BioStar, to estimate the bioenergy potential of the entire region. As it was discussed in Sections 5.2 and 5.3, biogas and lignocellulosic biofuels have a high potential of synergy, as they can be both compatible and complementary. The information from Forest Biomass Explorer is used in the next Section's analysis, where the possibility of implementing the German concept of bioenergy villages to Los Ríos Region is investigated.

5.5 Local Qualitative Interactions: Bioenergy Villages and Los Ríos Region

5.5.1 IZNE and the first Bioenergy Village in Germany

Based on the principles of sustainability science (Schmuck et al., 2013), the Interdisciplinary Centre for Sustainable Development (IZNE, Interdisziplinäres Zentrum für Nachhaltige Entwicklung) at the University of Göttingen, Germany, developed the first project of an electricity-and-heat autonomous bioenergy village in Germany, Jühnde, consisting of 800 inhabitants in Lower Saxony (Ruppert et al., 2008). The system is based on a biogas reactor

that uses manure from livestock and crop silage from the surrounding farmland. The energy crops provide approximately 90% of the biogas and the manure only 10%. The biogas goes to a central cogeneration heat-and-power unit (CHP) where it is burned in an internal combustion engine, powering an electric generator. The heat released during that process is transferred to a hot water pipeline, which brings thermal energy to 75% of the houses in the village. In Winter, additional heat is provided from a central heating facility burning woodchips.
There are many advantages of such combined heat and power biogas systems (Ruppert et al., 2008; WBGU, 2008; USDA, 2014; Wüste and Schmuck, 2012), also if applyed to non-industrialized countries. Some benefits are as follows: high energy efficiency through cogeneration of electricity and heat (85%), decentralized structure, autonomy, integration of fermentable biological waste, complete nutrient recycling without the need of additional fertilizers, tested-simple-safe-clean-commercial technology, high social impact and community strengthening due to its participative characteristics. Among the disadvantages of such a model is primarily the use of land for energy crops, which in the case of Jühnde reach approximately 300 to 320 ha of agricultural land. The biogas produced from energy crops in that area provide two to three times more electricity than the population of Jühnde (800 inhabitants) and its local businesses need. Additionally, bioenergy villages need the agreement of many people involved in the system with regards to the production of biomass, the distribution and feed in system for heat into the households, etc. and sometimes such complex agreement is difficult to achieve.
Bioenergy villages should not be confused with Ecovillages. The latter are associations of people that are willing to live together with organization for everyday tasks and the use of common facilities and resources, who share values and a sense of community (Sevier et al., 2008). This way of living allows them to incorporate common environmentally-friendly practices and technologies, and to achieve ecological engagement such as less resource consumption or a share-based economy, among other alternative habits. Bioenergy villages, on the other hand, are specifically focused on energy management within conventional villages, although this model works better in well-organized communities.
Given such an interesting model of energy management, it is of high interest to know if such a model is replicable, and if it could be realized in Los Ríos Region. As it is discussed in Chapter 6 (epistemological considerations) this question has no direct answer. However, some technical criteria can be used to assess the feasibility of implementing the German bioenergy village model in Los Ríos Region.

5.5.2 Bioenergy in rural areas of Los Ríos Region

Chile has a wide variety of climates due to its north south configuration and its extraordinary length of almost 5000 kilometers. Four main climate zones can be found: desert (north), Mediterranean (central north), temperate rainy (central south) and Patagonian (south). Los Ríos Region is located in central south Chile, where biomass productivity is high and irrigation is generally not necessary. Most countryside households and rural villages of Los Ríos Region greatly depend on wood biomass for heating, hot water, and cooking. As appreciated in Figures 32 and 33, there is a direct latitude relationship between the presence of more productive forests and the use of firewood, and an inverse relationship in regard to the use of liquefied gas for domestic thermic use.

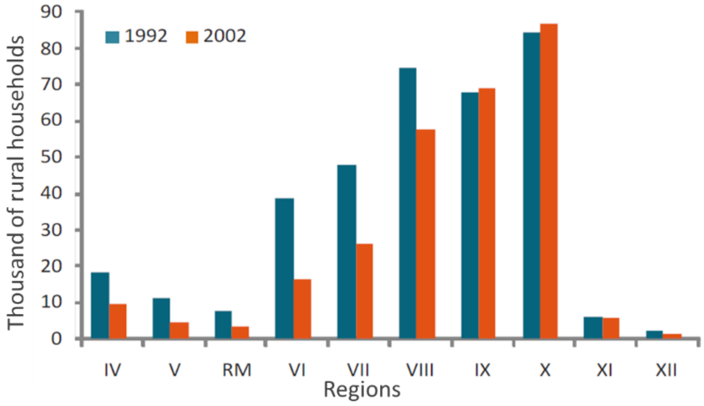

Figure 32: Rural households that consume wood fuels for cooking and water heating in the residential sector. Census of 1992 and 2002 (Reyes and Neira, 2012). North-south distribution of regions from left to right. Los Ríos Region (named XIV Region in 2007) was contained in X Region until 2007.

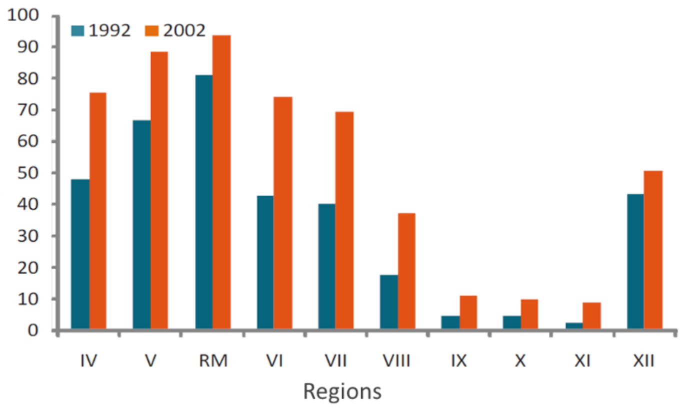

Figure 33: Ratio of households that consume liquefied gas for cooking and water heating in the rural residential sector, Census of 1992 and 2002 (Reyes and Neira, 2012).

Although the substitution of native forests by fast growing tree plantations of exotic species for the forestry industry was for decades the most important degrading factor of native forests, today firewood extraction is critical (Echeverria et al., 2006). In a non-formalized firewood market feed by a mainly unmanaged forest resource with very low-capacitated operators in the sector, firewood extraction is today the principal factor for regional forest degradation and deforestation. From the 15.2 million m^3 of wood annually extracted in Chile from native forests, the portion extracted for firewood is 9.3 million m^3 (AIFBN, 2011). However, southern Chile possesses vast areas of native forest of more than 14 million hectares with more than 6 million younger successional forests that can be restored and managed for multiple integral uses and services, such as wood, energy, biodiversity, and water production. As described in Section 6.4 and shown in Figure 34, half of the region is covered by native forests, and almost one third by grasslands. With less than half a million inhabitants, the region has abundant bioenergy resources for the population, representing a promising future for their development.

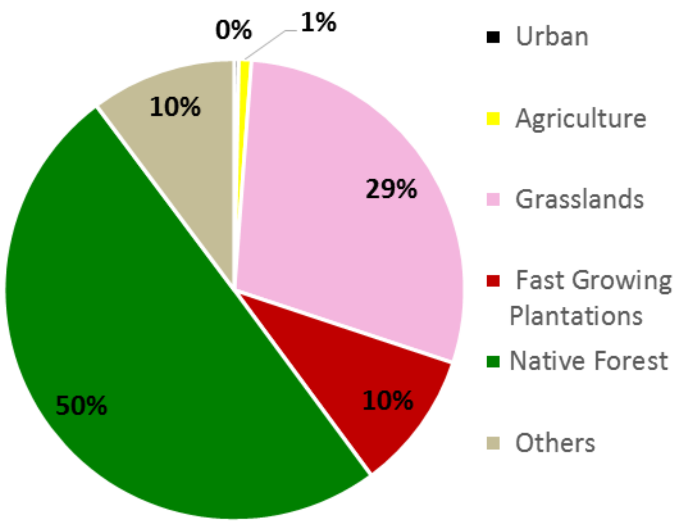

Figure 34: Distribution of land uses in Los Ríos Region

5.5.3 Testing the German bioenergy village (BEV) concept in Los Ríos

In order to test the feasibility of the German bioenergy village concept, rural villages are studied in terms of their surrounding land use and biomass availability. Based on a model of energy management, the local land domains used for bioenergy and the productivity of biomass must correspond with the local electric and heat demand of the population (see Figure 35). To establish this, an area with a 5 kilometers radius from the center of the villages is specified, according to Bauböck (2013), which is the maximum distance to avoid economic losses due to the transport costs for green biomass. This is not the case with wood, which is dense and dryer, allowing distances of up to 50 km for cost-effective transportation (CCA, 2008). A circle with a 5 km radius translates to an area of 7,850 hectares. The populations of the villages in the region are variable. For the analysis, a population size of 2,000 inhabitants per village is assumed (apart from the regional capital of Valdivia, the other cities in the region have an average of 10,000 inhabitants). In Jühnde, the ratio of surface area for energy crops per capita, necessary to cover the population's need (electricity and 72% of heat) is roughly 0.2 ha/p (150 hectares for 800 people). Therefore, assuming that the rural people in Los Rios region consume the same amount of electricity as the typical Jühnde resident, a village of 2,000 people requires 400 hectares of surface area for energy crops, which is only 5% of the whole area defined by the 5 km radius. In Figure 36 some villages are shown on a map with both bioenergy potentials highlighted: the potential of energy crops modeled with BioStar and the potential of forest biomass modeled with *Explorador de Biomasa Forestal*. With the combined information provided by the two models it is possible to calculate the agricultural and bioenergy capacity around each rural village and to roughly estimate the potential population that could be self-sustained in terms of food and energy.

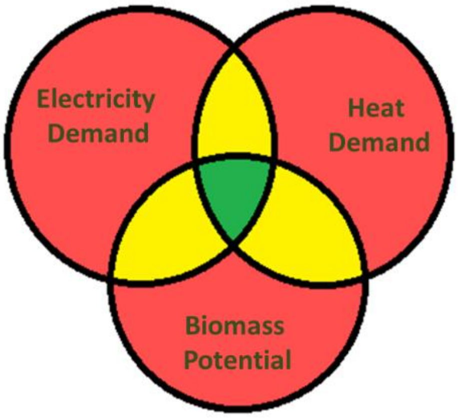

Figure 35: Land interactions for the German concept of a bioenergy village. The best case scenario (green) is when biomass is available in the same location where heat and electricity are in demand. The worst situation (red) is when only one of the three factors is present in a given area, without interaction from the other two factors. In the case of rural villages, heat and electricity are needed simultaneously, which creates a basis for the synergic effect of biogas cogeneration.

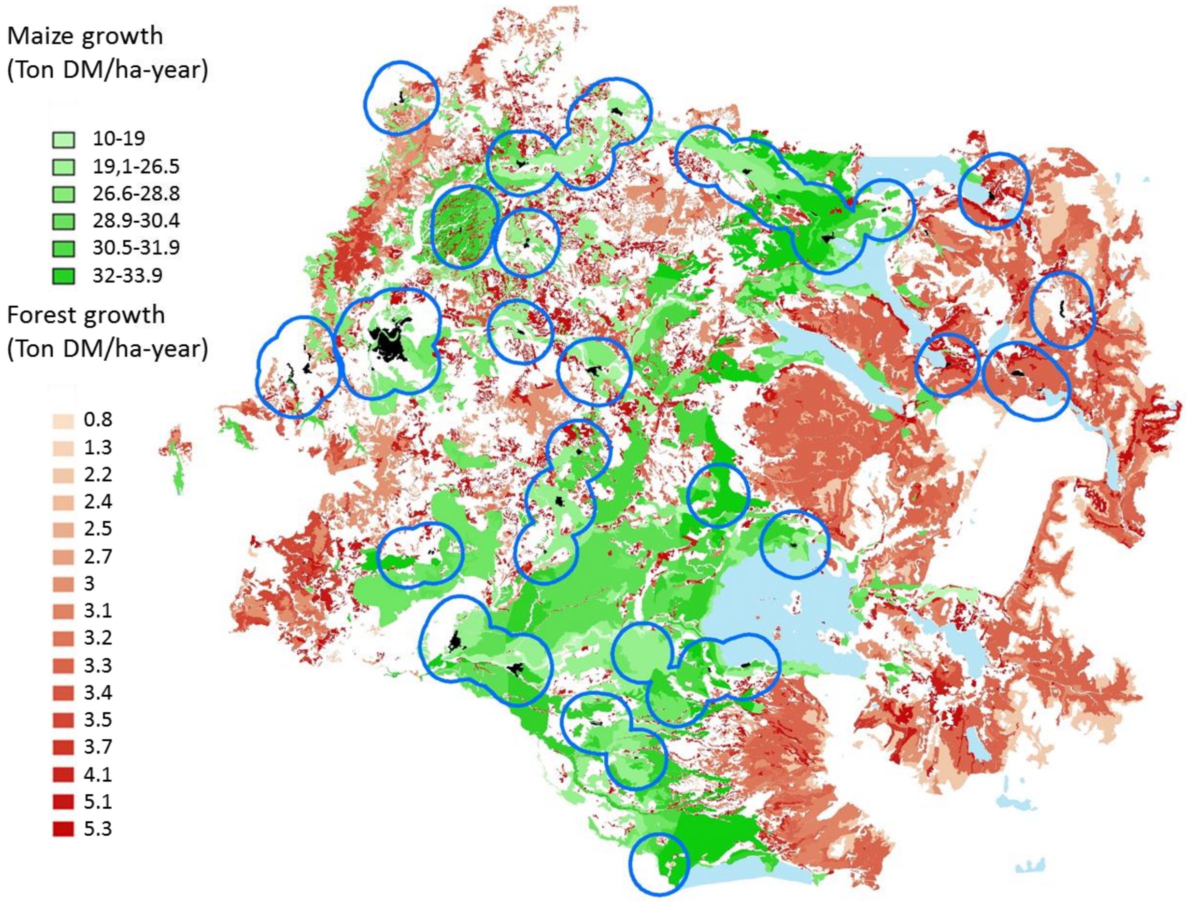

Figure 36: Regional biomass potential from maize modeled with BioStar and native forest modeled with *Explorador de Biomasa Forestal.* Circles (in blue) define areas around cities and villages (in black) with a 5 kilometer radius from the center.

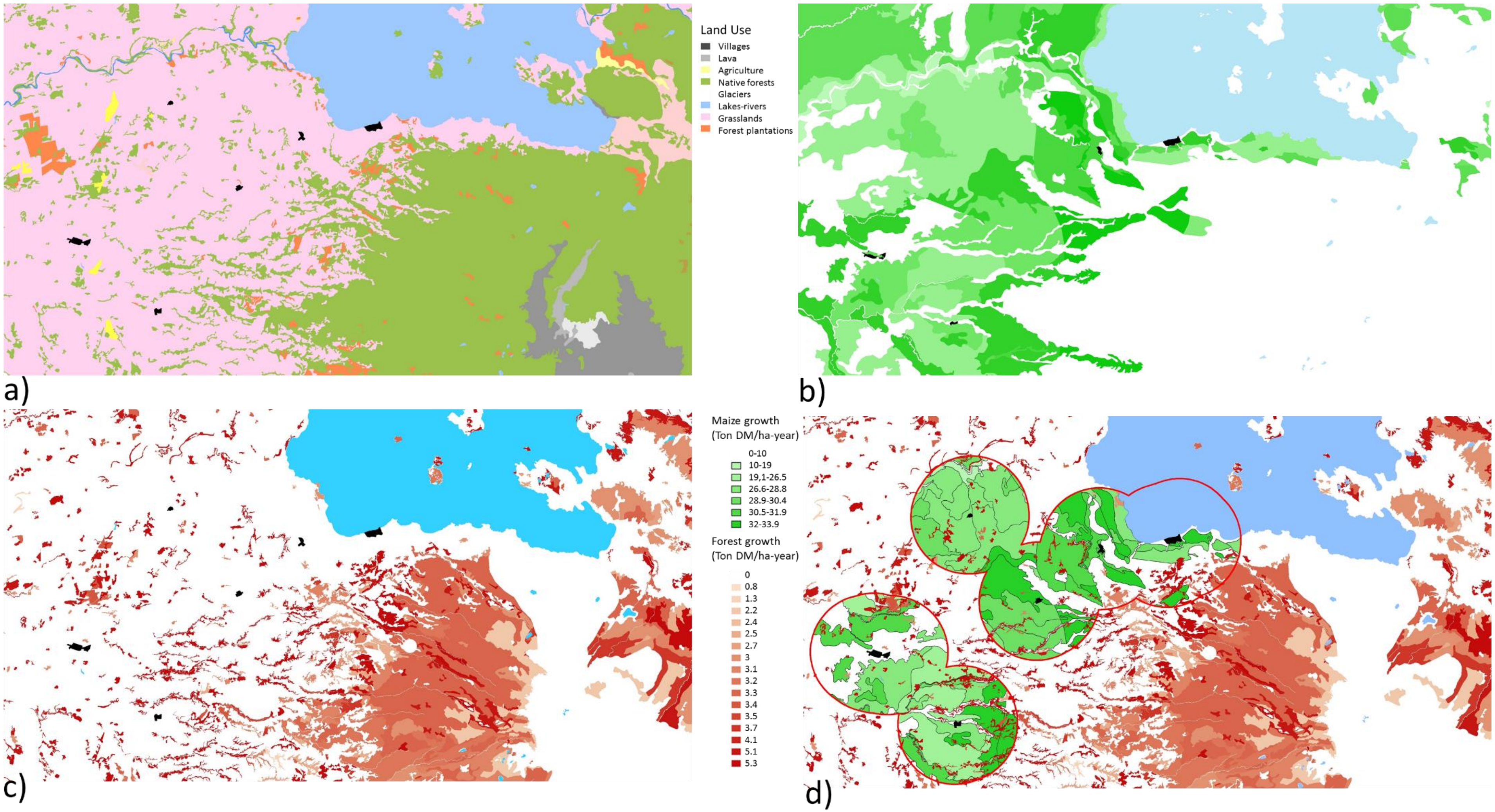

Figure 37: Biomass potential for several rural villages in the area surrounding Lake Ranco. a) Current land use, b) Maize potential, c) Native forest potential, d) Agriculture and forest potential. Agriculture biomass is restricted to a 5 km radius due to transport cost-effectiveness.

As can be seen in Figure 37, there is abundant biomass potential to supply the energy demands of the villages, as all of them have far more than 5% of their surface area available for the generation of biomass. Therefore, from a technical point of view, without regarding environmental restrictions for bioenergy development in the area, it seems clear that the German concept of a bioenergy village is certainly applicable. However, some other factors exist that may restrict the development of such a concept, which will be discussed next.
First, there are economic restrictions. Since wood is so abundant in the region, it is also very inexpensive, especially in the countryside where it is produced. Details of prices are shown in Table 8.

Table 8: Comparison of energy prices in Germany and Los Ríos Region.

Heat Los Ríos	
Price of firewood logs in Los Ríos Region[27] in €/m^3 ($CP= 730/€)	At source farm: 25 At villages: 33 At cities: 41
Wood density (Kg/m^3)	600
Wood energy content (KWh/kg)	4
Heat price (villages, €/KWh)	0.0137
Traditional wood stoves thermal efficiency (AIFBN, 2008)	25%
Useful heat price (villages, €/KWh)	0.0548
Heat Jühnde	
Heat price in Jühnde (€/KWh) (Ruppert et al., 2008)[28]	0.049
Heat net thermal efficiency	75%
Useful heat price (€/KWh)	0.0653
Electricity Los Ríos	
Farmers buying price (€/KWh) [29]	0.163
Farmer selling price (€/KWh)	0.0746
Electricity Jühnde	
Germany (€/kWh)	O.205 (without EEG)

Regarding heat, according to the shown data it seems that the conditions to achieve a similar scenario in Los Ríos as in Jühnde is not difficult, but still not economically feasible. In 2008, Jühnde has a 19% more expensive heat price (when using useful heat in the calculation), but charge nearly three times higher prices for electricity, even without the EEG subsidy. Furthermore, it is assumed that Chile has the same potential efficiency of providing heat via a hot water pipeline as Germany, which is probably not true. On the other hand, Chile has projected a future subsidy for renewable energies, but this is not possible or available in the short term.
Secondly, it is important to consider that the German concepts do not consider local cooking devices, such as the traditional kitchen woodstove, which is culturally the central hearth of the rural household in Chile. There is no cultural adaptation towards electric cooking devices, in part because the price of electricity and their related devices are too high. In fact, the abundance of forests is very high in the region and most of the household energy consumption is spent on thermic energy, as it is shown in Figure 38. Therefore, wood biomass should have a

[27] Prices of certified wood. More than 90% of the market is informal with no certification, which implies at least a 19% lower price.
[28] The heat in summer is nearly free (surplus heat), but in wintertime woodchips have to be burned in separate boilers.
[29] Selling prices for electricity are used: between $CP 76 and 180 depending on the load factor.

culturally, prioritized place as a bioenergy source in the region, which is not the case in the German concept of a bioenergy village.

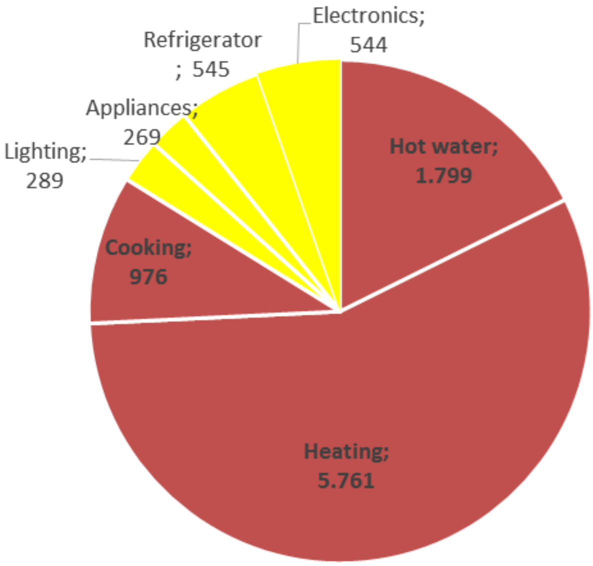

Figure 38: National average per household of final energy consumption (CDT, 2010) in KWh per family per year. In yellow: electricity; in red-brown: thermal energy.

Additionally, rural villages in Chile have different conditions than German villages:

- The population purchasing power is very low, because of poor income.
- The education level is also low in comparison to the more urban areas and even more so in comparison to the rest of the country.
- There is a very restricted ecological interest and environmental consciousness.
- Due to the economic standard of living and the local culture, people use less energy than the rest of the region, and definitively less than in Germany.

Finally, there exists a small, but real public opposition toward the use of agricultural land for energy production. Although the concept of bioenergy in Chile is still in a very early development stage, the eruption of fast growing plantations of exotic trees over the previous decades has set a bad precedent, especially as these plantations were originally established through environmental arguments such as providing erosion control and renewable energy production (through carbon sequestration). Over time, the Chilean forestry model of fast growing trees has shown several weaknesses (Little et al., 2009; Erlwein et al., 2007). Additionally, global concerns over the costs and availability of food/gasoline has pervaded Chilean society more than concerns over ecological consciousness, and citizen opposition to bioenergy concepts may in fact be a valid reflection of the country’s social inequality, which only allows a powerful minority of firms to access the energy business.

In light of these socio-political complications, the direct application of the German concept of a bioenergy village to Los Ríos Region seems to not be feasible at the present moment. However, three new concepts derived from the original German model of bioenergy villages may have better prospects. Those concepts are developed in the following subsections.

5.5.3.1 BEV-alternative concept 1: Rural village with (non-electric) biogas network

The first model proposed consists of replacing the use of the traditional kitchen woodstove in rural villages by biogas stoves supplied with organic residues and complimented by energy crops. This model also works for single countryside houses. The reasons and details for such a concept are explained below.

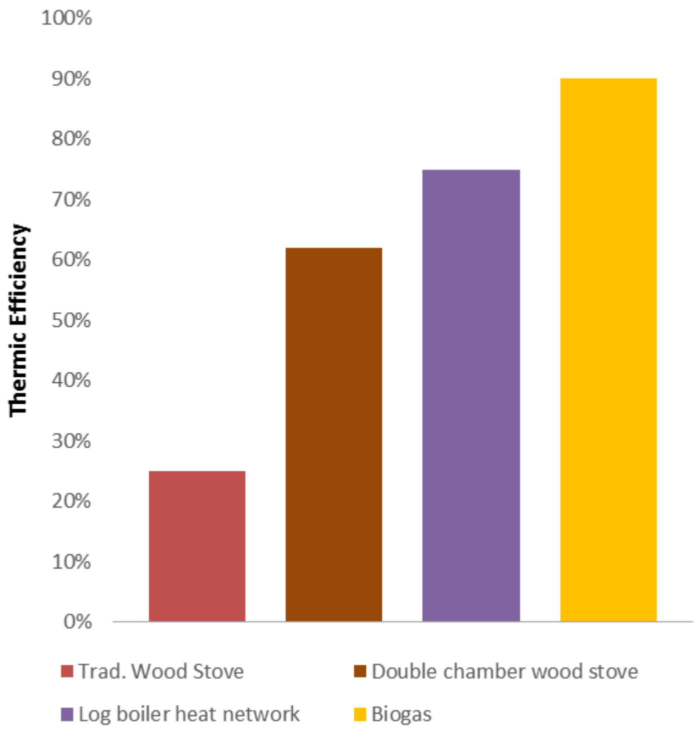

Figure 39: Thermal efficiencies of different heating and cooking devices

- Traditional wood stoves have low efficiency. Most of the present-day rural kitchens cook with traditional wood stoves that reach low heat efficiencies compared to other thermic devices. Figure 39 shows the thermic efficiencies of different heating devices.
- Firewood and other fuels are increasing in price as its abundance decreases and population increases. The costs for most heating fuels increased in the last decades (Reyes and Neira, 2012).
- LPG and city gas (natural gas networks) are industry standards. Many cities and villages, also in Chile, use a gas network infrastructure for cooking, heating water, and heaters, so the firms, technical services. A general knowledge on this technology exists. Double chamber woodstoves are standard and presently the most traded heating device. Double chamber woodstoves are not so expensive and are commonly wide-spread in southern Chile. They have more than double efficiency when compared to traditional wood stoves. Due to this and to reduce air pollution in big cities, the Chilean Government set-up a program to replace traditional or defect wood stoves (CCA, 2008). Additionally, some double chamber stoves come with heat exchangers that allow for the heating of water. In the region there are a variety of small firms that offer the installation of a heat exchanger on the chimney tube where exhausting gases are released, recovering part of the residual heat from combustion. Stoves and the heat exchanger are shown in Figure 40.
- Electricity can be obtained through other renewables. According to the German Academy of Science Leopoldina (Anton and Steinicke, 2012), "*ideally the local electricity supply should be covered by other renewable sources, as bioenergy can produce fuels that are otherwise scarce, so that the conversion of biomass should be concentrated on biofuels for*

such uses as heavy vehicles, airplanes, and large ships that most likely cannot be powered by electricity".

- Compatibility of biogas with the current agriculture of Los Ríos Region. Leopoldina also suggests that energy crops should be used for biogas production only as far as this is needed for the stabilization and optimization of the overall process of utilizing agricultural wastes and for stabilizing fluctuating energy demands. This is precisely the function that energy crops play in the proposed concept.

Figure 40: Existing heating devices in Los Ríos Region. a) Traditional wood stove (cooking, heating, and hot water), b) Double chamber wood stove (with or without heat exchanger for hot water), c) Heat exchanger that can be installed on either type of stove to heat water from the residual heat of the exhausting gas.

- Compatibility of biogas and grasslands. According to the large extension of grasslands in the region Los Rios, there is a very strong bioenergy potential for grass, although that productivity is more land demanding than energy crops as grass has lower yields per hectare. This is a limiting factor, since for grass harvest more distance needs to be traveled and surface to be covered to gather the same amount of biomass as energy crops. As fresh, green biomass is both voluminous and humid (high water content), its transport is rather expensive per unit of dry mass, and therefore it is limited to shorter distances between the field and the biodigestor. In the case of the bioenergy village in Jühnde, the critical distance is a radius of about 5–7.5 km around the biodigestor (Bauböck, 2013). However, the use of perennial grasslands for bioenergy production seems to have some relevant advantages, such as the following:
  - The GHG reduction is much higher than with energy crops because (WBGU, 2008):
    - Less fossil energy is needed (low inputs, no tillage)
    - No indirect land use change emissions are produced[30]
    - High soil carbon sequestration (no tillage)
  - Low cost biomass production
  - Higher biodiversity
  - Compatibility with land management
  - Lower landscape impact

  Regarding land management, there is an important land extension in the region that is "sub-utilized", which is traditionally "left to rest ("resago") or set aside between harvests. These land areas are usually covered with a species of grass and bushes of low feeding value for animal production that could be used for bioenergy production as part of an overall land use management plan.

[30] When iLUC are included, grassland GHG emissions can be 1/3 compared to energy crops.

- Not many energy crops are needed. In the concept proposed, hot water is heated by a heat exchanger standardized for a double chamber woodstove, so that the heat energy comes from wood sources. Although the availability of biomass is huge and plentiful, as shown in the previous Section, a very small amount of energy is needed for cooking (which is only 9.5% of total household energy, Figure 38). Moreover, organic residues of the village can be used, further reducing the need for land for energy crops and with less environmental impacts. When domestic organic waste is used[31], a very small amount of extra biomass is needed to satisfy the cooking demand. Calculations using best estimate values are shown in Table 9.

Table 9: Calculations of biomass needed for cooking with biogas, self-sufficiency

Biogas demand of kitchen	
Members per family	4
Burner consumption (m^3 / hr)	0,3
Hours of use burner / day	2,2
Heat efficiency burner biogas	95%
Heat transmission efficiency burner biogas	40%
Total biogas / family (m^3 / year)	241
<u>Replacing liquefied gas</u>	
Heat efficiency gas burner	95%
Heat transmission efficiency, gas burner	40%
Equivalence kg LPG / m^3 biogas	0,43
Liquefied gas equivalent (kg / year)	104
Equivalent $[32] / year (kg liquefied gas = $ 1,100)	113946
<u>Replacing firewood (cooking)</u>	
Wood heat (GJ / m^3)	5
Efficiency kitchen stove	35%
Heat transfer of efficiency woodstove	20%
Heating use efficiency woodstove (%)[33]	70%
Equivalent firewood (m^3 / year)	8,1

Biogas offer from available biomass	
Family organic waste	
Organic waste / person / day (kg)	0,5
Biogas from organic waste / person / day (m^3)	0,075
kg solids from human waste / person / day	0,3
Biogas from human waste / person / day (m^3)	0,028
Total waste biogas (m^3 / family / year)	150,4

[31] Surrounding rural waste is probably also available, but is not considered in the calculations.
[32] $= Chilean Pesos (1 Euro= $750 CLP)
[33] Portion of the year in which residual heat is used for heating

Fresh biomass

Grass (silage)	
Average grassland biomass (ton DM / ha / year)	7,0
Fresh biomass (30% DM) (kg / m^2)	2,3
Biogas / kg fresh biomass (m^3)	0,18

Wheat (silage)	
Average biomass (ton DM / ha) (approx. 45 quintals)	10,4
Fresh biomass (35% DM) (kg / m^2)	3,0
Biogas / kg fresh biomass (m^3)	0,22

Maize (silage)	
Average biomass (ton DM / ha)	25,0
Fresh biomass (35% DM) (kg / m^2)	7,1
Biogas / kg fresh biomass (m^3)	0,20

Biomass needed for self-sufficient supply of cooking gas

	Biomass to be used	
Area per average family (m^2)	Grass	Wheat silage
Without household waste	574	370
With household waste	216	139

Area per 800 inhabitant village (hectares)	Grass	Maize silage
Without household waste	45,9	13,5
With household waste	17,2	5,1

Area per 10000 inhabitant city (hectares)	Grass	Maize silage
Without household waste	574	169
With household waste	216	63

As can be observed, for an 800 inhabitant rural village only 4.2 hectares of maize are needed for self-sufficient cooking. This replacement might have a positive impact on the standard of living as well, as the simplicity and fastness of cooking with gas does not require the longer waiting periods of warming up as with a woodstove, nor the constant feeding process with wood to avoid letting the fire go out. Nevertheless, at the level of a village a gas network would be needed, which implies associated costs. There are already plans of gas networks (city gas) in the region, but not any consolidated projects yet. In any case, the emissions of harmful particles (PM2.5) and noxious substances from burning wood would decrease tremendously and air quality would considerably improve, if biogas would replace wood. Gas burning is the cleanest option to produce bioenergy. Split wood logs have the worst environmental performance (see Seidel et al., 2013).

Once biogas is supplied for household cooking, a thermal device is needed for fulfilling the replacement of traditional woodstoves. Based on the efficiencies presented in Figure 39 it is possible to infer the effect of changing the heating device to rise the overall heating efficiency. Heat from cogeneration and from a log boiler heat network are not considered here due to economic reasons as explained in the previous Section. Therefore, in this proposal, the choice for heating house and water will be the double chamber woodstove or a similar device. Figure 41 shows the effect of the proposed replacement in terms of the reduction of energy demand and the forest surface area necessary to satisfy the wood demand.

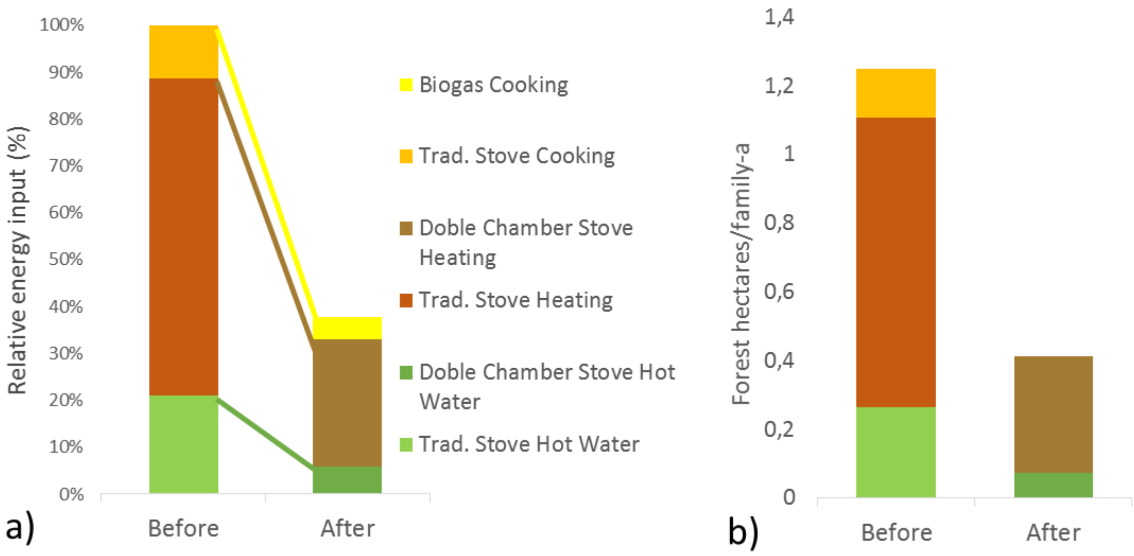

Figure 41: Effect of the replacement of the traditional woodstove with biogas for cooking and a double chamber woodstove for house and water heating. Reduction of a) energy demand, and b) forest surface area for covering the wood demand.

In Figure 41 it can be seen that the proposed replacement implies a savings of 0.78 hectares per family for wood exploitation, which means a reduction of 62% in the needs for forest land. Such a reduction can definitively contribute toward diminishing the pressure on native forests and their corresponding degradation.

This concept could be applied without the need of a village gas network, but in turn, it would require the transformation of biogas into biomethane, containing the gas, and using it in gas cylinders as it is done today with LPG. Although biomethane is not as easy to liquefy as LPG, which probably may result in more complex and expensive solution than a city gas network, containing it in cylinders might be a mid-term solution. Another fairly inexpensive alternative is a biogas pipeline. In this case it is not necessary to transform biogas into biomethane, but requires to build a pipeline.

In any case, the concept of a village gas network is also compatible with the production of biomethane from lignocellulosic gasification-methanation. Considering the increasing problem of bad air quality in Valdivia, such a concept might be amplified not only for cooking, but for heating as well, radically reducing gas and particle emissions.

Finally, this concept could also be applied to countryside houses and farms, as long as each location has a biodigestor. Although this would conceptually imply positive impacts previously explained, family-scale biodigestors bear certain risks. First, every family should know how to manage a biodigestor, which demands certain technical and theoretical skills. Secondly, materials and the quality of construction are very important elements if biodigestors are expected to prevent the emission of the greenhouse gas methane. The assumption that biogas reduces by 90% a household's carbon footprint is in relation to fossil fuels, so that a loss of only 4.5% of the methane produced in a family-scale biodigestor could entail a total loss of the attempted reduction of the carbon footprint, since methane has a global warming potential about 20 times stronger than carbon dioxide (CO_2) (4.5%*20 =90%).

5.5.3.2 BEV-alternative concept 2: Urban neighbourhood with heat network

The second bioenergy village alternative concept is simply to create a central heating system and district networks only for heating purposes. As it was discussed in the previous concept, heating networks can be more expensive and complicated than the traditional, individual system in some aspects. However, a lot of efficiency is gained in the process, which compensates for the higher implementation costs, especially in cities, where wood is more expensive. Moreover, wood burning is critically relevant in the case of cities with air pollution problems. As it will be discussed in next Chapter, a central heating system can radically reduce noxious gas emissions, and because of its automation, implies comfortable operation for the home-owners. In fact, in Chile some new projects using this concept are slowly beginning to appear. Such initiatives are shown in Box 5.5.3.2.

BOX 5.5.3.2: Cases of district heat networks in Chile

A. One already built case is the residential condominium project Frankfurt in the city of Temuco. It is the first neighborhood that has set-up a district heat network for the distribution of geothermic heat in the country. The project is unique in its type, but faces many problems with Chilean regulations:
http://www.frankfurt.cl/wp-content/uploads/2013/08/geotermica.pdf

B. The Pilot Project of district heating in Coyhaique (Proyecto Piloto De Calefaccion Distrital En Coyhaique) developed for the Ministry of Energy (Renewable Energies Centre) and the Ministry of Environment. Given the climatic conditions of southern Chile and the abundance of forests, the government of Chile has decided to study the feasibility of developing a heating plant district based on renewable energy to deliver heat and hot water to a new social-service housing and middle-class houses:
http://sig.goreaysen.cl/pedze/161_Calefaccioon_Distrital_Coyhaique.pdf
http://www.ebpchile.cl/servicios/recursos-naturales-y-cambio-climatico/aktuell/sistema-de-calefaccion-distrital-a-base-de-biomasa.html

C. Biomass Center in Coyhaique, where development of the next generation of products and services for heating and biomass energy is researched and implemented, realized by the Agrarian Innovation Fund (Fondo Innovación Agraria, FIA):
http://www.ebpchile.cl/servicios/recursos-naturales-y-cambio-climatico/aktuell/centro-de-biomasa-en-coyhaique-desarrollo-de-la-siguiente-generacion-de-productos-y-servicios-de-biomasa-para-calefaccion-y-energia.html

D. Co-generation Bio-Energy Plant *Bioenergía de Los Ríos*. A 9 MW electric power plant with 35 t/h of condensed steam for a district heat network from a gasification plant within the border of Valdivia city is planned to be designed. The plant would consume 2,500 m^3/d of forest biomass and 71 m^3/h of water:
http://www.bioenergiadelosrios.cl/

Finally, according to the CCA (2008), the exclusion of concomitants in regards to the use of firewood such as deteriorating air quality in large cities or a loss of environmental services, plus the uncertainty about wood's caloric content, physical characteristics, moisture content, dispersion qualities, origins, among other concerns, support the conclusion that not only price signals are inaccurate and misleading, but also prevent or limit designing a sound public policy. The absence of measures to clarify real prices and standardize the quality of firewood makes resource management difficult and reduces the chance of incorporating innovative and environmentally sustainable technological options like district heating, even though local conditions suggest that they are promising for the country.

5.5.3.3 BEV-alternative concept 3: Urban community with cogeneration from OMSW

In the next Section the third bioenergy village alternative concept is developed and quantified in detail. It is important to note that such a concept is not necessarily restricted to a university campus, but to any kind of community setting with a size similar to a rural village. Also, such a setting should ideally entail a public facility where the bioenergy is publically used. The organic municipal solid waste (OMSW) must be separated by the citizens at home, and therefore they should share the benefits of such management, in order to feel engagement and collaborate within the system. Another way to engage people could be the development of an interesting price system.

5.6 Local Quantitative Interactions: Case Study – Bioenergy Campus.

5.6.1 Paper 3: Sustainability of implementing a biogas cogeneration unit on a university campus in Valdivia, southern Chile

Please reference the paper *"Sustainability of implementing a biogas cogeneration unit on a university campus in Valdivia, southern Chile"* submitted to the Journal of Cleaner Production and attached next. After it, Boxes 5.6.1.1 and 5.6.1.2 are aggregated as a complementary information.

Sustainability of implementing a biogas cogeneration unit on a university campus in Valdivia, southern Chile.

Key words: bioenergy campus, biogas CHP, carbon footprint, organic municipal solid waste, anaerobic digestion

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ABSTRACT

Universidad Austral de Chile's Isla Teja Campus, located in the city of Valdivia, obtains electricity from the national grid, and heat from diesel and wood boilers. Simultaneously, in Valdivia there is no separation of the organic fraction of municipal solid waste (OMSW) from the rest of its solid waste. We propose to separate the city´s OMSW, digest it anaerobically, and burn the biogas in a combined heat and power plant at Isla Teja campus, similarly as in German bioenergy villages. At the beginning, the biogas plant is fed with energy crops that are gradually replaced by Valdivia's OMSW. In this study, the sustainability performance of such a system is estimated for 3 stages: S0 current stage; S1 based on energy crops; S2 based on OMSW.

When compared to S0, S1 stage reduces energy costs (30%) and GHG emissions (75%), but if land use change effects (from 272 ha of energy crops) are included, GHG emissions do increase in 61%. Regarding noxious gas emissions S1 reduces PM_{10} (29%), NO_x (46%) and SO_2 (82%), however increases CO (36%).

Compared to S0, S2 increases energy costs (59%) but since it avoids the release of methane gas from the landfill, it significantly reduces the GHG emissions (940%). Regarding noxious gas emissions S2 increases CO (26%) but reduces PM_{10} (41%), NO_x (33%) and SO_2 (76%). S2 avoids transporting 34,000 tons of organic waste (with 17,200 m3 of water) to the landfill, and prevents the chemical pollution created by leachate generation. S2 also recovers 340 tons of nitrogen, 68 tons of phosphorus and 238 tons of potassium. Such amounts satisfy the fertilization demand of 1,800 to 15,900 agricultural hectares, depending on plant species and nutrients involved.

Both S1 and S2 imply several social benefits and would result in a campus which comes close to energetic autonomy.

Contents

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ABBREVIATIONS

AD: Anaerobic digestion
BioSTAR: **Bio**mass **S**imulation **T**ool for **A**gricultural **R**esources; a model to estimate biomass energy potential (developed in the University of Göttingen's Department of Cartography, GIS and Remote Sensing)
CHP: Cogeneration of heat and power
CO_2eq: Carbon dioxide equivalent
DM: Dry matter of plant material
GEMIS: **G**lobal **E**missions **M**odel for **i**ntegrated **S**ystems; a public domain life-cycle and material flow analysis model developed by the **I**nternational **In**stitute for Sustainability **A**nalysis and **S**trategy (IINAS)
GHG: Greenhouse gases
GWP: Global warming potential
IZNE: Interdisziplinäres Zentrum für Nachhaltige Entwicklung (Interdisciplinary Center for Sustainable Development), University of Göttingen
kWh_e: kWh electricity
kWH_h: kWh heat
LUC: Land Use Change
MSW: Municipal solid waste
OMSW: Organic fraction of municipal solid waste
RE: Renewable energy
SIC: Central Interconnected Electrical System of Chile
SRES: Santa Rosa Experimental Station, UACh
UACh: Universidad Austral de Chile, Valdivia

1 INTRODUCTION

1.1 Climate change and the end of fossil fuels

The current scenario of energy availability for our societies is rapidly changing. It is now clear that the fossil fuel reserves that run most human economical activities will become scarcer and more expensive in future (Chapman, 2014). At the same time, it is obvious that the climate change is mainly caused by the use of fossil fuel combustion and land use change. It threatens the core of western civilization, but even more so underdeveloped countries (IPCC, 2011a). Agriculture also plays a significant role in global warming and climate change. The most important greenhouse gases (GHG) emitted by agriculture are CO_2 emissions from land use change, methane from livestock breeding and rice cultivation, and nitrous oxide N_2O from fertilizer applications (IPCC, 2014; Negri et al., 2014).

1.2 Renewable energies as a new paradigm of development: bioenergy, biogas and bioenergy villages

In order to change our current energetic situation, which is mostly based on fossil fuels and atomic power, there is an urgent need to supersede our energy sources and consumption patterns. Renewable energy (RE) and efficiency are seen as appropriate measures since they can effectively reduce our GHG emissions in addition to producing further social and economic benefits (IPCC, 2011a). REs have been elaborated by technicians and scientists, and encouraged by politicians, NGOs and many stakeholders concerned about the long-term sustainability of our energy supply. Among non-conventional REs, bioenergy is the energy obtained from any biological organic source, which includes the use of different types and forms of biomass, such as fresh or stored, humid or dry, gaseous, solid or liquid, whole organisms or parts of organisms, or organic waste from rural or urban domestic households, gardens, parks, or industrial sources. It can also provide a new opportunity for safe waste management. Bioenergy represents a key technology in the transition towards a RE era (WBGU, 2008).

Biofuels are storable sources of concentrated bioenergy for combustion. The discussion of biofuels ability to mitigate climate change is controversial and depends on their type and the context of their use (Giampietro and Mayumi, 2009); (FAO, 2008). However, scientific organizations suggest that bioenergy policies should encourage energy production from local biomass by-products, wastes and residues, in order to avoid the environmental impacts of energy crop production and competition with food production (Anton and Steinicke, 2012); EEA, 2011; Bringezu et al., 2007). Among biofuels, the production of biogas can create a highly efficient, biologically innocuous and versatile energy system, able to use different plants and/or organic residues. This fuel is storable and can be used in internal combustion engines, boilers, turbines, stoves, fuel cells, and other devices for the production of electricity, heat/cold, light or mechanical power (Deublein and Steinhauser, 2011); (Vögeli et al., 2014). Also, biogas can be purified into biomethane, which is considered a highly promising bioenergy carrier (WBGU, 2008). Unlike other biofuels, biogas production from energy crops does not require the use of specific plant species or parts of the plant (like starch for ethanol or oil for biodiesel). Therefore, most of the plants' embodied energy (except the roots) is used, allowing the utilization of different species simultaneously or sequentially (rotations), including those commonly considered as weeds (Karpenstein-Machan, 2013). Multi-species grasslands designed for bioenergy production have a good energy yield and improve environmental services (Rösch et al., 2007). They also facilitate environmentally friendly practices like minimal pesticide application or organic farming and zero or minimal tillage. Since external fertilisers (and the high energy inputs they imply) are also not necessary due to the complete recycling of nutrients with the digestate (residue of the biogas plant), crop farming with a low energy input is possible.

Following the principles of sustainability science (Schmuck et al., 2013), the Interdisciplinary Centre of Sustainable Development (IZNE) at the University of Göttingen, Germany, developed the first project to create an electricity-and-heat autonomous village in Germany. Jühnde, a village with 800 inhabitants located in Lower Saxony, was the first bioenergy village we know (Ruppert et al., 2008). The approach used there (Ruppert et al., 2008;Wüste and Schmuck, 2012) has also benefits for non-industrialized countries (WBGU, 2008; UDA/EPA/UDE, 2014), high energy efficiency through the cogeneration of electricity and heat (85%), a decentralized structure, energy autonomy, chance of waste management, complete nutrient recycling without the need of additional fertilisers, and the implementation of well-tested, simple, safe, clean, commercial technology. This biogas system also has a high social impact, strengthening the community due to its participative character. The disadvantages of such a model include the use of land for energy crops, which in the case of Jühnde reach 300 to 320 ha of agricultural land. The biogas produced from energy crops in this area provide two to three times the electricity needed by the Jühnde population (800 inhabitants) and of local business. On the other hand, bioenergy villages need the agreement of many people involved in the system (from the production of the biomass to the energy's distribution to each household involved). Such complex agreements are in many times difficult to achieve.

1.3 Biogas from urban waste

Biogas production is one of the best technologies available to manage the organic fraction of municipal solid waste (OMSW) (Calabrò, 2009; Kern et al., 2012; Lönnqvist et al., 2013; Vögeli and Zurbrügg, 2008). After separating the organic fraction and transforming it into biogas by anaerobic digestion, the organic waste is greatly reduced to approximately one third its previous amount. The end product of the digestion is a valuable, stable, odourless, hygienic organic substance, in which most seeds (weed control) and pathogenic germs are degraded (Deublein and Steinhauser, 2011). Additionally, greenhouse gas (GHG) emissions can be substantially reduced by using biogas technology for waste management (Zhao et al., 2009; Lou and Nair, 2009). Higher GHG reductions may even be reached by separating organic from other valuable recyclable wastes, lowering the demand for new materials and the energy involved (Calabrò, 2009). A strict separate collection of the organic waste is necessary to minimize the contamination of the organic fraction by inorganic materials. This organic material can be transformed into compost or into biogas digestate. Both the digestate from biogas production in a fermenter and the compost may serve as soil improvers and may replace conventional fertilisers. The biogas track however reduces GHG emissions more than composting (Kern et al., 2012). Batool and Chuadhry (2009) and Kern et al. (2012) concluded that the overall result of separating organic wastes and producing biogas is remarkably good for the environment, since it strongly reduces GHG emissions compared to that from fossil fuel burning. In Germany, there are 132 biogas plants for OMSW and another 190 that use the cogeneration of OMSW and organic waste together with other biomass sources (Schüch et al., 2014). In this regard, OMSW can be used as a substitute for energy crops in biogas production (Pognani et al., 2009).

1.4 Drawbacks of Valdivia's current urban waste management system

The Chilean city of Valdivia does not yet have an urban solid waste separation system. All of the domestic solid wastes are brought to Morrompulli landfill, approximately 25 kilometres south of Valdivia. An average citizen produces approximately 1.25 kilograms of waste a day. The content of such waste for the Valdivian province is: 55% organic matter, 8% paper and cardboard, 11% plastic, 4% glass, 3% metal, and 19% other (AMRR, 2015). Morrompulli landfill has no sealing system. There is no physical barrier for capturing the liquid waste (leachate) produced, and there is no system to treat this leachate. Therefore, this leachate, diluted by the abundant rain in the area, ends up in the soil, the groundwater reservoirs, or goes directly through the aquifers into the rivers surrounding Valdivia. Also, the gaseous compounds originated in the landfill are freely emitted into the atmosphere, since there is no gas capturing system.

1.4.1 High carbon footprint

Among other gases, methane from the natural degradation of organic matter in the landfill is released into the atmosphere. Methane is responsible for 16% of the global GHG effect (IPCC, 2014). Biogas has an equal amount of CO_2 and methane (CH_4). Methane has between a 21 and 25 times stronger global warming potential (GWP) than CO_2. (IPCC, 2007). Also, since half of the organic waste consists of water, the transport of this organic waste is highly inefficient, producing large carbon emissions at a high economic cost due to the fuel consumed. Finally, the fact that the biogas generated in the landfill is not used as a fuel implies the loss of a chance to mitigate GHG emissions and to harvest energy. Altogether, Valdivia's waste management system has no material recycling or energy extraction, leading to a high GHG footprint.

1.4.2 Nutrient loss

The loss of all of the nutrients contained in OMSW deserves special attention. These nutrients cannot be recycled when mixed with the rest of the municipal solid waste (MSW), which is highly contaminated with toxic compounds. The recovery of nutrients (and of other valuable materials) is a key factor for the sustainability of waste management. A group of renowned researchers (Steffen et al., 2015) identified and quantified nine environmental planetary boundaries that should not be overpassed in order to maintain a safe operating space for human life. Two from the nine boundaries do exceed the limit of high risk: biosphere integrity (biodiversity loss), and the biogeochemical flows of nitrogen and phosphorus. Most of these flows result from agriculture and show the relevance and urgency of nutrients management. Nutrient loss is synergistically negative, as it implies a loss of resources (for agriculture) as well as ecological degradation such as the eutrophication of water bodies. Also, nutrient loss implies GHG emissions since the production and transport of fertilisers requires large amounts of fossil fuels.

1.4.3 Water contamination and other environmental aspects

The high chemical toxicity, cancerous and mutagenic effects of landfill leachates have been reported in several studies on microbial organisms, plants and aquatic animals (Li et al., 2008; Tewari et al., 2005). It has been demonstrated that a small amount of landfill leachate may cause severe pollution of groundwater aquifers and surface waters (Pivato and Gaspari, 2006), (Garaj-Vrhovac et al., 2013). Also, the high nutrient content in the leachate is often an important cause of the eutrophication of surface waters (Sharpley et al., 1994; Jokela et al., 2002). Palma-Fleming et al. (2000) found high levels of toxic compounds, such as heptachlor and endosulfan sulphate in the sediments of a small river adjacent to the Morrompulli landfill which receives some percolated leachates. Estuarine benthos species, *Mulinia edulis* (clams) and *Cancer coronatus* (crabs) showed significant levels of zinc in both species, nickel in clams, and copper and arsenic in crabs. Significant levels of total benzene hexachloride, 4,4-dichlorodiphenyldichloroethylene, aldrin, endrin ketone and heptachlor epoxide were observed in *Mytilus chilensis* (mussels).
Valdivia has around 145,000 inhabitants (INE, 2003). Assuming that the water content of the MSW is approximately 26% and the average waste production is 0.46 tons per capita per year, the liquid phase of the MSW is 17,300 m^3/a. Moreover, the amount of leachate might be significantly higher due to the addition of rainwater. With an average annual rainfall of about 2.04 m at the landfill (CIREN, 2003), and an assumed evaporation of about 0.8 m per year, around 1.24 m^3 of rainwater per square meter percolate through the landfill. Assuming the landfill comprises an area of 14,266 m^2 (areas of the active and the old landfill are 8,763 m^2 and 5,463 m^2 respectively according to Palma-Fleming et al. (2000), around 17,700 m^3 of water passes through the landfill resulting, together with the water in the waste, in approximately 34,900 m^3 of contaminated leachate.

Removing the organic materials from the waste would bring about many benefits, including: the reduction of the amount of waste to nearly half; a significant decrease in dissolved organic carbon, corresponding to a lower biological oxygen demand in the leachate; an important reduction in methane emissions; and a reduction in the nuisances caused by rats, flies, offensive smells, etc. In addition, the time for closing the landfill will be much shorter, if the reactive organic fraction is low.

2 PROPOSED SYSTEM: A BIOENERGY CAMPUS

2.1 Technical concept

Inspired by the Bioenergy Village concept in Jühnde (Germany), a specific bioenergy systemic approach called "Bioenergy Campus" is designed for Valdivia, located in Los Ríos Region, southern Chile. Synergic interactions relying on high environmental, social and economic standards are the base of this approach. In this work, such concept is analytically tested with specific local information to get estimates for its sustainability performance. The Bioenergy Campus considers a bioenergy unit to supply Universidad Austral de Chile's (UACh) Isla Teja campus with electricity and heat. The proposed technology consists of a biomass fermentation plant that would produce biogas. The digester would be located at the UACh's Santa Rosa Agricultural Experimental Station (SRES), and would be connected via a gas pipeline with a heat and power cogeneration (CHP) unit located on the campus. The unit would burn the biogas in a conventional engine, powering an electric generator while delivering hot water from the heat exchanger of the gas engine into a campus hot water pipeline.
During the first stage (S1), the digester would be fed with silage of energy crops and agricultural residues produced mainly at the University's experimental station. During the second stage (S2), the digester would use the organic fraction of municipal solid waste (OMSW) from the city of Valdivia, through a waste separation plan managed by the municipality. S1 would allow for a smooth transition into S2 by gradually reducing the area needed to produce energy crops as the city develops a separation system for their organic waste. A diagram of the system analysed is shown in figure1. Locations are shown in figure 2. The organic material can be preserved as silage over several month.

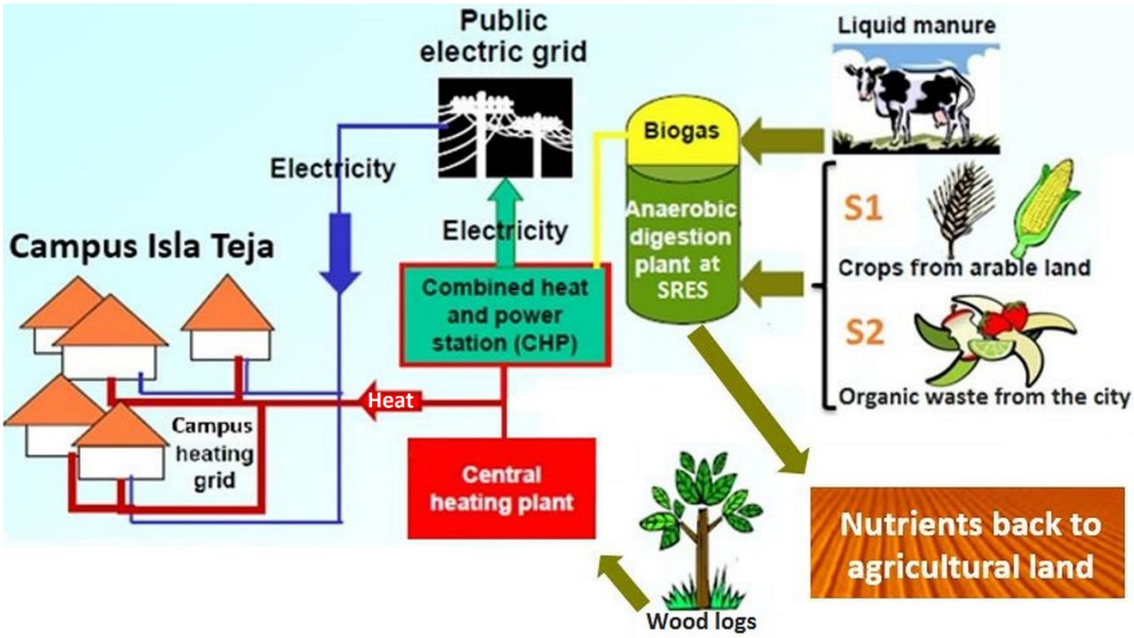

Figure 1: Sketch of the technical concept of the Bioenergy Campus (adapted from Ruppert et al., 2008).

Figure 2. Location of Universidad Austral de Chile's (UACh) facilities in the context of Valdivia. A) Chile. B) Geographical context of Valdivia and Morrompulli landfill. C) Campus Isla Teja (purple borders) and SRES (green borders) and their spatial relation to the centre of the city. Satellite images provided by Google Earth^{TM}. D) Detail of the Campus Isla Teja and its buildings (DDSS, personal communication)).

2.2 Why create a Bioenergy Campus

2.2.1 The university campus as a village

Campuses can be considered as "small cities" considering their size, population, and the various complex activities that take place within them (Alshuwaikhat and Abubakar, 2008; Saadatian et al., 2013). As in villages, campuses have a certain degree of autonomy in regards to administration, territoriality and basic services supplied (building, energy and water supply, waste management, etc.). Therefore, campuses are units that fulfil the requirements necessary to be eligible for the bioenergy village concept. Indeed, the fact that the land and energy use are in the hands of only one institution instead of several farmers and families as in villages, makes the consensus and administration processes far simpler.

2.2.2 The university as an educational basis for sustainability and new environmental concepts

Education for sustainable development is essential to transform our society's lifestyle and counteract the current global environmental crisis trend (UNESCO-UNEP-Government of India, 2008; Mason et al., 2003). Therefore, educational institutions are privileged places for implementing this type of education (Faghihi et al., 2014; Tan et al., 2014; Li et al., 2015). In this sense, academic initiatives and demonstrative projects have high social value (Müller-Christ et al., 2014; Chung and Rhee, 2014). Many scientific and social achievements for society, including initiatives for sustainable development, have their origin in universities. Successful experiments can be replicated or serve as models for other universities and as incentive for local developments. Additionally, there is no stimulus to save energy within campuses, as students and university staff receive no direct feedback regarding their energy consumption, which leads to excess usages (Emeakaroha et al., 2014). Usually no energy conservation mechanisms are implemented on campuses and energy saving practices are also not part of people's daily behaviour. Therefore, there is an urgent need to improve the technical and behavioural patterns to save energy on campus but also to bring this knowledge from the university and its students to other people.

2.2.3 Availability of required resources at Universidad Austral de Chile

Relevant information

A lot of detailed information is required for the analysis and optimization of a bioenergy concept that has not yet been implemented in Chile. This specific information is currently not available for most towns in the region, but it is available for the Universidad Austral de Chile's Isla Teja campus. The databases include:

At Isla Teja campus:

- Electricity consumption and its costs
- Heat consumption and its costs
- Petrol consumption
- Wood consumption
- Current heating and electrical infrastructure
- Campus' current carbon footprint

At Santa Rosa Agricultural Experimental Station (SRES):

- Specific local climatic information (from the farm's weather station)
- Soil databases
- Wheat and maize theoretical and tested productivities (trials)
- Wheat and maize production costs

Additionally, the City of Valdivia has detailed information regarding the:

- Amount of biological material in the waste produced by its citizens
- Waste management system

Existing heat network on Isla Teja campus

Some university campuses are starting to implement RE systems that include heating networks (Yildirim et al., 2010; FCB, 2010). On the Isla Teja campus, most medium and large-sized buildings already use hot water heating systems. Also, the University's Direction of Services is developing a heating district network for the existing wood boilers. All of this makes the implementation of a CHP system compatible and easy to install on the current campus.

University´s Santa Rosa Agricultural Experimental Station (SRES)

Producing bioenergy from forests biomass or from energy crops is a feasible way to reduce the University's demand for fossil fuels (McComas et al., 2011). SRES belongs to Universidad Austral and would fit into a bioenergy campus concept in many ways:

- It has a cow barn that could provide slurry.
- It comprises enough area to grow energy crops to satisfy the campus' demand for energy.
- It is located in a non-urban area, making waste management feasible.
- It is located only one kilometre away from Isla Teja campus; thus, biogas could be pumped to the campus, allowing on-campus cogeneration of heat and electricity.
- It facilitate a smooth transition towards the use of urban OMSW digestion for bioenergy production.

3 METHODOLOGY

3.1 The three evaluated stages: the current system, bioenergy with energy crops and bioenergy with organic waste

This article will compare three stages of energy production/consumption on the Isla Teja Campus in terms of their environmental, economic and social implications:

- S0: Current Stage
- S1: Bioenergy campus Stage 1, run with energy crops
- S2: Bioenergy campus Stage 2, run with OMSW

S0 is the campus as it is today, consuming power from the regional electric grid and wood and diesel for heat.

S1 is designed as a transitional stage towards a system based on OMSW from the city (S2). S1 would include a CHP unit on the Isla Teja campus connected to a biodigestor plant, which would use biomass from energy crops. The crops would be cultivated mainly on SRES. This stage is important because it provides a buffer period for the latter implementation of OMSW separation in homes along with an effective collection system in the city of Valdivia. The implementation of this last step depends on individual, social, and cultural backgrounds and the flexibility of the population to change its attitude toward waste separation. Waste separation cannot be spontaneously implemented as it takes time to explain the new system and to change customs, especially in a country without much experience or tradition in this regard. Since this transition would probably be slow, the bioenergy campus would first run on energy crops. This interim solution would gradually be replaced in favour of OMSW over the course of time. Today's land use in the area where the experimental station is located is shown in figure 3.

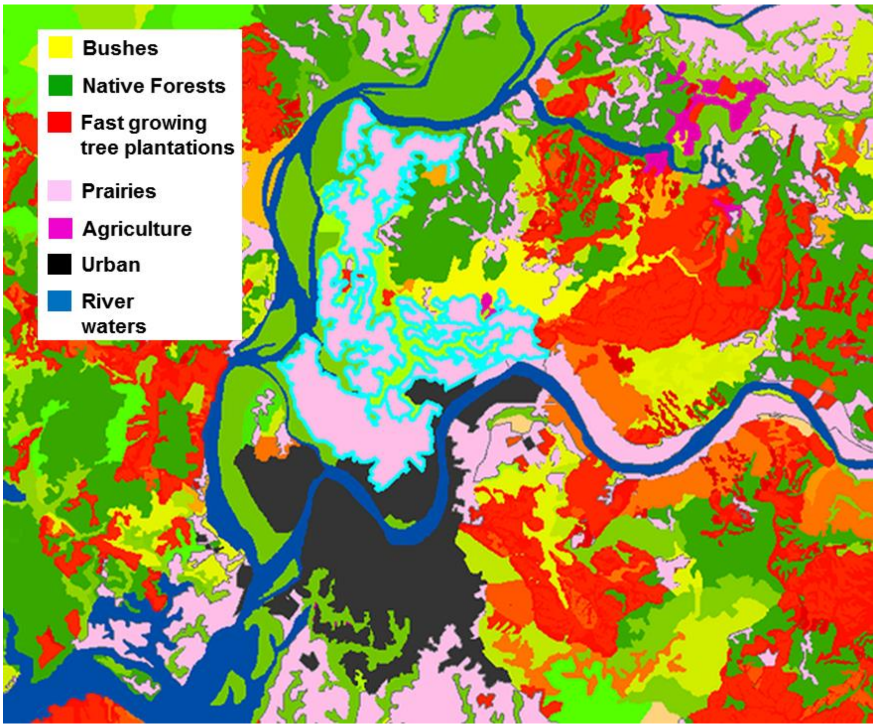

Figure 3: Land uses north of Valdivia. Grasslands and agricultural areas technically able to cultivate energy crops, that include SRES and are equivalent to 1,792 hectares, are highlighted with light blue borders.

S2 is similar to S1 in terms of the cogeneration of heat and power, but the source of the biomass would change from crops to OMSW from the city of Valdivia. This would avoid a) the transport of the OMSW to the Morrompulli landfill (25 km), b) the release of methane from the landfill, c) the excessive production of leachate, which pollutes both the water and soil. The OMSW could be used as a source of energy and as an organic fertiliser rich in nutrients. The details of these aspects are developed in the following chapters.

3.2 Sustainability performance

While environmental and ecological research describe changes in the quality of water, air, soil, organisms, and biodiversity, research in sustainability includes economic and social aspects as well. According to Schmuck et al. (2013), sustainability science is a way to attain sustainability through a science that explicitly supports sustainable development[35], uses a transdisciplinary approach and undertakes action-oriented research during the transition process by interacting with the main players of the pursued change. Following the Göttingen approach (Eigner-Thiel et al., 2013), the evaluation of sustainability objectives for the bioenergy campus concept can be described according to different criteria, targets, and attributes (Table 1).

[35] In contrast to a more value-free science.

Table 1: Objectives for the sustainable use of bioenergy resources to establish a bioenergy concepts: Criteria, targets and attributes (modified from Eigner-Thiel et al., 2013).

Criteria	**Targets**	**Attributes**
Technical	Simplicity	Low complexity compared to other energy technologies
	Availability	Established in the market
	Technically tested	Tested quality, stable use and long lifetime
	Security	Low risks compared to other energy technologies
	Energy efficiency	Low total energy consumed, high effectivity of energy use and little energy wasted
Environmental, ecological	Air quality	Low emissions of $PM_{2.5\ or\ 10}$, NO_x, CO and SO_2 and other harmful compounds
	Water quality	Low waste water production with low contaminant concentrations
	Soil quality	Low loss of nutrients (N, P and K) and organic matter, low erosion and contamination
	Energy & resources	Low carbon footprint; saving resources by smart conceptions, easy recycling or recovery
	Biodiversity[36]	Support for stabilization or increase of species diversity
	Land use/ landscape	Low land use requirements; landscape preservation and improvement
Economical	Economic feasibility	Cost effective solution
Social	Social welfare	Satisfaction by meeting social needs[37] including health issues

3.2.1 Technical performance

The technical criteria already mentioned are not quantitatively analysed in this research. As it is previously stated, regarding the South American perspective, the CHP biogas concept could satisfy many important requirements: it is a proven, well-known, available and commercial technology. Compared to other energy sources it is simple, relatively safe and delivers a steady energy supply with high efficiency. It also has a decentralized structure (Buddensiek, 2015), which makes it interesting for rural and peri-urban areas. Due to the diverse uses of biogas, this technical concept could make way for other future alternatives like providing energy to surrounding neighbourhoods, producing fuel for vehicles, or biomethane for the urban net. This is especially relevant with the current increase of MSW over time.

Regardless of the latter, it must be said that even though CHP biogas is technically a fairly simple technology, its implementation would still imply a new complexity compared to the current situation, in which the energy is not produced but simply consumed from external sources. Considering that Chile has little experience with such a system, its implementation may imply new challenges.

[36] Biodiversity is not specifically analysed, but its protection is derived from land use, amount and kind of fertilization, agricultural practices and contamination sources.

[37] Understood as a good performance of the Human Needs Matrix developed by Max-Neef (Max-Neef, 1991). See chapter 4.3.8.

3.2.2 Energy balance (electricity and heat)

For S0, the Isla Teja campus' electricity and heat consumption is provided by the University's Services Direction for 2014 (DDSS, personal communication)). Electricity is obtained from the public grid. Heat is produced in buildings from wood and diesel boilers. The consumption of firewood is 2700 m^3/a, and that of diesel is 476,000 litre/a. For the calculation of the total heat, the following variables are used: boiler efficiency for wood: 85% and for diesel: 90% (Richardson et al., 2002). Firewood parameters (AIFBN, 2008) included: density 0.6 tons/m^3 and energy content 4.07 kWh/kg. Corresponding diesel parameters are: density 0.8 kg/litre and energy content 11.63 kWh/litre.

For S1, the area of energy crops (maize) and therefore the total biogas demand are adjusted to supply 100% of the campus' current electricity consumption. The basis for this calculation include the following assumptions:

- Amount of manure from the SRES milking parlour with 125 grazing cows: 8.3 m^3 of collected manure/cow per year and 25 m^3 biogas/m^3 manure
- 20,900 kg (DM)/ha for the yield of maize[38]
- 544 m^3 biogas/ton of dry matter (Loewe, 2012)
- 2.30 kWh_e/m^3 of biogas for electricity and 2.81 kWh_h/m^3 of biogas for heat
- 8000 hr/a biogas CHP operation time
- 25% of the cogenerated heat would be used to heat the biodigestor (FNR, 2013).

Since the Campus only requires heat during the 6.5 cold months of the year, the heat cogenerated by the biogas CHP unit in the 5.5 warmer months of the year is not considered in the heat calculations. The heat that cannot be produced by the biogas CHP unit during the colder months is supplied by burning wood, as it is done in most of bioenergy villages in the winter. The already existing wood boilers on the campus can be used. Although technically the heat surplus produced in the summertime can be used for other purposes, like drying wood or supplying heat/cold to nearby industries, this surplus heat is assumed to be wasted to simplify the calculations.

For S2, the amount of electricity and heat is calculated on the basis of biogas provided by all the theoretical OMSW from the city, plus the manure from SRES. These are the assumptions:

- Population of Valdivia: 146.231 (INE, 2003)
- 0.64 kg OMSW per person per day (AMRR, 2015), which is consistent with the record of Morrompulli landfill (Vermehren, 2014).
- Biogas yield: 120 m^3/ton of OMSW (StMUGV, 2004; Deublein and Steinhauser, 2008; Oviedo, 1997; CME-GIZ, 2012; Waterleau Group, 2014; FNR, 2006).

It is assumed that the energy content of the biogas obtained from energy crops and OMSW are the same. In the case of an electricity surplus, and considering that the campus is connected to the regional electric grid, it is assumed that the surplus can be sold at market price. Regarding heat, the same criteria as that of S1 is applied.

It is important to note that values used for electricity and heat demands are annual averages, as the fluctuation curves of the campus' heat and electrical consumption throughout time (day, season) are not available for this study. Therefore, to calculate the cogeneration's energy balance, electricity is assumed to be constant throughout the year and heat is assumed to be constant during the 6.5 colder months of the year.

[38]Values are taken from a modelling result using BioStar software (Kappas, 2013), with 75% of the maximum potential (27,878 kg DM/ha) and supported by site trails in Santa Rosa Agricultural Experimental Station (D Pinochet et al., 2011) and from interviews with farmers (Celedón, 2014). If maize would be produced with eco-farming, a lower productivity must be assumed.

3.2.3 Carbon Footprint

Effectively measuring GHG emissions is not an easy process. Even when using only one standardized methodology, such as the Life Cycle Analysis, there are many ways and different levels of detail at which one can calculate the carbon footprint (ISO, 2006; WWF, 2012). In this study, only the effect of changing the current system into a bioenergy campus concept is analysed to calculate the carbon footprint, leaving aside whatever does not change in the process.

For S0, the carbon footprint of the campus' current energy consumption is calculated to sum up the GHG emissions from the consumed electricity and heat in terms of wood and diesel. For electricity, the carbon footprint of Chile's Central Interconnected Electrical System (SIC) is used, which is 0.306 kg CO_2eq/kWh (CONAMA, 2008). The SIC is based on 58.9% of the energy originating from fossil fuels (CNE-GTZ, 2009). A loss of 10% due to high voltage transmission lines is considered. Regarding heat boilers, 2.51 kg CO_2eq/litre of diesel are considered, and for wood 0.022 kg CO_2eq/kWh of heat are used in the balance (Richardson et al., 2002), which corresponds to 5% of the total CO_2 emitted. For wood, an average of 50 travel-km, with an efficiency of 0.035 litre diesel/ton-km, is considered. The total CO_2eq emission per year for the current stage (S0) is calculated as follows (unit in kg CO_2eq/a):

$$\text{GHG emissions}_{S0} = \mathrm{E}_{ES} + \mathrm{E}_{WB} + \mathrm{E}_{DB}$$

E_{ES}: Emissions from electricity production (SIC)

E_{WB}: Emissions from heat production in wood boilers

E_{BD}: Emissions from heat production in diesel boilers

For S1, the carbon footprint of the bioenergy produced is estimated according to the following calculation (unit in kg CO_2eq/a):

$$\text{GHG emissions}_{S1} = \mathrm{E}_{F} + \mathrm{E}_{LUC} + \mathrm{E}_{WB} + \mathrm{E}_{BD}$$

E_F: Emissions from cultivation and harvesting the energy crop (maize silage, no external fertilization)

E_{LUC}: Emissions from land use change from grassland

E_{WB}: Emissions from wood boilers

E_{BD}: Emissions from the biodigestion process

The emissions produced by farming are taken from modelling with GEMIS (Öko-Institut e.V., n.d.) for a 2 MW CHP biogas unit operating with 94% maize silage and 6% cow manure. The GEMIS model incorporates detailed input options for crop farming, biomass transport, manure addition, biogas digester, CHP unit, heating network etc. It is important to note that fertiliser inputs are eliminated from the computation, since a nearly perfect recycling of the nutrients can be obtained from the biodigestion process (Ruppert et al., 2013). This results in a reduction of 0.115 kg CO_2eq/kWh_e, or 48.6% compared to a fertilized crop, which is rather high but similar to the 44.1% of the energy inputs for maize farming calculated by Pimentel and Patzek (2005) and consistent with the values provided by Pimentel and Pimentel (1996), González (2010), Schmuck et al. (2013) and El Bassam (2010). The parameters modelled are shown in figure 4a.

In addition, GHG emissions are calculated for wood boilers using the same assumptions as those in S0. For the land use change (LUC) from grassland to maize, data from WBGU (2008) are applied. For the direct LUC effect, 2,630 kg CO_2eq $ha^{-1}a^{-1}$ is used, which considers the direct release of carbon from the transformation of the land area. The indirect LUC effect, which considers the effect of the displacement of the previous land use to elsewhere, is assumed to be 63 tons CO_2eq/TJ of the crop gross energy. Both LUC effects are considered for a 20 year period.

For S2, the bioenergy carbon footprint is calculated considering the collection and biodigestion of all of the OMSW from the city. To achieve this, modelling with GEMIS is applied again for a 2 MW CHP biogas unit operating with household wastes and following the ratio of 96% organic waste and 3% cow manure. The GHG contribution of a new collection system which would be required to separate the organic fraction of waste is included in the modelling with 10 travel km (the average distance from the city to the digester in SRES), plus the CO_2eq emissions of the biogas plant and CHP unit. The parameters modelled are shown in figure 4b.

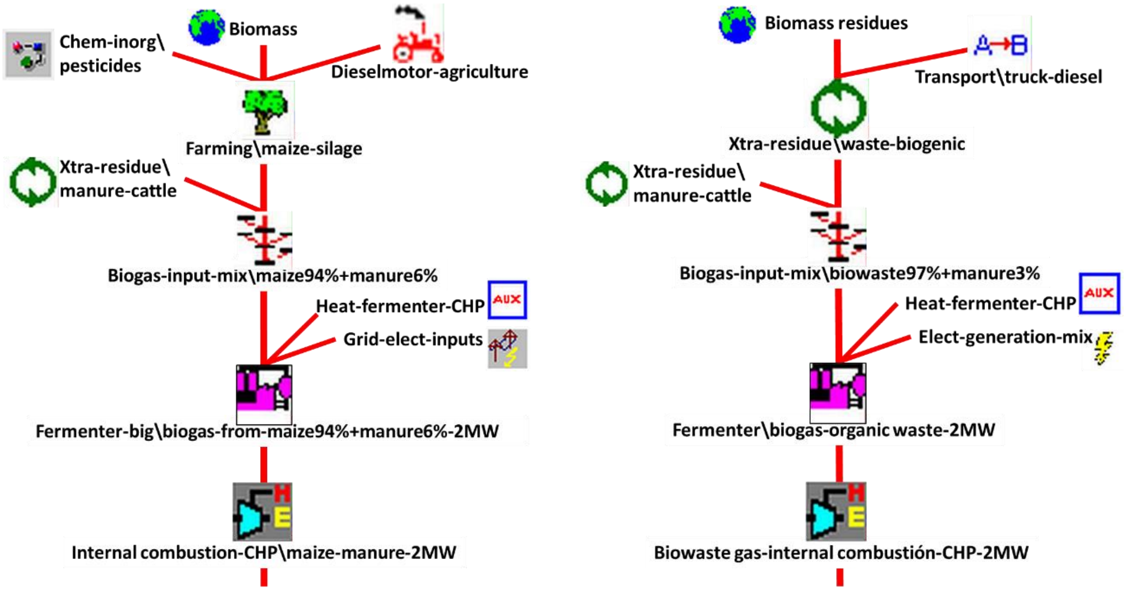

Figure 4: Chart with the modelling parameters of CO_2-eq. emissions with GEMIS. a) S1: production and biodigestion of maize silage and manure. b) S2: collection and biodigestion of OMSW and manure.

Additionally, a GHG emission reduction effect is included as a complementary mitigation, given the emission reductions as a result of avoiding the transport of OMSW to the landfill (0.64 kg/person and day, 25 km distance) as well as preventing the release of methane into the atmosphere from OMSW at Morrompulli landfill. For transport, 0.8 kg/l diesel density, 2.51 kg CO_2eq/l diesel and a fuel efficiency of 0.035 l diesel/ton-km of OMSW is used. Methane is considered with a 22 times stronger GWP than the same amount of CO_2. The methane density is 0.72 kg/m^3 and its biogas content is 60% (CME-GIZ, 2012). Although there is a great variation in terms of the GHG generated from 1 ton of waste at landfills (Lou and Nair, 2009), a methane transformation efficiency of 80% is considered based on González (González, 1997). GHG emissions are calculated according to (units in kg CO_2eq/a):

$$\text{GHG emissions}_{S2} = \text{T}_{BD} + \text{E}_{BD} - \text{T}_{L} - \text{E}_{L} - \text{E}_{F}$$

T_{BD}: Emissions from the transport of OMSW to the biodigester
E_{BD}: Emissions from the biodigestion process
T_L: Emissions from the transport of OMSW to the landfill
E_L: Emissions of methane produced by the OMSW in the landfill
E_F: Emissions from the production of recovered fertilisers

By replacing artificial fertilisers with biofertilisers GHG emissions could be considerably reduced since the energy for their production and transport would be prevented by OMSW nutrient recovery. According to Snyder et al. (Snyder et al., 2009), values of 2.9, 1.33 and 0.88 kg of CO_2eq emission per kg are used for the production and transport of N, P and K, respectively. Additionally, applying N fertilisers to soils can greatly contribute to the carbon footprint since this practice leads to strong emissions of nitrous oxide N_2O. An emission factor of 0.00996 kg N_2O-N/kg N input[39] and a N_2O GWP of 298 relative to CO_2 (IPCC, 2006), taken for 100 years) produces 2.97 kg of CO_2eq emission per kg of N applied, by means of N_2O. Nevertheless, in S2 the application of reduced forms of nitrogen, added to the soil as biofertilisers, would still produce N_2O emissions. Therefore, the N_2O emissions generated by N fertiliser applications to the soil are not included in this calculation.

3.2.4 Economic calculations

For S0 the main annual costs C_{so} (in €/a) for electricity and heat are calculated on the following basis:

$$C_{S0} = \mathrm{E} + \mathrm{H_W} + \mathrm{H}_D$$

E: Electricity consumption (7,150,000 kWh) multiplied by the price of 0.176 €/kWh

H_W: Heat consumption from wood boilers (5,596,000 kWh) multiplied by the price of 0.016 €/kWh

H_D: Heat consumption from diesel boilers (4,963,000 kWh) multiplied by the price of 0.088 €/kWh

Regarding S1, a production cost of 1,077 €/ha is used for maize silage, based on studies conducted in the region by Schnettler (2013) and Celedón (2014). A cement floor for storing the silage is included, using 2,500 m^2 and € 44/m^2 for calculations. It is important to note that although the annual average power needed is 817 KW, the campus' demand of electricity and heat is concentrated in 12 hours, between 7:30 am and 7:30 pm (DDSS, personal communication), which is also when the price of electricity generated by the Central Interconnected Electrical System of Chile (SIC) is higher (Chilectra, 2014; SAESA, 2014). Therefore, storing gas for 12 h/d (night time) would allow doubling the installed power for the 12 hours of high demand for electricity and heat on the campus, also obtaining better prices for electricity sold back to the SIC. Such a system would also contribute to a more balanced generation of renewable power in the region. Therefore, the value for the biogas plant corresponds to a 1 MW plant (Gamma Ingenieros S.A., 2011) plus 30% additional cost for an additional electric generator (CHP) as well as gasometer units (CME-GIZ, 2012), which would allow the plant to produce 2 MW of installed power. Altogether, the investment considered would be about 3.9 Million €. For the biogas pipeline that connects the biodigestor to the CHP unit, an investment of € 50/m, for 5 km of pipeline is used, plus an additional € 250.000 to cross the nearby river[40]. The operating costs are considered equal to 5% of the investment of a 1 MW plant (Gamma Ingenieros S.A., 2011; CNE-GTZ, 2007; Deublein and Steinhauser, 2008), which is € 197,000/a. The cost to buy a 20,000 m^2 plot of land for the bioenergy plant is about € 36,700. For the capital costs, the biogas plant, pipeline and site are divided into 10 years, with an interest rate of 6%. Although 10 years is a rather short lifespan for such a facility, some parts of it would last less time. This period is also used to simplify calculations and reduce capital interests. Regarding the costs of wood for complementary heating, S0 prices are maintained. Finally, the cost of the heating network is not considered because there is already a wood boiler heating network project near completion for the campus' buildings. Therefore, the heating network investment is not economically considered.

Regarding S2, much higher investments would have to be made because besides the biogas plant, an OMSW pre-treatment system must be built. A biogas plant that receives OMSW should have mechanical separating systems to remove eventual contamination by inorganics from imperfect separation at homes. This would be especially mandatory if the final biofertiliser (digestate) from the biogas plant will be used as a fertiliser which has no

[39] IPCC data from the Emission Factor Data Base for Chilean conditions.

[40] Mr. Andreas Krieg, HAWK, Göttingen. Personal communication.

enrichment of toxic substances. S2 also includes the additional costs of gathering, treating and disposing of different kinds of wastes. As there are many technological alternatives, an average operation cost of € 45/t waste is used based on experiences in Germany (Kern et al., 2012) and within the European Commission (Baxter and Al Seadi, n.d.). The capital investment for the biogas plant with the OMSW pre-treatment is assumed to be € 14 million (Murphy and McKeogh, 2004; Baxter and Al Seadi, n.d.; Monet, 2003). The cost for the site (ca. 60,000 m^2) of the biogas plant and the separation system is set to € 125,000. As in S1, the costs for the biogas plant, pipeline and site are allocated into 10 years, with an interest rate of 6%. The heating network investment is also not considered in S2. The OMSW is assumed to be delivered to the biogas plant for free, since the municipality will be able to save money through effective solid waste separation, as is explained below. The costs of wood for complementary heating and for the biogas pipeline are the same as in S1. Costs reduction through the sale of surplus electricity is assumed to be the same as in the previous scenario. Although the amount of heat surplus is relevant, its sale is not considered. Finally, the sale of the recovered nutrients from the organic waste is included. The referential nutrient price (Pinochet, 2014) per ton of element is € 1181 for N (urea based, 46% N), € 1420 for P (triple superphosphate based on 48% P), and € 1600 for K (potassium sulphate based, 50% K). However, to calculate the income obtained from nutrient sales, only half of the market price is used, as it is assumed that some barriers like quality, physical format or farmers' rejection could be a deterrent to its sale.

This new management system of the MSW will imply important savings in terms of reduced waste transport to the landfill, reduced solid and liquid waste treatment and higher quality recyclable waste. In addition, due to the reduction in landfill leachate there will be less risk of infectious vectors and better quality of recyclable waste, and the soil and groundwater quality in the area would be enhanced. Thanks to the reduced atmospheric pollution, indirect savings related to better public health and other environmental impacts will also be attained. These eventual cost savings as well as incomes from clean development programs or subsidies are not considered in this economic calculation.

3.2.5 Land use effect

Land-system change is a planetary boundary that has already trespass the barrier of a safe operating space, located now in the zone of uncertainty, with increasing risk on a global scale (Steffen et al., 2015). Bioenergy may imply new risks on this issue. Therefore, the land-use effects of implementing a CHP biogas unit on the Isla Teja campus are analysed in terms of the land area needed to produce wood for heat and energy crops for biogas. For wood, an annual renewable productivity of 20 m^3/ha is used, as a regional commercial average, which implies an average of species (native and exotic), density and forest age (UACh, 2013b).

3.2.6 Nutrient recovery

It is assumed that all of the nutrients from Valdivia's OMSW are currently lost as explained in chapters 3.5.3, 3.5.4 and 4.1.6.

For S1, the recycling of nutrients from energy crops can be assumed to be almost complete as the whole digestate is returned to the fields as biofertiliser (Ruppert et al., 2013). Therefore, calculating the nutrient balance at this stage is not necessary. The recycling of nutrients in S1 implies neither nutrient recuperation nor nutrient loss. Nevertheless, this should not be confused with the recovery of nutrients from OMSW in S2.

For S2, the nutrients contained in Valdivia's OMSW are calculated. Typical concentrations for fresh OMSW are taken from several studies (Hargreaves et al., 2008; Warman et al., 2009; Lo et al., 2009; Eder and Krieg, 2012; Zhao et al., 2009; Avendaño, 2003) and are similar to the composition of local fresh organic waste and compost[41]. The macronutrient concentration values (NPK) used are listed in table 2 together with their recommended and used doses for the fertilization of grasslands and cereal croplands in Chile (Pinochet, 2003).

Table 2: Average concentration of the macro-nutrients nitrogen, phosphorus and potassium in OMSW and recommended and used doses of these elements in Chile

	N	P	K
Concentration in OMSW (weight %)	1.0	0.2	0.7
Regional average recommended doses for grassland (kg/ha/a)	60-90	10	5-25
Regional average recommended doses for cereal cropland (kg/ha/a)	180-200	25	50-75

3.2.7 Atmospheric pollution

According to the World Health Organization, in Chile atmospheric pollution is responsible for 4000 premature deaths yearly, which implies an economic impact of 670 million dollars associated with medical expenditures and loss of work productivity (MMA, 2014a). In 2014, Valdivia was declared as a "saturated zone" for atmospheric contaminants, especially because of the accumulation of air particulate matter mainly from firewood burning for heat in the cold season (MMA, 2014b). As any attempt to reduce air pollution is important, the effect of implementing a bioenergy campus in terms of atmospheric pollution is analysed. The emission factors used for the national grid (SIC) are estimated from different sources (MMA, 2012; KAS-GeoAire, 2009; Ulloa, 2014; Ambar, 2001; Eula, 2011). For biogas they are taken from BMU (2009), that are the average of 30 biogas-driven engines measured by the German Federal Environmental Agency. For wood boilers, the data are taken from CONAMA (2009) and Seidel et al. (2013), and for diesel boilers from CONAMA (2009). Additionally, double chamber house stove emissions taken from CENMA (2011) and Seidel et al. (2013) are included as a reference, as this is the most commonly used heating system in the city. The emission factors in grams of material emitted during the production of 1 GJ of heat, electricity or both are listed in table 3:

Table 3: Emission factors (g/GJ) for particulate matter PM_{10}, NO_x, CO and SO_2 for different energy sources.

Energy source	**PM_{10}**	**NOx**	**CO**	**SO_2**
National grid SIC (Power)	54	356	149	650
Diesel boiler (Heat)	6.5	63.1	15.8	93.7
Wood boiler (Heat)	108	54	606	1.9
Biogas (Heat and power)	0.5	89	133	58
Double chamber wood stove (Heat)	240	90	3000	20

Particulate matter emissions from a biogas CHP unit are more than 200 times lower than those of wood stoves and boilers. In the case of carbon monoxide it is between 5 and 21 times lower. NOx emissions from biogas are similar to those of the other heating devices but much lower than the SIC. Regarding SO_2, emissions produced by CHP biogas units are much higher than those from burning wood, but lower than those from diesel boilers and much lower than the SIC.

[41] Analysis of samples of fresh domestic organic waste from an average Valdivian family were carried out at the laboratory of the Soil Science Institute, Faculty of Agrarian Sciences, Universidad Austral de Chile (Valdivia).

3.2.8 Social implications

Data from the social dimension differ from the classical quantitative and technical data used in other parts of this research. Our human domain of existence is complex, often irrational and emotional and deeply rooted in a cultural and historical process (Maturana and Varela, 1987). From the view of society and the individual, the debate of specific subjects such as energy access, climate change, land use, and waste management is usually much more multifaceted than the scientific basis behind it. The inclusion of this debate is very complicated and beyond the scope of this work; thus, the social implications will only be covered superficially. Here, a short summary is considered in consistency with the active feedback approach between science and community used by IZNE in bioenergy villages (Schmuck et al., 2013). Three methods are used to gather information regarding the social implications of the implementation of a bioenergy campus: 1) evaluations of the corresponding main literature (Schmuck et al., 2013; Eigner-Thiel et al., 2013; Senge et al., 2011; Maass, 2013), 2) interviews, and 3) workshops for project development with local stakeholders. For the latter the methodology "Dragon Dreaming" was applied, which is a participative methodology used internationally for the enhancement of creative, collaborative and sustainable projects and organizations (Blanke et al., 2013).

Therefore, based on the information gathered, a list of social effects that are potentially triggered through the implementation of the bioenergy campus concept is presented under the structure of the Human-Needs Matrix created by Max-Neef (1991). Every category denotes a basic human need that must be satisfied, and without which the individual and social life quality would be compromised. Environmental impacts (positive or negative) imply consequences for human life. Life quality, welfare and happiness are deeply connected to the state of the environment. Environmental changes have physical, psychological or emotional effects on the people that experience them. However, these effects are complex and this study does not delve further into them. Consequently, this research limited its investigation of the social dimension to identifying direct or indirect implications of the analysed concept on basic human needs.

4 RESULTS AND DISCUSSION

Based on the parameters and facts presented in chapter 3, the results of the energy consumption, environmental effects, economical results and the social implications of implementing the bioenergy concept on UACh's Isla Teja campus are described in this chapter.

4.1 Energy balance (electricity and heat)

For S0, the electricity consumed on the campus was 7,150,000 kWh/a in 2014. The total amount of heat was 10,558,000 kWh/a, 5,596,000 kWh/a corresponding to 2,700 m^3 of wood, and 4,963,000 kWh/a corresponding to 476 m^3 of diesel.

To implement stage S1, an area of 272 hectares of maize silage will be necessary to meet all of the campus' electrical demands. In addition, 6,556,000 kWh/a of heat must be produced through cogeneration. Furthermore, 3220 m^3 of wood are needed to supply 6,684,000 kWh/a of heat during the 6.5 colder months of the year. At this stage, diesel would be totally replaced by heat from wood and biogas.

Although the annual fluctuations of the campus' heat and electricity consumption are not available for this study, it is known that both peak in the wintertime. Consequently, concentrating the cogeneration in the winter would imply higher energy efficiency, a smaller

carbon footprint, and a significant reduction in wood consumption, thus generating savings in terms of costs and forested land. This concentration of the cogeneration in a certain season is technically feasible for maize silage, as it can be stored and used as desired.
For S2, the calculated total cogenerated electricity from Valdivia city´s OMSW is calculated to be 9,431,000 kWh/a and for heat 8,645,000 kWh/a. There would be electricity surpluses of 2,277,000 kWh/a from biogas cogeneration relative to S0, but a wood supplement of 2,626 m^3 would be needed. At this stage, the campus would become a net renewable power and heat producer. A summary of the relative effects of the different stages on the energy balance is shown in figure 5.

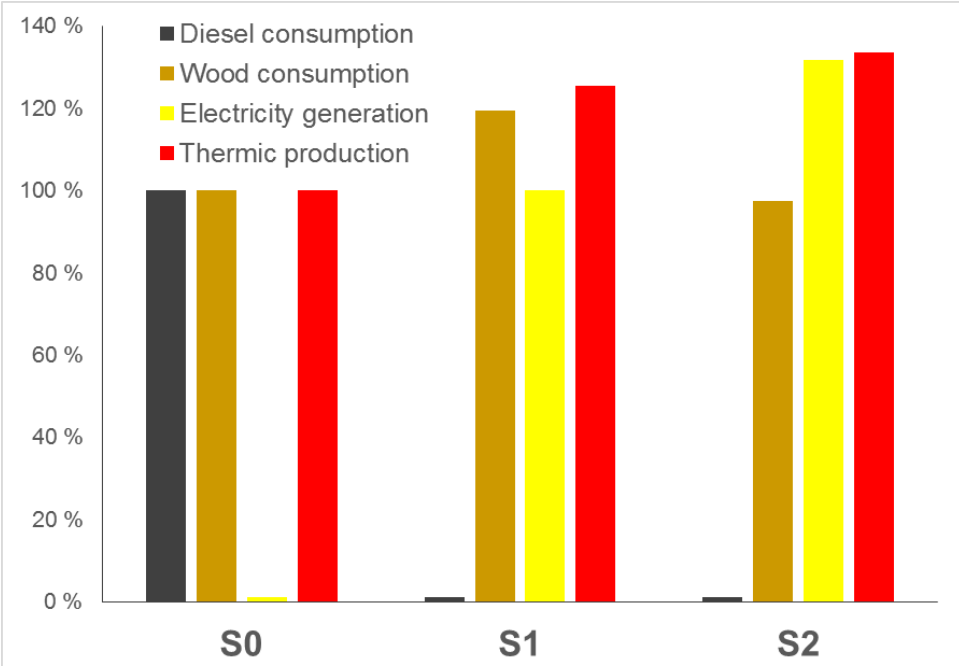

Figure 5: Relative changes in fuel and energy parameters in relation to the current stage (consumption of S0 = 100 %)

Unlike the situation in S1, the amount of fresh OMSW obtained throughout the year will be nearly constant. A preferential energetic use in the colder months seems questionable, because the storage of OMSW over longer time periods is not feasible because of hygiene, smell and other additional reasons.

4.2 Carbon Footprint

For the current situation (S0), the total GHG emissions from the campus are 3,757,000 kg CO_2eq/a (2,434,000 kg from electricity, 125,000 from firewood and 1,197,000 from diesel). 2,372,000 kg CO_2 released from the burning of firewood are not taken into account because they are carbon neutral.
For S1, GEMIS modelling provides a GHG emission of 0.113 kg CO_2eq/kWh$_e$ for both farming the energy crops and the biodigestion process. The campus' total GHG emissions would add up to 957,000 kg CO_2eq/a (807,000 kg from energy crop biodigestion and 150,000 kg from firewood); this does not include the effect of land use change (LUC). It is interesting to note that the reduction of the carbon footprint at this stage would reach 74.7% compared to S0, no more. This is so because almost half the proportion of the current energy consumption (S0) comes from hydroelectricity (electricity from SIC) and firewood (heat), which are close to carbon neutrality. A critical aspect is the inclusion of LUC in the calculation. The direct effect of

LUC increases the emissions by 714,000 kg CO_2 eq/a, producing a total emission of 1,663,000 kg CO_2eq/a, meaning a reduction of only 55.6% compared to S0. Especially critical would be the inclusion of the indirect LUC effects, which would add up to 4,375,000 kg CO_2eq/a, resulting in a net increase in the total emissions by 61% compared to S0. This increased emission is related to an assumed expansion of agriculture into native forests or wetlands. This is, however, not valid for Los Ríos region, as there are many sub-utilized grasslands or field areas that could be transformed into areas dedicated to energy crop production. Native forests are relatively protected against land use change and wetlands may also be protected soon. Although there are real risks involved in displacing current land uses through the introduction of energy crops, there may be also some opportunities of developing it at low scale. Thanks to various factors, a current pattern in land use change in the Los Rios Region is moving towards a more intensive agriculture. Agricultural productivity and energy prices suggest that land use change towards energy uses may increase significantly. If S1's energy crops are cultivated on farmland in competition with food plants, there could be a direct and an indirect LUC effect. In any case, following the WBGU methodology (WBGU, 2008), after 20 years (see item 4.3.3) the LUC effects will be null and void, eliminating both direct and indirect effects of LUC in the calculation, and therefore greatly reducing the GHG emissions of S1.
Regarding S2, the GEMIS modelling provides a GHG emission of 0.07 kg CO_2eq/kWh_e for the OMSW biogas plant. The system's total emissions calculated are 709,000 kg CO_2eq/a (123,000 kg CO_2eq/a from firewood, 660,000 kg from the OMSW Biogas CHP unit, and 74,000 kg due to waste collection). Nevertheless, the effect of burning the biogas from OMSW (3,300,000 m^3/a) implies avoiding the emission of 31,000,000 kg CO_2eq/a from the methane release at the landfill. Nutrient recovery would also avoid an additional 1,287,000 kg CO_2eq/a. Consequently, the overall emission of S2 would be -31,600,000 kg CO_2eq/a, implying a reduction of 940%, or a negative footprint equivalent to 8.4 times the emissions produced in S0. In other words, an extremely beneficial reduction of GHG could be achieved. Although simply burning the methane that would otherwise be emitted from the landfill would imply a reduction of emissions by a factor of 22, the overall reduction is only around half of that, since an important proportion of the current energy consumption (S0) is renewable. The comparison between the three stages analysed is shown in figure 6.

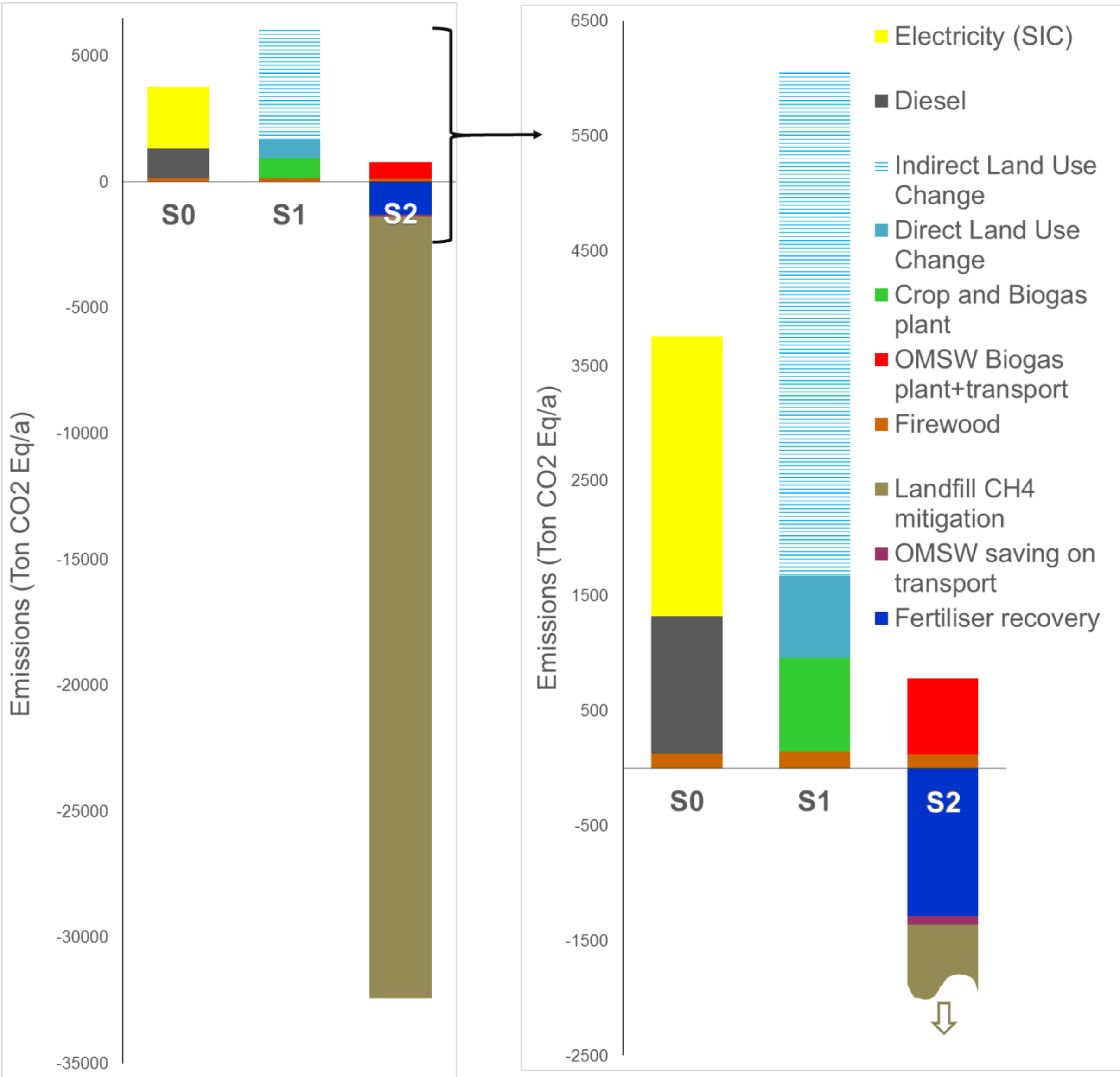

Figure 6: Comparison of the total GHG emissions (tons of CO_2eq/a) of the three analysed stages. S2 shows negative emissions from the mitigation of the methane released at the city´s landfill and avoided fertilizers production. The right plot is an enlargement of the uppermost section of the left plot.

4.3 Economic performance

For the current situation (S0), the total cost of the campus' energy consumption is 1,791,000 €/a: 1,260,000 € for electricity, 91,600 € for firewood and 439,000 € for diesel.

For S1, the annual cost of the whole system is 1,257,000 €/a: 293,000 € for maize silage, 132,000 € for firewood, 197,000 € for operation costs of the biogas plant and 454,000 € for the capital investment (11,000 € silage plate, 390,000 € biogas plant, 50,000 € pipeline, 3,700 € terrain) and 180,000 € for the capital interests. It is interesting to note that the costs per hectare of this maize silage production are 37% cheaper than that of a regular maize production, because the cost-intensive external fertilisers are not needed in this system. The overall annual costs for S1 are as follows (in €/a):

$$C_{S1} = C + B_O + C_C + C_I + H_W$$

C: Costs for energy crop cultivation and harvesting
B_O: Operation cost of the biogas plant
C_C: Capital investment
C_I: Capital interests
H_W: Cost of firewood for heat boilers

For S2, the annual costs of the whole system are aprox. 3,700,000 €/a: 1,531,000 € for the OMSW plant operation costs, 108,000 € for firewood, 1,474,000 € for the capital investment (11,000 € silage plate, 1,400,000 € OMSW biogas plant [treatment: aprox.70%, biogas reactor: 30%], 50,000 € pipeline, 12,500 € terrain) and 585,000 € for the capital interests. Nevertheless, if surpluses of electricity (412,000 €/a) and nutrients (440,000 €/a) are included as sales, the overall balance of energy consumption would be reduced to 2,829,000 €/a as a net cost. The overall costs of C_{S2} in €/a are calculated as follows:

$$C_{S2} = B_O + C_C + C_I + H_W - E - F$$

B_O: Operation cost of the biogas plant
C_C: Capital investment
C_I: Capital interests
H_W: Cost of firewood for heat boilers
E: Income from the sale of surplus electricity
F: Income from the sale of biofertiliser

The summary of the economic results is shown in figure 7.

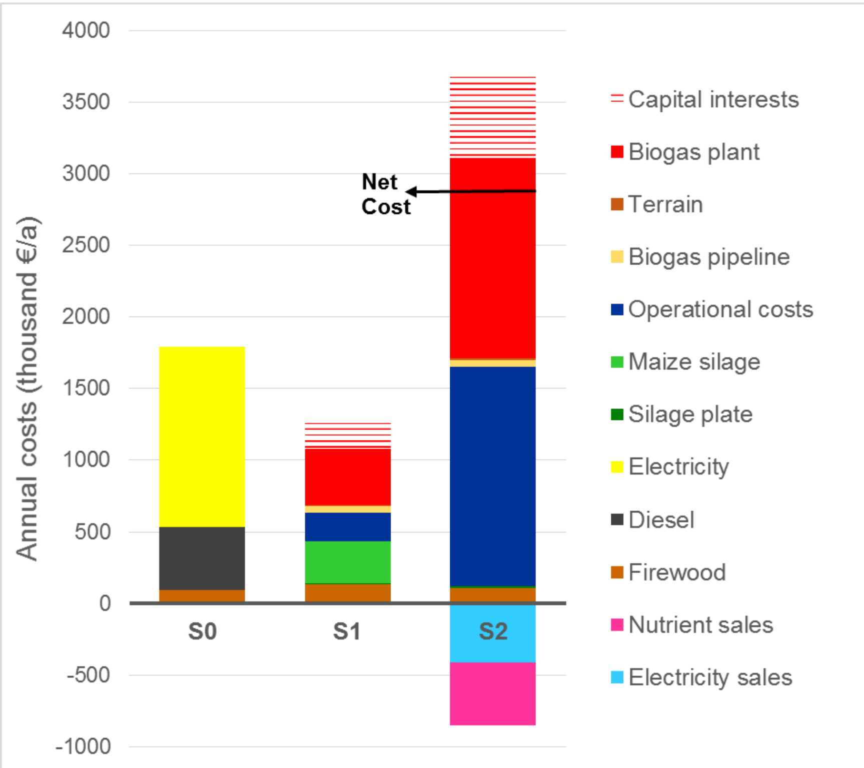

Figure 7: Annual overall costs (€/a) for the different stages analysed.

Regarding profitability, S1 includes the extra cost of producing energy crops for biomass, while S2 would require establishing and operating a much more expensive biogas plant. These results confirm that nowadays biogas production from energy crops can be profitable, while biogas from OMSW cannot be financed only by its ability to generate energy (Monet, 2003). Nevertheless, considering what municipalities currently spend on MSW management, segregated OMSW management may imply significant savings that could finance the concept making it commercially viable. Another important factor is that the OMSW pre-treatment system considered here implies a very sophisticated cleaning system that might not be necessary if local OMSW were well separated at its source (homes). This is a key issue that requires further investigation.

If the capital costs of the OMSW biogas plant were externally financed, the overall economic cost would decrease to € 798,000/a, which would result in a total reduction of 55% in relation to S0. As S2 implies many environmental and social positive impacts, its external financing may be possible. Since post-Kyoto financial/subsidizing mechanisms are currently under development, new levels of profitability could be reached. Considering Aguilar-Virgen et al. (2014) as a reference, an average value in the carbon market of US$11.00/t of CO_2eq would imply an income of € 433,000/a. Finally, the capital cost of the OMSW biogas plant chosen for this study is cautious as other authors proposed much lower capital costs (Rajendran et al., 2014). With reductions of around 50% of the calculated S2 capital cost, positive NPV could be reached.

4.4 Land use effect

For S0, 135 hectares of forested area are required for firewood supply, for S1 161 hectares. An additional surface area of 272 hectares would also be needed for energy crop production (maize silage). For S2, only 131 hectares of forested area are necessary as S2 provides 32% more cogenerated energy than S1.

If all of the residual heat produced in warmer months would be used for other purposes, the wood savings would be equivalent to 104 hectares of forest compared to S0. So far, this option is not evaluated here since it requires further research.

4.5 Nutrient recovery

In S0, there is no nutrient recovery.

S1 does not recover nutrients either, except for a nearly complete recycling of the nutrients from the fermentation plant back to the farmland.

In S2, according to the parameters presented in chapter 4.3.6, the amount of recoverable nutrients from Valdivia’s OMSW include 340t/a of nitrogen, 68 t/a of phosphorus and 238t/a of potassium. Based on the recommended doses for the region proposed by Pinochet (Pinochet, 2003), the land area which could be fertilized with this amount, is presented in table 4:

Table 4: Area of land which could be fertilized with the nutrients from Valdivia’s OMSW, based on recommended doses for the region.

	N	P	K
Nutrients recovered from OMSW (t/a)	340	68	238
Doses used for grasslands (kg/ha/a)	75	10	15
Doses used for cereals cropland (kg/ha/a)	190	25	65
Fertilizable grassland area (ha)	4,537	6,805	15,879
Fertilizable cereal cropland area (ha)	1,791	2,722	3,664

It is important to emphasize that the recovery of these nutrients and their balanced application on farmlands would also mean the prevention of water and soil contamination by leachate waters from the landfill. We have also taken in our mind that especially phosphorus belongs to the nutrients group with shortages in a few future decades (Vaccari et al., 2014).

4.6 Atmospheric pollution

Based on the emissions factors presented in chapter 4.3.7, the emissions from particulate matter and noxious gases, according to the different calculated stages, are shown in figure 8:

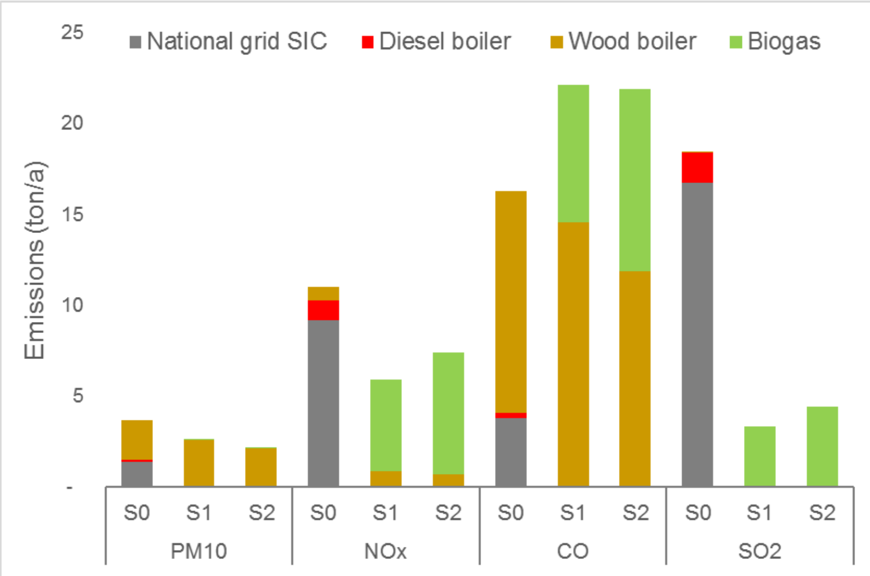

Figure 8: Emission results (tons/a) from different sources of the Isla Teja campus' energy system for the different stages analysed.

In relation to the values obtained, firstly it is important to note that as almost 60% of the SIC is based on fossil fuels (mainly coal and gas power plants far from Valdivia), the total emissions of S1 and S2 are considerably lower for all the considered gases, excepting carbon monoxide. However, S0 emissions from electricity production (from national grid) are not emitted locally, so that the good performance of S1 and S2 would not be appreciated in the city, as the relevant emissions for the city's air quality include only those that are released locally. It is also important to note that diesel boilers present low emissions, so that their replacement by a CHP biogas unit would increase the emissions released, excepting particulate matter that would be reduced to a third. Also, the effect of using the warmer months' cogenerated heat might have a considerable reduction on the overall PM_{10} and CO emissions, since replacing firewood with biogas heat could significantly reduce those emissions per unit of heat.

4.7 Social implications

As previously explained, a list of social effects that would potentially be triggered by the implementation of the bioenergy campus concept is presented on basis of the structure of the Human Needs Matrix created by Max-Neef (1991). Only axiological categories are considered. Some implications could be classified in more than one category, but only the best attribution is chosen. See table 5:

Table 5: Potential social implications from the implementation of the bioenergy campus concept.

	Basic direct and indirect socially relevant implications of implementing the Bioenergy Campus concept	
Axiological categories	**S1**	**S2**
Subsistence	(+) Possibility of redistributing economic resources associated with the university's energy consumption (+) Additional jobs (-) Additional efforts by the University (+) Chance of getting national or international resources from clean development programs.	(+) Possibility of redistributing economic resources associated with the university's energy and communal waste management (+) Additional jobs (-) Additional efforts by municipality and university (-) Aesthetics, eventual smell and noise of the pre-treatment plant[42] (-) More noise and traffic congestion from an additional waste recollection system (+) Chance of getting national or international resources from clean development programs
Protection	(+) Reduction of GHG (+) Enhanced University autonomy (+) Alternative for reducing pressure on deforestation (-) Increase of land use change	(+) Reduction of GHG (+) Reduction of pathogenic risks (AD disinfection) (+) Reduction of pollution from the dumping of organic material (+) Enhanced public and animal health (breaking the chain of diseases vectors) (+) Enhanced University autonomy (+) Alternative for reducing deforestation and land use change. (-) Increased noise (CHP unit, university)
Affection		(+) Strengthening of solidarity
Understanding	(+) Attraction of expertise (+) Development of new knowledge, expertise and capacities (+) Education and training (+) Practical experience (+) Contribution to cultural paradigm shift towards a global consciousness, respect for nature and future generations	(+) Attraction of expertise (+) Development of new knowledge, expertise and capacities (+) Increased awareness about waste management and generation (+) Education of promoters and proponents for sustainability (+) Generation of occasions for large-scale environmental education (+) Contribution to cultural paradigm shift towards a global consciousness, respect for nature and future generations
Participation	(+) Carrying out sustainable projects with engaged people (+) Opportunity to implement national goals regarding clean energy (+) Potential for replicability	(+) Collective project towards sustainability (+) Governance: Chance of involving city´s stakeholders (academic, public, private, political, civic organizations) (+) Opportunity to support national goals regarding clean energy (+) Chance for community access to information, planning and decision-making (+) Development of citizen engagement (+) Enhanced City - University links (+) Potential for replicability

[42] This place is currently rural, but might become urban with the eventual expansion of the city.

		(+) Inclusiveness of the initiative's benefits
Leisure	-	-
Creation	(+) Alternative for electricity generation based on renewable resources (in the context of a developing country) (+) Nationwide pilot project (+) Chance to carry out a collective dream (sustainable campus initiative)	(+) Alternative for electricity generation based on renewable resources (in the context of a developing country) (+) Nationwide pilot project (+) Chance to carry out a collective dream (Valdivia's sustainable city initiative)
Identity	(+) Improve the prestige of the university (+) Pride and meaning	(+) Improve the prestige of the city and the university (+) Opportunity of individual citizens to improve their ecological footprints (carbon and waste) (+) Creating a sense of identity and belonging for community members (+) Pride and meaning
Freedom	(+) Reduced dependency on national grid and energy delivery from abroad (+) Independence from external fossil energy	(+) Reduced dependency on national grid (university) and energy delivery from abroad (+) Independence from external fossil energy (university) (+) Decentralization through an inclusive model of territorial management

4.8 Overall sustainability performance

According to the objectives stated for the sustainable use of bioenergy resources (chapter 3.2) a table summarizing the overall sustainability performance is developed for the analysis of the Bioenergy Campus. Results are shown in table 6.

Table 6a: Sustainability performance of the two stages (S1 and S2) of the Bioenergy Campus concept in relation to the current situation (S0). Performance is established with specific information for the given criteria and targets.

Criteria	Targets	S1	S2
Technical	Simplicity	Fairly simple additional system	Complex additional system
	Availability	Commercially available	Commercially available
	Technically tested	Currently used technology	Currently used technology
	Security	Safe technology	Safe technology
	Energy efficiency	Over 80% energy efficiency.	Over 80% energy efficiency. Obtaining electricity and heat as sub-products of waste management. Reduction of city waste management energy consumption from avoiding transport of organic waste to landfills
Environmental / ecological	Air quality	Reduction of particulate matter emissions, rises in NO_x, CO and SO_2 emissions. Eventual savings from wood replacement.	Reduction of particulate matter emissions, rises in NO_x, CO and SO_2 emissions. Eventual savings from wood replacement.
	Water quality		Reduced water pollution from landfill leachate.
	Soil quality	Increase in agricultural production.	Agricultural nutrient recovery. Reduced soil pollution from landfill leachate.
	Energy & resources	GHG emissions reduction of 74.7% if land use change is not included, but a 61% increase if LUC is included.	GHG emissions reduction: less transport, no methane production at landfill, nutrients recovery and much lower campus emissions from energy consumption. Reduction of 940 % on Isla Teja campus (or 222 kg CO_2eq/a per person in Valdivia by means of their waste management).
	Biodiversity	Biodiversity reduction due to direct land use change. Habitat reduction due to indirect LUC.	Reduction of pressure on forests for firewood. Reduced habitat degradation due to less pollution from landfill leachate.
	Land use/ landscape	Use of agricultural land for energy crops.	Reduction of forested areas needed for firewood.
Economical	Economic feasibility	Energy costs reduction	Campus energy costs rise. Reduction of city's waste management energy costs.
Social	Subsistence	New economic resources	New economic resources. More management.
	Protection	Energy autonomy, reduction of GHG	Energy autonomy, reduction of GHG, hygiene, healthy environment
	Affection		Collective solidarity
	Under-standing	New capacities, enhanced environmental consciousness	New capacities, enhanced environmental education and consciousness
	Participation	Institutional engagement	Collective engagement (whole city)
	Leisure		
	Creation	High innovation & development	High innovation & development

	Identity	Pride and meaning	Pride and meaning. New collective culture.
	Freedom	Energy autonomy. 100% fossil fuel reduction.	Energy autonomy. 100% fossil fuel reduction. Partial fertiliser autonomy.

Table 6b: Overall sustainability performance (in relation to S0) is assessed qualitatively for the given criteria and targets.

Criteria	Targets	S1	S2
Technical	Simplicity	Worse	Much worse
	Availability	Better	Better
	Technically tested	Better	Better
	Security	Better	Better
	Energy efficiency	Better	Much better
Environmental, ecological	Air quality	Better	Better
	Water quality	Similar	Much better
	Soil quality	Worse	Much better
	Energy & resources	Worse	Much better
	Biodiversity	Worse	Much better
	Land use/landscape	Much worse	Better
Economical	Economic feasibility	Better	Worse
Social	Subsistence	Better	Similar
	Protection	Better	Much better
	Affection	Similar	Better
	Understanding	Better	Much better
	Participation	Better	Much better
	Leisure	Similar	Similar
	Creation	Much better	Much better
	Identity	Better	Much better
	Freedom	Better	Much better

Performance	
Much better	(dark green)
Better	(light green)
Similar	(white)
Worse	(orange)
Much worse	(red)

The Bioenergy Campus may be feasible, if policymakers, public administrators and other decision-makers were to get involved in the arguments given in this paper. Furthermore, such a concept only works if the treated organic matter is not contaminated, which implies the introduction of a new waste separation system and to inform citizens about its advantages, so that eventually achieve their acceptance and participation, voluntarily or through a reward system. Therefore, a substantive program capable of involving all citizens and guiding a cultural change is needed.

5 CONCLUSIONS

OMSW biogas is an increasingly used technology worldwide with many environmental advantages, but it can supply a limited amount of energy, which in the case of Valdivia it is similar to the energy demand of UACh's Isla Teja Campus. As the Campus is suited for the implementation of a bioenergy village concept, and considering that universities have an active role in environmental education, an implementation of a "Bioenergy Campus" is proposed. In this work, such a concept is tested in terms of its sustainability performance.

Results show that the implementation of the "Bioenergy Campus" based on OMSW (S2) would imply the improvement of the sustainability performance of both UACh's Isla Teja campus' energy system and Valdivia's waste management system. Notable improvements could be obtained in terms of carbon footprint, energy efficiency, nutrient recovery and social dimensions, while serious chemical contamination of both soil and water from landfill leachate would be avoided. Regarding air quality and land use, moderately positive and negative impacts are found. However, S2 would imply a much more complex management than the current system S0 (due to the separate collection of OMSW and biodigestion process). S2 is also not economically feasible without external financing sources. The transition stage (S1) would imply a high demand of land use for energy crops and an increase for 20 years in the carbon footprint due to indirect land use change GHG emissions, but it would be profitable compared to the campus' current energy expenditures.

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BOX 5.6.1.1: Comparing organic waste biodigestion with other alternatives

Compared to aerobic composting, incineration, or disposal on landfills, anaerobic digestion (AD) of OMSW shows significant resource savings and is the most environmentally favourable solid waste management option in terms of both GHG saving and a minimum impact on the terrestrial and aquatic environments in a southern Chile context (Tiwary et al., 2015). Here are some arguments that support these statements:

Sealed landfill

A landfill without sealing the base and the surface area releases toxic leachates and emits a lot of GHG methane and nitrous oxide (N_2O) into the atmosphere. Sealing a landfill has important advantages, because the leachate and part of the emitted methane can be collected. Regarding energy and resource efficiency, as well as environmental performance, landfills with unseparated MSW have many disadvantages compared to the AD of OMSW:

- The mix of organic with inorganic wastes has negative synergies (Schulte, 2014):
    - Water from the waste generates highly toxic leachates that need special management to avoid chemical contamination in river or underground water.
    - The decomposition of organic matter degrades other valuable, recyclable materials.
    - The organic matter and their nutrients cannot be recovered, as they get mixed with different pollutants what makes the nutrients unusable for agriculture.
    - When not well-captured or treated, leachate with nutrients can be an important source of eutrophication (Sharpley et al., 1994).
    - Even in the case of sealed landfills leachate may leaking through cracks.
- Even if landfills have a gas capturing system, they need to remain open for further waste input. The amount of methane harvested may vary from 30 to 90% (Oviedo, 1997; Calabrò, 2009), and are typically around 50% (Zhao et al., 2009; Udomsri et al., 2011; Singh et al., 2011). The remainder goes into the atmosphere increasing the GHG footprint. One of the most advanced landfills in Chile shows only 50% efficiency for methane retention (KDM ENERGIA S.A., 2010).
- When CHP is used for landfills, heat cogenerated (which implies 55% of the energy harvested) can often not be used, as landfills are normally located far away from populated or industrial areas of high heat demand.
- Overall, losses from methane harvest and unused heat might imply losses of more than 75% of all the total energy residing in the biological fraction of the waste.
- The efficiency of landfills to produce methane per unit of organic matter is lower than in a separate AD process of the OSMW (González, 1997), probably because of the compartmentalization through plastics, envelopes, bags, etc.
- After closing the landfill, the organic degradation (and methane emissions) might last several decades or even centuries according to the IPCC 1st order decay model (Intergovernmental Panel on Climate Change, 2000; Lou & Nair, 2009). The landfill is not stable because the continuous transformation of organic solids into gas results in subsidence and has to be supervised for decades.

For these reasons in many countries in Europe the organic content of the MSW must be strongly reduced before it can be deposited in landfills (European Council, 1999).

Incineration (waste to energy)

According to different authors (Ghosh and Prelas, 2011; Sharma and Mudhoo, 2011; Whiting and Azapagic, 2014; Murphy and McKeogh, 2004; Baxter and Al Seadi, n.d.; Li et al., 2011; Eunomia Research and Consulting, 2009; Calabrò, 2009; Zhao et al., 2009; Economopoulos, 2010; Pognani et al., 2009; Singh et al., 2011), advantages and disadvantages of incineration of OMSW compared to anaerobic digestion are compiled here (this is a general list, so that specific technologies might not fit):

Advantages of incineration

- No need for a separation system - easy to implement
- No leachate production
- Big reduction of final waste (mass and volume)
- Use of energy from non-organic combustible fraction of wastes (like synthetics, etc.)

Disadvantages of incineration:

- High costs
- Higher GHG emissions
- Higher complexity of the plant
- Not profitable for small scale (village)
- Risks of (and big efforts to avoid) harmful emissions
- Nutrient and carbon loss (by volatilization or by mixing them with toxic elements)
- Difficult use of cogenerated heat (50% of total energy)[43]
- Less energy efficiency (around 50% of OMSW is water that has to be evaporated in the process)
- Reduction of non-organic recycling[44]
- Polluted residues such as ashes and slags which need a special depository.

Composting

When separated at home, composting of the organic fraction of waste in specific sites share many advantages compared to anaerobic biodigestion of the organic matter. Composting of OMSW is seen as a method of separating organic materials from waste while creating a low-cost product that is suitable for agricultural purposes if not contaminated (Hargreaves et al., 2008). That view may be attributed to economic and environmental factors, such as a limitation in the municipal landfill capacity, costs associated with landfills and transportation of materials, adoption of legislation to protect the environment, decreasing the use of commercial fertilizers, increasing the capacity for household waste recycling, and the improved quality of compost products (Hargreaves et al., 2008). Nevertheless, direct composting without previous anaerobic digestion present some disadvantages, like the loss of energy embodied in OMSW, the instability of a putrescible material, and the risk of odours, infections and vectors (insects, birds, rodents, or others). Anaerobic biodigestion is a fast and better process in order to reduce, stabilize, and disinfect organic matter, which makes its management easier.

In the case of the system proposed in this work, the solid biodigestate of OMSW could also be composted, but this alternative is not analysed in this research. Additional composting could facilitate the cleansing of inorganic contamination, as there is a break-down in the fibres and the structure of organic matter is homogenized, which might significantly facilitate mechanical cleansing. Some composting plants use a cleaning system after composting (Cuhls et al., 2015). It also can reduce the amount of organic matter, thereby improving the solid fertilizer produced because the nutrient concentrations increase and the amount of material to be transported is reduced.

[43] Heat is normally demanded in housing or industrial zones of urban areas. Potential emissions from incineration make it less suitable for such populated areas. Industries located outside of populated areas might have higher chances of cogeneration, but much less demand for their heat.

[44] As they are burned, recyclable materials like paper, carton, or plastics are not recycled.

Box 5.6.1.2: Best use of OMSW biogas available

A very important question is to decide what to do with the biogas from the city OMSW, as it is a resource that depends on all the area's citizens and in some ways belongs to them. Therefore, it makes sense that the energy should be used for a public purpose, unless a good economic incentive is developed. Since the average OMSW of a family (or a village or city) is generally not enough to cover the energy needs of an average household, concerning heat and electricity, the idea of autonomy cannot be realized through this source of energy.

Concerning the situation in Valdivia, the city has no gas network yet, so the transport of biogas from any fermentation plant to Valdivia is not feasible. As it is shown in Section 5.6.1, Paper 3, subsection 4.1, the whole OMSW of the city of Valdivia transformed into biogas can provide a bit more energy than the university campus of UACh at Isla Teja demands. More importantly, the most efficient way to use biogas is through a CHP unit, which delivers electricity and heat in a specific ratio. The demands of the university campus at Isla Teja coincide with just the right delivery rate for electricity and heat, but also with the right synchronization meeting the electricity and heat demand during day and year cycles. In addition, electricity and heat could be delivered at external peak energy prices. Considering these arguments, together with the other aspects explained in mentioned Paper, the use of Valdivia´s OMSW biogas in the Isla Teja Bioenergy campus is a feasible and efficient way to use such energy from city waste.

6 Epistemological considerations

"Learn how to see. Realize that everything connects to everything else."
Leonardo da Vinci

6.1 Limitations during the research process

During the research process, some limitations of using a classical scientific approach became evident. These restrictions are related to this specific research process, which is not empirical but analytical, interdisciplinary and perhaps even transdisciplinary. In the search for bioenergy systems, the limitations mentioned are related to the epistemology of information and testing processes, and the differences between the scientific method of basic and applied sciences. Epistemology is a branch of philosophy that investigates the origin, nature, methods, and limits of human knowledge.

In the following sections, some specific cases which demonstrate the limitations of using a classical scientific approach are presented in order to set the stage for a discussion about the epistemological findings of this research.

6.1.1 Complexity of the system analyzed

The following section explores the limitations in processing information and obtaining outcomes, according to the complexity of the system analyzed. Just as an exercise of falsification (see section 6.2.2.1 on Popper), it starts by assuming that a rigorous scientific quantitative analysis is possible.

Let´s take the example of the combinatory of a chessboard, a very simple, basic-structured system. According to Shannon (1950) the number of possible positions, could be …

"of the general order of $\frac{64!}{32!8!^2 2!^6}$, or roughly 10^{43} ".

If the same calculations are done for the combinatory of the system defined in section 5.3.1 (Table 6), considerably larger numbers would result. Although a great degree of complexity has already been reduced by pre-identifying specific component alternatives for a bioenergy system (see Table 6), the degree of information that must be managed is still very high. For example, for the considered alternative components of a bioenergy system [biomass sources (26), energy carrier obtaining process (6), energy carrier (7), energy carrier transformation process (8), energy forms (3), and final use (7)] the theoretical total amount of combinations can be calculated as:

26*6*7*6*3*7=183,456

If the diversity of agricultural sites specified for the region (3,500 polygons of soil-weather combination identified with GIS (see Figure 4 of Paper 1, Section 5.4.4.1) is considered and every polygon is assumed able to theoretically sustain its own bioenergy system, the optimization process should deal with the following number of possible combinations:

$$183{,}456^{3500}$$

It is estimated that the number of atoms in a grain of sand is greater than the number of all of the grains of sand on Earth and that the number of atoms in the entire observable universe is approximately 10^80 (Dilworth, 2011). For a rough reference of how big the obtained number of possible combinations is, considering the number of possible combinations for the bioenergy case, what is obtained is[45]:

$$183{,}456^{3500} = (1.83456 * 100{,}000)^{3500} =$$

$$= 1{,}83456^{3500} * 10^{5*3505} = 10^{922.362} * 10^{17{,}500} =$$

$$10^{18{,}422.362} = (10^{80})^{230.28}$$

This exercise shows that the number of possible combinations of bioenergy alternatives for Los Ríos region, when only taking into account a few number of crops, technologies and energy uses, is equivalent to the number of atoms the universe to the power of 230. This amount reflects only the combinations of bioenergy alternatives, but to choose the best alternative among those $183{,}456^{3500}$ alternatives, an optimization process must be carried out, which has to deal with the relational configuration of such alternatives. In other words, those alternatives must be compared to one another according to certain relational configuration parameters. In this research, such parameters are the technical, environmental, social and economic performances. For example, each bioenergy alternative should have a certain productivity, profitability and resource efficiency, in addition to all of the environmental and social impacts that must be considered, to name just a few.

It is very important to notice that the previous calculation only includes the structure of the system defined in section 5.3.1 (Table 6), and does not include numberless additional factors that could be included in the analysis, which would increase the level of details, like:

Biomass sources

- Plant varieties
- Crop management (tillage, organic, irrigation, etc.)
- Quality of the biomass

Energy carrier obtaining process

- Manufacturer
- Size
- Model
- Availability - Technical Support

Energy Carrier transformation process

- Manufacturer
- Size
- Model
- Availability - Technical Support

Final use

- Power needed by specific engines
- Type of heating system
- Type of cooking devices
- Etc.

Smaller and larger scale interactions:

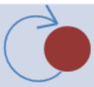
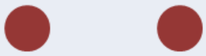
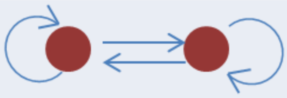
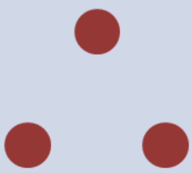
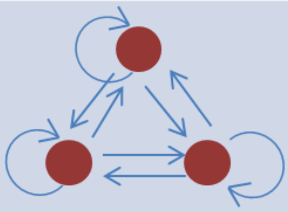
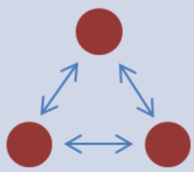
- Soil characteristics (organic matter content, fertility, chemistry, biology)
- Agricultural pests,

[45] Simply using logarithms in the operation is not possible under the possibilities of this research, as the size of the number is not computable by ordinary calculating devices.

- Rural traditions and capacities
- Farmers' differences (size, economy, education)
- Geographical variability (altitude, light exposure, hydrological cycle)
- Economic standards of energy producers and users
- Distances to urban centres
- Social structure
- Political situation
- Etc.

Most importantly, every single bioenergy system configured by a specific combination of the components listed above would have a specific environmental, social, and economic performance, which is specified by many factors and variables: physical impacts [air, water, soil], biological impacts [plants, animals], social fairness [equity, participation identity, etc.]. Depending on the scope of analysis, the amount of information required in the comparison could increase dramatically.
In addition to the last calculation, another way to quantify the complexity of a system would be to quantify its internal interactions. In other words, how many connections can exist between the components of a system? This is a way to figure out the inner organization of the system, in terms of how every part is related to the others. In Table 10, a quantification of the interactions of a system is shown.

Table 10: Complexity of internal interactions for a given system.

V	C =V^2	I= (V^2-V)/2
1 	1 	0 
2 	4 	1 
3 	9 	3 

Where:
V: Number of variables, parts or components
C: Total unidirectional interactions (causal relations)
I: Total bidirectional interactions (connectivity[46])

According to Table 10, and considering the 3,500 polygons obtained from the GIS work for the region, the number of interactions between polygons would be:
Unidirectional: $3,500^2$ = 12,250,000

[46] In this case, only interactions between 2 variables are considered, but configurations of more than 2 variables at the same time can also be included, further increasing the number of possible interactions.

- Bidirectional: $\frac{(3{,}500^2-3{,}500)}{2}$ = 6,123,250

This last number further amplifies the previous number of combinations of bioenergy systems for Los Ríos Region obtained for the system discussed. This section's explorative exercise clarified that as more variables are considered in the analysis, the complexity grows exponentially without showing any sign of finitude, limit, border or end.

Nonetheless, even if all of the combinations within a complex system could be theoretically calculated, when dealing with the environmental dimension, due to its dynamic and systemic nature, such a system cannot be understood without considering how this system relates to its environment as a whole. This must be taken into consideration since no system is completely isolated from a larger context. In other words, one cannot understand a system by studying only the system itself, but must also consider its external relations. Many contributions to this problem have been made by different scientific disciplines, including biology (Maturana, 1978), physics (Heisenberg uncertainty principle and Einstein relativity theory), mathematics (Gödel, 1931), cybernetics (Foerster, 1960) and epistemology of science (Popper, 1959; Kuhn, 1970; see Section 6.2.2). Therefore, regarding the research questions in this work, it seems that it is not possible to strictly optimize any parameter at local scale (farm or county) that also interacts to others parts of the Region. That might include many, if not all, of the system internal variables. For example, resources that have other uses apart from bioenergy (food, material production, etc.) could have a greater demand, or be better grown in another part of the Region, rendering the local optimization inefficient in the end. The same would occur on larger scales, like nation or macro-region (continent) in relation to Los Ríos Region: if another region had a better potential for any bioenergy resource, Los Rios Region's ability to satisfy certain demands would fall short in comparison, and the local optimization results would lose its purpose. In other words, the accuracy of certain calculated efficiencies is dependent upon the degree of autonomy of the system itself. Therefore, considering a much more complex system with a theoretically limitless degree of detail and a theoretically limitless number of external interactions, seems to be impossible and therefore unresolvable in pure mathematical terms.

Finally, as it is discussed in next Section 6.1.3, the question of which modelling software to use for the comparisons expands the complexity instead of reducing it, since choosing one software program requires different software programs for comparison and validation. As long as the determination of the best software depends on the system analyzed, such software cannot be tested with the same system that must be validated, as such a testing process would be tautological. Most of these models are also quantitative, but the great majority of the real figures needed to operate them in this case are not available, as there are not many bioenergy experiences in Los Ríos Region. Again, in strict terms, for a valid comparison all the alternatives should be compared. However, even if all of the information is available, taking into account the enormous number of alternatives, the comparison process would be tremendously long and impossible to compute.

All in all, such an extremely precise approach is not common in conventional research processes, where assumptions and prioritizing criteria are usually used. In fact, the limitations of a quantitative approach in subjects like this are very relevant. It could thus be said that a typical procedure in a conventional research process is simply to choose using discrimination criteria. When confronted to complexity in studying a phenomenon, it is normally assumed that the researcher has to choose a way (specific parameters, specific assumptions) to operate. The resulting questions are two:

1 Why? (Must the researcher leave parts of the phenomenon studied away?) and
2 How? (Can the researcher do that scientifically without the chance of a proving the process for the correctness?)

Certainly, such discriminations must be supported by accepted general scientific criteria, but they cannot be proven with a quantitative approach. Also, a testing or verification process is, apparently always, restricted to the same variables previously specified by the researcher. In other terms, what can be proven are independent variables (e.g. species frequency), but not whole phenomena or subjects (e.g. animal wildlife diversity). Therefore, choosing variables must be, at least partially, based on assumptions, or (consciously or not) by intuition.

The resulting findings, if correct, suggest three important insights:

a) In the subject of this research, a rigorous empiric demonstration approach seems to be impossible, as all of the alternatives should theoretically be tested for comparison. Even in a falsification process, the system's limits cannot be rigorously specified as such limits cannot be demonstrated.
b) A strict quantitative enquiry is not possible. At some level assumptions must be made. Therefore, the question remains, at what level can an assumption be considered scientific?
c) The astronomical number, that can grow or decrease according to the criteria used, is coherent with the idea of a limitless reality. That is, the number of factors and variables are not fixed realities in an objective world, but emerge from the cognitive distinctions of determined observers: the number of observations, as the number of questions, is potentially infinite. This suggests that science does not operate by recording and classifying discrete natural phenomena, but by generating partial categories (distinctions) according to the particular needs and motivations of the researcher, which generate the research objectives and criteria under a scientific (rational) background.[47]

6.1.2 (Transdisciplinary) research questions

Considering that sustainability involves at least three main components (environmental, social and economic) it can be considered an interdisciplinary topic (UNO, 1992). Therefore, research on sustainability and the issues related to it requires interdisciplinary or even transdisciplinary methodologies (Schmuck et al., 2013). Given that the general research question of this work (see Section 3.1) is:

What bioenergy system(s) is (are) the best choice to be developed in Los Ríos Region?

The question involves the quest for the most practicable, suitable and economic alternative. It is thus a quest of system analysis, design and optimization. Therefore, a highly qualified research organization in sustainability and energy systems optimization would be expected to be able to fully address such a question. In this regard, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT could be considered one of the leading research organizations in the field. Consequently, during the 2014 IFAT fair (see illustrations of the fair in Figure 42), some members of the institute who participated in the trade fair were interviewed.

[47] This last point is discussed in section 6.4 on cognition.

a) b)

Figure 42: Logos of a) IFAT (Internationale Fachmesse für Abwassertechnik ab.) 2014. IFAT is one of the world's leading trade fairs for water, sewage, waste and raw material management, held in Munich every two years, b) Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, which participated in the trade fair with a stand.

Regarding the general research question of this thesis, the members of the stand made clear that the institute has plenty of experience in designing and optimizing energy systems around the world. They specified that they have highly specialized scientists that are fully trained to develop solutions for situations such as that of Los Ríos Region. Until this point, everything indicated that the Institute was an ideal organization to cope with such a question. However, it seemed that the Institute specializes more or less in technical solutions, which suitability for the Latin American context remained unclear. Therefore, a second question was expressed in order to check the real applicability of their proposed solution in the southern Chilean context. The question is:

How can we know that your proposed technical solution would be useful for the southern Chilean reality?

After pondering this question for a while, the principal member at the stand simply shrugged his shoulder and answered, “I don´t know, we are engineers.”

In fact, “Chilean reality” is a complex subject, because it involves all the dimensions of Chilean life: technical, economic, cultural and environmental, to name but a few. The answer received suggests that a monodisciplinary focus cannot answer a problem involving a wider range of disciplines. In resolving a multi-dimensional problem (that is one involving many fields of knowledge) many variables from different disciplines have to be connected. In this specific case, the best bioenergy system for Los Ríos Region must be feasible not only in technical terms, but also in economic and cultural terms, which include social, education, ethnic and legal dimensions, among others. Similarly, if a certain technological solution for the local situation is too expensive or complex (regarding the local population’s capacities/educational level) then the solution is not practicable.

Therefore, new interrogations arise, which are addressed in the following Sections, such as:
- *Can the general research question be resolved by any one discipline?*
- *Can these kinds of questions be resolved by any scientifically proven methodology?*

6.1.3 Choosing a (transdisciplinary) modelling software

Mental and computer models are at the foundation of intelligent human decisions, and they are intimately related to one another (Jebaraj and Iniyan, 2006). Since a comparison of different bioenergy alternatives is essential to start answering our general research question, a comparison method is needed. Considering the complexity of such a comparison, one common way is to use modelling software in which the performance of different alternatives can be estimated in a detailed and rigorous but reproducible way, and therefore compared. Hence, a new question arises: Which software program should be used? Different software programs have different structures that determine what questions can be asked, what information is required and therefore what outcomes result from the process. Most software programs relate to a specific subject, associated with a specific discipline, since specific models have been developed within every specific discipline. This research is searching for the most sustainable bioenergy system for Los Ríos Region. As will be seen in Section 6.3, this implies the best performance in terms of technical, environmental, social and economic dimensions; it therefore requires models that can integrate these different dimensions in a systemic manner. As these different dimensions are addressed by different disciplines, modeling the best performance requires an interdisciplinary or transdisciplinary model.

The last issue is related to the problem of the transdisciplinarity of the general research question presented in the previous section. As models tend to be disciplinary, using them for a transdisciplinary comparison seems very difficult. In choosing the software, an epistemological problem is found. In a mathematical optimization, one must have access to the required data for all of the parameters of all of the elements that are to be compared and optimized. Therefore, the elements and parameters must already be chosen in order to initiate the comparison process with a software program. How then can these choices be made if different bioenergy systems and software programs are also related to different variables? One possibility could be a previous broader (more elements) and simpler (less parameters) optimization process. Another could be a qualitative process, which might involve choosing parameters under certain non-numeric criteria. This last option is the method chosen in this research to deal with the complexity of having so many diverse variables involved (see chapter 4: General Methodology).

The next sections provide the details of the search for modelling software programs that could help to compare bioenergy systems with a transdisciplinary approach.

6.1.3.1 Multicriterial Analysis & PROMETHEE

MCDA models permit working with variables of different kinds; they are therefore ideal for multidisciplinary problems. As Brans and Mareschal (2002) state: "*When analysing a problem, the expectation of the decision-maker is to identify an alternative optimising all the criteria. Usually this is an ill-posed mathematical problem as there exists no alternative optimising all the criteria at the same time. However, most (nearly all) human problems have a multicriteria nature. According to our various human aspirations, it makes no sense, and it is often not fair, to select a decision based on one evaluation criterion only. In most of cases at least technological, economical, environmental and social criteria should always be taken into account. Multicriteria problems are therefore extremely important and request an appropriate treatment.*". On the other hand, according to Jebaraj and Iniyan (2006), "*decision analysis in engineering-economic modelling has shown uncertain outcomes and difficult trade-offs when evaluating and ranking the alternatives available to decision-makers in light of their information and preferences.*"

Regarding the given arguments, and considering IZNE's previous experience in the field of bioenergy, the MCDA software PROMETHEE was used by the IZNE research team for a community decision making process (Eigner-Thiel et al., 2013) in which three bioenergy concepts were offered to the community of Jühnde in order to come up with a collective selection process. The different bioenergy concepts were:

- central biogas plant
- farmer's biogas plant
- bioenergy village

The general sustainability criteria include ecological, economic, social and technical criteria. General objectives, such as sustainability, economic viability and technical feasibility, must be broken down into operational criteria that can be measured and are decision-relevant, i.e. to allow one to distinguish between alternatives. The operational criteria were as follows.

Technical criteria

- efficiency
- ease of operation
- frequency of transport

Ecological criteria

- eutrophication
- crop diversity
- global warming
- toxic contamination
- preservation of energy resources

Economic criteria

- regional value added
- net present value
- cost of heat supply
- price of raw materials

Social criteria

- group feeling
- self-efficacy
- acceptance of energy crop cultivation (especially of maize)

However, when such a method is applied to this research process, strong arguments for not utilizing the MCDA modelling method are found such us:

1. Decision must be made by many people, and every person specifies the conditions for the answers or results, when specifying the curves of weighing. In many cases this is a proper tool, since it unifies information from different sources. However, to use a MCDA model for the selection process in this thesis, it would mean that the question and the answer would be made by one same person, so it does not make sense to use such an intermediary tool, although it could help to structure/order the process. Additionally, it is tedious and rather impossible to apply the MCDA tool to a question that involves theoretically many other questions.
2. In the case of Jühnde, the community chose among three bioenergy system concepts. Taking into consideration the enormous number of potential bioenergy alternatives for Los Ríos Region (see section x on the total combinatory of chances), start modelling with few previously defined alternatives may be considered as an intentional, partial or "subjective" pre-selection, especially if there is no community involved in the research.
3. Apart from the above mentioned reasons, the MCDA has some limitations such as:

- One relevant fact in the case of this research is that multicriterial matrixes tend to perceive reality as divided into components (soil, air, organisms, etc. addressed by different disciplines) in a matrix-like division. It then further separates the components into subcomponents, and so on. Therefore, in a complete analysis, as the number of variables grows exponentially in relation to the scale of detail, simplifying this analysis is impossible, unless operational criteria are intentionally defined. Under this structure, a criterion is a portion (%) of reality because different criteria are all "weighted" in the MCDA matrix. That is, the importance of a specific environmental issue is represented as a fraction of the total matrix designed. Let's say, for example, that an MCDA matrix has 4 general criteria (environmental, social, economic and technical) and 10 operational criteria for each general one. Thus, the total amount of operational criteria is 40. In a decision matrix through ponderation, a single operational criteria (such as water quality or social governance) would weigh 2.5% of the total score. If more precision or quantification is needed, then the operational criteria should be broken down again into more sub-criteria (e.g. in water quality: content of pathogens a, b, c…heavy metal d, e, f…). This division further reduces the importance of every aspect of reality (in our example, a high cadmium content in water may weigh less than 0.1 % in the whole matrix). This is obviously erroneous, as reality is not a matrix, but a complex epiphenomenon where all of its components interact strongly and recursively. In summary, the environmental dimension cannot be separated into a discrete number of environmental components, nor is any environmental component totally assessable.
- Finally, this method's "democratic" structure is also a problem because every user's opinion in the MCDA weighs similarly (unless pre-defined), thus an expert and an uninformed community member's opinion have essentially the same importance in the process.

MCDA is an interdisciplinary model and not a transdisciplinary one, according to the criteria defined by Max-Neef (2005). Using the MCDA can be an efficacious solution in concrete problems, when decided by many people all of whom share some common ground. It is useful to compare and discriminate, but its use is questionable when the understanding of a complex problem is necessary.

6.1.3.2 Survey for searching and choosing a modelling software program

As developed in Section 6.3 in the search for an optimization process capable of comparing bioenergy systems for Los Ríos Region, specific modelling software programs are explored. For this purpose, a survey among worldwide researchers on bioenergy is carried out with the web page RESEARCH GATE, a social networking site for scientists and researchers. The question asked in the researchers' website is as follows:

Does anyone know a method or software for modelling a set of different renewable energies in order to get the best combination of them? *I am working on the most adequate combination of sources of renewable energies for the needs of rural communities in the south of Chile. I am using variables of economic, energy efficiency and environmental performance of such combination of sources. Thanks!*

The query received 170 answers from 90 researchers belonging to 81 research organizations (universities, institutes, centres, colleges, government administrations). From the diversity of software types mentioned in the survey, there are many alternatives suitable for comparing the optimization processes of renewable energy sources. Therefore, the modelling of different renewable energies, instead of simplifying the research can in fact further complicate issues, since choosing a software program requires comparing the different options available to find the optimal alternative for the specific features of this research.

In order to reduce the aforementioned complexities, the survey scored the answers and thus focused on the consensus of the majority of the researchers. Consequently, the survey had two objectives: to become better informed about the available software programs and to find the best alternative according to the researcher's criteria.

According to the results shown in Figure 28, the survey's objectives were reached since some preference for certain programs was determined. However, apart from some multicriterial decision analysis (MCDA) programs like AHP and TOPSYS, most of the proposed models are quantitative and many of them are specifically designed for electrical grids. Since this research does not look for grid optimization but sustainability performances such software programs are not optimal for this analysis. Therefore, the results of this survey cannot be implemented in this research. A probable reason for such an incompatibility is, as previously mentioned, that a software program designed for a certain discipline (for example, mathematical optimization) cannot resolve problems outside of that discipline. As the modelling process needed here requires a transdisciplinary approach, such limited models are not useful in this research process.

Finally, it is also possible that the survey question was poorly formulated. However, this doesn't seem to be the case, since only one critical answer was received. It is included below:

Kadal Amutham · 8.47 · Freelancer
Ten years down the line, some one may pose a question in RG as follows:
Does anyone know a method or software for modelling all my girl friends in order to get the best combination of them?

Obviously this is a sarcastic answer, but it is interesting because it metaphorically shows the limitations of a transdisciplinary question, suggesting that there is no answer for such questions, but without presenting diverse arguments. Regardless of this, the extraordinary diversity of opinions and results obtained from the survey, which were sometimes even contradictory, reveals that there is not a clear way to address such issues, even among experts of a specific subject (bioenergy). Even more so, the question caused some debate, as can be appreciated in the following examples:

Aug 26, 2013
Ogheneruona Diemuodeke · University of Port Harcourt
@Kadal, I'm aware that the RG platform is for cross-breeding and refining of research ideas and it would be out of place for some "Know-it-all researchers" to make mockery of research questions posed by other fellow researchers. Anyway, I'm aware that the most "stupid" research question provokes the most intellect, probably, because it is the most difficult to tackle.

Sep 6, 2013
Raphael Akam · SSI UK

This was not a bad question afterall, considering the variables/areas Alfredo would be covering in the software he is seeking. Let's say the environmental aspects for instance: people do make the mistake of taking renewables as zero carbon options, forgeting the upstream manufacturing processes of renewable energy generation equipments. Some of these general sofware mentioned here are unfit for the purpose of accounting and comparing the benefits of options in this regard (e.g Life cycle assesment - LCA). Exploring for suitable software for this purpose does not put a researcher in picture of the narrows.

Mar 7, 2013
Uday Guntupalli · Missouri University of Science and Technology
Dear Mr. Alfredo ,
I have been working on a similar problem and from experience I know how hard it can be to get rooted to one of these options.

6.1.3.3 Multi-objective iterative procedures

There are software programs with a mathematic optimization approach designed to deal with multi-objective issues. Among them are linear programing, evolutionary (or genetic) algorithms, multiple regression analysis or neural networks/fuzzy logic. According to Rizzo and Savino (2012) "*several models have been developed to study and plan the evolution of complex systems involving the interaction of economic, energetic and environmental aspects"*.

Linear programming is one of the most commonly used techniques to deal with energy planning problems (Rizzo and Savino, 2012). According to Ho et al. (2014), multi-objective linear programing (MOLP) is a well-defined mathematical method that covers several decision making objectives to effectively reflect the real situation for decision-makers. MOLP's core concurrently satisfies a variety of objectives that should be achieved under limited resources. Although these objectives are normally established based on conflicting or paradoxical value judgments, the method is "compromising" in that it weighs the selection under conflicting situations to find the solution that minimizes the losses of each aspect. This provides decision-makers with a basis to select a design.

Also, to consider different objectives in optimization techniques and find global optimum solutions, evolutionary algorithms can be employed. Shamshirband et al. (2015) tested such a method in a region where "*the main goal of this study is to optimize the use of agricultural inputs in an agricultural production system using a multi-objective genetic algorithm (MOGA*)".

However, most of these types of models work with specific quantitative information, so that, in general, such models work for specific already defined situations and parameters that are normally reduced in systemic terms. That is, for example, that the environmental dimension is reduced to specific parameters like emissions of GHG, energy efficiency of certain process (like harvest of solar radiation, a technological process or biofuel transformation into energy) or waste production, instead of utilizing a broad systemic assessment, since the complexity of such systems tends to be too high.

In the case of this research, which starts with no previous structure of a bioenergy system, the analysis of the alternatives through these types of models tends to be either incomplete or simply too complex to manage.

6.1.3.4 Network analysis

Network theory is a branch of systems theory and cybernetics. It allows working with a broad range of complex phenomena, exceling in social network analysis. There are many software packages for network analysis. Many of them offer a variety of possibilities, but can be more difficult to interact with.

This approach is interesting because complex phenomena, like social interactions, can be addressed, through the transformation from a qualitative to a quantitative approach, and by working with variables that can be diffuse, non-discrete, or even with a group of variables gathered into one (for example, overall environmental performance). This is possible since network analysis shares a systems approach, which focusses on the system's organization rather than its constituent parts or discrete variables. Therefore, it is possible to work with the configuration of factors that are known to be related, even if they are difficult to quantify, like, for example, the interrelations of power within a community.

In other words, given the non-objective paradigm of systems thinking, models are recognized as part of an observation system fully embedded in a communication network, so that the environment is not a discrete reality, but a co-constructed concept from our particular (cultural, biological) set of distinctions (Lavanderos 2002; Varela et al. 1991). In this concept, the construction of an idea or the description of a phenomenon is not only elaborated from certain criteria or conventions, but also responds to a particular strategy and cognitive style (Maruyama, 1980).

At the same time, the network approach is established under Graphos theory, which allows qualitative information to be represented. Graphic tools have the power of images, which can access the gestaltic[48], synchronic and synthetic faculties of vision; these are better able to transmit organizations that are difficult to express through serial text or linear interpretations. A representation based on Graphos (images) allows us to suggest the visualizations of hidden patterns in quantitative data (Reynoso, 2011).

Considering all of the aforementioned reasons, a network analysis model was chosen to preliminarily compare different biofuels in the context of Los Ríos Region, an exercise that is developed in chapter 6.1.3.4. However, such a model, by no means, is the only method for dealing with the research problem, nor provides an absolute result for such an analysis, since it has all the accuracy problems of a qualitative "subjective" model.

6.1.4 Scientific Methods in Applied Sciences

One important limitation during my research process is the fact that the general research question of this thesis is not a search for the causes or reasons of some phenomenon, as in the traditional scientific method, but the quest for a goal (regarding the search for the best bioenergy alternative for Los Ríos Region). In other words, the question is not "Why does X happen?" but "How can Y happen?" or "Which method should be used for Y to happen?" To illustrate this, a traditional scientific method is shown in the Table 11.

[48] In the context of Gestalt psychology.

Table 11: The Scientific Method. Although the methodologies shown from Grotzinger and Maturana come from very different disciplines (geology and neuroscience), they share the same principles related to the scientific method.

Source	(Grotzinger et al., 2007)	(Maturana and Varela, 1987)
Step 1 Research	Make an observation about the sensible world.	Description of a phenomenon to be explained, acceptable for a (scientific) community
Step 2 Hypothesis	Develop an explanation (hypothesis) that predicts the outcome of other observations or experiments.	Proposition of a conceptual system (hypothesis) capable to generate the phenomenon
Step 3 Observation	Make new experiments/ observations	Deduction of other phenomena from 2
Step 4 Conclusion	Test the Hypothesis	Observation of those phenomena

As can be appreciated in Table 11, the scientific method is an *explicative* method designed to answer a specific question, usually related to natural phenomena. However, in the present research there is no such "observable phenomenon" to be explained. Instead, a non-existing system that must be designed scientifically (bioenergy in southern Chile). If it is assumed that a sustainable solution is one that must satisfy certain criteria established by the sciences of sustainability, which include natural and social sciences, therefore, a sustainable solution must, at the very least, have a scientific background.

Consequently, the general research question can be considered as a question of applied sciences, such as engineering, agronomy and planning, all of which have strong elements of design. Scientific design is a complex process that involves both science and design. Design has traditionally been developed by arts, like in architecture, as it requires a creative process.

Applied sciences uses scientific concepts to design specific *solutions* for their benefit. In these specific disciplines (domains of knowledge), the use of scientific data and criteria is expected, but it seems that there is no scientific method to guide through the process. According to Wright (2002), a number of engineering writers have set forth a list of steps or phases that comprise the "engineering design method." This could be considered as a scientific method of applied sciences. Typically, the list includes:

1. Identification of the problem.
2. Gathering needed information.
3. Searching for creative solutions.
4. Stepping from ideation to preliminary designs (including modeling).
5. Evaluation and selection of preferred solution.
6. Preparation of reports, plans, and specifications.
7. Implementation of the design.

To begin a research process, "general criteria" are normally used. That is to say, a set of assumptions that is coherent with the natural science from which they were derived. When "prioritization" or "selection of the more relevant" criteria is used in these disciplines, intuition or what is supposed to be "common sense"[49] is normally used, as opposed to the scientific method as such, since the "selection" is commonly based on criteria chosen by preference, not by a strict validation process. This prioritization is commonly carried out by considering one critical parameter or variable (criterion) instead of many others. This is consistent with what

[49] In terms of current scientific consensus, or what is frequently assumed among scientist.

anthropologist of science have found, in terms that the choice in causal model types of research is dependent on the researcher's personality and background (Maruyama, 1980).

On the other hand, it seems that in the applied sciences, the scientific method is used in two scenarios:

1. When a certain concept is wanted to be tested, the concept becomes the hypothesis.
2. During the process of design. But it is used iteratively, step by step, recursively, in the act of designing, similar to the trial & error approach. Many hypotheses that include new steps are established and tried during the search for a solution. This way the design process is an ongoing ever-improving process whose results cannot be anticipated *a priori.*

6.2 Foundations for a transdisciplinary scientific approach

6.2.1 The relativist view of science; Gödel's Theorem

Kürt Gödel (1931) established the "incompleteness theorems", in which he proved that for any computable axiomatic system that is powerful enough to describe the arithmetic of natural numbers:

- If the system is consistent, it cannot be complete.
- The consistency of the axioms cannot be proven within the system.

In brief, the theorems state that every formal system is incomplete and that the consistency of such systems is impossible to prove. This was not the end of formalism, but did strongly criticize it. For logical positivists, meaningful statements are only those that are based on the verifiable empirical evidences of our senses. Any statements that go beyond this are by definition "metaphysical", and therefore meaningless (Goldstein, 2006).

This was an important basis for relativism in science, establishing that every set of beliefs is connected to a bigger system that supports it. Therefore, knowledge comes from a specific background (a historical perspective), which has been named differently: cognitive bias, organizing principle (reference point) or conceptual framework.

6.2.2 The evolutionary view of science: Popper, Kuhn and Feyerabend

In a related approach that negates the immanence of scientific truth, some of the most influential scientific philosophers of the 20th century proposed that what is sustained as scientific truth does in fact change throughout time in an ever improving process involving the human dimension of the scientific community.

6.2.2.1 Popper and Falsification

Karl Popper introduced the concept of falsification as a criterion for scientific validity instead of the inductivist logic of the scientific method (Popper, 1959). The falsification concept makes sense, as no theory can be completely proven, even if much evidence is shown to support the theory. However, only one falsification is enough to prove a theory false. The falsification never ends as every theory could be falsified in the future (Tambolo, 2015). Therefore, in his approach Popper specifies:

- that scientific theories are not totally demonstrable,
- that no one scientific systems can be taken as correct forever, as it is not possible to guarantee that a scientific system will be refuted through facts in the future

In other terms, science can never reflect nor obtain the whole truth of nature, but only an ever-increasing approximation to it. Therefore, strict objectivity is never achieved. Regarding objective knowledge, Popper affirmed: "*while we can never have sufficiently good arguments in the empirical sciences for claiming that we have actually reached the truth, we can have strong and reasonably good arguments for claiming that we may have made progress towards the truth*" (Tambolo, 2015).

This approach is coherent with the limitations encountered during this research. The section about complexity in this chapter shows that a strict demonstration of the research question is not possible as the system does not demonstrate discrete borders. On the contrary, it tends to increase its complexity as more questions are added to the analysis. Similarly, in the section on a transdisciplinary research question, a demonstration was not possible as no interdisciplinary criterion was found to be sufficient to fulfill a demonstration process.

6.2.2.2 Kuhn and Paradigm

For Thomas Kuhn (Kuhn, 1970), as for Karl Popper, there was no such thing as a fixed truth or reality. Furthermore, Kuhn highlighted the social nature of science, considering that every generation has its own way of seeing reality. That is, every scientific truth has its own historic and cultural background. Even the most awkward theory seemed logical at a specific time in history. Thus, comparisons between past and present theories make no sense at all. This way, Kuhn criticized formalist science in favor of a historicist approach. In his view, every now and then, mainstream ideas are challenged by a new set of ideas, called "paradigms". By paradigm Kuhn meant "*to suggest that some accepted examples of actual scientific practice-examples which include law, theory, application, and instrumentation together provide models from which spring particular coherent traditions of scientific research*." (Kuhn, 1970).

Kuhn believes that (the history of) science is not a simple accumulation of knowledge, but a history of changes (paradigm shifts). He also believes that the scientific method can give different outputs of results or hypotheses depending on the education and point of view of different observers. Scientists have a natural tendency to defend their theories, and in doing so to adjust reality to their models. The process of such conflict is resolved periodically through "scientific revolutions" that are carried out not by one, but by many scientists. The steps involved in this cyclic process of paradigm shift are as follows:

1. Normal science (established paradigm)
2. Anomalies
3. Crisis
4. Scientific revolution
5. Setting of a new paradigm

Therefore, as also suggested by Popper, according to Kuhn, science behaves more as a historic cultural process than as a cumulative process. It never reaches the whole or absolute truth of nature; it only experiences an ever-increasing approximation. Hence, science has a contextual, paradigmatic character, which suggests that strict objectivity is never possible.

6.2.2.3 Feyerabend and Epistemological Anarchism

Paul Feyerabend realized a strong critic to the scientific method and the discussed about the contextual and incomplete character of science (Feyerabend, 1993). According to Tambolo (2015) Feyerabend "*forcefully disputed the claim that modern science is the only or the best way to investigate the world*", affirming that other kind of knowledge can help to understand nature and reality. Feyerabend understood the implications of the consensual nature of science, and warned about its risks, in terms that an homogeneous scientific community would not be open to novel ideas, so that diversity of views are always needed. In this way, he proved that without proliferation of thoughts, "*testing of theories is impossible*" (Tambolo, 2015).

Feyerabend recalled the need for space within science for non-established views, as the source of new knowledge. Without this, Feyerabend affirms, science risks getting stuck in an established, "mainstream" view that is pernicious for science itself. Feyerabend thus utilizes anarchism as a way to get rid of mainstream science or any kind of role regarding it. According to his view, in a peer reviewed process, if there is no diversity among the scientists that carry it out, the acceptance of a new vision would most certainly never occur. He argues that a monistic model, which he views as "*clearly implied in almost all investigations which deal with questions of confirmation and test*", ought to be replaced with a pluralistic model of theory testing, revolving around the following maxim: "*The methodological unit to which we must refer when discussing questions of test and empirical content is constituted by a whole set of partly overlapping, factually adequate, but mutually inconsistent theories*" (Tambolo, 2015).

With such a statement, Feyerabend also recognizes the cultural dimension of science, thus emphasizing that its development depends on the history of the scientific community as a social phenomenon. As will be explored in the section on cognition, any cultural process, including science, entails the process of a social network of consensual interactions.

6.3 Transdisciplinarity

Spangenberg and Bonniot (1998) reviewed different sustainability indicators and conclude that for the development of sustainability indicators the "interlinkages" need to be studied in order to understand the indicators on a macro-level. This way, the multidisciplinary approach uses different indicators for different components, but with no integrated parameters that cluster them together. In the other hand, interdisciplinary processes are very useful tools allowing to integrate parameters on a common ground. However, such parameters use to be simply mathematically related in a matrix-like structure, which is practical but not necessarily realistic (Hüging et al., 2014; Florin et al., 2014). This problem was already discussed in section 6.1.3.1 when multi-criterial decision analysis was addressed.
Therefore, the next question is if transdisciplinary methods can better handle the challenges of sustainability. As every discipline works in a different operational domain with its own logic, a logical integration seems to be very difficult. Thus, apparently a transdisciplinary work must transcend the logical, formal or conceptual borders of every discipline involved. This can be accomplished by recognizing that:

- Every discipline works within different levels of reality.
- Every discipline works within different linguistic domains.
- The nature of "languaging" is the interplay of emotions and reason, so that communication happens when one person accepts another as a legitimate counterpart, and is therefore open (which involves reason and emotions) to the influence of their ideas.
- Transdisciplinarity include the challenge of leaving personal conceptual certainties and structures aside in order to allow a creative process in which a transpersonal ideation can emerge.

According to the latter, a transdisciplinary approach would be a process among researchers involved, rather than methodologies or logics to follow. Binder and Thorsten (2015) proposed that a typical transdisciplinary project consists of three phases:

1. *Problem framing and team building. Scientists and practitioners clarify their perspectives, problems, and expectations and try to agree on a common set of goals to frame the project.*
2. *Project work and (co)-generation of knowledge. This can include different types of actor involvement and interdisciplinary work.*
3. *Knowledge integration. This includes the process of making results useful for both scientists (new insights regarding methodology, theory development, or empirical evidence) and practitioners (solving societal problems).*

Binder and Thorsten (2015) experiences in the field also confirm that at the core of transdisciplinary work is the communication among researchers or participants. Max-Neef (2005) brings the concept of transdisciplinary approach deeper, and proposes that it is fully accomplished only through the integration of the different levels of interaction, transcending the disciplinary approach to even ethical values. For that he proposes a pyramid (Figure 43). Reading the graph from bottom to top, the lower level refers to what exists. The second level to what we are capable of doing. The third to what we want to do. And finally, the top level refers to what we must do, or rather, how to do what we want to do. In other words, we travel from an empirical level, towards a purposive or pragmatic level, continuing to a normative level, and finishing at a value level. Any multiple vertical relations including all four levels, defines a transdisciplinary action.

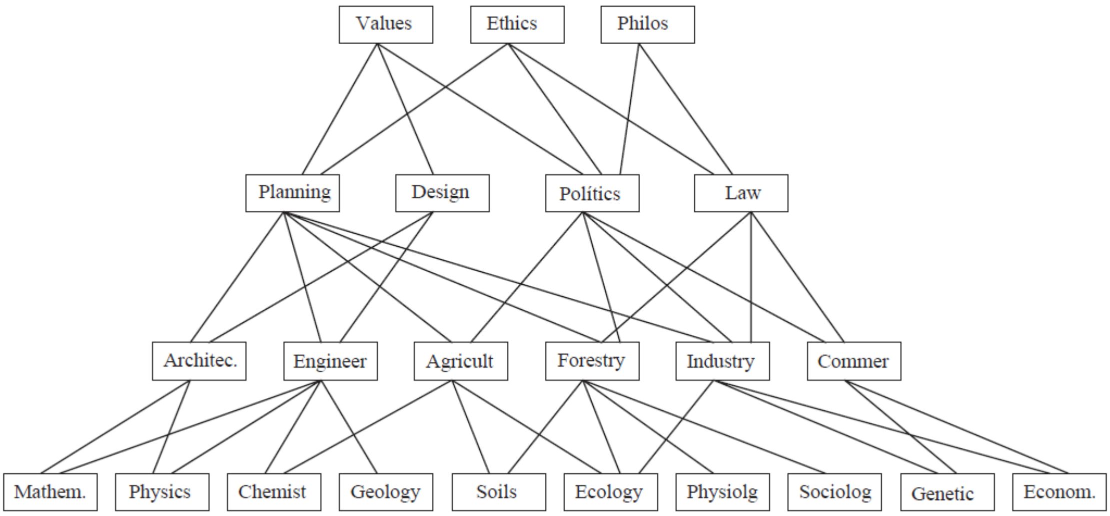


Figure 43: Transdisciplinary pyramid (Max-Neef, 2005).

He then identifies what he calls "strong transdisciplinarity" as the one based on three fundamental pillars:
a) levels of reality (see next section 6.4)
b) the principle of the included middle [50],
c) complexity (see section 6.1.1)

It is very interesting to explore how the scientific method could be used to solve a transdisciplinary problem. In a traditional use of the scientific method, hypotheses are made that must then be proven. This is carried out through the method of demonstration. But what

[50] In opposition to the axiom of the excluded middle in Aristotelian tradition. A non-dichotomic vision of reality like in classical philosophy. *Contraria sunt complementa* (the opposites do complement with each other) as coined by Niels Bohr.

can be proved are in fact problems of every discipline that are proved within themselves. That is, every discipline has its own set of foundations and logical structures that determine whether or not something has been proven; thus, every discipline operates within its own internal coherence carrying on a specific kind of scientific conversation. In other words, every discipline can be considered as a level of reality, and as Max-Neef (2005) states, "*no rigorous mathematical formalization has been found, to interpret the transit from one to another reality"*. In the case of a transdisciplinary research question, the demonstration should be done in a transdisciplinary domain that does not operate within specific disciplines. Considering that in transdisciplinarity there are no pre-defined logical structures that are already accepted as universal methodologies, the chances of obtaining a strict demonstration seems to be impossible or irrelevant. This give support to the idea that "*we can no longer assume that there is just one reality, fully describable and understandable in terms of pure reason*" (Max-Neef, 2005).

6.4 Cognition

Cognition is the science of the process of knowing. Provided that it has inputs from different disciplines (philosophy, neuroscience, semiotics), it is an "interdisciplinary discipline". Cognition can be considered "a promising starting point towards an appropriate and unifying paradigm" in relation to the needs of interdisciplinary approaches (Röling, 2000). As the evolutionary views of sciences presented in Popper and Kuhn Sections, cognition is also a relativistic view of reality, culture and science, since the cognitive process is determined by the structure of the organism involved, and therefore knowledge is restricted by the context of that organism (biological, cultural, ecological, etc.). According to Maturana (1988) "t*here are as many cognitive domains as there are domains of existence*", that can be interpreted as there are as many cognitive domains as living organisms. That entails the notion of different levels of reality. In the case of humans, Maturana states that "*the basic operation that an observer performs in the praxis of living is the operation of distinction*", "*Language is the human cognitive domain*" (in terms of that language is a characteristic cognitive domain of humans), and "*Human beings, exist in the domain of objects that they bring forth through languaging"*, connecting the operation of distinction with the operation in language.

In previous sections of this chapter it is stated that the process of proving a scientific hypothesis is restricted to the testing of variables, but during the election of such variables or before it, proving or demonstrations do not take place. It was also said that the process may be guided by choice, intuition or "common sense". This is coherent with some cognitive approaches, such as the cognitive school of biology of knowledge (Maturana, 1978). According to this approach, rationality belongs to the operational coherences of languaging. Language is specified in a collective domain as a human consensual behavior. It is in consensus where communication takes place, revealing that what is frequently described as objective truth, is in fact a linguistic consensus among a community of subjective observers, a phenomenon known as inter-subjectivity (Varela et al., 1991). Science shares this consensual nature of language and culture. Experiences are not transferable through language. A real experience is not the same as the reproduction of that experience in language (narration). Different rational domains (schools of thought, political opinions, spiritual beliefs) are constituted by different basic notions that are accepted *a priori*. That is, they are accepted based on preferences and not as a result of analytic deduction (Maturana, 1988). These statements are in coherences with the statements of Kuhn (Section 6.2.2.1) and Feyerabend (Section 6.2.2.3) regarding the consensual nature of science.

According to Maturana (2015) a scientific argument is realized when the explanation that it is proposed for an experience is based on other (scientific) experiences and the precision and coherence of these experiences is preserved in the description. Science has nothing to do with the search for reality, nor with being objective, but with explaining; explaining the experiences and questions of our life experiences through the coherences of our life experiences. Provided that we don't have access to an independent reality, we don't have the chance to say something about a phenomenon in which we do not participate. The organization of the nervous system is closed in respect to the environment of an organism, that is, it operates by realizing internal correlations, and not processing external information. This way, the nervous system relates to the external environment through sensor-effector correlations mediated by the rest of the organism (body), but does not directly interact with the environment itself. Therefore, the environment only triggers internal processes determined by the structure of the nervous system and not by the environment itself. As a result, an observer cannot make reference to an external reality independent of him/herself, as the observer is involved in the process of cognition (Maturana and Varela, 1987; Bortoft, 1996). Therefore, there is no way for us to refer to an objective reality independent of ourselves. This, in fact, questions the very use of the term objectivity. These statements are in coherence with the statements of Gödel (Section 6.2.1) and Popper (Section 6.2.2.1) regarding the relativity of scientific knowledge.

Ludwig von Bertalanffy (1955), the creator of the General Systems Theory, published the following text, known as The Whorfian Hypothesis:
"That the commonly held belief that the cognitive processes of all human beings possess a common logical structure which operates prior to and independently of communication through language is erroneous. It is Whorf's view that the linguistic patterns themselves determine what the individual perceives in this world and how he thinks about it. Since these patterns vary widely, the modes of thinking and perceiving in groups utilizing different linguistic systems will result in basically different world views (Fearing, 1954)."
"We are thus introduced to a new principle of relativity which holds that all observers are not led by the same physical evidence to the same picture of the universe, unless their linguistic backgrounds are similar... We cut up and organize the spread and flow of events as we do largely because, though our mother tongue, we are parts of an agreement to do so, not because nature itself is segmented in exactly that way for all to see (Whorf, 1952, pg. 21)."

Linguistic distinctions, e.g. questions, can be as much as they can be imagined. As science takes place through language, from a cognitive prospective, information is potentially infinite as its creation is determined by the researcher's distinctions. Regarding the problem of complexity found in this research, either reductionist or holistic approaches can be deep or shallow depending on the background they use in their analysis.
Following the analysis of Section 6.1.1, as reality cannot be reduced to a mechanistic structure, (e.g. corpuscular worldview; Latour 2005) from a cognitive point of view, there is no more information in a larger scale of analysis than in a smaller one, as information emerges in the process of knowing, which is related with the observer and not with an objective reality. It is possible to analyze a grain of sand or an entire sandy beach with the same level of sophistication. Both analyses can deal with the same amount of information, but both would deal with different information, as every level of complexity entails a specific kind of information. In brief, an observer can ask infinite questions regarding any phenomenon, regardless of the scale or size. A good example is the study of matter. The atom is one of the smallest known particles, and yet a huge field of research with thousands of scientists are devoted to it.

Everything can be connected under an ecosystemic view. Taking this into consideration in a relational view, ultimately everything could be more or less related, and so any study of any phenomenon could be related to any other phenomena or dimension based on an observer's point of view. Following the previously mentioned example, the atom cannot be studied

independent of the history of atomic physics, which means the history of physics, energy, matter, and so on. In this manner, scientific information emerges through the interaction that takes place between the observer and the phenomenon observed, as cognitive distinctions within the domain of science. Whether studying the small or the big picture, the researcher uses all of his/her cognitive capacities, which are limited to a certain extent. This limited capacity, also related to imagination, might be called mind resolution (Erlwein-Vicuña, 2002).
As Heisenberg (1952) affirmed, what we observe is not nature itself, but nature exposed to our method of questioning. According to this statement, information is potentially infinite at any scale, because it is dependent upon (and is generated by) our questions, which can be endless. Therefore, the set of criteria works as the "organizing idea" from which specific distinctions are made in order to obtain useful information (Bortoft, 1996).

Regarding structure and order in nature and science, an example of what is discussed can be made using the art of scientific classification: taxonomy. The following paragraph presents the criteria for the Categories of Soil Taxonomy provided by the Natural Resources Conservation Service of the United States Department of Agriculture (USSSS, 1999):

"*In one sense, soil taxonomy is a sorting process. In the highest category, one sorts all kinds of soil into a small number of classes. The number of classes is small enough for one to comprehend and remember them and to understand the distinctions among them. The sorting must make distinctions that are meaningful for our purposes. When all soils are sorted into a very few classes, such as the 12 orders, each order is very heterogeneous with respect to properties that are not considered in the sorting and that are not accessory to the properties that are considered. For some purposes, however, the order level may provide sufficient information. As one continues to classify a soil at lower and lower levels of soil taxonomy, more information is conveyed about the soil. This method of conveying information is one of the advantages of a multicategoric classification system*."

Considering this text, it can be noticed that:

- The number of soil classes is determined according to the researcher's convenience (*to be comprehended and remembered*) and not necessarily based on a given number found in nature.
- The sorting process is guided by the researcher's purposes (so that the classification depends on what is *meaningful* for the researcher. His meaning configures how the phenomena is categorized).
- Such a classification structure is biased to the criterion of distinction (as soils are *heterogeneous with respect to properties that are not considered in the sorting*. That is, when criteria are changed, the classification structure may change completely*)*.
- Lowering levels of taxonomy does not necessarily imply less information (according to the text, the contrary may be the case).

In social sciences, problems related to the scientific method can become even more complex. Bruno Latour (2005) developed the Actor-Network Theory (ANT) which states that bigger scales do not necessarily mean more information: "*With this principle we should not consider that the macro encompasses the micro, but that the micro is made of a proliferation of incommensurable entities which are simply lending one of their aspects, a 'façade of themselves', to make up a provisional whole. The small holds the big. Or rather the big could at any moment drown again in the small from which it emerged and to which it will return*." He calls this macro context "plasma". On this topic, Latour quotes the ethnologist Harold Garfinkel

(2002): “*The domain of things that escape from formal analytic accountability is astronomically massive in size and range*”.

It is often thought that one limitation of scientific development is that available information is incomplete (Grotzinger et al., 2007). Although this idea makes sense and can help to understand concepts like complexity, it supports the belief that information can be fully obtained. In other words, it implies that information exists in a finite quantity. This idea dismisses the concept presented here of a cognitive-linguistic reality, where the distinctions that one observer can make are endless and the number of parameters observed are determined by the distinctions that the observer makes and not by the phenomenon itself.

The view exposed in this section can be a contribution to mainstream science, as such an approach reveals our cognitive determination, and therefore, the big influences of predominant views (paradigms, set of beliefs, fashion) at every epoch. Ruppert Sheldrake (2012), an English biologist, wrote what he considers to be a set of dogmas of modern science. The main dogma is called the science delusion: “*The science delusion is the belief that science already understands the nature of reality in principle, leaving any of the details to be filled in*.” Regardless of the validity of this statement, it is always interesting to get in touch with the notion of science as an evolutionary ever-changing process, where dogmas (beliefs that have not been proven) are “subjective” but a predominant part of science, which can be seen as a cultural network. This collective nature of science, functioning as a network of conversations, is at the core of what is accepted as scientific by the scientific community: the consensus and transmission of knowledge. As stated by Grotzinger et al. (2007) “*Scientist operates within a system of open communications. It is the essences of science that scientists build on one another´s work*”.

Finally, coming back to the core of this research, after the many issues discussed in the previous sections it seems that the general research question, about the best bioenergy alternative for Los Ríos Region, is a non-sense question, as it is not possible, within specific disciplines, to prove that one of the alternatives is the best, nor is it possible to quantify transdisciplinary variables. It is only in applied sciences & design that it makes sense to ask about a “best solution”, nonetheless, **the result of any design is always the best solution**, that is, the best solution that a researcher can reach with his/her capacities, knowledge and conditions (i.e. with his/her specific background). The result of the design process would never consciously be mediocre, as the goal of the creative process is always to come up with the best design possible.

Regarding the first research hypothesis, the difficulty of its demonstration could lay in its linguistic structure. Empiric science tends to be positivistic, as numbers and quantities are related to a material domain of reality, which can be measured as input for a demonstration. In the hypothesis mentioned, the qualitative nature of the concepts involved makes a strict demonstration impossible. However, as it has been demonstrated in different steps of this research, the results suggest that this hypothesis is fundamentally correct.

6.5 Sustainability of bioenergy

It is not the intention of this section to delve deeply into the concept of sustainability. This concept has already been discussed at length, and has different approaches which can be focused on (Spangenberg and Bonniot, 1998). As it has been lengthly discussed in this chapter, sustainability entails the encounter of many disciplines, and therefore requires an interdisciplinary or transdisciplinary approach. In regards to bioenergy, as it is seen in the next section, the criteria for sustainability are inclusive, conceptual and multidisciplinary, rarely restricted to specific parameters. However, they share the same problems found in transdisciplinary criteria since they are difficult to assess or quantify.

A number of different visions of the sustainability of bioenergy are provided below as general criteria regarding the research questions. They consist of a small selection of the most relevant sources, formats and criteria, pared down from the amplitude of sources reviewed.

6.5.1 The IZNE criteria

A general criteria for sustainability was developed by Schmuck et al. (2013), in which there are 5 principles that must be followed in order to reach sustainability:

- *The respect principle (for all forms of life)*
- *The precautionary principle (avoiding irreversible human caused impacts)*
- *The principle of participation (of all people in searching sustainable ways of life)*
- *The efficiency principle (to avoid wasting limited resources).*
- *The consistency principle (replacing the use of finite resources with renewable recyclable resources, without any waste)*

Ruppert et al. (2013) describes the advantages and disadvantages of bioenergy use in regards to other renewable energies based on the following list of attributes:

Bioenergy PROS:

Bioenergy has three main advantages over other renewables:

- *Reservable: Bioenergy is easy to store and can be used as required. It can therefore balance the fluctuation of wind and solar power (regulating energy).*
- *Different usable forms: Plant material can be used in a solid (e.g., wood), liquid (biodiesel and bioethanol) or gaseous state (biogas); the liquid and gaseous states are easily obtained through chemical transformation processes.*
- *Versatility: The different states can be used for heat and power production, or as fuel for mobility and other purposes. The other renewables produce mostly electricity.*

Bioenergy production has additional advantages:

- *Promotes biodiversity: Energy plant cropping may increase the biodiversity of arable land if energy plantation concepts are realized as double cropping during the year, or as the cultivation of plant mixtures instead of monocultures. Weeds can also be used if they do not lower yields in general. In addition, short-rotation cropping or agroforestry can be incorporated into energy crop farming.*
- *Ensuring good yields: These diversification concepts ensure energy plants' yields, decrease soil erosion and increase the attractiveness of the environment by providing more diversified landscapes.*
- *Element recycling for fertilization: If remnants of the energetic use of crops, such as the residual digestate from biogas plants or wood ashes, are recycled to the areas from which the plants were taken, a nearly perfect recycling of the elements is possible (except for nitrogen). This fertilization can be done when the growing plants need nutrients. It saves money and fertilizer resources (an important example is phosphorous, whose extraction maximum should be reached in 2030).*

- *Monetary advantages: Bioenergy offers local farmers new income opportunities, which could also reduce rural exodus and alleviate poverty, thereby decreasing the gap between the rich and the poor in developing countries (WBGU 2011). Bioenergy production can also decrease dependence on imported fossil fuels, thus improving countries' foreign exchange balances and energy security. Furthermore, it can expand access to modern energy services and bring infrastructure, such as roads, telecommunications, schools and health centers, to poor rural areas.*
- *Job creation: The introduction of bioenergy may create new jobs. Growing, harvesting and distributing bioenergy feedstock are specifically very labor intensive. Additionally, biomass, biofuels and biogas production have created approximately 2.5 million technological jobs globally.*

Bioenergy Cons

Despite these benefits, the use of bioenergy has some limitations:

- *Land use conflicts and food-fuel competition: The production of energy plants on farmland leads to a competition for arable land for the production of food and animal fodder.*
- *Monoculture: The production of only one high-yield plant, such as maize, in consecutive years leads to an area poor in biodiversity, decreases the landscape's attractiveness, degrades soils through humus losses, increases the erosion risk and requires substantial fertilisation.*
- *Acceptance: In Germany, the increase in maize for energy use has decreased the acceptance of bioenergy production. Moreover, the comfort of people who live near a biogas plant might be affected due by increased traffic during the harvest season.*
- *Greenhouse gas balance: The greenhouse gas balance is not neutral, especially if the strong greenhouse gas methane escapes from fermentation plants during biogas production. Furthermore, the intensified application of nitrogen to increase energy crop yields produces the very strong climate gas nitrous oxide (N_2O).*
- *Emissions of toxic compounds: The ineffective burning of wood or charcoal in developing countries, but also in old fireplaces in industrialised countries, emits toxic compounds into the atmosphere.*
- *Financial implications: Besides breathing life into rural economies and the creation of new jobs, the competition for land increases the price of comestible goods if the production of food plants decreases due to increased energy croplands. Additionally, the rent for farmland may increase.*

6.5.2 The WBGU criteria

Following the same analysis, WBGU (2008) proposes the next list of advantages and disadvantages of bioenergy use based on the following list of attributes:

Bioenergy PROS:

- *Energy system transformation and climate change mitigation*
- *Energy system transformation and energy poverty*
- *Biomass as:*
    - *energy carrier*
    - *carbon sink and carbon reservoir*
    - *industrial feedstock*
    - *Substitute for energy sources.*

Bioenergy Constraints

- *Ecological*
    - *climate protection*
    - *biosphere conservation*
    - *soil and water protection.*
- *Socioeconomic*
    - *access to sufficient food*
    - *access to modern energy services*
    - *health risks through energy use.*
- *Competing uses*
    - *Competition with food and feed production*
    - *Using biomass as an industrial feedstock*
    - *Competition with biological diversity*
    - *Land-use options for climate change mitigation*
    - *Competing use of soil and water.*

In terms of using crops or land for energy production, WBGU (WBGU, 2008) recommends a minimum standard for bioenergy:

- *Reducing greenhouse gas emissions by using bioenergy carriers*
- *Avoiding indirect land-use change*
- *Preserving protected areas, natural ecosystems and areas of high conservation value*
- *Maintaining soil quality*
- *Ensuring the sustainability of logging by-product use*
- *Managing water resources sustainably*
- *Controlling the effects of genetically modified organisms (GMOs)*
- *Observing basic social standards.*

6.5.3 The RIRDC criteria

Another set of criteria for bioenergy sustainability is provided by the Rural Industries Research and Development Corporation from the Australian Government (O'Connell et al., 2009):

Bioenergy value chains and sustainability issues are complex, especially when they interact with a number of other incumbent industry value chains (for food, fiber and fossil fuels). Sustainability issues that arise throughout value chains are described below.

<u>Biomass feedstock production and harvest</u>

- *Maintenance of critical ecosystem functions, as well as value delivery differs vastly between feedstock types, production systems and geographic regions of the world.*
- *Land and water resources will be increasingly contested and pressured for production of food, fiber, water, biodiversity, carbon storage and urbanization. Bioenergy value chains which rely on diversion of materials from production systems which are already stressed will inherit many of the sustainability issues associated with the incumbent production system.*
- *Natural systems may undergo incremental degradation while still maintaining ecosystem function and value delivery, but are prone to unexpected non-linear and irreversible 'threshold' or 'tipping point' changes.*
- *Producing lignocellulosic biomass can be cost-effective with low-input production systems, on low-productivity or under-utilized land.*
- *The use of land to feed local and global populations, as well as more focal issues of regional and rural livelihoods and landscape amenity are important interpretations and value judgments of developed nations with respect to some of these issues – for example the issues of child labor and gender equity in developing nations - can be problematic.*
- *Production of algal biomass may circumvent many of these sustainability issues, but requires basic research into the production systems.*

<u>Pre-processing and transport</u>

- *Infrastructure is required for transport and pre-processing (e.g. pelletizing, drying) in order to transport the biomass to the conversion facility.*
- *There are trade-off between scale and distance (increased efficiency through increased scale means greater transport distance) and in processing (in-field chipping can increase efficiency of transport, but uses smaller, less-efficient chippers).*

<u>Processing</u>

- *Existing infrastructure can be used (e.g. coal-fired power stations) or could be used with minor modifications (e.g. adding an ethanol distillery to a sugar or flourmill).*
- *Small-scale bioelectricity facilities (e.g. small-scale gasifier) or medium- to large-scale enzymatic or thermochemical plants could be used for off-grid or supplementary generation. Issues include noise, dust, emissions, water use and other standard industrial issues.*
- *Community concerns about the location and operation or large new facilities must be balanced with jobs, regional diversification, livelihoods and stimulus to the focal economy during the establishment and ongoing operation.*

<u>Product streams</u>

- *There are few sustainability issues associated with the products of heat and power per se, unless additional infrastructure is required.*
- *The rise in aggregate demand for heat and power is, however, a key sustainability concern at national and global scales.*
- *New technology products may (e.g. bio-plastics, paint additives and adhesives) may have specific sustainability issues depending on type of combustion and emissions, as well as consequential impacts (positive or negative) through replacing particular existing product markets.*

Transport and distribution for retail

- *As before*

Domestic and international markets

- *Depending on the particular product or suite of products, there may be new markets or existing markets (e.g. petrol, diesel, electricity, plastics and adhesives) for which the new products provide functional equivalents.*
- *For electricity, there are debates and tradeoffs between centralized electricity generation and distributed generation with electricity produced close to demand centers, requiring less distribution infrastructure and losses, as well as spreading of risk.*

Consumption

- *Biofuels must be compatible with the engine technologies for which they are intended to be used. There are economic issues of transition times and strategies given the residence time of vehicles, machinery and aircraft fleets.*
- *These issues are less important with bioelectricity since it is a standardized product.*
- *There is a societal view that new biofuel value chains should be demonstrably "more sustainable" than incumbent energy, agriculture or forestry value chains.*

Sustainability issues indirectly arising from bioenergy value chains

- *A rapid international expansion in biofuels led to an increased demand for sugar corn (for ethanol), and rapeseed (canola) and palm oil (for biodiesel). This is in turn led to many unintended consequences in terms of contributing to price rises for some commodities, and to undesirable land use changes.*
- *The negative impacts of the production of biofuels include displacement of food producers and generating higher food prices on net consumers (mostly affecting poor, vulnerable and food insecure households).*
- *Biofuels were not the sole reason for food price hikes; other drivers are also poor harvest in major grain producer countries; high cost of fertilizers, transport and energy; regulatory policies; increase in demand for food; change in diet in emerging economies; increase in demand for biofuels; US dollar exchange rate changes; speculation.*
- *Biofuels could also have some benefits for developing regions by opening new market opportunities for biofuel feedstock crops, increasing farmer´s income due to higher product prices, and potential reduction of emissions.*
- *The capacity to expand supply of feedstocks varies in different regions of the world. Expansion of supply may be achievable in many areas of the world (e.g. where land is not producing profitable goods, known as "set-aside" land). There are resource constraints on arable land and water in many areas of the world, however. Expanding supply may lead to other land uses becoming displaced- often in locations distant to the actual industry driving the demand. This is referred to as "land use substitution", "indirect land use change", or "leakage".*
- *The indirect causes and impacts of bioenergy and use change are complex to determine, difficult to manage, and contested. This is because the science methods are immature, the data sparse, and because the benefits and costs are distributed differently among different social groups.*
- *The same issues still have the potential to arise in production of lignocellulose for second-generation biofuels or electricity. Replacing high-productivity land currently used for agriculture, with dedicated energy crops could occur, whereas other combinations of policy and economic settings could provide new profitable energy production from lower-productivity land.*

6.5.4 The Leopoldina Criteria

Finally, the German National Academy of Sciences Leopoldina (Anton and Steinicke, 2012) provides some recommendations in regards to bioenergy sustainability (citation):

- *When evaluating the GHG emissions of bioenergy, the full suite of emissions (CO_2, N_2O and CH_4) resulting from fertilizer application, from fossil-fuel consumption during production and conversion of the biomass and from manpower for operations all need to be separately addressed and taken into account. Also the effects of direct and indirect land use change on the GHG balance, on ecosystem functions and biodiversity have to be considered.*
- *All GHG emissions have to be included in a comprehensive climate policy framework, preferably by including these sectors in an emission-trading scheme. This is necessary to provide the right incentives for switching towards low-emission production technologies in agriculture (e.g. mixed systems, precision farming) and restricting additional land conversion for bioenergy production.*
- *To find the best solutions, further research is required on the measurement of land-use related GHG emissions and on consequential comprehensive GHG life-cycle assessments of different production systems for agriculture, food, and bioenergy. Consequential life-cycle assessments have to be based on models, which are able to reliably calculate the total change in global GHG emissions due to bioenergy deployment.*
- *Production of biogas from agricultural and municipal wastes deserves to be developed further. From the perspective of waste disposal, alternatives such as direct combustion or pyrolysis should also be included. The decision on which of these techniques to use depends essentially on the water content of the waste material: the lower the water content, the more direct combustion or pyrolysis is recommended. Energy crops should be used for biogas production only as far as this is needed for stabilization and optimization of the overall process of utilization of agricultural wastes and for the stabilization of fluctuating energy demands.*

Until now, biomass was mainly used for heating (most of the wood) and for electricity production (most of the biogas) rather than for transport. This is of concern since transport fuels are in the long run most difficult to replace. Therefore, the conversion of biomass should concentrate on biofuels for heavy good vehicles, airplanes and large ships that probably, also in the future, cannot be powered by electricity.

7 General conclusion

Different aspects analysed in this research suggest that Los Ríos Region has a large potential for introducing bioenergy as a renewable energy alternative. Its implementation is compatible with current agriculture and might imply new opportunities for regional development. However, in terms of its implementation, sustainability criteria (involving technical, environmental, economic and social dimensions), should be seriously observed in order to harmonize bioenergy with other interests and to avoid uncontrolled bioenergy expansion.

Specific results:

I Biofuels comparison

- A general comparison of the different bioenergy technological approaches currently available in the Chilean and international markets has some restrictions, as focuses, components, locations and methods of different available studies are different. However, through parameter transformation or normalization processes comparable information levels can be obtained.
- Many solutions applied in central Europe seem to be technically feasible in Los Ríos Region, probably because of the climate similarities. However, the different living standards in central Europe and southern Chile, that include economic and cultural factors, make European solutions uncertain for Los Ríos Region.
- Combinations of biomass resources, biofuel technologies and biofuel uses only for Los Ríos Region can be gigantic in number. A systemic view and a specific network analysis can be a good tool to reduce the complexity of the system and to optimize qualitative parameters otherwise difficult to manage.
- Among biofuels, the results of technical and environmental performances have shown that the origin of the biomass is more important than the type of energy carrier, with residues demonstrating the best performance of all, independent on which energy carrier alternative is used. A middle environmental performance was shown by high productive crops with low fossil inputs, like sugar cane ethanol, maize silage biogas or Jatropha biodiesel. The previously existing land use is decisive for the performance. In the case of Jatropha or Palm oil biodiesel the use of degraded/marginal land gave high performance, whereas the use of rainforest land gave very low. The lower environmental performance was reached by bioethanol and biodiesel from crops. In case of and Palm oil, the previously existing land use is also decisive. Correlations were found between GHG reduction and output/input energy ratio, and between GHG reduction and cultivation assessment.
- Regarding the techno-economic performance, the less management and transformation a biomass need to become a biofuel, the more cost-efficient is. That is why residues are expensive to be transformed into biofuels compared to oil plants. An interesting trade-off between environmental and economic performances was found, that may explain big extensions of soy plantations in South America or palm oil plantations in Southeast Asia, but also big opposition from environmental groups.
- On the General Quantitative level biogas shared the high score with lignocellulosic biofuels. However, they are not yet an established technique, have size and technical limitations, but presents high compatibility with biogas. Anaerobic digestion (biogas) is very restricted for lignocellulosic biomass, which is one of the most abundant in Los Ríos Region. However, combustion of lignocellulosic biomass is compatible with biogas cogeneration systems. Even more, gasification of lignocellulosic biomass, a technic in development, may allow to use such abundant resources in the region as wood and crop straw for

biomethane production, which is a fuel that can also been obtain from biogas, and may become a promising energy carrier.

- On the Prioritized Qualitative level, biogas it was found that biogas production has additional strengths such as the use of many kinds of energy crops and plants (diversity) and of organic residues, and high nutrient recycling. After a qualitative exploration through a model of network analysis (Ucinet-Netdraw) that included specific crops, biomases and energy demands from Los Ríos Region, biogas showed the highest relational richness among energy carriers, due to its high versatility (of biomass sources, potential transformation processes, forms of energy and uses), in combination with a high technical performance (resource/energy efficiency and practical feasibility).

II Bioenergy Potentials

- On the Regional Quantitative level, bioenergy potentials for Los Ríos Region are modelled with BioStar for biogas potential from energy crops and with “Explorador de Biomasa Forestal” (Forest Biomass Explorer; UACh, 2013) for bioenergy potential from forest biomass. According to results of modelling biomass potentials with BioStar for the entire region, and supported by field trials and recent national studies of bioenergy potentials, it can be affirmed that Los Ríos Region delivers a high potential for bioenergy development. Results suggest that energy crops could theoretically reach 18% of the regional surface if technical restrictions are observed. In terms of electricity, such biogas production would be equivalent to 20 times the regional demand. However, such expansion would compete with current food production (mainly grassland for cattle), so that land use criteria need to be developed. Other sources of biomass like cow slurry from milk production, industrial and urban organic wastes have lower potential, but still important. Regarding forest bioenergy, results suggest that the amount of thermic energy by far satisfy the demand of village and cities, although a technical and sustainable management of this resource is key to ensure its supply in the future.
- On the Local Qualitative level, it was found that the German model of bioenergy village is not feasible for Los Ríos Region, as prices of buying heat and selling electricity are much lower than in Germany. Therefore, heating networks and biogas electricity cogeneration are too expensive for the regional village reality. However, modifications of such the German bioenergy concept seem to be very interesting for the region. Firstly, in small villages non-electric biogas network could reduce the firewood demand in almost 60%, improving the air quality and improving waste management. Secondly, in medium or bigger cities, where atmospheric pollution is problematic, heating networks can be successfully applied in small urban units, allowed by the efficiency gained through centralized boilers. Thirdly, in big cities, as part of the organic municipal solid waste (OMSW) management, the German bioenergy village concept can be applied to urban units with the size of a village, performing many environmental, economic and social advantages.

III Bioenergy area (case study)

- On the Local Quantitative level, the third concept of bioenergy village above mentioned is studied in detail, applied to a University campus in Valdivia, the capital of Los Ríos Region. Results show that campus Isla Teja could be completely supplied for electricity and half supplied for heat form biogas cogeneration, supplementing the heat gap through firewood boilers. When biogas is produced from local maize silage, energy costs of the campus drop in one third and noxious emissions drop significantly on three of the four parameters studied, although CO emission increases in on third. The GHG reduction is positive or negative depending on if the indirect land use change is considered or not in the calculations. When biogas is produced from OMSW, energy costs of the campus rise in almost two thirds (59%). However, noxious gases perform the same situation as with energy crops, and GHG reduction reach 940%. This big reduction is produced by the reduction of current fossil energy consumption and the avoidance of methane release at landfill, transport of half of the total city waste (organic fraction) and nutrients wastage, all of which imply less air, soil and water pollution. For setting such a system, a big cultural change is needed, so that its implementation can be a motivation to rise environmental innovation, education, participation and consciousness.

Regarding the general research question (*What bioenergy system(s) is(are) the best choice to be developed in Los Ríos Region?)* (Section 3.1), many of the specific research questions were addressed and answered in order to answer it. However, the general research question itself can be answered, but cannot be proved, as it is analyzed regarding the third research hypothesis XX. In the other hand, residual biomass has shown the best sustainability performance among the various biomasses evaluated. Therefore, bioenergy technological alternatives that work with residual biomasses also present good performances. On the other hand, such technological alternatives should also be flexible in terms of operational size, kinds and formats of input biomasses and use of their produced biofuels. Finally, such technological alternatives should show high efficiencies and should be able to work with the more abundant biomasses in the region or the ones with more potential. Regarding all these criteria, and the specific context of Los Ríos Region, evidences and results in this research have shown that biogas behaves as the best alternative among biofuels at all levels of analysis realized and the complementarity between anaerobic digestion (biogas) and combustion of lignocellulosic biomass as a bioenergy system present the best performance for the region.

Regarding the first research hypothesis: cycling systems, the fact that residues show the best performance gives good reason to consider that the first hypothesis is correct, as the use of residues is a concrete way to recycle matter and energy in any given system. The use of residues reduces external inputs and outputs, which is a pre-condition for good technical and environmental performances, and for land self-sufficiency and autonomy. Similarly, local systems that naturally configure recycling processes have shown better sustainability performance than other alternatives. A model developed through network analysis (Section 5.3.2.1) can be considered as an antecedent in the direction of accepting the hypothesis and suggesting a mathematical formalization of it. However, considering the conceptual and linguistic complexity of the hypothesis, its complete demonstration seems not to be possible, especially with regards to a formal mathematical expression.

Regarding the second research hypothesis: advantages of biogas, considering the results of the different levels of analysis, the second research hypothesis is accepted, in terms that biogas shows the best sustainability performance.

Regarding the third research hypothesis: a systemic epistemological view, the use of an epistemological model resulted a contribution to the research process. Such approach suggested that the complexity and transdisciplinarity of the problem make that answers to the research questions cannot be proven in strict scientific terms, as there is no a logical common ground to enable a demonstration among all of the disciplines involved. This can be either a weakness of the transdisciplinary approach or a limitation of disciplinary science when applied to transdisciplinary issues. This approach also suggest that the complexity of the here studied problem is determined by the scale and detail of the distinctions made in this research itself, and not by a discrete number of variables preexisting in nature. Additionally, searching for the "best alternative" is a question of design and development, not a search of causes, as in basic sciences. In this way, the result of the design process is always the best solution, that is, the best solution that a researcher can reach with his/her capacities, knowledge and conditions, relative to a specific local-temporal situation, namely, his/her specific cognitive domain.

Therefore, it is not possible to demonstrate that any one alternative is the best; it is only possible to demonstrate that an alternative is not the best through falsification.

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9 Appendix

9.1 Tables of qualitative biofuel comparisons

Table A1: Qualitative comparison: advantages, disadvantages and global production of different biofuels in 2013 (Guo et al., 2015)

Biofuels		Advantages	Disadvantages	Annual production
Solid	Firewood	Renewable, readily available, cheap, most energy efficient	Bulky, low in energy density; high hazardous emissions from incomplete combustion; unsuitable for automated burners	17×10^8 m^3
	Wood chips	More convenient to transport, handle, and store than firewood; lower SO_2 and NO_x emissions than coal upon combustion	Involves chipping cost; tends to decay during storage; bulkier and lower in energy density than coal; ash slagging and boiler fouling; unsuitable for precise combustion	3.5×10^8 t
	Wood pellets	Convenient to transport, handle, and store; low SO_2 and NO_x emissions; suitable for precise combustion	Higher processing cost; lower energy content than coal; only be used in solid fuel burners	20×10^6 t
	Charcoal	Stable, high energy content, clean burning	High production cost; bulk, inconvenient for transport; cannot be used in liquid fuel and gas burners	51×10^6 t
Liquid	Corn/sugar ethanol	Renewable substitute for gasoline; low combustion emissions; existing feedstock production systems	Low net energy efficiency; corrosive to existing gasoline fueling devices; competing with food and feed for source materials	23×10^9 gal
	Cellulosic ethanol	A gasoline alternative from non-food biomass	Low net energy efficiency; not cost-effective	$< 5 \times 10^6$ gal
	Biodiesel	Renewable substitute for petro diesel; existing feedstock production systems	Competes with food production; feedstock is limited to lipids; corrosive to existing diesel fueling devices; substantial processing cost	63×10^8 gal
	Pyrolysis bio-oil	Renewable feedstock; simple conversion technology	Upgrading is needed prior to fuel uses; immature upgrading techniques	Pilot production $< 1 \times 10^6$ gal
	Drop-in fuels	Renewable feedstock; gasoline substitute; compatible with existing fueling systems	Immature, complicated conversion technology; high cost	Early development stage
Gaseous	Biogas	From organic waste and residues, wide feedstock sources; fits the existing natural gas grid	Usually in rural areas; requires intensive feedstock collection and waste disposal	$\sim 25 \times 10^9$ m^3 CH_4
	Syngas	Mature production technology; as feedstock for industrial chemicals	Char and bio-oil as byproducts; stringent requirements for feedstock	4.5×10^{11} m^3

Table A2: Summary of qualitative environmental rating of different biofuel cultivation systems (WBGU, 2008)

Summary and qualitative rating of the productivity and impact on biological diversity and carbon sequestration in the soil of the proposed cultivation systems. A yellow rating indicates that different impacts on these factors are possible, depending on previous use and cultivation methods. The colour for the overall rating corresponds to the colour rating of the majority of the factors studied.
Sources: Productivity: see caption; biological diversity and carbon sequestration in the soil: WBGU qualitative estimate

Cultivation systems	Productivity [t of dry matter/ha/year]	Sources	Productiv-ity rating	Biodiver-sity rating	Soil carbon rating	Overall rating
Tropical monocultures						
Annual						
Sugar cane	10–120; 80; 70 (a)	1, 3, 5	green	red	red	red
Perennial						
Sugar cane	10–120; 80; 70 (a)	1, 3, 5	green	red	yellow	yellow
Oil palm	30; 13,8 (b)	3, 5	green	yellow	yellow	yellow
Jatropha	0,2–8; 0,5–12 (b)	3, 4	yellow	yellow	yellow	yellow
Temperate Monokulturen						
Annual						
Maize	8–14*; 9; 9 (d)	2, 5, 6	green	red	red	red
Rape	4,1; 3,4; 3 (c)	1, 5, 6	yellow	red	red	red
Triticale	3,5–9**; 5,6; 6 (d)	2, 5, 6	green	red	red	red
Perennial						
Miscanthus grass	up to 30; 10–27,5; 11-40 (a)	1, 2, 3	green	yellow	yellow	yellow
Switch grass	12–17; 5,2–11,1 (a)	7, 8	green	yellow	yellow	yellow
SRPs: poplar/willow	4–16/2–14; 12–15/5–20 (a)	2, 3	green	yellow	yellow	yellow
Grassland						
Tropical grassland, pasture	not specified		yellow	green	green	green
Temperate grassland, grassland systems						
Grass leys	7–15 (e)	2	green	yellow	green	green
Permanent grassland	7–12 (f)	2	green	green	green	green
Forests						
Agroforestry	not specified		yellow	green	green	green
Wood residues from forests						
Tropical	not specified		red	red	red	red
Temperate	not specified		red	green	green	green
Boreal	not specified		red	green	green	green

Impacts
- red: negative
- yellow: unclear
- green: positive

Sources
1: Lieberei et al., 2007
2: KTBL, 2006
3: El Bassam, 1998
4: Openshaw, 2000
5: FAOSTAT, 2007
6: LfL Bayern, 2008
7: TFZ, 2008
8: Schmer et al., 2008

(a) Worldwide
(b) Seed yield, worldwide
(c) Seed yield, Germany
(d) Grain yield, Germany
(e) In rotation, Germany
(f) Permanent grassland

* DM content = 70 %
** DM content = 86 %

Table A3: Compilation of LCA (Life Cycle Analysis) based on studies of non-food biomass by Bringezu et al. (2007)

Study	Scope	Environmental impacts
	Biofuels	
Worldwatch Institute 2006	Review of studies on current generation biofuels for transportation – Global scale	Greenhouse gas emissions
EUCAR, CONCAWE and JRC (2007)	Evaluation of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond.	Energy use and greenhouse gas (GHG) emissions
Reinhardt and Helms 2006	Review of biofuels from crops and from residues, compared against each other and to their fossil fuels counterparts – Global scale	Energy consumption and Greenhouse gas emissions for all fuels studied. In addition, Acidification, Eutrophication, and Ozone depletion for Biodiesel from rapeseed.
Reinhardt et al. 2006	Biomass-to-Liquid (BtL) by different technologies and from different residues or crop biomass, compared to other biofuels and fossil diesel, and compared to electricity/heat generation from biomass – Germany	Energy consumption, Greenhouse gas emissions, Acidification, Eutrophication, Ozone depletion, Photosmog, Toxicity for humans
Reinhardt et al. 2007	Biofuel and electricity/heating from palm oil in South East Asia, derived from cleared natural forest, tropical fallow, or other plantations	Energy consumption, Greenhouse gas emissions
WRI 2007; Marshall and Greenhalgh 2006	Bioethanol from corn kernels and from cellulose (corn stover, switchgrass) – USA	Greenhouse gas emissions, Water pollution (from N-fertilisers, pesticides), Water requirements, Impaired soil quality, Habitat quality
	Bioenergy	
IE 2005	Biogas from manure, crop biomass or organic waste; for electricity, heat or use as fuel – Germany	Energy consumption, Greenhouse gas emissions, Acidification, Eutrophication
IE 2006	Biogas for electricity from manure, crop biomass or organic waste, by farm type (milk producing or pig breeding), and compared to electricity/heat from other sources resp. natural gas used as fuel – Germany	Energy consumption, Greenhouse gas emissions, Acidification, Eutrophication
Nitsch et al. 2004, (resp. DLR et al. 2004)	Biomass for electricity, heat or fuels, compared to electricity mix, heat mix, resp. fossil diesel – Germany. Biomass comprises wood, short rotation wood, biogas from manure, straw from wheat, Ethanol from sugar beets, Biodiesel from rapeseed	Consumption of non-renewable/non-energy resources (iron ores, bauxite); Energy consumption (non-renewable); Greenhouse gas emissions; Acidification; Eutrophication; Photosmog
	Biomaterials	
Weiss et al. 2006	45 bio-based and fossil-based product pairs, of which are 21 Materials, 7 Fuels and 17 Energy (power/heat) – Germany	Energy consumption (non-renewable); Global Warming Potential; Acidification Potential; Eutrophication Potential; - detailed and all aggregated to one environmental index

9.2 Original Figures of biofuel comparisons used in Section 6.2

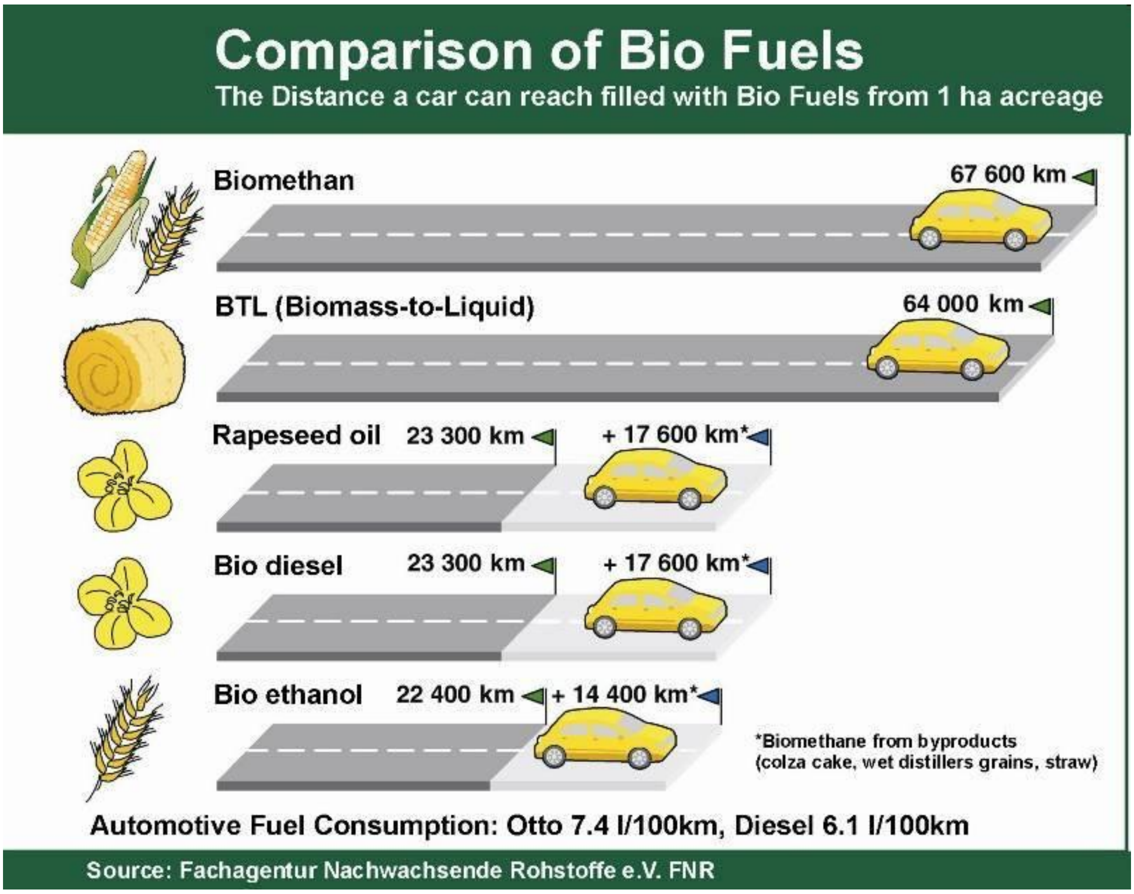

Figure A1: Comparison of kilometers driven with a mid-class car, depending on the biofuels, used (FNR, 2014)

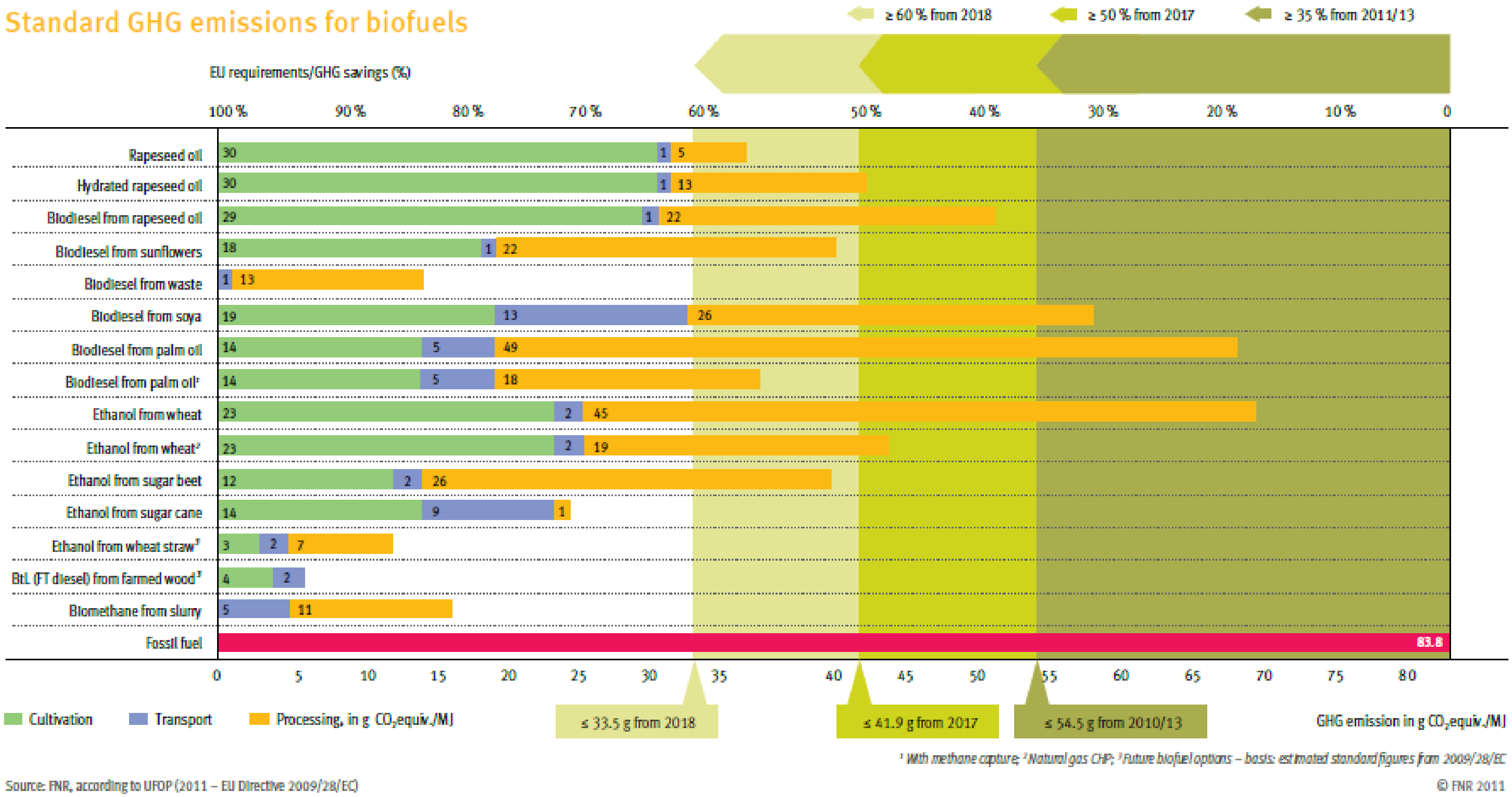

Figure A2: GHG reduction of different biofuels compared to fossil fuel (FNR, 2014)

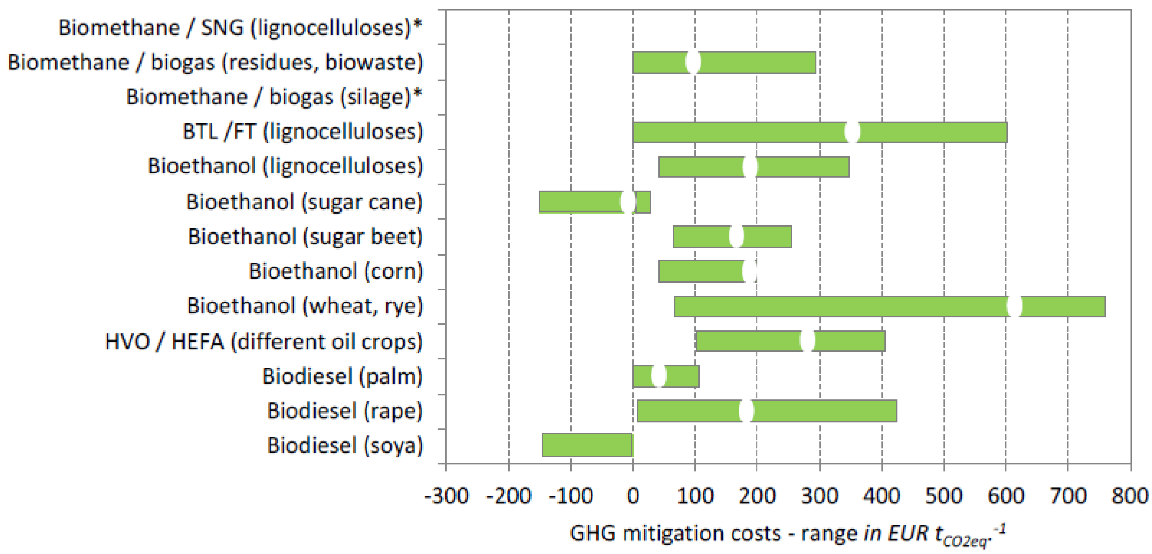

Figure A3: GHG mitigation costs in Euro per t CO_2-eq. (Müller-Langer et al., 2014)

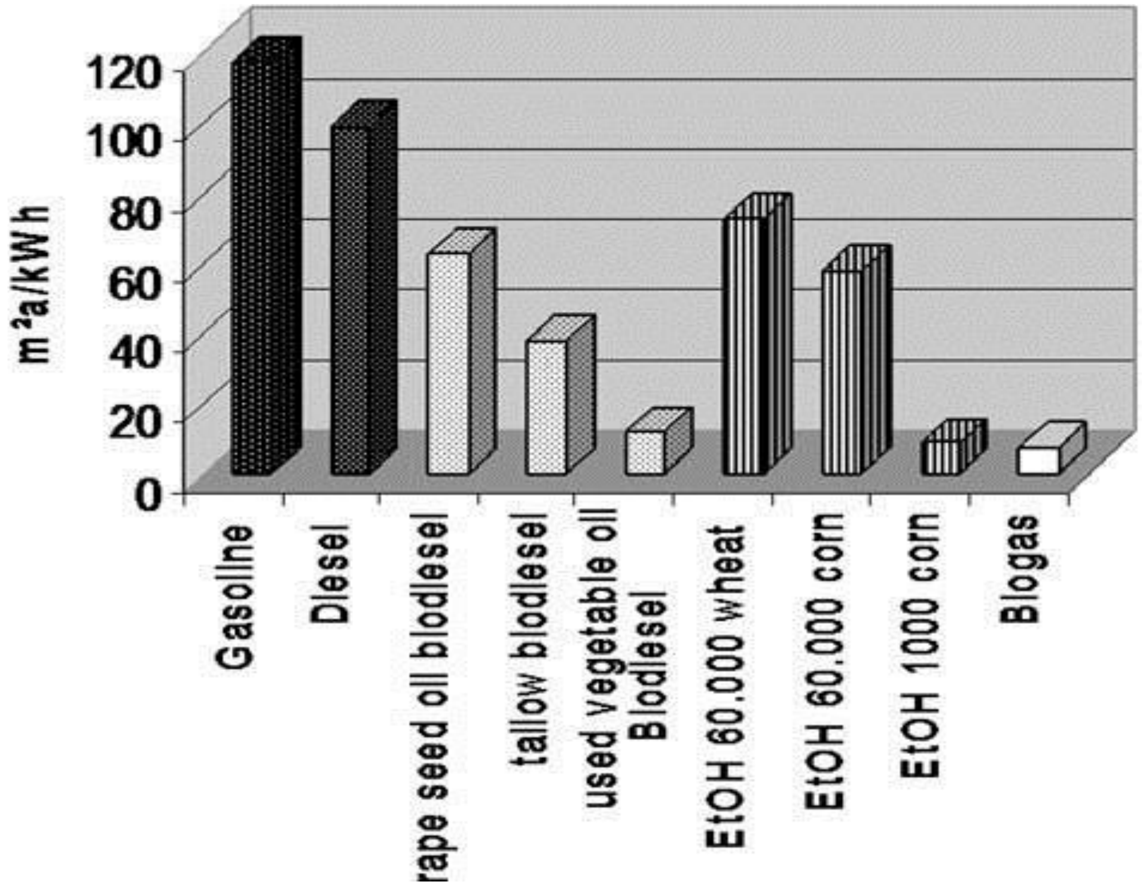

Figure A4: Ecological footprint of different biofuels compared to fossil fuels expressed as m^2/kWh (Stoeglehner & Narodoslawsky, 2009).

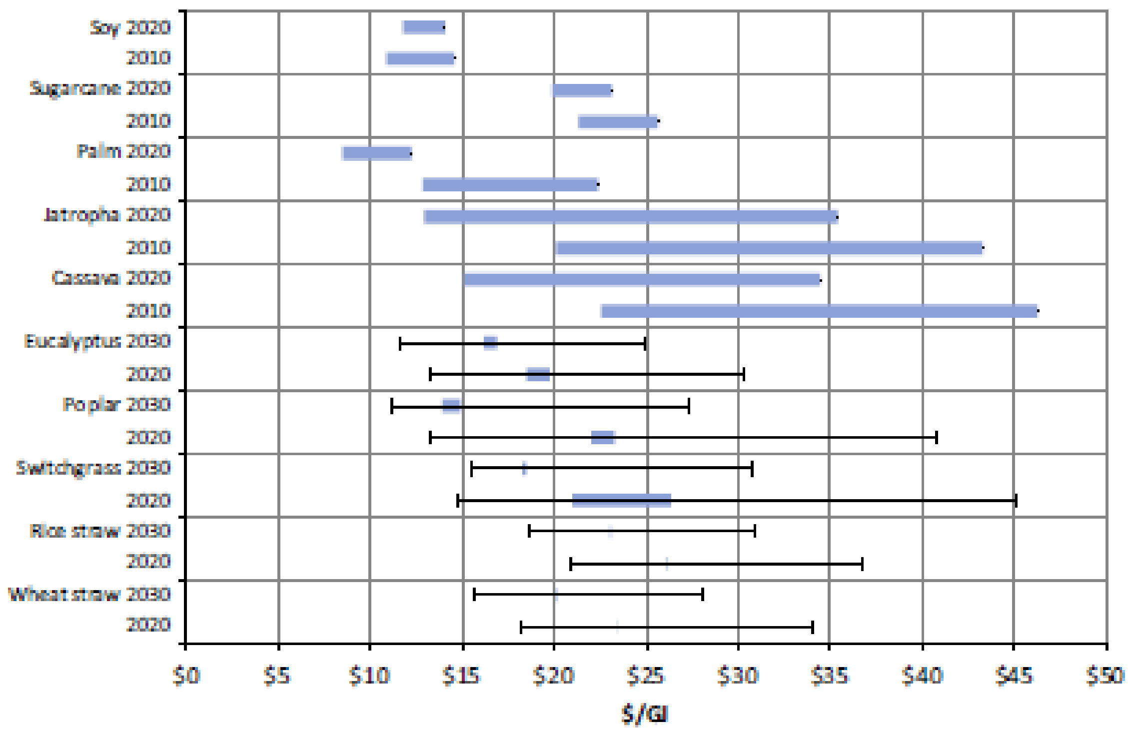

Figure A5: Overview of biofuel production costs per plant in $/GJ including ranges for 2nd generation crops, all settings combined (including the uncertainty ranges for 2nd generation feedstocks) (van Eijck et al., 2014).

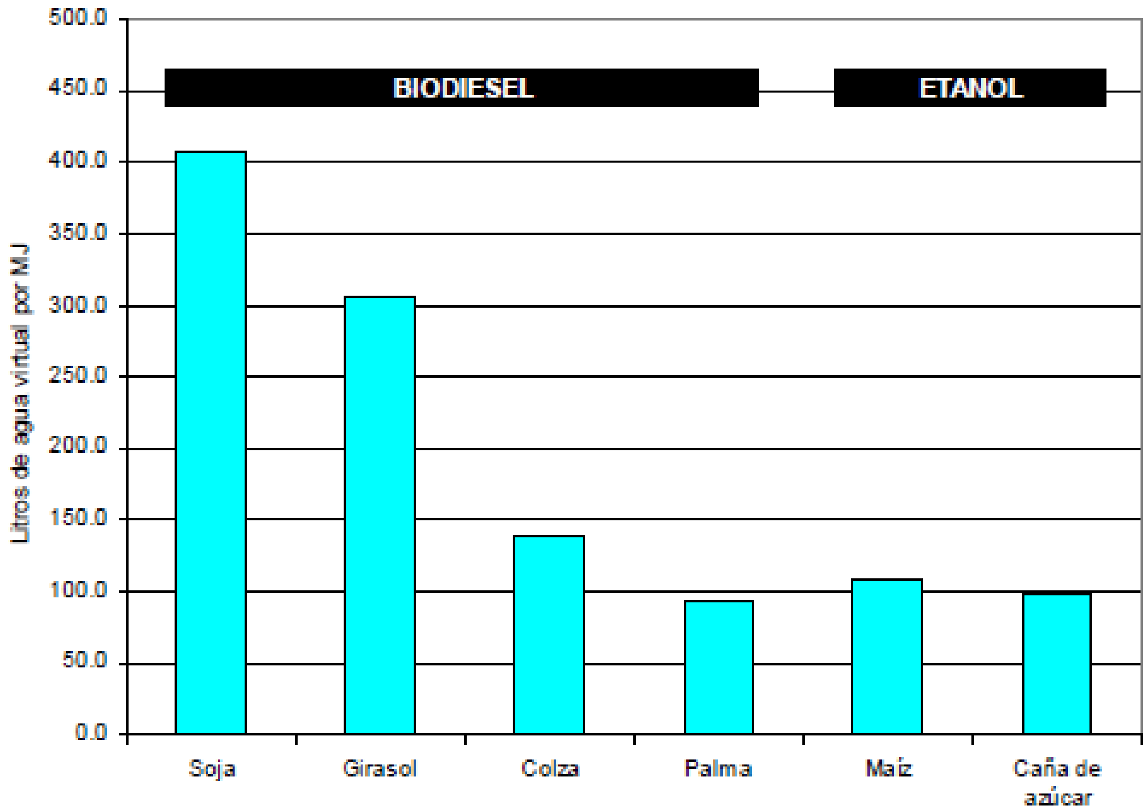

Figure A6: Virtual water consumption (water footprint) in the agriculture production per unit of energy generated as biofuel (Samaniego & Antonissen, 2008)

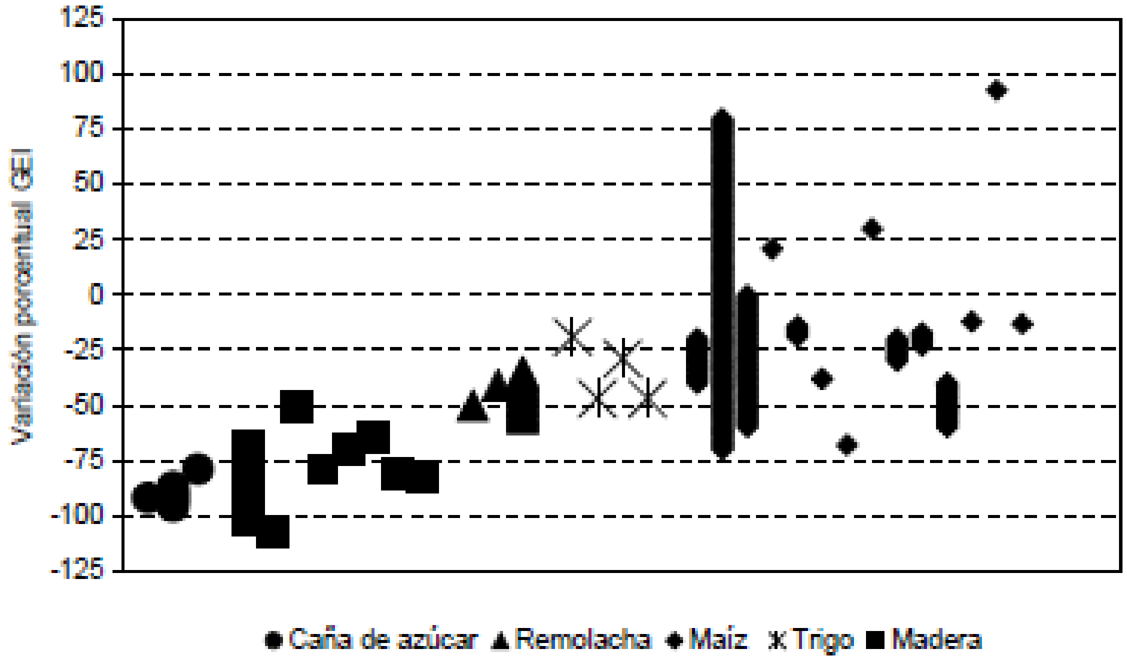

Figure A7: GHG reduction (% in relation to fossil fuels) of different biofuels in relation to fossil fuel use. Caña de azucar: sugar cane, Remolacha: sugar beet, Maíz: maize, Trigo: wheat, Madera: wood (Samaniego & Antonissen, 2008).

Table A4: Life Cycle Energy Efficiency (LCEE), Fossil Energy Ratio (FER), Contribution to Global Warming (GW), Land Use Intensity (LUI), and Carbon Stock Change Emissions (CSCE) (Mata et al., 2013).

Selected sustainability indicators for comparing gasoline, fossil diesel, bioethanol and biodiesel from various feedstocks [16,20,52–54].

Indicator/fuel type	LCEE (dimensionless)	FER (dimensionless)	GW (kg CO_2-eq/MJ fuel)	LUI (m^2 yr /MJ fuel)	CSCE (kg CO_2-eq/MJ fuel)
Gasoline [58]	5.18	5.18	0.08	–	–
Fossil diesel [1]	6.25	6.25	0.10	–	–
Sugarcane bioethanol [21,58]	7.63	7.63	0.06	0.03	0.07
Corn bioethanol [21,59,60]	1.53	1.84	0.06	0.11	0.29
Tallow biodiesel [1]	1.66	1.66	0.13	–	–
Palm biodiesel [1]	1.28	1.28	0.04	0.05	0.08
Sunflower biodiesel [1]	1.04	1.04	0.05	0.28	0.70
Rapeseed methyl ester [1]	2.90	1.15	0.04	0.31	0.78
Rapeseed ethyl ester [1]	2.97	1.32	0.07	0.31	0.78
Soybean biodiesel [1]	0.41	0.41	0.13	0.46	1.66
Microalgae biodiesel [1]	1.84	0.56	0.14	0.01	0.01

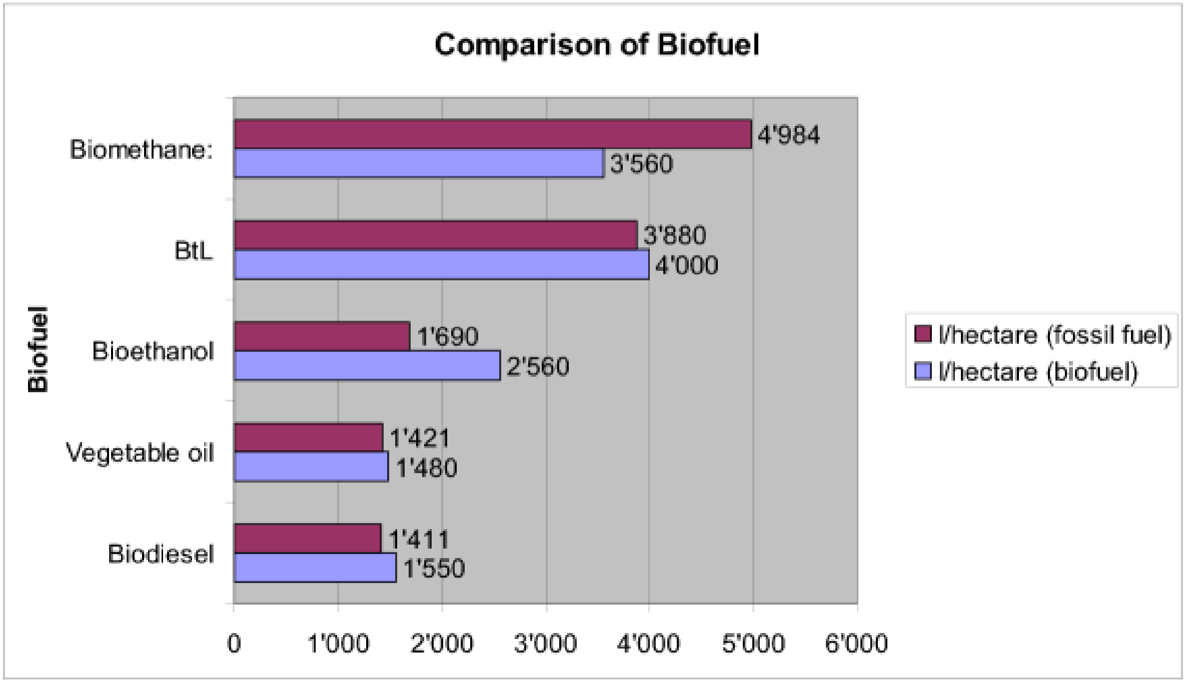

Figure A8: Summary of the comparison of biofuel (Kleinschmidt, 2010)

Table A5: Energy return on investment (EROI) and area efficiencies of fuel and electricity production (Anton and Steinicke, 2012).

	EROI	Area efficiency ($W\,m^{-2}$) (year's average) [e]
Firewood (Germany)	10 [a]	< 0.2
Biodiesel from rapeseed (Germany)	< 2 [a]	< 0.2
Bioethanol from maize (USA)	1.5 [a]	< 0.3
Bioethanol from sugar beet (Germany)	3.5 [a]	< 0.4
Bioethanol from sugar cane (Brazil)	8 [a,b]	< 0.5
Bioethanol from Triticale/maize (Germany) (combined production)(Chapter 2.11)	8 [a]	< 0.3
Bioethanol[a] methane[a] and electricity from lignocellulose (Chapter 2.11)	3	< 0.5
Bioethanol from switch grass (USA)	5.4 [a]	< 0.2
Bio-butanol	< 1 [a]	
Biodiesel from algae (Chapter 1.17)	< 1 [a]	
Biogas from maize silage (Germany)	4.8 [a]	< 1.1
Biogas from maize silage (Germany) (electricity)	1.4	< 0.4
Photovoltaic (Germany) (electricity)	7	> 5
Photovoltaic (Brazil) (electricity)		> 10
Wind turbine (Germany) (electricity)	18	2 – 3 [c]
Nuclear power (electricity)	10 – 20 [d]	
Hydropower (electricity)	100	

a) Combustion energy
b) This high EROI is reached only when bagasse (the residue from sugar cane after it has been crushed to extract the juice) is used as the main energy source for distillation, which is not sustainable because of the resulting loss in soil carbon (Chapter 1.12).
c) Land based standard wind farms; the land between the turbines may be used for agricultural or other purposes.
d) EROI estimates for nuclear power as low as 1 and as high as 50 can be found in the literature.[70] The estimates are problematic because of the still poorly developed database for the costs of deconstruction and making good the damage caused by catastrophes.
e) Average power during 365 days and 24 hours a day

Table A6: Synthesis of the evaluation of bioenergy pathways, separated according to cultivation systems, technical analysis, and greenhouse gas balance. Pathways shaded grey are residue pathways. *For pathways that have grass silage/slurry as a substrate, it has been assumed that in Germany grass silage does not cause any emissions from land-use changes; this does not necessarily apply to the rest of the world. Source: WBGU (2008) based on the data of Fritsche and Wiegmann (2008) and, Müller-Langer et al.(2008).

Pathway	**Cultivation systems** (overall assessment)	**Technical analysis** (Energy efficiency [%])	**GHG balances** (GHG reductions with iLUC per unit of raw biomass [t CO2-eq/TJ])
Positive impact	1	over 60	over 60
Unclear impact	2	18–30	30–60
Negative impact	3	below 18	below 30
Switchgrass-pellets-heating-2030	2	17	17
Short rotation-pellets-heating-2030	2	20	-1
Wood residues-pellets-heating-2005	1	19	61
Straw-pellets-heating 2005	1	15	46
Oil palm (rainforest)-vegetable oil-small-scale CHP-2030	3	23	-185
Oil palm (degraded)-vegetable oil-small-scale CHP-2005	2	23	190
Jatropha-vegetable oil-small-scale CHP-2030	2	34	27
Jatropha (degraded)-vegetable oil-small-scale CHP-2030	2	34	176
Rape-vegetable oil-small-scale CHP-2005	3	43	29
Maize silage-biogas-small-scale CHP-2005	3	33	37
Switchgrass-biogas-small-scale CHP-2030	2	36	54
Grass silage/slurry-biogas-small-scale CHP-2030*	1	30	107
Maize silage-biogas-fuel cell (SOFC)-2005	3	36	57
Switchgrass-biogas-fuel cell (SOFC)-2030	2	40	63
Grass silage/slurry-biogas-fuel cell(SOFC)-2030*	1	33	112
Maize silage-biomethane-small-scale CHP-2005	3	29	30
Switchgrass-biomethane-small-scale CHP-2030	2	31	53
Grass silage/slurry-biomethane-small-scale CHP-2030*	1	26	84
Maize silage-biomethane-combined-cycle power plant-2005	3	30	44
Switchgrass-biomethane-combined-cycle power plant-2030	2	32	49
Grass silage/slurry-biomethane-combined-cycle power plant-2030*	1	27	93
Short rotation-biomethane-combined-cycle power plant-2030	2	30	29
Short rotation-raw gas-gas turbine-2030	2	28	9
Short rotation-raw gas-fuel cell (SOFC)-2030	2	41	31

Pathway	**Cultivation systems** (overall assessment)	**Technical analysis** (Energy efficiency [%])	**GHG balances** (GHG reductions with iLUC per unit of raw biomass [t CO2-eq/TJ])
Short rotation-wood chips-central CHP-steam turbine-2030	2	33	47
Short rotation-pellets-coal-fired power plant-2030	2	43	38
Harvest residues/slurry-biogas-small-scale CHP-2005	1	24	113
Organic wastes-biogas-small-scale CHP-2005	1	29	88
Harvest residues/slurry-biogas-fuel cell (SOFC)-2005	1	27	122
Organic wastes-biogas-fuel cell (SOFC)-2005	1	32	91
Harvest residues/slurry-biomethane-small-scale CHP-2005	1	20	94
Organic wastes-biomethane-small-scale CHP-2005	1	26	80
Harvest residues/slurry-biomethane-combined-cycle power plant-2030	1	21	103
Organic wastes-biomethane-combined-cycle power plant-2005	1	27	86
Wood residues-biomethane-combined-cycle power plant-2030	1	30	100
Wood residues-raw gas-gas turbine-2030	1	29	86
Wood residues-raw gas-fuel cell (SOFC)-2030	1	41	109
Wood residues-wood chips-central CHP-steam turbine-2005	1	33	112
Straw-wood chips-central CHP-steam turbine-2005	1	30	107
Wood residues-pellets-coal-fired power plant-2005	1	38	101
Straw-pellets-coal-fired power plant-2005	1	35	87
Oil palms (rainforest)-biodiesel-car-2030	3	11	-257
Oil palms (degraded)-biodiesel-car-2005	2	10	149
Jatropha-biodiesel-car-2030	2	16	-13
Jatropha (degraded)-biodiesel-car-2030	2	16	63
Short rotation-Fischer-Tropsch diesel BtL-car-2030	2	15	-13
Rape-biodiesel-car-2005	3	23	-28
Rape-vegetable oil-car-2005	3	19	-56
Sugar cane-ethanol-car-2005	2	8	-3
Sugar cane (degraded)-ethanol-car-2030	2	9	47
Maize grain-ethanol-car-2005	3	11	-10
Cereals-ethanol-car-2005	3	11	-45
Maize silage-biomethane-car-2005	3	9	-28

Pathway	**Cultivation systems** (overall assessment)	**Technical analysis** (Energy efficiency [%])	**GHG balances** (GHG reductions with iLUC per unit of raw biomass [t CO2-eq/TJ])
Short rotation-biomethane-car-2030	2	20	-15
Grass silage/slurry-biomethane-car-2030*	1	15	53
Switchgrass-biogas-small-scale CHP-electric car-2030	2	30	40
Wood residues-wood chips-central CHP-steam turbine-electric car-2030	1	31	116
Harvest residues/slurry-biogas-small-scale CHP-electric car-2005	1	20	97
Wood residues-Fischer-Tropsch diesel BtL-car-2030	1	16	51
Straw-Fischer-Tropsch diesel BtL-car-2030	1	14	49
Waste fat-biodiesel-car-2005	1	25	80
Straw-ethanol-car-2030	1	11	32
Wood residues-biomethane-car-2030	1	20	63
Harvest residues/slurry-biomethane-car-2005	1	9	36
Organic wastes-biomethane-car-2005	1	13	34
Wood residues-hydrogen-fuel cell (PEM)-car-2030	1	16	52

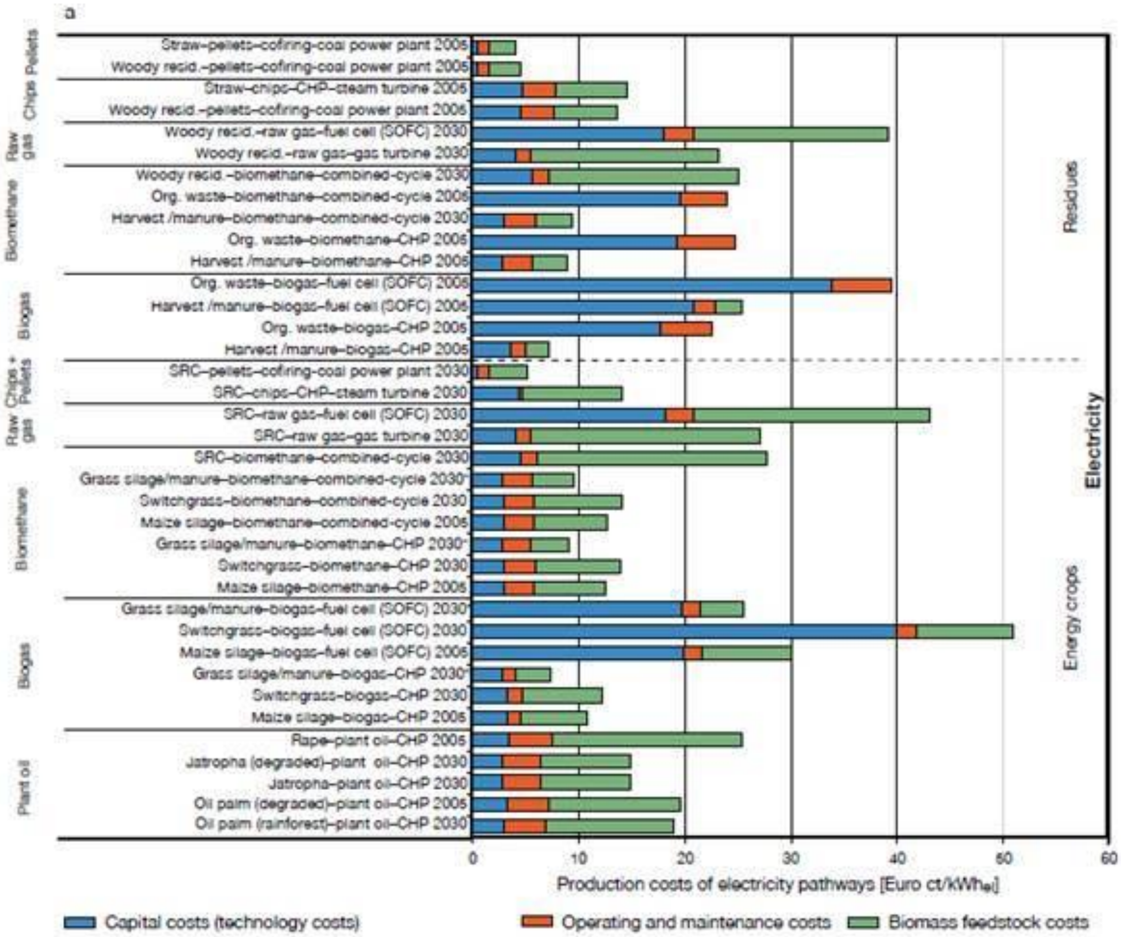

Figure A9: Production costs of bioenergy pathways for electricity generation. The proportions of capital/technology costs, operating costs, and feedstock costs are shown in each case. *For these pathways, a mixture of 70% grass and 30% manure is assumed (WBGU, 2008).

Table A7: Efficiencies and allocation factors[51] for the bioenergy pathways with CHP analysed in the report. Source: Müller-Langer et al, 2008 (quoted by WBGU, 2008).

Technology	Electrical efficiency η_{el} [%]	Thermal efficiency η_{th} [%]	Allocation factor for electricity as main product
Small-scale CHP unit	38	44	0.68
Fuel cell (SOFC)	48	23	0.84
Steam turbine	23	60	0.49
Gas turbine	25	55	0.53
Hard coal-fired power plant	45		1.0
Combined-cycle power plant	43	30	0.78

Table A8: Characteristic values for the vehicle types used in mobility pathways, as per the New European Driving Cycle. The MJ quantity related to input describes the energy carrier in the vehicle, i.e. one MJ fuel or one MJ electricity. Source: Müller-Langer et al. (2008, quoted by WBGU, 2008).

Vehicle type –drive system	Time horizon	Mileage related to input [km/MJ]	Efficiency (mechanical drive energy related to input)
Otto combustion engine for petrol and gas (methane)	2005	0.37	0.26
	2030	0.48	0.29
Diesel combustion engine	2005	0.43	0.29
	2030	0.53	0.32
Electric motor	2030	1.11	0.78
PEM fuel-cell Passenger car with electric motor	2030	0.71	0.39

[51] In order that by-products (co-products) are also included in determining the specific energy expenditure, a proportion of the expended energy is assigned to these in what is known as allocation. Allocation is done on the basis of allocation factors along the inventory boundaries. These factors determine what fractions are allocated to the main product and what to the co-product. In CHP, electricity is considered a main product and heat a co-product (WBGU, 2008).

9.3 Different representations of biomass transformation processes

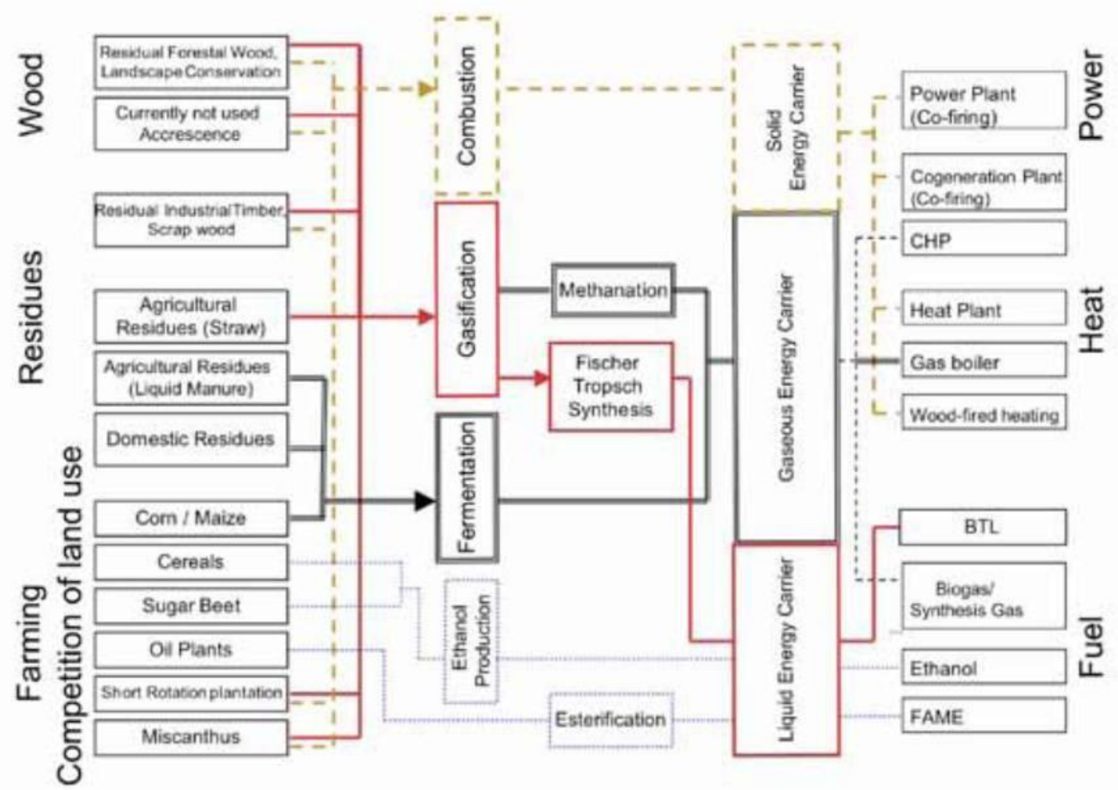

Figure A10: Example of main pathways used for transformation of energy (Bringezu et al., 2007)

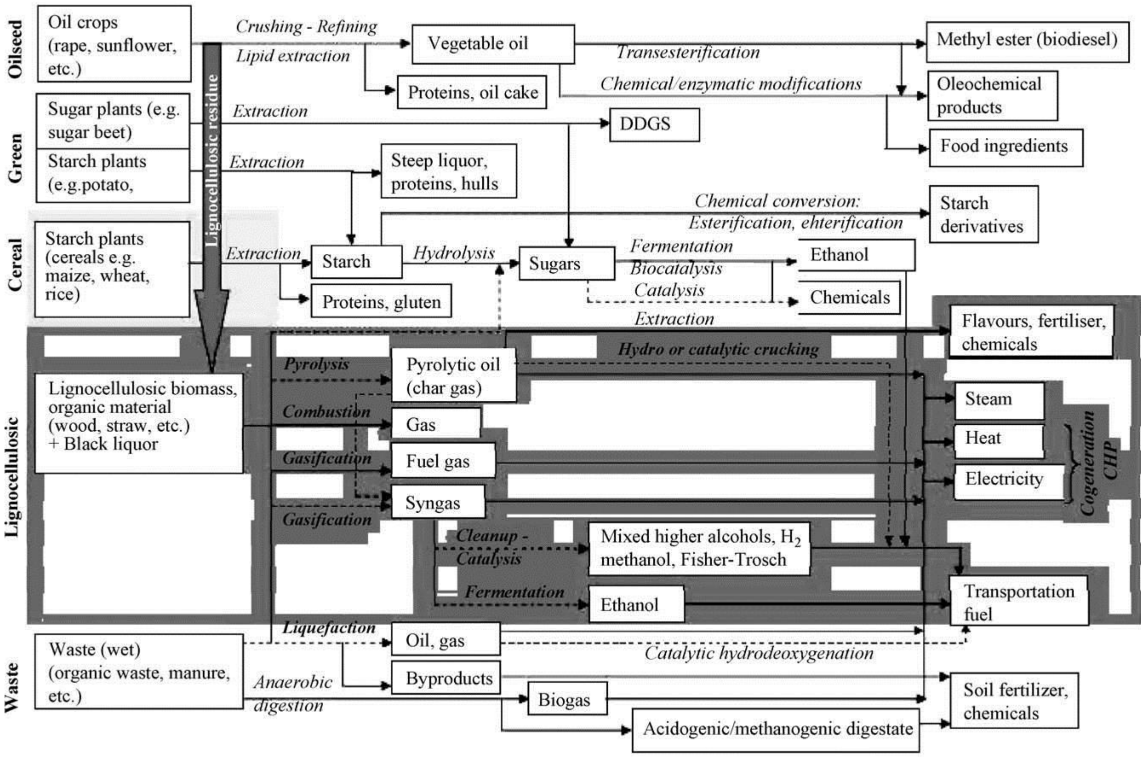

Figure A11: Example of pathways used for an integrated biorefinery (www.biorefinery.euroview.eu)

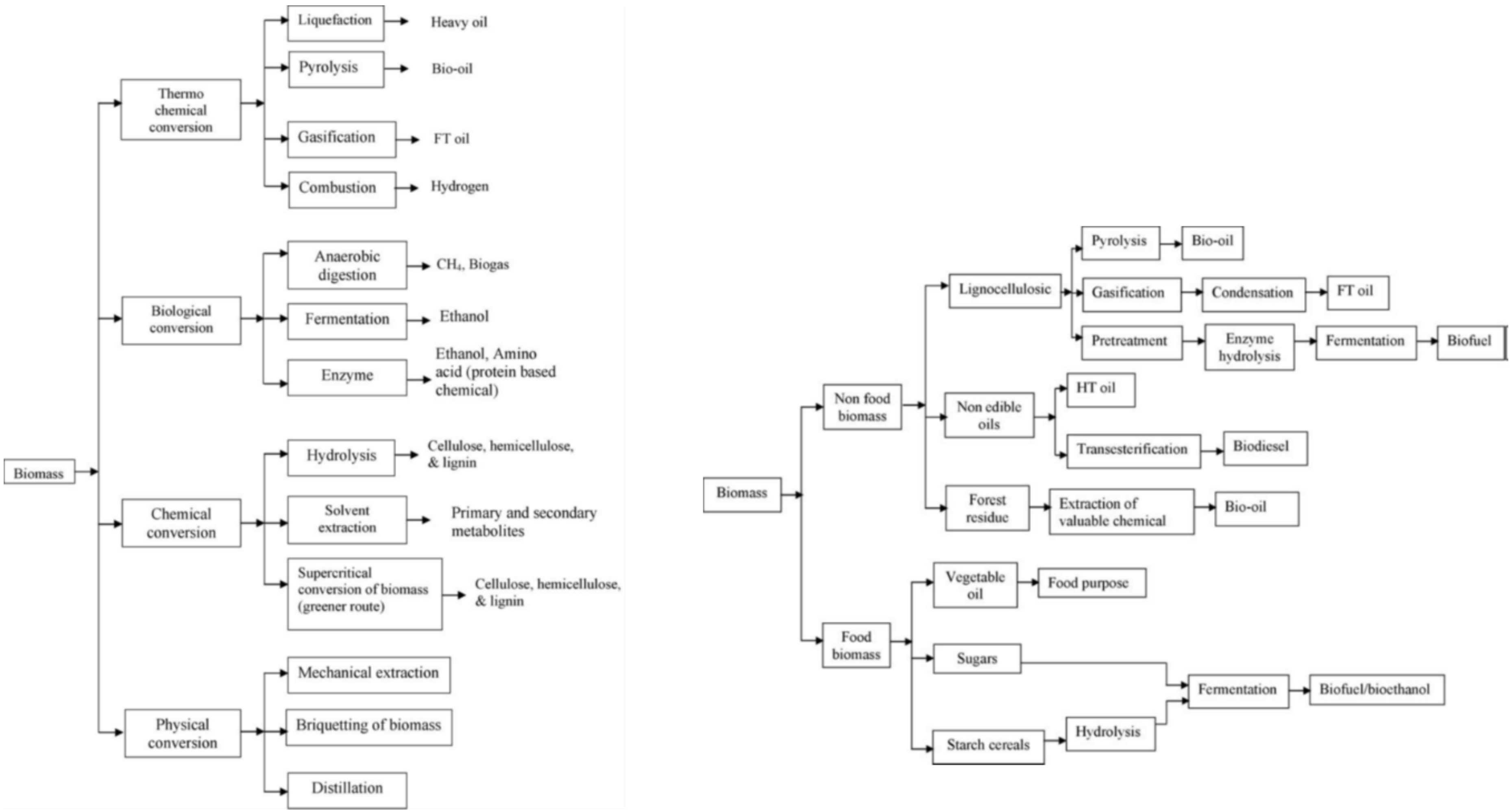

Figure A12: Example of biomass transformations. a) Biomass conversion processes b) Second generation biofuel production from biomass (Naik et al., 2010).

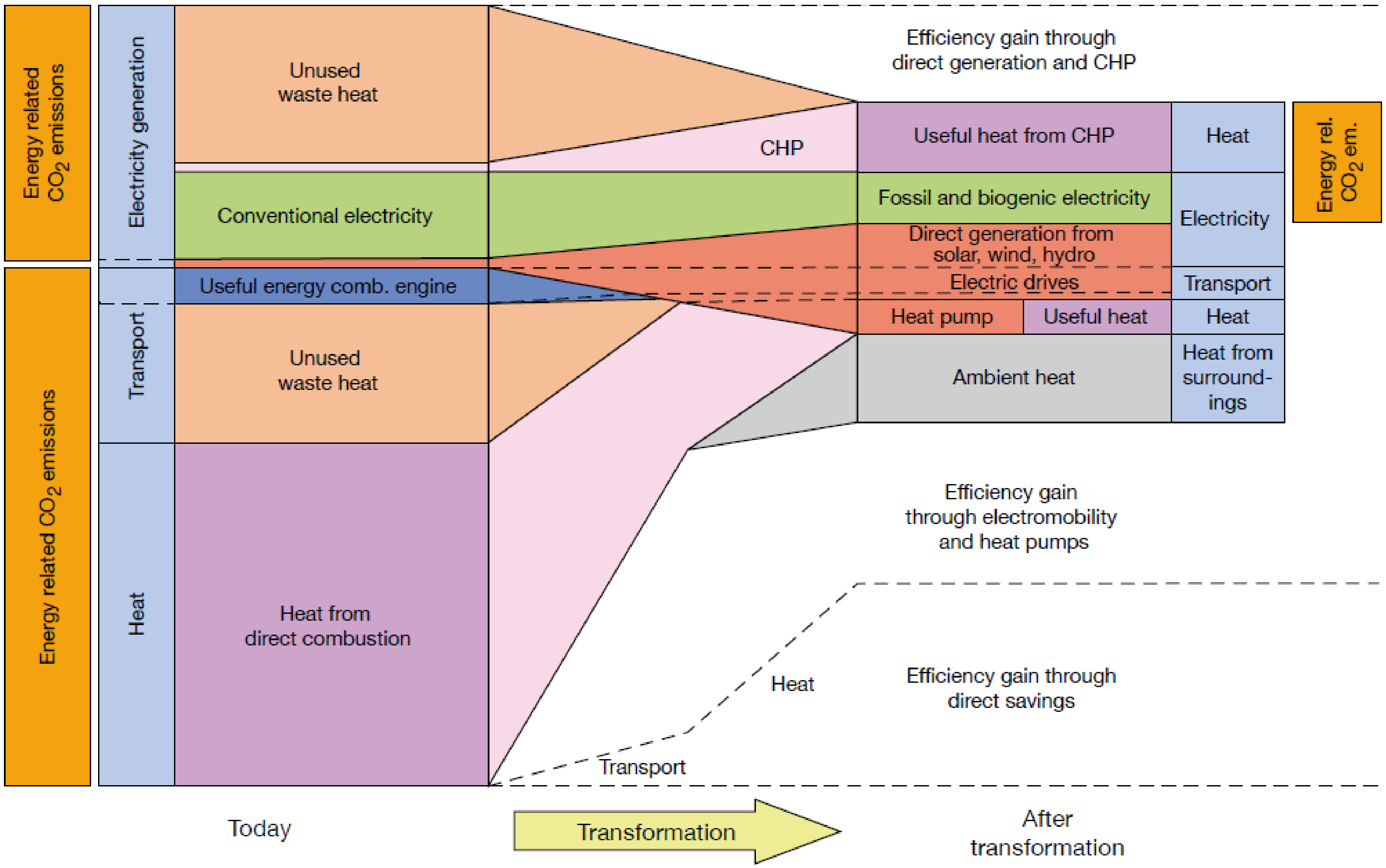

Figure A13: Energy system transformation from fossil to renewables sources and measure to a much higher efficiency – the example of Germany, an industrialized country (WBGU, 2008).

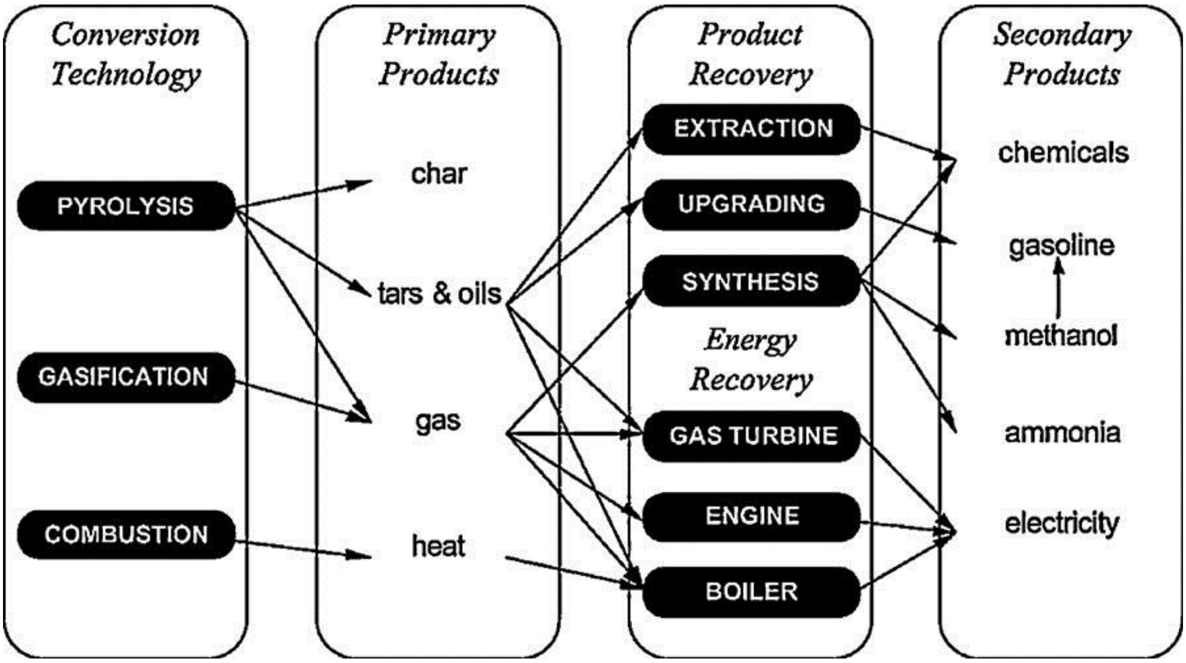

Figure A14: Different transformation pathways of organic matter (Bridgwater quoted by (Singh et al., 2011))

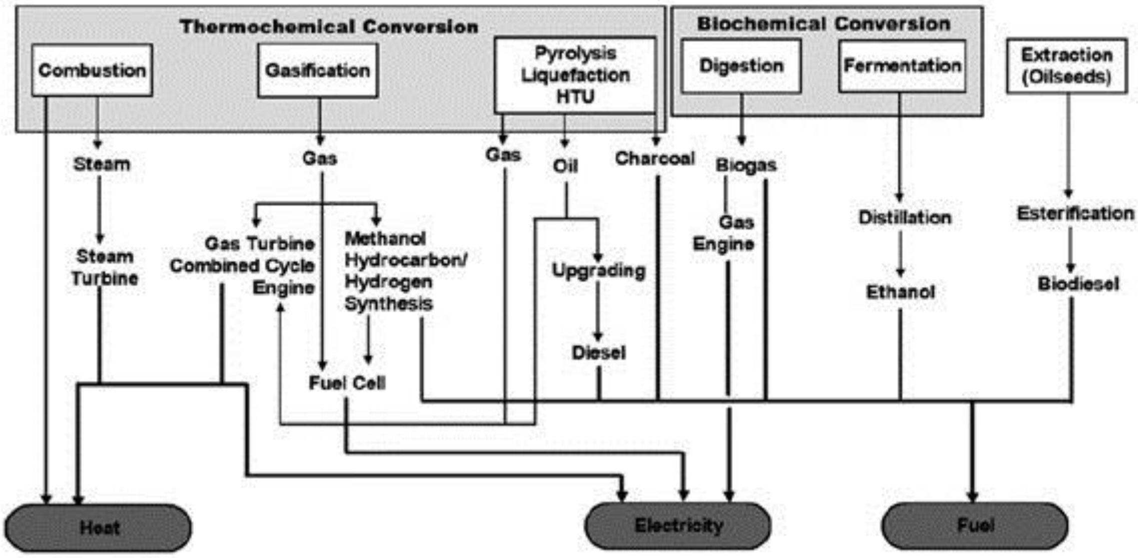

Figure A15: Pathways for biomass conversion to secondary energy carriers (International Agency of Energy, quoted by Ghosh and Prelas, 2011).

9.4 Answers to the survey for energy researchers in the social network RESEARCH GATE

The information from the survey carried out through the social network Research Gate is provided in this section. After the main question, only the date and author of the response is given, as a way to reduce the extension of the text.

Question

Does anyone know a method or software for modelling a set of different renewable energies in order to get the best combination of them?
I am working on the most adequate combination of sources of renewable energies for the needs of rural communities in the south of Chile. I am using variables of economic, energy efficiency and environmental performance of such combination of sources. Thanks!
Modified Mar 1, 2012 by an editor in Topics / Renewable Energy

Date and name of authors of the response

Mar 1, 2012, Ahmed Ali · 5.80 · 4.18 · Egypt-Japan University of Science and Technology
Mar 1, 2012, Jiby Kurian · McGill University
Mar 1, 2012, Dr. AJAO K.R · 2.77 · 0.18 · University of Ilorin
Mar 1, 2012, Jorge Alé · 0.46 · Pontifícia Universidade Católica do Rio Grande do Sul
Mar 1, 2012, Juan Carlos Ortega Bravo · 0.32 · Universidad Católica de Temuco
Mar 1, 2012, Kai Wu · 0.14 · University of Massachusetts Amherst
Mar 1, 2012, RAMANA S V · 8.74 · 10.25 · Universidade Técnica de Lisboa
Mar 1, 2012, Taofeeq Ibn-Mohammed · 0.05 · De Montfort University
Mar 1, 2012, Nestor Rojas · 9.81 · 10.39 · Universidad Nacional de Colombia
Mar 1, 2012, Marcos Gomes · 0.06 · University of Aveiro
Mar 1, 2012, Jake Tan · 0.25 · National University of Singapore
Mar 2, 2012, Roland Magiera · 0.67 · Ventilatorenfabrik Oelde
Mar 2, 2012, Mounir Bouzguenda · 0.06 · Sultan Qaboos University
Mar 2, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Mar 2, 2012, Roland Magiera · 0.67 · Ventilatorenfabrik Oelde
Mar 2, 2012, Anastasia Chrystyanty · 1.22 · Universitas Gadjah Mada
Mar 5, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Mar 5, 2012, Adamson Thengolose · 0.06
Aug 21, 2012, Andreas Bloeß · 0.16 · Technische Universität Berlin
Aug 21, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 21, 2012, Ramli Mat · 10.80 · 11.72 · Universiti Teknologi Malaysia
Aug 22, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 23, 2012, Andreas Bloeß · 0.16 · Technische Universität Berlin
Aug 23, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 23, 2012, Thiago Lima · 0.46 · Universidade Estadual de Campinas
Aug 23, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 24, 2012, Lucian Mihet-Popa · 7.84 · 2.47 · Technical University of Denmark
Aug 29, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 29, 2012, Divya Thangamani · 3.83 · Fachhochschule Flensburg
Aug 30, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Aug 30, 2012, Mehdi Kazemi · 0.54 · Mapúa Institute of Technology
Aug 30, 2012, Deleted
Aug 31, 2012, A.M. Sharaf · 28.72 · 58.96 · University of New Brunswick

Aug 31, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Sep 4, 2012, Claudia Viegas · 6.13 · 2.73 · Universidade Federal de Santa Catarina
Sep 6, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Sep 6, 2012, Mukesh Goel · 8.02 · 6.74 · Indian Institute of Technology Delhi
Sep 11, 2012, Gabriel Negreanu · 0.48 · Universitatea Politehnica Bucuresti
Sep 12, 2012, Humayun Shahid · Universität Bremen
Dec 6, 2012, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Dec 6, 2012, Humayun Shahid · Universität Bremen
Dec 6, 2012, Abubakar Sani Hassan · Cardiff University
30 days ago, Mahdi Moghimi Zand · 11.44 · Isfahan University Of Technology
30 days ago, Salma El Aimani · University Ibn Zohr - Agadir
27 days ago, Ramesh Babu · 0.25 · Vellore Institute of Technology
22 days ago, Michael Bielmann · 20.40 · 45.01 · Empa - Swiss Federal Laboratories for Materials Science and Technology
22 days ago, Leonard Malczynski · 3.30 · 2.28 · Sandia National Laboratories
21 days ago, A.M. Sharaf · 28.72 · 58.96 · University of New Brunswick
20 days ago, Javier Alonso · 2.30
16 days ago, Dr Dharmasa Hemadrasa · 4.11 · Caledonian College of Engineering
16 days ago, Ahmed Elsafty · 6.73 · 4.36 · Arab Academy for Science, Technology & Maritime Transport
15 days ago, Ahmed Elsafty · 6.73 · 4.36 · Arab Academy for Science, Technology & Maritime Transport
15 days ago, Ahmed Elsafty · 6.73 · 4.36 · Arab Academy for Science, Technology & Maritime Transport
15 days ago, Samane Fakourian · Sharif University of Technology
11 days ago, Dr Dharmasa Hemadrasa · 4.11 · Caledonian College of Engineering
11 days ago, Karthikeyan N · 2.18 · National Engineering College
6 days ago, Gianfranco Rizzo · 7.14 · 4.56 · Università degli Studi di Salerno
5 days ago, hamid reza Hooshangi · Amirkabir University of Technology
5 hours ago, Alfredo Erlwein · 3.14 · Universidad Austral de Chile
Jan 10, 2013, Christopher J. Koroneos · National Technical University of Athens
Jan 11, 2013, Danijel Topić · University of Osijek
Jan 11, 2013, Alvaro Estupinan · University of Luxembourg
Jan 11, 2013, Ogheneruona Diemuodeke · University of Port Harcourt
Jan 12, 2013, Andreas Poullikkas · Cyprus University of Technology
Jan 14, 2013, Mohit Bansal · Indian Institute of Technology Roorkee
Jan 15, 2013, Doreen Bayer · Technische Universität Bergakademie Freiberg
Jan 15, 2013, Kharchi Razika · Centre de Développement des Energies Renouvelables
Jan 15, 2013, Hesamaldin Maaleki · Universiti Tenaga Nasional (UNITEN)
Jan 16, 2013, Alfredo Erlwein · Austral University of Chile
Jan 16, 2013, Javier Alonso
Jan 16, 2013, Gregory Diana · University of KwaZulu-Natal
Jan 18, 2013, Alfredo Erlwein · Austral University of Chile
Mar 6, 2013, Nicolus Rotich · Lappeenranta University of Technology
Mar 6, 2013, Alfredo Erlwein · Austral University of Chile
Mar 6, 2013, Orazio Barbera · National Research Council
Mar 7, 2013, Uday Guntupalli · Missouri University of Science and Technology
Mar 7, 2013, Yaser - Sahebi · Houston,Texas,United States
Mar 8, 2013, Imene Yahyaoui · Universidad de Vitoria
Mar 8, 2013, Alfredo Erlwein · Austral University of Chile
Mar 12, 2013, Arun Kumar N K · Mitsubhishi Electric India
Apr 2, 2013, Mohammad Bagher Lak · Tarbiat Modares University

Apr 4, 2013, Yaser - Sahebi · Houston,Texas,United States
Apr 4, 2013, George Perkoulidis · Aristotle University of Thessaloniki
Apr 5, 2013, Zahari Zarkov · Technical University of Sofia
Apr 9, 2013, Alfredo Erlwein · Austral University of Chile
Apr 10, 2013, Shahnawaz Farhan Khahro · Alternative Energy
Apr 11, 2013, Arun Kumar N K · Mitsubhishi Electric India
Apr 11, 2013, Davide Papurello · Politecnico di Torino
Apr 14, 2013, Shahnawaz Farhan Khahro · Alternative Energy
Apr 14, 2013, Peter Ansgar Nelson · University of California, Santa Cruz
Aug 19, 2013, Naga Bhaskar Reddy · Rajeev Gandhi Memorial College of Engineering and Technology
Aug 24, 2013, Yaser - Sahebi · Houston,Texas,United States
Aug 24, 2013, A.M. Sharaf · SHARAF ENERGY SYSTEMS, Incorporated
Aug 24, 2013, Ioannis Mandourarakis · Technical University of Crete
Aug 26, 2013, Ogheneruona Diemuodeke · University of Port Harcourt
Aug 26, 2013, Sadegh Amanibeni · Tarbiat Modares University
Aug 30, 2013, Qing Yang Jiao · Centennial College
Aug 30, 2013, Julian Grodzicky ·
Sep 3, 2013, Ernst-Eckart Schulze · Fraunhofer Institute for Transportation and Infrastructure Systems IVI
Sep 3, 2013, Tamara Schapitz · Universität Stuttgart
Sep 3, 2013, Olusola Solomon Amodu · Cape Peninsula University of Technology
Sep 4, 2013, Constantinos S. Psomopoulos · Technological Educational Institute of Piraeus
Sep 6, 2013, Raphael Akam · SSI UK
Sep 6, 2013, Gol Hej · University of Porto
Sep 9, 2013, Kharchi Razika · Centre de Développement des Energies Renouvelables
Sep 9, 2013, Gol Hej · University of Porto
Sep 9, 2013, Saheb Djohra · Centre de Développement des Energies Renouvelables
Sep 10, 2013, Yogendra Reddy · Koneru Lakshmaiah University
Sep 21, 2013, Alfredo Erlwein · Austral University of Chile
Sep 23, 2013, Khalid Farooq · Asian Institute of Technology
Sep 24, 2013, Gordon J Dalton · University College Cork
Nov 1, 2013, A.M. Sharaf · SHARAF ENERGY SYSTEMS, Incorporated
Nov 1, 2013, Javier Dominguez · Centro Investigaciones Energéticas, Medioambientales y Tecnológicas
Nov 6, 2013, Cheng Zhou · University of Newcastle
Nov 25, 2013, Ssennoga Twaha · University of Nottingham
Dec 5, 2013, Dharmasa Hemadrasa · Caledonian College of Engineering, Oman
Dec 7, 2013, Numan Kaya · Karamanoglu Mehmetbey Üniversitesi
Dec 9, 2013, Antonio Rosato · Second University of Naples
Dec 10, 2013, Saheb Djohra · Centre de Développement des Energies Renouvelables
Dec 10, 2013, Brian Kermath · University of Wisconsin - Oshkosh
Dec 11, 2013, Mohit Bansal · Indian Institute of Technology Roorkee
Dec 27, 2013, Binod Prasad Koirala · Universidad Pontificia Comillas
Apr 20, 2014, Saheb Djohra · Centre de Développement des Energies Renouvelables
Apr 20, 2014, Orazio Barbera · National Research Council
Apr 21, 2014, Marianne Salomón · KTH Royal Institute of Technology
Apr 26, 2014, Julian Grodzicky ·
Apr 27, 2014, Julian Grodzicky ·
Apr 27, 2014, Karolis Janusevicius · Vilnius Gediminas Technical University
May 6, 2014, Eduardo Ramon Galvan · Universidad de Sevilla
May 8, 2014, Rhona Diaz · Tecnologías Sostenibles S.A.

May 15, 2014, Henrique Rego Monteiro da Hora · Instituto Federal de Educação, Ciência e Tecnologia Fluminense (IFF)
May 22, 2014, Alfredo Erlwein · Austral University of Chile
May 23, 2014, Henrique Rego Monteiro da Hora · Instituto Federal de Educação, Ciência e Tecnologia Fluminense (IFF)
May 23, 2014, Mahamad Nabab Alam · Indian Institute of Technology Roorkee

9.5 Experimental biodigestor: Design and construction

a)

b)

Figure A16: Pictures of an experimental biodigestor designed from recycled components and built as experiential work with biogas. a) Steps of building and setting, b) steps of storing and using the biogas.

9.6 Abstracts of theses guided as part of the research project

- Mario Alejandro Celedón Martínez (Celedón, 2014)
- Rodrigo Schnettler Sabugo (Schnettler-Sabugo, 2013)
- Martín Vermehren Parra (Vermehren, 2014)
- Manuel Antonio Ríos Gutiérrez (Manuel Ríos, 2013)

9.6.1 Bachelor thesis "Estimation of the potential biogas generation from energetic crops of wheat (Triticum aestivum L.) and maize (Zea mays) based on their current surfaces and productivities in Los Ríos Region"

Estimación del potencial de generación de biogás a partir de ensilajes de cultivos de trigo (Triticum aestivum L.) y maíz (Zea mays) en base a sus superficies y productividades para la Región de Los Ríos.

Mario Alejandro Celedón Martínez
Faculty of Agrarian Science
Universidad Austral de Chile
Valdivia – Chile
2014

"The purpose of this research was to determine the potential of biogas production in the Region de Los Rios using a non-experimental method of research, based mainly on crop production areas of wheat (Triticum aestivum L.) and maize (Zea mays) obtained from the database of the VII censo nacional agropecuario y forestal de Chile conducted in 2007 and those provided by agricultural enterprises and the private sector. Thus, farms are analyzed at the communal level and are classified according to terrain surfaces. For this, we rely on the definition of yielding Chile homogeneous areas classification grouping into four categories of surfaces (subsistence agriculture, small, medium and large farmers) with their size limits and thresholds via weighting. Additionally, three types of existing technologies to be implement (by type of farmer and business model) were economically evaluated according to the cogenerated power from biogas produced from wheat and corn silages, taking into consideration the engine power , the size of the plant and its lifespan and investment for small, medium and large farmers. The results show that the amount of wheat and corn in the total land use in the Region de Los Rios is less than 2% and within this large farmers include a total of 17.524,1 hectares area. The regional theoretical potential to generate biogas from wheat silage, mainly includes the communes of La Union and Rio Bueno with 43% and total productive potential 70.562.734,2 m3 of biogas, while corn silage tops in the town of Mariquina with 28% and a productive potential of 7.602.692.2 m3 of biogas. Thus, in the potential for electricity generation from wheat silages excel large farmers with power range from to 9 MWh annually and 1 to 4 MWh from corn silage annually. Based on all this measurement two models of business are technically and economically evaluated, as defined (self-producer and associations), for different electric power production scales (10 kW, 50 kW, 100 kW and 500 kW) by type of farmer. Profitability yielded return rates of 13% to 46% showing that is feasible for implementation and whose values are very attractive for investment."

9.6.2 Bachelor thesis "Technical and economic analysis of a plant producing biogas from maize (Zea mays) for combined heat and power"

Análisis técnico económico de una planta productora de biogás a base de
maíz (Zea mays) para la cogeneración eléctrica y térmica.
Rodrigo Schnettler Sabugo
Faculty of Agrarian Science
Universidad Austral de Chile
Valdivia – Chile
2013

"Chilean electric matrix is composed in great extent of thermoelectric power plants and hydroelectric dam. This model faces several economic, environmental and social problems due mainly by the investment costs, the international dependence for the supply of raw material, the carbon footprint involved, and the environmental impacts implied. An economical, clean, and sustainable energetic alternative is to use non-conventional renewable energy sources (NCRE), which to manifest and/or regenerate naturally, offering the possibility of operating at different scales of production. In this sense, the combustion of biogas produced by the anaerobic degradation of biomass is a mechanism of electrical generation increasingly used in the world. A proposal for installation and operation of a plant of biogas based on the cultivation of 20,000 tons of forage maize in the Empresa Formio, Comuna de Máfil, Provincia de Valdivia, was technically and economically analyzed. This project offers produce 8,000 MWh per year of electricity marketable to the Sistema Interconectado Central and 10,000 MWh of heat energy for drying of wood and/or certified firewood. The business model is a corporate structure with a private investor to contribute with 98% of the investment and get 65% of annual profits. An initial investment of $ 2,090 million is required, and five years after a return from $1,126 million will be obtained. Within this period a NPV and IRR of $ 664 million and 29% respectively is estimated. Under the corporate structure predetermined, if the investor contributes with $ 2,060 million, he will get a utility more than $1,052 million after five years, but with a NPV and IRR of $ -269 million and 16% respectively. The proposed business model is not attractive. However, the added value of autonomy provides an opportunity to expand the activities to other productive areas."

9.6.3 Master thesis "Estimation of the potential biogas generation from biodegradable residues in Los Ríos Region"

Estimación del potencial de producción de biogás en la región de Los Ríos
a partir de residuos biodegradables.

Martín Vermehren Parra
Faculty of Agrarian Science
Universidad Austral de Chile
Valdivia – Chile
2013

"The lack of fossil fuels, high rates of growth in the national energy consumption, and environmental problems makes necessary to find new sources for clean and safe energy matrix. This paper preliminarily estimated the potential of biogas production and its economic assessment in the Region of Los Rios, from urban and agro-biodegradable waste. For this, we quantified dairy waste, slaughterhouse sludge, water treatment sludge and household waste performing a compilation, standardization and information processing available. Then, using factors found in different databases, generate biogas, methane, electricity, heat and power load for the main plants of the region was estimated. Finding that the highest potential was in the dairy industry, using cheese whey. The slaughter industry had the lowest potential. The total potential for the region reached 7.500.000 m3and would install an electrical output of 9.1 MW. This energy could supply the requirements for more than 170,000 people. Economic evaluation indicated feasibility for most of the projects evaluated. The economically feasible potential for the región reached 6.2 MWe."

9.6.4 Bachelor thesis "Estimation of Biogas Potential Production from Cattle Manure in Los Ríos Region (Chile)"

Estimación De La Producción Potencial De Biogás A Partir De Purines Bovinos
En La Región De Los Ríos (Chile)
Manuel Antonio Ríos Gutiérrez
Facultad de Ciencias Veterinarias
Universidad Austral de Chile
Valdivia – Chile
2013

"In the agricultural and forestry Seventh Census conducted in 2007 (INE 2007) reported that the country has a total of 3.79 million head of cattle. The region of Los Rios is the one with the second largest inventory, 20% of the national total. Veterinarians have a key role in planning efficient and sustainable livestock productive ecosystems. Being the management of manure generated in the livestock industry one of the edges to ensure the common good. According to Holm-Nielsen et al (2009), the alternative of anaerobic digestion of manure is the way to be sustainable in the cattle industry. This research databases were conducted from the VII census of agriculture and forestry 2007, and cattle producers were classified by commune, province and by the size of their herds in three layers, consistent with the studies conducted by the National Statistics Institute (INE) and the Office of Agricultural Policy (ODEPA) both Chileans institutions, this classification is: small producers, 50-99 cattle, medium, 100-199 and large, 300 and more. From these data, was estimated the average size per stratum, was calculated volume of manure generated in the region of Los Rios, his conversion to biogas through anaerobic digestion and energy generation potential, with a total theoretical housing of all herds. In the region of Los Rios is generated 8.240.850m3 cattle manure per year, equivalent to 166.3 MW, and this can becomes into, from this source of biomass, to 1.456.982MWh per year. In specific, in the region the small strata had 59 cattle herds average, in Chinese equivalent reactors with fixed gasometer, and can transforms their manure into 443kWh per day at a cost of CLP $16.55 per kWh. The middle has an average herd of 164 animals, the digestion of her manure is equivalent on plastic sleeve reactors to 1.371kWh in total energy per day, at a cost of CLP$12.68 per kWh. The larger average herd has 715 animals, their manure treated with mixed reactor can be transformed into 5.695kWh per day, and annual operating costs make the cost per kWh is of CLP$25.17. It can be seen from these results that are larger producers, especially in the town of Rio Bueno, who throng the largest number of cattle, and therefore has the greatest potential, about 50% of the possible energy of this kind in the region."

Curriculum Vitae

Alfredo Nicolás Erlwein Vicuña

Birthday and place of birth: 17.02.1971 in Santiago de Chile
Nationality: Chilean and German

TRAINING
HIGHER EDUCATION : Agricultural Engineer, 1995, Department of Agronomy and Forestry Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile (Distinction awarded).

POSTGRADE : Master Science in Holistic Science (systems and complexity in ecology). Schumacher College-University of Plymouth, England (Distinction awarded).

RESEARCH LINES
-Sustainable use of energy: biofuels technologies, efficiency and carbon footprint of energy use, organic waste management, bioenergy and sustainability.
-Land Use Planning of Rural Ecosystems: ecosystemic land use planning, land and energy, cognition and territory, landscape ecology, ecological design, native forest forestry.

PROFESSIONAL EXPERIENCE
AS LECTURER AND RESEARCHER
Current researcher and lecturer at the Institute of Agricultural Engineering and Soils, Faculty of Agricultural Sciences (since 2008) and at the Transdisciplinary Center for Environmental Studies and Sustainable Human Development, CEAM (since 2005), both from Austral University of Chile in Valdivia. Lecturer invited to various courses in colleges of Agronomy, Forestry, Architecture, Design and Urban Studies, and Economics in the following universities: Catholic of Chile, of Chile, of Santiago, Mayor and Iberoamericana.

AS ENVIRONMENTAL CONSULTANT
Since 2005, coordinator or director of studies for the United Nations Program for Development, the Global Environment Facility and the Chilean Ministry of Environment. From 1997 to 2004, participating in the development of soil components, flora and fauna, and as a project coordinator in various studies of impact assessment, Diagnostics and Environmental Management Plans for government agencies such as Ministry of National Property, Environmental National Commission, Regional Governments of I, III, and VII Regions and National Energy Commission, and for companies such as Codelco, Chilectra SA, Endesa, Enersis and Sacyr SA.

LANGUAGES
Spanish mother tongue. English and German spoken & written. Basic Italian and Portuguese.