INTERNSHIP REPORT

SYNTHESIS OPTMIZATION OF ENERGY SYSTEMS MAXIMIZING REGIONAL PROFIT

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GRAZ, AUSTRIA

15-08-2016 TO 04-11-2016

UNIVERSITY OF TWENTE.

ABSTRACT

The energy sector plays an important role in the mitigation of climate change impacts. Renewable energy technologies have been increasing their market share but there are still much to be improved in order to assure better acceptance of these technologies. Several solutions can be investigated; this work assumes that the best strategy for a successful energy transition is based on a bottom-up approach and that there is need to make projects more attractive for local stakeholders. Also, it is assumed that, in order to make renewable energy projects more attractive, they need to be more sustainable.

Sustainability is analyzed considering the triple-bottom line framework. The environmental dimension is already contemplated by the nature of the projects. Therefore, there is need to include the social and financial spheres. The social, due to its subjective facet, is included qualitatively in the decision making process during the development of the project. The financial is included in the model by seeking the maximization of the profit. Therefore, the attractiveness problem can be defined as the design of a renewable energy system that can simultaneously maximize the profit for a certain region and respect the local economy/community.

The energy system is analyzed as a process network and optimized considering a synthesis approach based on well-established tools. The theoretical background is presented and a case study performed over a Brazilian region in order to assess if the results obtained can help the proposal of more attractive renewable energy projects. The region was considered isolated from the surroundings and there was no heat requirement. Therefore, the focus was the production of electricity to fulfill the internal demand. At all stages, it was assumed that no change in the current regional agriculture practices is desired as a way to englobe the social dimension. The initial scenario is based on the use of the regional agriculture streams in order to produce electricity from biomass.

It was concluded that the tool can help the identification of solutions that give the region a higher level of profit when compared with the current situation. Even though the initial scenario was not able to produce enough electricity to fulfill the internal demand, the approach enables the identification of alternatives for the expansion of the electricity production and its impacts. Furthermore, it enables the identification of critical aspects of the project that could be overlooked if only the technical perspective was considered.

This work supports the concept that renewable energy projects need to be approached from a socio-technical perspective. It is possible to couple a technical optimum design respecting the regional practices with an enhanced profit for the region. Considering that these projects enhance stakeholder satisfaction they are more likely to be successfully implemented than project based only in a technological design. Also, since the methodology of this work is not time consuming it can be used as a first assessment of the region's possibilities. It enables the design of better interconnected systems and also the maximization of the profit.

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LIST OF ABBREVIATIONS

ABB	**Accelerated Branch-and-Bound**
GHG	**Green House Emission**
MSG	**Maximal-Structure Generation**
NIMBY	**Not In My Backyard**
PNS	**Process Network Synthesis**
PV	**Photovoltaic**
SSG	**Solution-Structure Generation**
TBL	**Triple Bottom-Line**
TT	**Technological Transition**

INTRODUCTION

This chapter aims to give an overview of the motivation and structure of the following work. In section 1.1 the purpose of the work is described followed by its significance in the current climate change context, in section 1.2. This leads to the research question presented in section 1.3. Finally, some main assumptions valid throughout the development of the project are presented in section 1.4 and the report structure in 1.5.

1.1. Purpose

As a part of the curriculum of the master in Sustainable Energy Technology (SET) of the University of Twente a mandatory internship is required. The purpose of this report is to describe the results of a three-month internship in the Institute of Process and Particle Engineering located in the TU Graz, Austria. The institute consists of five independent research areas, each committed to high-level basic and applied research [1]:

- Pharmaceutical Engineering and Particle Technology,
- Mechanical Process Engineering,
- Process Evaluation,
- Energetic Biomass Utilization, and
- Zero Emissions Techniques and Systems.

The area of Process Synthesis and Evaluation, within this institute, has been active in the field of optimal technology networks for regional and urban context [2]. That is the field of development of this internship project, which is interdisciplinary considering the five research areas. The main purpose of the internship is to get acquainted with the tools used by the research group focusing on the **Optimal Technology Networks for Regional and Urban Utilization of Renewable Resources (RegiOpt)** and **PNS Studio**. After the tools are comprehended with sufficient depth, the internship shifts to a more practical vies; the actual planning of a technology network for a chosen region.

1.2. Significance

One of the current challenges faced by humanity is climate change. This worldwide effect has impacted many regions, causing changes on temperature levels and hydrological systems [3], for example. These effects already can impact both wild life and human activities. And, it has been shown that anthropogenic greenhouse gas (GHG) emissions have increased when compared to the pre-industrial era. After greenhouse gases are emitted they take a long time to disperse from the atmosphere. Therefore, their concentration has increased together with the magnitude of the greenhouse effect, which is very likely to be the dominant cause for the warming of the world since the 20th century [3].

Between the years of 2000 and 2010, the annual GHG emissions have increased drastically; around 47% of this increase is due to energy supply [4]. Therefore, actions in the energy sector have an important role in the mitigation of climate change impacts. One of the strategies that have been growing in the past years is the introduction of renewable sources for energy generation. This introduction aims to change the current technological regime and this cannot be done without a proper macro-strategy due to the complexity of such systems. Several methods can be used in order to execute energy transition but it is clear that purely technical or purely social approaches are not efficient enough.

On one hand, without the technical approach it is impossible to plan systems that will effectively fulfil energy demands. But, on the other, these technical systems impact directly society and human relationship with the environment. Therefore, people’s perspectives must be taken into consideration during the design. Another way to phrase this is to state that technical systems must be attractive to the stakeholders.

1.3. *Research Question*

The climate change challenge is huge and there is no attempt to find a unique solution for it. Nevertheless, a broad question that needs to be answered is,

How is it possible to make renewable energy solutions more attractive to stakeholders?

This question raises several others like, for example, who are the important stakeholders or which types of variables can be used to influence behavior; the answers generate infinite ramifications. Due to that, certain assumptions are made to narrow down the scope of this work and to arrive in a more feasible research question.

First of all, it is assumed that the best approach for energy planning is to make it locally, and change will emerge for several decentralized locus. Also, it is considered that instead of making the solutions attractive to all stakeholders, there is only need to make it interesting for a key player. That could be a municipality or a company with enough influence over a region, for example. Furthermore, it is considered that in order to make a solution attractive there is need for it to be sustainable. Here, we define being sustainable based on the triple bottom-line framework. The TBL is an accounting framework that includes environmental and social dimensions to measure corporate performance, instead of only a financial one [5]. To be sustainable is to be in equilibrium among these three dimensions.

I posit that shifting to renewable energy is already a step towards the environmental dimension and in order to make it more attractive to stakeholders it is necessary to include the other two dimensions as well. The social dimension is included qualitatively; during the design decisions should be made trying to impact the least the local economy. Therefore, changes should try to cause few to none impact in the current habits of the population; merging with the current scenario instead of disrupting it. One requirement is that it has to be combined with existing structures, since it is unfeasible to build the energy sector from scratch and also respect natural limitations of the region. The financial dimension can be included quantitatively. For example, by asking which solution, among a manifold of possibilities, maximizes the financial return.

Therefore, considering that natural resources are material of a process network, energy is a product and the technological network is composed by a set of operating units. Thus, the following research question can be formulated:

Given an amount of natural resources and a demand that needs to be met; what is the technological network that will maximize the revenue function for a certain region, while respecting the local economy?

Obviously, there is no unique answer for this question since the technological network is always dependent on the constraints of each region. So, in order to answer this question for a broader range of cases, it was decided to investigate tools that will provide the answer for any set of materials, products and operating units. The project purpose may seem excessively specific, due to the fact that it is about understanding tools, but it is directly related to a broad and complex problem of resource management in rural or urban areas. To assess if these tools are effective to answer the research question a case study is performed based on a Brazilian region.

1.4. Assumptions

The main assumptions of this work are related to the modelling of the energy system of the Brazilian region. First, it was assumed that the region has interest in becoming electricity neutral. The Brazilian energy market is structured in a way that cities are not allowed to produce electricity for their own use. Therefore, all electricity has to be sold to the grid. Thus, the concept of being electricity neutral; the region produces the same amount of electricity it needs to supply the current demand.

Also, the decision maker or key player, hereafter named as the region, is a fictional entity that owns all the land available within the borders of the city. It means that issues of land ownership are not discussed in this work, the obstacles that can be possible faced when dealing with this are considered out the scope of this project. Furthermore, it is assumed that this is the player that will decide to implement or not the project. Therefore, the revenue is maximized based on the region perspective, which may result in not optimum situation for other players.

Furthermore, it is assumed that there are no practical limitations for the financial resources of the region. All monetary flows are calculated in euros. If the reference for investment costs, for example, is in US$ or BRL the value is converted to euros based on the exchange rate from 17/08/16.

1.5. *Report Structure*

Chapter 2 gives an overview on the literature background needed for the development of this project. This chapter also englobes the theoretical part of the project, which regards the understanding of the underlying mechanisms of the software used for the optimization of regional systems. On chapter 3 the research method is outlined, the tools described and the region's choice justified. Finally, in chapter 4, the application of the theory and tools in a region starts with data collection. This chapter provides information used in both tools used in the project, RegiOpt and PNS Studio, indistinctively. After the information is collected, the tools are used and the results presented in chapter 5, together with several scenarios used to complement the research. The results are discussed in chapter 6 and main conclusions of the research summarized in chapter 7.

LITERATURE BACKGROUND

This chapter aims to give an overview of the background theory used during the development of this project. In section 2.1, the technological transition to renewables will be presented as an innovation spur from decentralized systems. After that, in section 2.2, the theory of Process Network Synthesis is presented in order to provide a framework for the modeling of energy systems. In section 2.3, the algorithms used to solve the PNS problem are described. Finally, in section 2.4, some final remarks regarding the literature are made.

2.1. *Energy transition in a multi-level perspective*

As posited before, one of the great challenges of the 21st is climate change mitigation. Since energy represents a big role in the emissions of GHG it is important to shift from a fossil fuel to a renewable based energy production. There are different strategies to execute this transition; some researchers even work on simulating energy costs of energy transition and climate change damage as a function the cooperation between agents in a global scale [6]. But another way to understand energy transition is using a multilevel perspective on technological transitions (TT). There are three levels considered by [7] in this perspective are:

- Landscape: it provides an external structure or environment for stakeholders' interaction. They consist in a set of deeper trends that are strongly embedded in society.
- Regime: this environment is related with the routine based behavior of the stakeholders of a certain field. Technological regimes result in technological trajectories and also create stability since they work on incremental improvement on these trajectories.
- Niche: these are the smaller and protected structures responsible for the generation of radical innovations in TT.

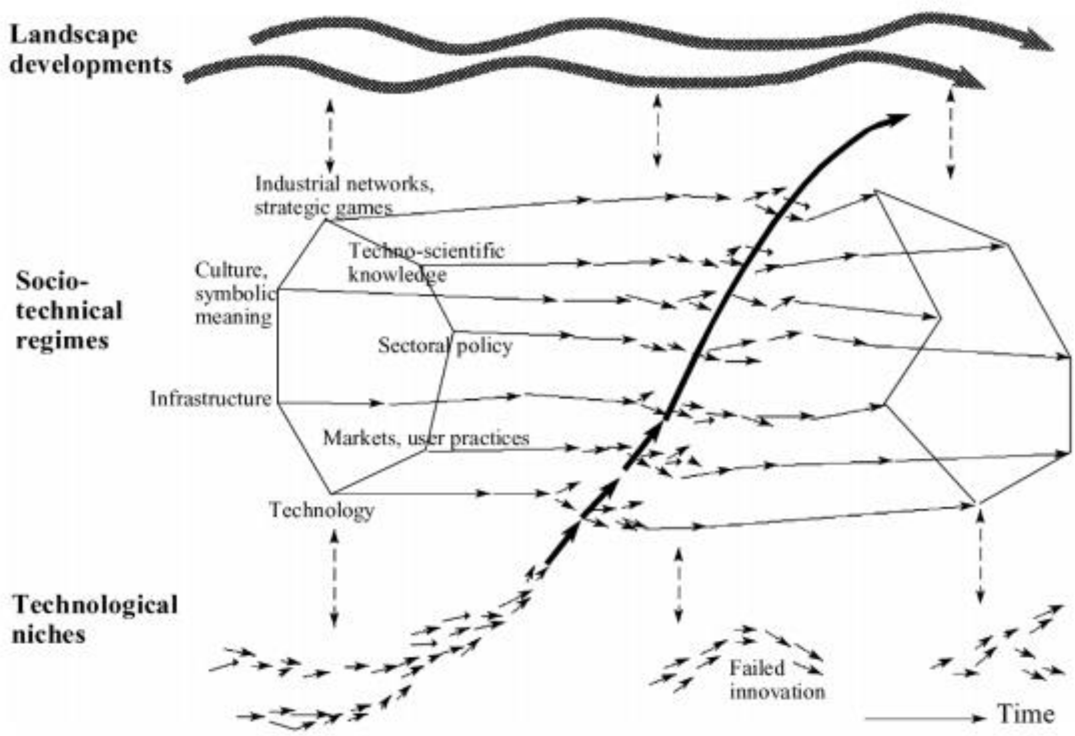

Figure 1 A dynamic multi-level perspective on TT [7]

TT occurs when there are linkages between multiple levels. Radical innovations spur from the niches when the regime and the landscape provide an opportunity [7]. The diagram in Figure 1, developed by Geels [7], presents an illustration of the dynamic of technological transition.

The main idea for this discussion is that, through time, technological niches can evolve and become part of the socio-technical regime and that there are factors that differentiate these successful niches from the ones that culminate in failed innovations. Another point of interest is that this approach shifts the agent of change. The niches, which are *local units*, are the ones responsible for radical innovations. Therefore, under this perspective, until renewable energies are an established regime, energy transition has a local nature. TT does not happen because of a complete regime shift, but through a step by step process of reconfiguration [7].

Nevertheless, it is important to identify mechanisms that enable agents to break from the niche to the regime level. Geels [7] proposes two main mechanisms:

i. Ride along another market growth: New technologies break out of niches by using the trends of other markets.
ii. Add-on and hybridization: This means that new technologies are physically linked with old ones and do not compete head on;

The first mechanism is very pertinent in the case of renewable energies. The low oil prices, around USD 35 by January 2016, compared with over USD 100 per barrel in the first half of 2014 to has meant lower exports and revenue for several countries. The ongoing reform in the energy pricing and the inclusion of renewables gives an opportunity of further reducing the dependence of region's economy and energy sector on fossil fuels [8]. The current environment is favorable for emergence of renewable energy niches to the regime level. The second mechanism is not dependent on the environment only, but needs planning to be realized. In this case there is need for local planning of energy systems that considers the existence of other technologies, including ones depending on fossil fuels, and merge them with new technologies.

2.2. *Energy systems as a process system*

One way to interpret energy planning is seeing the energy system as a process system. This means that a set of raw materials, e.g. biomass or solar irradiation, is used to produce certain products, e.g. heat or electricity by the use a number of operating units. The design of the underlying structure of a process system is called process synthesis [9]. The mathematical programming to achieve this design has two steps: the generation of the model that describes the network and the solution of this model [10]. The application of process synthesis strategies to design networks is named process-network synthesis, or PNS.

The main goal of PNS is to identify the optimum process network. The method used in the assignment to solve the two steps mentioned above is based on the P-graph framework. This method was introduced because previous strategies were only able to solve the first step (model generation) for homogeneous networks and the second (model solution) for relatively small synthesis problems [10]. The P-graph method is based on a graph theoretical approach; these are bipartite graphs with nodes, representing materials and operating units and arcs connecting them [11], as depicted in the picture below:

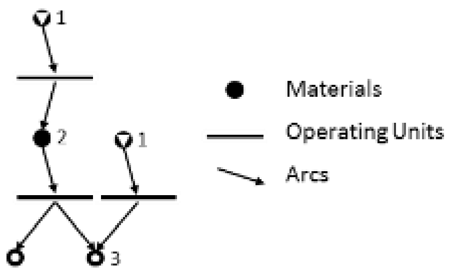

Figure 2 Visualization of P-graph framework

The materials shown above can be raw materials (1), intermediates (2) or products (3). The definitions are straightforward. Raw materials are only inputs for operating unit, intermediates are both inputs and outputs and products are only outputs. To illustrate the use of this approach for energy system, consider a solar power plant that possesses both concentrator solar power and photovoltaic panels. It is possible to visualize the system using exactly the structure presented in the diagram above.

Assume that the raw material is solar irradiation. Following the right-hand side of the diagram the first operating unit can be a steam generator that converts that solar irradiation into steam, which is an intermediate in this process. Steam is then an input for another operating unit, for example a steam turbine, which converts it into electricity and a byproduct, heat. On the other hand, following the left-hand side, PV panels are used directly to produce electricity from solar irradiation.

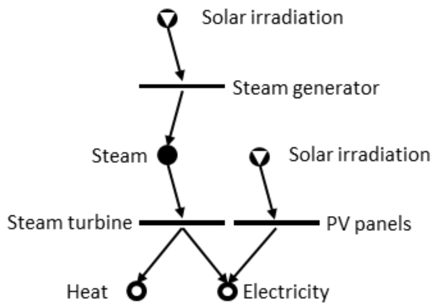

Figure 3 Example of energy system as a p-graph

The first step in solving the optimum network the framework problem is to build the maximal structure. The maximal structure includes all the possible solutions to provide a certain amount of products based on a given set of raw materials [9]. This is a combinatorial problem since there is need to assess all feasible solutions, therefore there is need to establish a set of axioms [11] to guarantee the existence of a solution:

i. Every demand is represented in the structure.
ii. A material represented in the structure is a raw material if and only if it is not an output from any operating unit represented in the structure.
iii. Every operating unit represented in the structure is defined in the synthesis problem.
iv. Any operating unit represented in the structure has at least one directed path leading to a product.
v. If a material belongs to the structure, it must be an input to or output from at least one operating unit represented in the structure.

This approach enables the use of a mathematical model to build process structures [12]. Each part of the solution will be described in the next section through the definition of the algorithms used by the tools to solve the process-synthesis problem.

2.3. *Algorithms for PNS application*

Considering the five axioms presented above and the graphic representation it is possible to write algorithms to model and solve the process-network problem [9]. Three algorithms are well established and have been developed for around 20 years [11]. The first one is MSG (Maximal-Structure Generation) and is responsible for the generation of the maximal structure. After the maximal structure is obtained, all possible solutions will be calculated with the use of the algorithm SSG (Solution-Structure Generation). When the feasible solutions are obtained, there is need to find the one that minimizes an objective function of choice. The algorithm used for this is the ABB (Accelerated Branch-and-Bound). The diagram below represents the path followed to find the solution:

Figure 4 Summary of algorithms for the determination of the optimum structure

MSG

This algorithm enables the obtention of solution networks by decision-mapping of the maximal structure, due to the fact that the solution is a subset of a maximal- or superstructure [10]. The complexity of this algorithm grows only polynomially with the size of the process [10], which enhances the efficacy of this algorithm for huge process systems. Using the axioms presented beforehand, the system finds all feasible solutions building the maximal structure. By doing this the algorithm already exclude unfeasible solutions, which accelerates the optimum solution search.

The example [12] below intends to make the functioning of the algorithm clear. First, there is the problem definition. The definition is done considering the fact that the materials and operating units are defined as mathematical sets.

- Products = P = {D}
- Raw materials = R = {A,B,F,H,J,K}
- Materials = M = {A,B,C,D,E,F,G,H,I,J,K}
- Operating units = O = {({A,B}{C}),({C}{D,E}),({C,F}{G}),({H}{I}),({E,J}{C}),({I}{D})} = {O1,O2,O3,O4,O5,O6}

The graphic representation of this example is presented below:

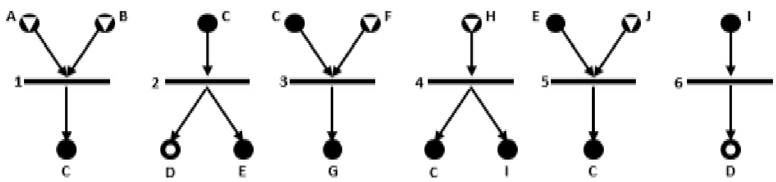

Figure 5 Graphic representation of problem definition

This is still only user input in a graphic representation. The software assembles structure based on the input and also on the axioms. The final structure is given in the maximal structure below:

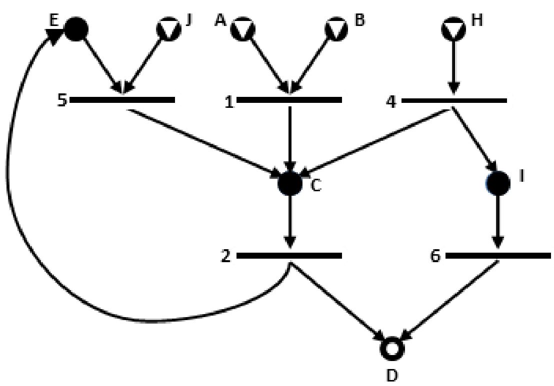

Figure 6 Maximal structure of example

Some important remarks help to understand how the software works. First, since raw material K is not an input or output to any operating unit it is not included in the maximal structure (axiom *v.*). Also, operating unit 3 is only producing the material G, that is not an input for any other operating unit the produced the product D. It has no path leading to a product. Therefore, it is also not included in the structure (axiom *iv*.) together with the materials produced and the raw materials used only by it. The result of this step is a maximum structure with all feasible combinations among the operating units and material defined by the user.

<u>SSG</u>

SSG is a recurrent algorithm that generates each and every solution once and only creates solution-structures [10]. Usually the set of solution generated by this algorithm is huge, due to the combinatorial nature of the problem; nevertheless, it is an efficient algorithm that produces results for fairly complex networks in seconds.

The algorithm uses decision mapping in order to find all possible solutions. It starts mapping all operating units that can produce a certain material. After this is done the software create all possible combinations of operating units that will provide a certain product. To illustrate we recur to the example used before. The materials used in the maximal structure are:

- M = {A,B,C,D,E, H,I,J }

Therefore, there is need to identify which operating units can produce these material and map them. This is done creating mathematical sets, as before. The maps will be denoted with the Greek letter α; the map α(A) represents all the operating units that can produce the material A. The first remark is that raw material are not created by operating units, therefore their map is an empty set.

- α(A) = α(B) = α(H) = α(J)= { Ø }
- α(C) = {O4,O1,O5}
- α(D) = {O6,O2}
- α(E) = {O2}
- α(I) = {O4}

With the maps defined the algorithm progresses to the creation of subnetworks. In order to do this, it builds active sets; active sets are materials that are going to be produced by the use of the subnetwork. With an active set the algorithm builds the networks that can generate those materials without violating the axioms. These networks, which are possible solutions, are going to be denoted by the Greek letter δ. The solution δ_1({C,D,I}) is one network that produces simultaneously the material C and I, and the product D. Considering the example, there are two possible variations that for δ({C,D,I}).

- δ_1({C,D,I}) = {(C,{O4}),(D,{O6}),(I,{O4})
- δ_2({C,D,I}) = {(C,{O1}),(D,{O2},{O6}),(I,{O4})

By creating active sets and finding all structures that can produce those materials the algorithm generates all possible solutions for the problem; the maximal structure is among the solutions. In the case of the problem presented, 7 other maps are possible and defined below:

- δ_3({C,D,E}) = {(C,{O1},{O5}),(D,{O2}),(E,{O2})}
- δ_4({C,D,E}) = {(C,{O1}),(D,{O2}),(E,{O2})}
- δ_5({C,D,E}) = {(C,{O5}),(D,{O2}),(E,{O2})}
- δ_6({C,D,E,I}) = {(C,{O1},{O4},{O5}),(D,{O2},{O6}),(E,{O2}),(I,{O4})}
- δ_7({C,D,E,I}) = {(C,{O1},{O4}),(D,{O2}),(E,{O2}),(I,{O4})}
- δ_8({C,D,E,I}) = {(C,{O4},{O5}),(D,{O2},{O6}),(E,{O2}),(I,{O4})}

- δ_9({C,D,E,I}) = {(C,{O4},{O5}),(D,{O2}),(E,{O2}),(I,{O4})}

Map δ_6({C,D,E,I}) is the maximum solution found by MSG. The diagram below shows the graphic representation of two of these subnetworks:

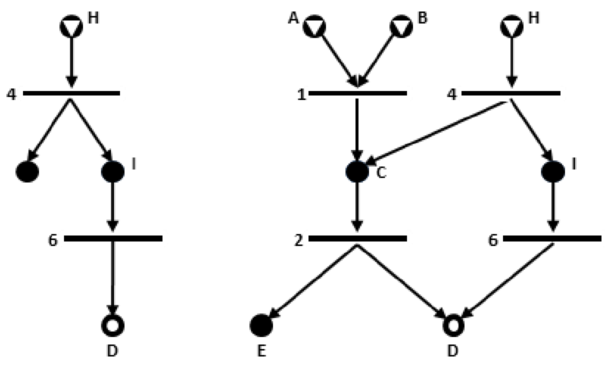

Figure 7 Subnetworks δ_1({C,D,I}) (left) and δ_2({C,D,I}) (right)

ABB

When all the subnetworks are created the algorithm explores the structural nature of the problem by initiating the process of ´search for best solution´ in the bottom of a decision tree and moves upwards asking at each branching step which operating unit or units should be used [11]. This three is built asking how the desired product can be produced. In this case, D can be produced from operating unit {O2}, from operating unit {O6} and also from a combination of them, {O2,O6}. Each one of these options may have several subnetworks or variations, δ_i.

The objective function used to find the optimum solution can be defined based on what suits the designer better, ranging from financial variables, like cost or profit, to environmental impact, like carbon footprint. After choosing an objective function the algorithm finds the subnetwork that is closest to the optimum, or maximizes the desired function. At the bottom of the decision tree there is the desired product, in the example, D. There are three possible ways to move up the decision tree. The algorithm will ask which one maximizes the revenue, for example. We can assume path {O2} is the one that maximizes this variable.

Considering only subnetworks that produce D through the operating unit {O2}, the set of possible solution is already smaller. Now, only five options are available, $\delta_{3,}$ δ_4, δ_5, δ_7 and δ_9. The algorithm asks the same question again and arrives to the solution that maximizes the overall revenue.

2.4. *Final remarks*

By looking at technology transition in the energy sector through the lens of a multi-level perspective it is possible to recognize the importance of regional initiatives in the global context. The current environment is promising for the introduction of renewable energies but there is need for better local planning in order to make the solutions more appealing to local communities. By using the process-network synthesis framework it is possible to design systems that are, on one hand, more environmentally friendly due to the use of renewable sources and, on the other hand, also financially appealing since the revenue can be maximized.

The construction of the maximum technological structure is the most important step for the user of the method. Since the algorithms are well established, the process of optimization revolves around the definition of the problem. This involves the definition of the availability of resources, the demand that needs to be met and the performance of the operating units. After the constraints of the process are defined there is need to define the operating units. For that, the inputs and outputs for each operating unit have to be chosen, together with the rates of consumption and production of these materials. Also, the cost function is required. With these parameters the operating unit is well defined and the problem is fully described [9].

The use of this framework enables the determination of the technological network that maximizes the revenue. Therefore, this method is ideal to answer the specific research question presented in the introduction:

Given an amount of natural resources and a demand that needs to be met; what is the technological network that will maximize the revenue function for a certain region, while respecting the local economy?

From a problem defined considering all the alternatives the user wants, it is possible to find the one combination that maximizes the revenue of the region. If keen choices are made during the modelling regarding how this will impact the local economy, it is possible to design systems that are attractive to the key stakeholders since they enhance the regional situation in the three dimensions of sustainability. Therefore, they rank higher in the TBL.

METHOD

In order to successfully design the technological network that maximizes the revenue for a certain region the research is conducted first with a more theoretical approach. This is done in order to obtain proper background to answer the research question and also to identify if the tools are sufficient to do so. A brief discussion, complementing the literature background, is presented in section 3.1. Then, the research shifts to a practical approach. In section 3.2, a region is chosen in order to apply the tools in a real context. In section 3.3, one of the tools used during this project, RegiOpt Conceptual Planner, is described. In section 3.4, the less standardized tool, PNS Studio, is also presented. To conclude, section 3.5, outlines the plan for the development of the research combining the tools.

3.1. *P-graph framework*

As discussed previously, one of the strategies to fight climate change is by the regional introduction of renewable energies. To do that, it is important to make project attractive to local institutions; it is assumed that making projects financially beneficial is the strategy to make the transition more sustainable. The P-graph framework is chosen due to its practicality.

For small regions, the algorithms described in the previous chapter provide results in less than one second. This gives the user the freedom to experiment with the network and material flows. This can be done due to the smart combination of the axioms and the algorithms, MSG, SSG and ABB. Since the construction of the maximal network, unfeasible networks are eliminated from the solution. When the combinatorial step starts, in SSG, the number of possibilities is already lower. And, again, in this step only networks that produce the desired product are considered. Together with the strategy of asking in every branch which one maximizes the objective function in ABB, the process is extremely efficient. Thus, it is considered as a very adequate tool for the simulation of process-network synthesis.

Also, considering the conversion nature of energy systems, seeing them as network processes is natural. Raw materials are input and products are outputs of operating units. The physical planning of an energy system is to assess which operating units should be used in a certain region and, equally important, what is the relationship among them. The P-graph framework enables all that while maximizing the revenue of the region, which proves its efficacy for the purpose of this work.

3.2. Region choice

Only a theoretical understanding of the algorithms and concept is not enough to assess if the results of such framework is successful. Therefore, it was decided to make a case study of a region. The first requirement was for the region to be in Brazil. This is done to avoid reuse of information. The research group has been working extensively in the European context. Since the goal was to apply the framework to its full extent it is considered better to apply it from scratch. Instead of working on the optimization of a ready-to-use maximal structure, in this research, the maximal structure will be built considering the reality and constraints of the region. Therefore, it was decided to apply the theory to a region where no work has yet been done.

Brazil is chosen due to its high commitment to sustainable energy. Brazil was in 2012 the third biggest producer of renewable electricity in the world [13]. By the end of 2015, 80% of electricity production came from renewable sources [14]. Furthermore, a prospect from Bloomberg estimates that until 2040 Brazil will receive more than US$ 200 MM only in solar, wind and biomass electricity generation [15]. Therefore, the country has high potential for projects like the one to be designed in this work.

Nevertheless, the concept of local energy initiatives is not popular in the country. Therefore, it is assumed that a prospect project would be easier implemented in a region that has high financial resources, imports all its electricity and is not big, so the project could be considered an experiment. Furthermore, since the project is being developed from Austria, it is better to work with a region that has enough online content so the model can be as accurate as possible.

Based on these criteria the city of Águas da Prata – SP is chosen. The city is located in the state with the highest GDP of the country, owns no energy production systems and has only 8,065 inhabitants. Nevertheless, it possesses a considerable amount of area available and the state has a good database for agriculture and energy information. More information about the city will be presented in chapter 4.

3.3. *RegiOpt Conceptual Planner*

RegiOpt in an online tool that supports decision making process in energy planning by providing optimized technology systems based on the locally available resources. This optimized technology system is evaluated economically and ecologically (through the calculation of the corresponding ecological footprint using the Sustainable Process Index method as well as with the Carbon Footprint) [16]. It can be assessed through the link regiopt.tugraz.at/. In this website, it is possible to find background information about the method and also the tool (prior authorization from the system administrators may be needed). One of the advantages of RegiOpt is that it can be handled by users without technical knowledge since the calculations are all performed in the background [17].

By changing the quantity and type of input resources (raw materials) and altering several parameters, the tool can calculate the required output products (energy, heating, etc.) and create different scenarios which are useful for example for policy makers, local or regional governments, utilities companies, etc. The procedure to use the tool is described in the following paragraphs: the first step is to fill a user-friendly questionnaire about the size of the region/settlement, availability of resources, required amount of output products and economic data. The accuracy and validity of the results are bound by the consistency and reliability of this data. The user has to input information in six different steps provided by the interface, these are:

1. **General Information:**
    - On this step the user is invited to provide basic information about the region and consumption of the inhabitants.
    - Input data: Number of inhabitants, yearly solar irradiance, meat and electricity demands, living space, individual mobility fuel consumption and maximum investment volume available.
2. **Existing Energy Supply:**
    - The user can fill all existing technologies for energy generation available in the region.
    - Input data: There is the option to define existing technologies based on the input or output of the system. Technologies that can be added are: biomass burners, ORC, wood gasifiers, biogas plant (with CHP), biogas plant, biodiesel plant with gas cleaning, biodiesel plant, bioethanol plant, photovoltaics, solar thermal, wind power, and hydro power.
3. **Livestock:**
    - Requires data to determine the necessary agricultural area to support livestock and also the degree of self-sufficiency in meat production. The values are also used to estimate possible biogas production.
    - Input data: Number of animals (cattle, sheep, goat, pig, and poultry)
4. **Area Availability**:
    - The user provides the distribution of land use in the region.
    - Input data: Available productive agricultural and forestry area, percentage of forestry and agricultural area.

5. **Energy Demand:**
    - In this section, the heat provision is detailed considering efficiency and type of buildings.
    - Input data: percentage of non-residential buildings, climate zone. Percentage of old, new, low-energy and passive buildings. Current heat provided by renewables or district heating, and industrial heat demand.
6. **Basic Economic Data:**
    - The user needs to provide costs for materials and products used in the system. Also, transportation costs can be added for each one of the pertinent materials.
    - Input data:
        i. Materials include: Corn silage, barley, wheat, rapeseed, sunflower, corn grains, miscanthus, shortrotation, sugar beet, manure from livestock, other oil seeds, other biomass for burning, other biomass for biogas, other cereals, grass silage, natural gas, diesel, $CaCO_3$, methanol and KOH.

        ii. Products include: Pallets, biogas manure, biodiesel, ethanol, vegetable oil, upgraded biogas, ash, K_3PO_4, district, individual and industrial heat, electricity from biogas, PV, biomass and wind.

Not all the information above needed to be provided, since there are some default values that can be used when information is unknown. Furthermore, other values that are calculated automatically can be further specified if the user has more detailed information about the system. After this information is provided the tool will use the theory described in the previous chapter to find the optimum network considering the given constraints.

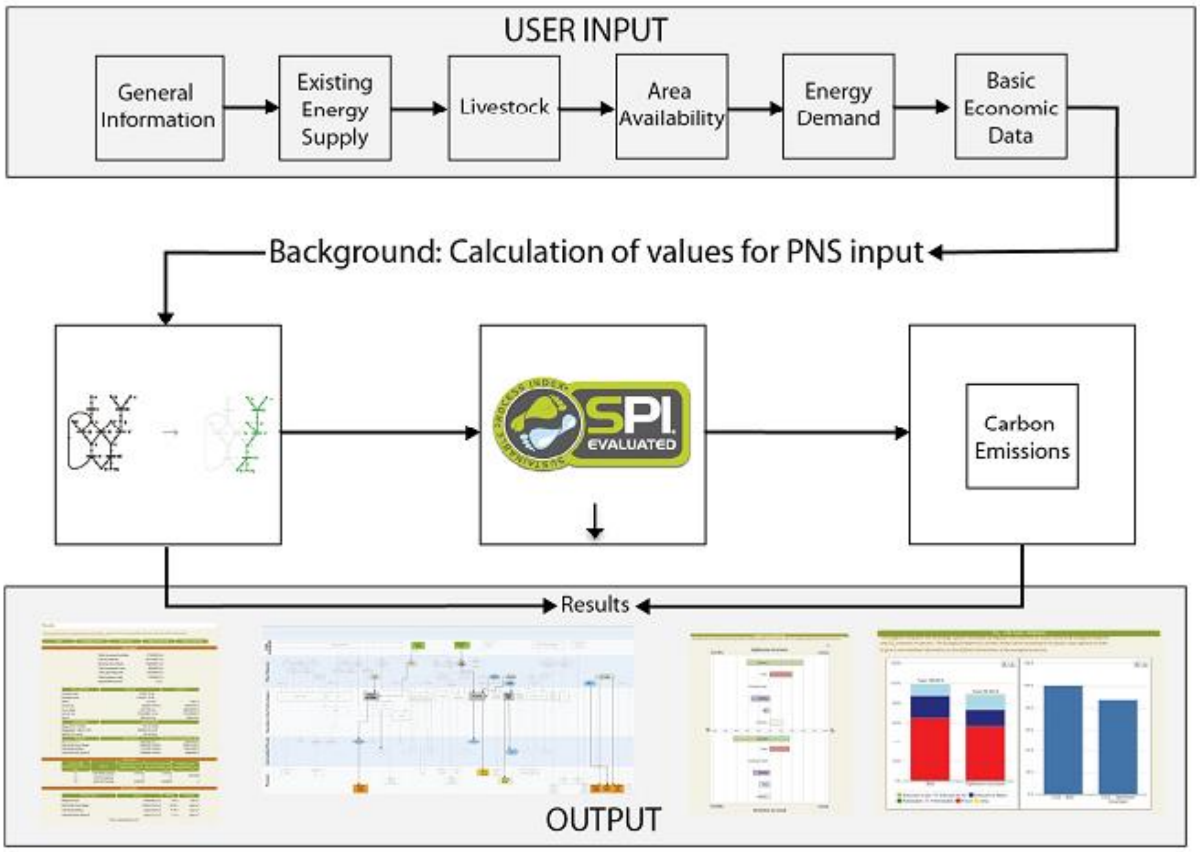

Figure 8 RegiOpt procedure scheme [18]

Then the tool enters this data into a pre-defined PNS network, which has been previously fed with information and data of conventional and renewable energy technologies. The obtained solution serves as the most economically feasible technology pathway for the region/settlement based on the available raw materials.

In the final step, the tool calculates the ecological footprint of the selected solution using the Sustainable Process Index (SPI) method. This user-friendly tool allows changing in an easy way the input parameters in order to create different scenarios and technology networks which are valuable tools for the decision-making process in energy planning tasks. In figure 8 a scheme of the described process is shown.

3.4. PNS Studio

The previously explained algorithms were also implemented in the software **PNS Studio** which is free and available on the web [19] to solve process network synthesis problems. This software is basically composed of a solver and a model analyzer. Easily allows constructing process network synthesis models using a “tree-view” and also editing the properties and units of the materials and operating units, as can be seen in the figure below:

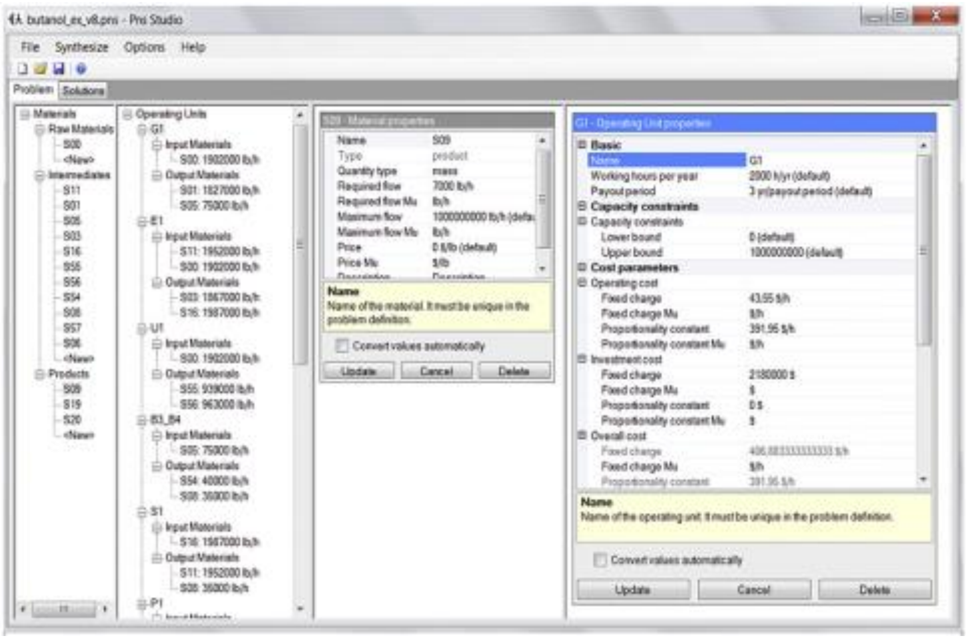

Figure 9 Tree view and properties edition [20]

To define the raw materials it is important to define the price and some constraint regarding the flow. For example, regarding crops, the maximum flow can be the maximum production of the region considering the area harvested. The definition of the operating units is of extreme importance since they are the ones that contain the relationships among materials and products and they represent a considerable part of the annual costs of the solution.

After implementing the PNS problem, the solver module generates the maximum possible structure following the combinatorial rule of the specific problem and generates optimal and suboptimal solutions taking into account cost minimization or profit maximization. If the rates of required product are defined, the solver will minimized the overall cost to achieve the goal otherwise if the rate of the available materials (with the corresponding price or production cost) is defined then the profit is maximized (if the optimal cost is negative then the solution is profitable). In the following below the solver and solution analyser can be seen.

It is important to notice that no sustainability impact tool is already embedded in this software. If an assessment of the impact is needed an outside tool should be used in parallel with PNS Studio. Nevertheless, this tool presents much more flexibility to model the system. And it demands a smaller amount of factual information about the regional current condition but it demands more research regarding possible solutions since it requires building the maximal structure and building the links among operating units and materials manually.

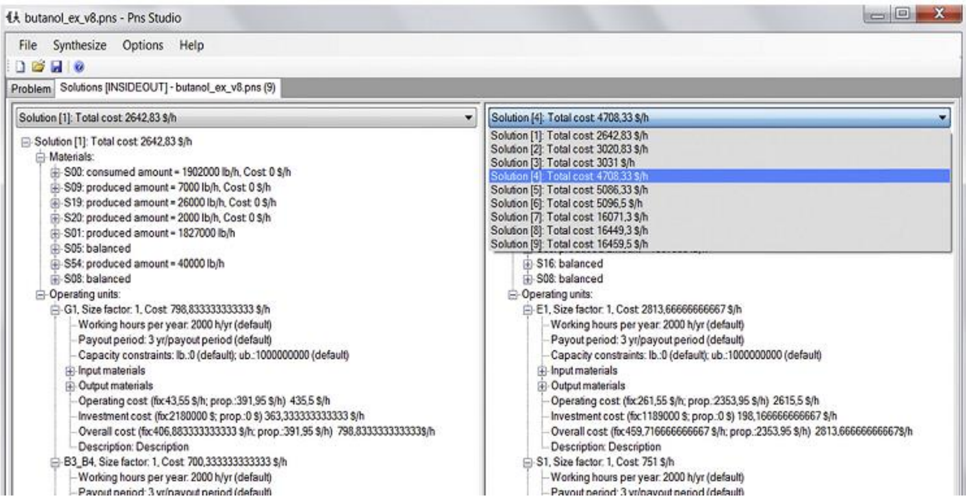

Figure 10 PNS Studio solution view [20]

3.5. Research Methodology

In order to comprehend the use of the P-graph framework for energy planning the following strategy was employed. First, all the theoretical background should be collected and studied to make adequate decision throughout the development of the project. Then, a locality is chosen to build a case study in order to assess less a less idealized scenario. After that, the preliminary data collection starts; the main goal is to collect macro information to be used in RegiOpt, but this is also information that will be used in the more accurate modeling using PNS Studio.

At this moment the research dismembers into two main branches, one using RegiOpt and another PNS Studio. RegiOpt is used first due to its more standardized nature. It is considered better to use this tool in order to understand the requirements and limitations of the region. If the results from RegiOpt are considered relevant for the region they will be used as an input for PNS Solution. This means that the results could work as guidelines for a more precise model for the energy system. On the other hand, if the results are proven unrealistic the optimization using RegiOpt will be abandoned and the modelling with PNS Studio will not consider the output provided by the web based tool.

Nevertheless, the modelling using PNS studio requires a more detailed data collection regarding the production chains that are going to be used. So, there is a second round of data collection that is defined after a careful analysis of RegiOpt solution. After enough information is obtained, the actual modelling of the system starts with the construction of a base scenario. For this scenario several assumptions are made to consider the social dimension of sustainability:

1. The base scenario will be constructed based on the use of biomass resources currently available in the region;
2. No change in the current agriculture practices can be assumed;
3. The region is limited to the physical borders of the city;
4. No neighboring cities participate in the energy system;
5. The main goal is to make the region electricity neutral.

Based on the results obtained several scenarios will be proposed in order to understand the stability and efficiency of the system. And finally, the final results will be discussed and analyzed in order to define if the tool can provide technological networks that are more sustainable for stakeholders.

DATA COLLECTION

This chapter aims to provide the most critical information used in the regional energy optimization of Águas da Prata. First, in section 4.1, the main information about the region itself will be provided, with focus on land use. Then, some preliminary information to be used in RegiOpt is presented in section 4.2. In section 4.3 and 4.4, the routes for the production of the selected crops are described regarding their efficiencies and streams. In section 4.5, an overview of the combination of both chains is presented, including a discussion about Brazilian subsidies for electricity production. Finally, the investment costs of such a system are presented and discussed in section 4.6. In section 4.7 the information is summarized and displayed in the way it was input in the software used for the optimization.

4.1. Region

The analysis of this project is focused in Águas da Prata, a municipality located in the state of São Paulo, Brazil. This municipality has a population of 8,065 inhabitants with approximately 90% of the population living in the urban area [21]. Although most of the population is located in the city, the municipality has a small portion of its area used by urban area. The total area of the region is $14{,}257\ ha$. Below, a graph of the land use distribution:

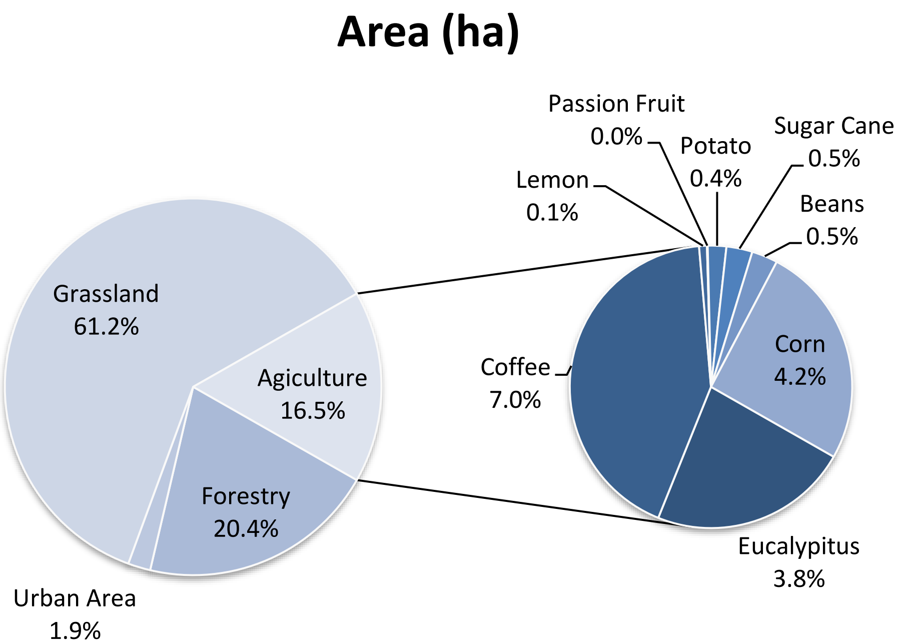

Figure 11 Land use distribution

The data for the agriculture area is detailed by the Brazilian Institute of Geography and Statistics [22]. Lemon, coffee and passion fruit are permanent crops and are not considered as a significant source of biomass considering this project, since they do not produce relevant waste. Furthermore, two crops grown in the region are appropriate for ethanol production besides electricity, corn and sugar cane. Because of that, it was decided to focus on these two agriculture sources as options for the optimization of the technological network. The agriculture area represents $16{,}5\%$ of the total area of the region, corresponding to $2{,}350\ ha$.

Forestry area could provide waste biomass, but the region has a small natural reserve within its borders, which limits human action. The area currently protected is $48.4\ ha$, but a project that intends to expand it to most of the forestry area in the region is currently in progress. In this area there would be two different sectors, one that the use of the natural resources is completely forbidden and another where sustainable use is allowed [23]. Due to this momentarily uncertainty over the forestry area it was decided not to consider its use for energy generation purposes. Therefore, these 2,913 ha are excluded from the analysis.

In order to determine the urban area inside the region an online tool was used. In this tool, the boundaries of the region which area needs to be determines are chosen and the occupied area is calculated [24]. The area calculated by the software is $275\ ha$, which represents $1{,}6\%$ of the total area available in the region. Although not all urban area is sealed, it was considered as such. This is due to the fact that the area recovered by an analysis non-sealed area would be negligible considering the grassland and agriculture area of the region. The map with the boundaries of the urban area is presented in the Appendix 1.

Moreover, most of the region's area is composed by grassland; it is characterized graminoid plants, herbs, bushes and sparse trees [25]. The most expressive use for this area is pasture for the cattle present in the region [25]. This area was calculated as the complement of all the other areas presented beforehand. This area is not considered for energy purposes due to one of the hypothesis used in this work; the project attempts to a maximum not to disturb the current economy of the region, merging with current practices.

Considering the fact that this area is currently used for cattle it should, based on the hypothesis, be kept like that at least in a base scenario. Therefore, the only possible way to produce electricity without taking off pasture from cattle would be to use manure to produce biomass. But, due to the nature of the cattle farming, the collection of the manure would be hard. Therefore, in principle, grassland will also not be considered for electricity production. The table below summarizes the information presented about the area use:

Table 1 Summary of land use information

Land Use	Area (ha)	%	Use for energy production
Grassland	8.719	61,2%	No
Forestry	2.913	20,4%	No
Urban Area	275	1,9%	No
Coffee	1.000	7,0%	No
Corn	**600**	**4,2%**	**Yes**
Eucalyptus	537	3,8%	No
Sugar Cane	**70**	**0,5%**	**Yes**
Beans	70	0,5%	No
Potato	50	0,4%	No
Lemon	21	0,1%	No
Passion Fruit	2	0,0%	No
Total	**14.257**	**100%**	**-**

Furthermore, the region is mainly residential; there is no heat use due to the absence of industries. The electricity demand is $\mathbf{3,087\ kWh_{el}}$ [26] per inhabitant per year, which can be provided by a $3\ MW$ system.

4.2. Preliminary information

Due to the macro perspective used by RegiOpt a lot of information is needed but with no depth. Therefore, there will be no discussion regarding the preliminary data acquisition. The data needed to fill the 6 steps of RegiOpt input is presented in the table below with a link to the source. If a field is not given in the table below is because the standard values provided by the tool were used. Some main data assumptions are presented right after the table.

Table 2 RegiOpt input

Item	Value	Unit
General Information		
Inhabitants [22]	8,025	[#]
Meat Demand [27]	112	[kg/inhabitant]
Electricity Demand [26]	3,087	[kW_{el}/inhabitant]
Average Individual Mobility [28]	7,044	[km/inhabitant]
Average Fuel Consumption [29]	3.02	[l/100 km]
Solar Irradiation [30]	3.42	[MWh/m^2]
Existing Energy Supply	-	-
Livestock		
Cattle [22]	8,183	[AUE]
Sheep [22]	0	[AUE]
Goat [22]	5	[AUE]
Pig [22]	2,147	[AUE]
Poultry [22]	40	[AUE]
Area Availability		
Available Productive Agricultural and forestry area [22]	12,983	[ha]
Forestry Area [22]	22	[%]
Agricultural Area [22]	10	[%]
Solar area for PV-parks on proper areas [assumption]	1	[ha]
Energy Demand	-	-
Basic Economic Data[1]		
M - Corn Silage [31]	190	[€/ton]
M - Barley [31]	184	[€/ton]
M - Wheat [31]	255	[€/ton]
M - Rapeseed [31]	323	[€/ton]
M - Sunflower [31]	276	[€/ton]
M - Corn Grains [31]	190	[€/ton]
M - Sugar Beet [31]	189	[€/ton]
M - Other Biomass for Biogas [31]	19	[€/ton]
M - Natural Gas [32]	0.53	[€/m^3]
M - Diesel [32]	592	[€/ton]
M - Electricity [33]	110	[€/MWh]
P- Biodiesel [33]	688	[€/ton]
P- Ethanol [32]	470	[€/ton]
P- Vegetable Oil [33]	688	[€/ton]
P- Electricity from PV [34]	83	[€/MWh]
P- Electricity from Biomass [34]	58	[€/MWh]
P- Electricity from Wind [34]	43	[€/MWh]

As stated before, the information presented at this stage is superficial. When more detailed information is used in the next steps there may be small discrepancies in values. This is also due to the fact that the tool is static; therefore, data should be displayed in a way to match the calculation methodology.

[1] M = Materials and P = Products

Currently the city does not produce energy. So, there is no information regarding the existing energy supply. To determine the energy demand, most information is related to heat and in countries like Brazil heat is not used for residential purposes. First, it is stated that the climatic zone is moderate warm. Then, since there is no option to turn off the heat use in residential areas it is decided to assume that all houses are Passive (houses with the lowest possible heat demand). Also, there is no industrial heat demand, since there are no industries in the region.

4.3. Sugar Cane

In the region of this study sugar cane is cultivated in small scale, but the state is the biggest producer in the country [35]. This crop is further analyzed in order to assess possibilities for expansion of cultivation area and energy generation. Basically two main raw materials were considered: the sugar cane and the trash. By sugar cane is meant the stalk which contains the juice that can be used for ethanol production, for example. The trash is composed by green leaves, the tops and the dry leaves that are usually left on the field after harvesting. For each ton of sugar cane harvested, in average, $140\ kg$ of dry residues are produced [36]. The region has an area of $70\ ha$ for sugar cane with a yield of $90\ ton/ha/year$ [22].

The production costs of sugar cane is not available for the exact location, therefore, the production costs regions close by were averaged. The total operational cost (TOC) is a combination of direct, *e.g.* seeds and fertilizers, and indirect expenses, *e.g.* machine depreciation. Considering the costs of crops that are planted manually, but harvested automatically, the TOC is € 11.28 in the region of *Ribeirão Preto* and € 13.34 in *Araraquara* [37]. So, the average production cost is € 12.31. An analysis of the trash, considering a specific route for harvesting that will be further discussed ahead, gives an opportunity cost of € 7.33. The sugar cane is directly sold; in the year of 2014 the total profit of the region by the commercialization of sugar cane was € 98,586 [22]. Dividing this by the production it is possible to obtain the profit per ton displayed in the table below. It is assumed that currently the trash is left in the field or burned *in situ*, therefore, there was no profit associated with this raw material.

Table 3 Summary of raw materials – Sugar Cane

Raw Material	Maximum flow (ton/year)	Production cost (euros/ton)	Selling price (euros/ton)
Sugar Cane	6,300	12.31	15.64
Trash	1,008	7.33	-

The route for collection and use of the sugar cane impacts strongly the costs and losses in production. Therefore, in the next steps the chosen production chain will be presented and characterized in terms of efficiency and costs. The proposed route is one that produces both ethanol and electricity. It is of interest to know which type of product would be favored considering the maximization of the region's profit and also if the available crop is enough to provide electricity to fulfil the demand. Therefore, the overall production chain below is proposed:

Figure 12 Simplified production chain – Sugar Cane

Each step of this production chain will be briefly discussed considering the main assumptions, together with the inputs, outputs and important operating costs.

1. *Harvesting*:

The first important assumption for the harvesting process is that it is mechanic. This is due to the fact that the state has a law that imposes the implementation of mechanic harvesting in 100% of the mechanizable harvesting area until 2021 and in the non-mechanizable area until 2031 [36]. Therefore, any planning should consider that manual harvesting cannot be relied upon. Also, there are still several options considering the use of trash. The trash can be separated in the farm or in the mill; it can be chopped or balled, etc. The routes are carefully analyzed by Paes, Hassuani and Filho [36] considering all equipment needed and costs associated.

The best alternative found is based on the partial cleaning of the field, which leaves some trash on the ground assuring that part of the nutrients will go back to the soil directly; in this route 29% of the trash is left on the ground. The rest of the trash is collected with the sugar cane and taken into trucks that will transport the biomass to the mill. Considering this alternative, the visible losses are taken as 1.60% and the invisible ones as 3.40% [36]. It is noteworthy that visible losses are the ones due to the absence of material and invisible losses are the ones due to loss in weight of material that happens because of evaporation, for example. Therefore, the total efficiency of the harvest is calculated as 91%.

Table 4 Summary of harvesting efficiency

Item	Mass flow (ton/year)	Losses (%)
Sugar Cane	6,300	-
Visible losses	101	1.60%
Invisible losses	214	3.40%
Trash	1,008	-
Visible losses	16	1.60%
Invisible losses	34	3.40%
Trash left on field	292	29.00%
Total to the mill (Trash + Sugar cane)[2]	**6,650**	**-**

After harvesting, since the sugar cane and trash are not separated, the selling price was considered to be the price of the sugar cane, € 15.64 per ton, as shown in Table 3. No investment costs are considered at this stage since it was assumed that all equipment for harvesting is already available to the farmers. In summary, the costs for harvesting are the same as the production costs presented beforehand.

2. *Transportation*:

The region of interest is not big and the goal is to use the resources locally. Therefore, transportation losses are not significant. In the model made by CTC [36] the biomass available after the harvest is the same available in the mill. As a measure of conservatism, it was decided to assume an efficiency of 99%; this considers that the losses are marginal but are taken into consideration. The delivery costs using the harvesting route with partial trash collection is € 2.43 per ton of dry biomass [36]. This cost is based on an average distance of 19 km between farm and mill.

3. *Treatment*:

The biomass that arrives on the mill is not appropriate for energy generation. It needs to be cleaned, grinded and the trash needs to be separated from the sugar cane. All these steps are developed in a central location. The first stage the material occurs in a cleaning station, which is located in the same place as the mill. The main

[2] The final value is the difference between the initial values and the losses in each step.

purpose is to eliminate vegetal and mineral impurities [36]. Then, the clean stream is directed to a grinder that will chop the biomass into appropriate sizes.

In the cleaning station there are losses during the washing process 0.81% and in the dry cleaning station, where the trash is separated from the cane, the losses are 1.69% [36]. During the milling, part of the biomass is lost; the mill considered has 96.24% efficiency [36]. Also, the separation process is not ideal, leaving part of the trash with the sugar cane, the separation efficiency is taken as 70% [36]. This means that, after separation, there will be 30% of the mass of trash after transportation still in the sugar cane.

Table 5 Summary of treatment efficiency

Item	Mass flow (ton/year)	Losses (%)
Sugar Cane + Trash (Input)	6,584	-
Cane washing losses	53	0.89%
Dry cleaning losses	111	1.69%
Milling losses	248	3.76%
Sugar Cane	**5,739**	**-**
Trash	**432**	**-**

The treatment step has a final efficiency of 94%, calculated as the ratio between output and input mass flows. The operating costs of such a facility are $€\ 4.28$ per ton of dry biomass [36]. At this point it is noteworthy that the production costs already surpass the market price for sugar cane in the region. Usually the sugar cane is sold right after harvest and has low vegetal impurity content. But, since there is intention to use the trash, the production costs also englobe the separation of the sugar cane and trash. Besides that, it also has to be transported to the mill. Considering all this, the production cost is $12.31 + 2.43 + 4.28 = 19.02$, which is considerably higher than the selling price of sugar cane.

Nevertheless, the region will benefit for the production of electricity from the trash. In principle, it is not necessarily damaging to have a loss in the sugar cane harvest selling. After the treatment step, there are two main streams of raw materials, one of sugar cane that is directed to an ethanol production plant and another with the trash that will be directly used for energy generation. In the next section the ethanol production will be discussed and the trash will be only discussed in step 5.

4. *Ethanol*:

The process of ethanol production can be of extreme complexity, because of that, it was decided to consider it as an one step process that has as an input sugar cane and as an output ethanol and by-products. No energy input is considered in this process because usually part of the bagasse generated is used for electricity production. Also, corn is also going to be used for ethanol production. Therefore, it was decided to consider that bagasse produced from the extraction of the juice is used to supply the necessary heat and electricity to run the plants. This assumption is reasonable, since usually plants have a surplus of electricity due to the combustion of the bagasse. The overall alcohol production efficiency is 90.30% [36], and was used to determine the products' mass flows.

The production of ethanol has three major by-products, being the bagasse, cake filter and vinasse. The bagasse is what is left after the juice is extracted from the stalk. $1\ ton$ of sugar cane generates approximately $250\ kg$ of bagasse [38], representing 25% of the mass flow. Cake filter is a byproduct of the industrial processing of sugar cane; it is generated in the process of filtering of the juice extracted from the stalk. Around $35\ kg$ of cake filter is generated per ton of sugar cane (approximately 4% of the total mass flow) and it can be applied as a fertilizer due to high mineral content [38]. The vinasse is a final residue of the production of ethanol by fermentation and also has high potential as a fertilizer [38]. The yield of vinasse was determined by complementarity. The price for both products, cake filter and vinasse, is estimated considering the difference in production costs using the usual fertilizers and by the use of the byproducts as substitutes. This difference is € 49.46 per hectare [39], or € 0.55 per ton, considering the region sugar cane yield. Also, the production costs of ethanol are € 62.49 per ton.

Table 6 Summary of flows – Ethanol production

Item	Mass percentage (%)	Mass flow (ton/year)	Cost (euros/ton)
Input	-	-	-
Sugar Cane	100%	5,739	19.02
Outputs[3]	-	-	-
Ethanol	5%	285	162.98
Cake Filter	3%	181	0.55
Vinasse	60%	3,421	0.55

5. *Electricity*:

For energy production it is assumed that the system used to generate electricity and steam for the internal processes can handle a higher mass flow and produce excess streams. In this way, the bagasse and the trash can be burned together. This system should be designed to enable the use of waste streams of other crops, like corn, to guarantee its better use. Considering that this system generates electricity using a steam turbine, it is possible to assume no efficiency loss in the boilers and consider that only the efficiency turbines and generators need to be taken into account. The values for these efficiencies are $\varepsilon_{turbine} = 55\%$, and $\varepsilon_{generator} = 96\%$ [40], resulting in an efficiency of 52.80%. This system demands around 4% of the investment costs for its operation [41].

For the ethanol combustion a small gas turbine adapted to use alcohol as a fuel is considered, the use of such technology is a reality in Brazil for large scales [42], but no information about small scale systems was found. Nevertheless, Siemens has in its catalogue a small gas turbine that can operate using ethanol with electrical power between 3.9 and 6.4 MW, with an efficiency of 30.60% [43]. The amount of energy that can be produced by such a system can be calculated considering the HHV of the inputs. Below, a summary of the heating values of the inputs considered in the electricity generation from sugar cane:

Table 7 Input High Heating Values (HHV) – Sugar Cane

Item	Mass flow (ton/year)	HHV (MJ/ton)
Bagasse [36]	350	18,750
Trash [36]	440	14,310
Ethanol [44]	285	29,847

4.4. Corn

In the region used for this study corn represents the second biggest crop in area, $600\ ha$ [22]. Its yield is $3.25\ ton$ per hectare [22], which gives a maximum flow of $1,950\ tons$ per year. Corn, as sugar cane, can be used for ethanol production; therefore, it is a possibility to combine both crops in the same installation to

[3] Values already considering the efficiency of 90.30%

maximize its use. When this crop is considered there is the also a byproduct of the harvest, the corn stover, which is composed by the leaves and stalks left over the soil after harvest. Corn has a higher ethanol yield when compared to sugar cane, but sugar cane has a higher production per hectare.

Differently from sugar cane and trash, corn and corn stover are harvested separately. Because of that, the materials have different selling prices that reflect on different harvesting methods. The first assumption is that the farms do not use state of the art technology, since it is small scale production. The production costs of the corn consider the expenses with farming, like fertilizers and machinery, but also with storage, financing and machine depreciation. All taken into account, the cost for corn production is € 60.60 per ton [45]. The selling price of corn in the region of Águas da Prata [46] is € 184.79 per ton. The costs of production of corn stover are the costs of the harvest, since it is a byproduct of the corn crop. These costs are, on average, € 39.91 and consider harvesting and storing [47]; the selling price is € 70.95 per ton [48].

Table 8 Summary of raw materials – Corn

Raw Material	Maximum flow (ton/year)	Production cost (euros/ton)	Selling price (euros/ton)
Corn	1,950	60.60	184.79
Corn Stover	2,100	39.91	70.95

The route for corn is similar to the sugar cane. After the harvest the materials are transported to a central installation where the corn is turned into ethanol and the corn stover is treated and put into a high efficiency boiler for electricity generation. The ethanol is also used for electricity generation.

Figure 13 Simplified production chain – Corn

Below, each step is described regarding the most significant aspects:

i. *Harvesting*:

The harvest of corn is mechanical; the machines are able to extract to grain from the cob. For a small crop the harvest losses represent 2% of production [49]. The corn stover is left in the ground after the grain harvest. Not all of it can be harvested due to soil protection and nutrition aspects, it is considered safe to remove up to 30% of the stover [47]. In order to collect it, a pass with a baller passes on the field. For ethanol production purposes square bales are preferred. The bales have to be removed from the field to avoid decomposition, therefore, there is need to store the corn stover. This can be done by using tarps to cover the bales, being an affordable and effective solution [47].

Table 9 Summary of harvesting efficiency

Item	Mass flow (ton/year)	Losses (%)
Corn	1,950	-
Harvest losses	39	2.00
Corn stover	2,100	-
Harvest losses	42	2.00
Stover left on field	1,365	70.00

Item	Mass flow (ton/year)	Losses (%)
Total[4] corn to the mill	**1,911**	**-**
Total corn stover to the mill	**693**	**-**

ii. *Transportation*:

It was decided to assume the same efficiency for transportation of sugar cane, 99%. The costs for the transportation were estimated as 10% of the full production cost provided in [47], € 4.43.

iii. *Treatment*:

As stated previously, the grain can directly be used for ethanol production, which eliminates the treatment step for this material. The corn stover, on the other hand, has to be unbaled and milled. The efficiency of the milling is taken as the same of the sugar cane, 96.24%. The requirements for grinding are not strict; it is important to lower particle size to enhance the heat transfer mechanism in the boilers. Since same type of mill can be used it is also assumed that the treatment costs are the same between the two crops, around € 1 per ton processed.

iv. *Ethanol*:

The corn grain is used to produce ethanol. In this project the concept of a *flex* plant is used. A flex plant is one that can run using more than one type of crop simultaneously. No details about the design of the plant will be presented in this work, for further considerations check [50] and [51]. The plant produces ethanol with the by-products being removed in several steps of the production, producing several byproducts. With 1 ton of corn it is possible to generate, using this technology, approximately 330 kg of ethanol and 193 kg of byproducts [50]. The ethanol selling price is the same of sugar cane and the price of the byproducts, which are named fractional products, combined is € 207.11.

v. *Electricity*:

The system that generates electricity is the same of the sugar cane; it comprises in a steam turbine based generator that burns the corn stover to generate steam and a gas turbine that uses ethanol as a fuel. The gas turbine has fixed operating costs around € 6.51 per kW per year [52]. For the steam turbine system these costs usually are around 3.7% of the investment costs. Therefore, the only information required is the HHV of the inputs. The table below gives its values:

Table 10 Input High Heating Values (HHV) – Corn

Item	Mass flow (ton/year)	HHV (MJ/ton)
Corn [53]	1,892	16,630
Stover [54]	560	18,610
Ethanol [44]	563	29,847

4.5. Overview of production chain

The diagram below intends to present a summary of all steps of the production chain presented above, including how they connect and efficiencies. The production chains from corn and sugar cane connect with one another in two points. The first is for ethanol production; both corn and sugar cane are used in the same *flex*

[4] The final values are the difference between the initial values and the losses in each step.

distillery to produce ethanol. As byproducts there are 4 categories presented: bagasse, cake filter, vinasse and fractional products. For corn, several byproducts are obtained throughout the process, for simplicity they are bundled together. The second interconnection happens in the electricity generating systems based on a steam turbine. In this system, sugar cane trash, corn stover and bagasse are burned together to produce energy. The bagasse is completely used for internal energy demand and the other materials are the ones responsible for external electricity production.

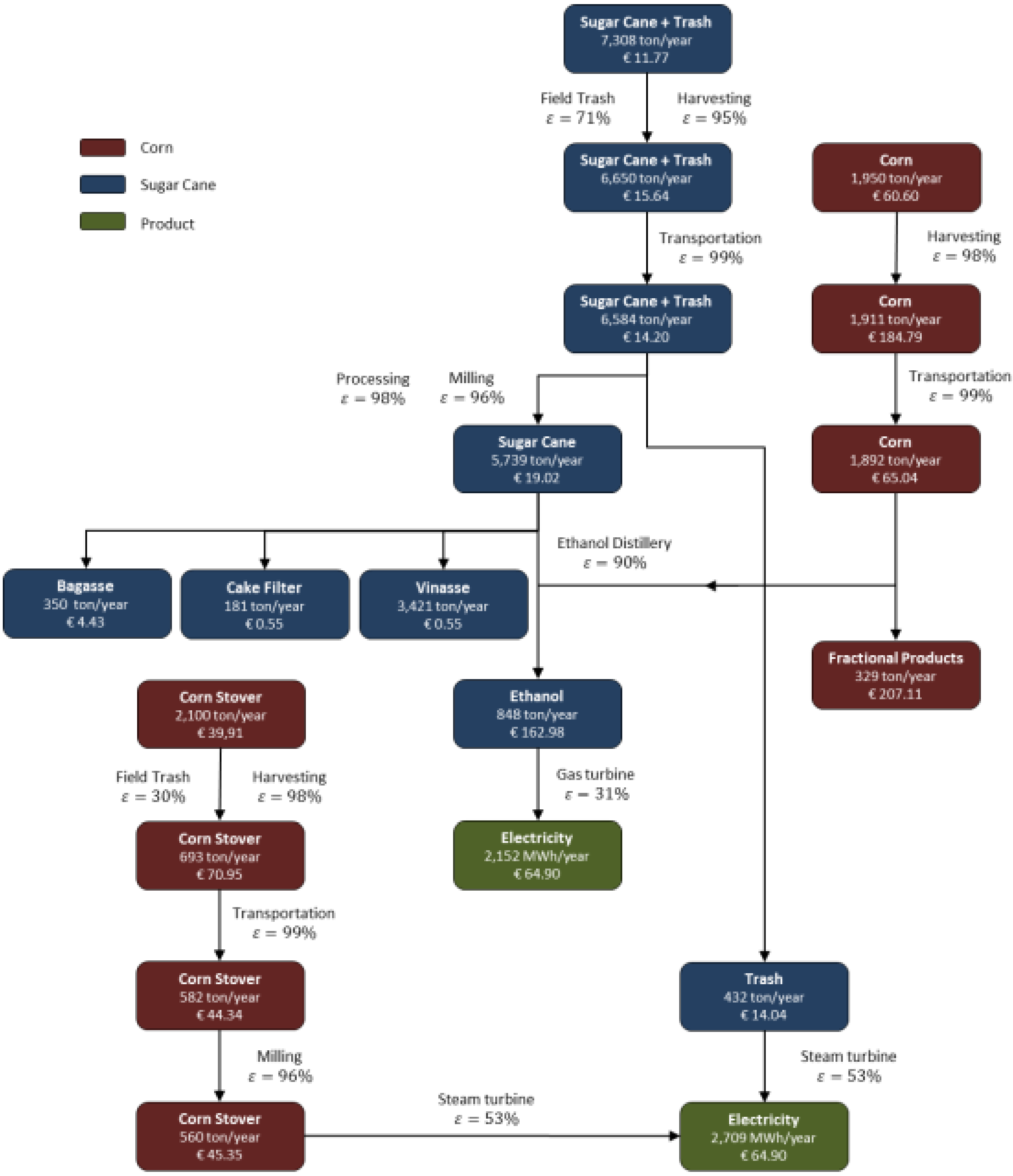

Figure 14 Overview production chain (Sugar Cane + Corn)

The diagram is structured based on the following assumptions:

i. The mass flow values are based on the initial condition. For example, 7,308 tons is the amount of sugar cane that **can be** harvested in the region.

ii. The first step of the diagram contains the production costs of that material, after the harvest the price presented is the market price. This represents the default situation – selling the production. If the production is not sold than the price is built upon the production costs. That is why the third step of the chains has always a lower price than the second.

iii. The arrows connecting stages are processes with a given efficiency. For example, because of the efficiency of harvesting and the trash that must be left on the field for sugar cane, only 6,650 tons are effectively available for transportation.

iv. The prices are given per unit; for mass it is the price per ton, for energy, per MWh.

v. Only electricity is considered a product since it is the target of the project. Nevertheless, all items have a price can be sold for revenue in the market.

It is also important to know that these values represent the potential of the region; they are based only in the data collected from the crops and usual route for conversion. The importance of this data collection is that it provides yields for the operating units and the maximum available flows for all the streams. This information will then be inserted in the PNS Solution software to be optimized. The resulting network may or may not use all the elements. Also, it can use fewer resources than the total available. Furthermore, the system designed in this project does not consider selling the heat produced during the processes of electricity generation. Although a significant amount can be produced, in the region there is no demand. As a potential aspect for investigation the connection of this system with a neighboring region can be another source of income.

Since electricity from biomass is the main product of this chain, it is important to understand how governmental subsidies can compose part of the revenue of the region. The Brazilian government has a program for the development of renewable energy projects called PROINFA. The goal of this program is to enhance the participation of renewable electricity produced from biomass, wind or small hydro systems [55]. In 2015 the average value of subsidies to biomass projects were determined as $€\,48.33$ per MWh produced. This subsidy is considered also a product of electricity generation and is parametrized as an output of the selling electricity operating unit, as will be presented in the final section of this chapter.

4.6. Investment costs

One important aspect in the establishment of a technology network is the investment costs the region would have to employ in order to make the plan into reality. It is assumed that no investment costs are needed in the harvesting or transportation stages of the production chain. In the case of harvesting, it is assumed that the farmers already use technology that fits the routes chosen in this project. Considering the transportation, in the region any production is moved using trucks and these are already owned by farmers, cooperatives or will be hired as third party associates; in any case it is implied that no extra investment costs are due. Therefore, three main costs have to be considered in the chain presented in the previous sections. These are (1) treatment plants, (2) ethanol production plant and (3) electricity generation systems.

Several possibilities for the combined generation of ethanol using corn and sugar cane [50]. The system chose in this project is based on a *flex* plant that produces ethanol with corn only in between harvests from sugar cane and removes the byproducts of the ethanol production throughout the process, not only at the end. Also, the system considers selling any excess of electricity and is optimized energetically, to be able to be self-sustaining. This plant is the ranked as the second best in both economic and environmental scenarios [50]. The investment in such a plant is around $€\,228$ million for a capacity of 5.5 million tons of biomass. This price includes the investment costs for the electricity generation system using steam and the treatment installations.

First, the value has to be corrected to consider the appropriate capacity. This is done by the use of an exponential relationship available in [56], using the standard value of $x = 0.6$.

$$C_2 = C_1 \cdot \left(\frac{Q_2}{Q_1}\right)^x \quad (1)$$

Where,

$\boldsymbol{C_2}$ is the desired cost of capacity $\boldsymbol{Q_2}$,

$\boldsymbol{C_1}$ is the known cost of capacity $\boldsymbol{Q_1}$ and,

$\boldsymbol{x}$ is the cost-capacity factor.

Since this value considers the treatment installation and the steam turbine system they have to be excluded from the calculation. According to [36] the investment costs for the pretreatment plant is around € 402 thousand for a capacity of 164 thousand tons of biomass. The cost for the electricity generating systems were taken from [41] and are given by unit of kW produced. The steam system of taken as a Stoker boiler; the lowest possible cost for this system is € $1{,}756$ per kW while the lowest price for a gas turbine is € $2{,}661$. Furthermore, it is known that a $3MW$ would provide enough electricity to the system. So, it was assumed that half of this electricity, or $1{,}500\ kW$, is generated by the steam turbine and the other half by the gas turbine in order to calculate the capacities of the systems and estimate the investment costs. Also, the corn stover treatment only demands a milling station. It was assumed that it represents 20% of the investment costs of the treatment plant of the flex plant. The table below summarizes the values given above and the correspondent adjusted price considering the current estimated capacity of the system:

Table 11 Summary of investment costs

Item	Original capacity (ton/year or kW)	Original cost (euros)	Capacity (ton/year or kW)	Adjusted cost (euros)
Flex plant	5,475,000	227,825,030	7,631	4,406,884
Treatment	164,250	402,093	6,596	58,359
Steam turbine	1	1,756	1,500	2,633,913
Ethanol plant	-	-	7,635	1,767,135
Gas turbine	1	2,661	1,500	3,990,777
Treatment corn	-	-	-	11,700
Total	-	-	-	**8,410,586**

The lifetime of the investments was assumed as 20 years, except for the treatment installations that were assumed to have a lifetime of 10 years.

4.7. Input data for base scenario

All the information presented in this chapter comprises the input for the optimization of a base scenario for the region. This means that the result obtained from this data is the current optimum situation and all scenarios will be developed from this stage. For the tool, it was decided to convert all mass streams that possess energy content into energy streams. This helps avoiding duplicity of operating units when more than one input material is considered. This conversion was done considering the HHV of the materials or products. The table below represents all the information used in the PNS Solution problem definition considering the raw materials, intermediates and products:

Table 12 Input information – materials and products

Variable	Unit in optimization	Mass Flow [ton/year]	Energy Flow [MWh/year]	Price [euro/unit]
r_sugar_cane_harvest	MWh/year	6,584	33,478	2.79
r_corn_stover_harvest	MWh/year	686	3,009	10.11
r_corn_harvest	MWh/year	1,892	8,739	14.08
i_sugar_cane	MWh/year	5,739	29,665	-
i_sugar_cane_trash	MWh/year	432	1,718	-
i_corn_stover	MWh/year	660	2,896	-
i_ethanol	MWh/year	848	7,034	-
i_vinasse	ton/year	3,421	-	-
i_cake_filter	ton/year	181	-	-
i_fraction_products	ton/year	329	-	-
i_electricity	MWh/year	-	4,862	-
p_sugar_cane_sell	MWh/year	-	29,665	3.08
p_sugar_cane_trash_sell	MWh/year	-	1,718	3.53
p_vinasse_sell	ton/year	3,421	-	0.55
p_cake_filter_sell	ton/year	181	-	0.55
p_ethanol_sell	MWh/year	-	7,034	19.66
p_corn_sell	MWh/year	-	8,739	40.00
p_fraction_products_sell	ton/year	329	-	207.11
p_corn_stover_sell	ton/year	-	3,009	16.18
p_electricity	MWh/year	-	4,862	64.90
p_proinfa	MWh/year	-	-	234,945.12

The limits established for the trading of products produced during the routes chosen in this report were fixed at the maximum flows for each one of the products. Furthermore, it can be seen that the only products that were not converted into energy streams are the byproducts of ethanol production. They were maintained in mass flows because of their use; most of these products are sold as fertilizers and it is only logical to measure the amount produced in tons, instead of MWh. The prefix $r\_$ indicates a raw material, or a material that is not an output of any operating unit. The prefix $i\_$ indicates an intermediate, which means that the material is both an output and input from operating units. Finally, the prefix $p\_$ indicates that the material is a product that, in this study, also means it can be sold. The subsidy has no mass or energy flow but was inserted in the optimization as a financial flow that is the electricity maximum flow times the average subsidy per MWh.

Table 13 Input information – operating units

Variable		Unit in optimization	Mass Flow [ton/year]	Energy Flow [MWh/year]	Investment costs [euro/year]	Operation costs [euro/year]
Operating Unit	**o_sugar_cane_treatment**		-	-	**5,836**	**28,201**
Input	r_sugar_cane_harvest	MWh/year	6,584	33,478	-	-
Output	i_sugar_cane	MWh/year	5,739	29,665	-	-
Output	i_sugar_cane_trash	MWh/year	432	1,718	-	-
Operating Unit	**o_corn_treatment**		-	-	**1,167**	**693**
Input	r_corn_stover_harvest	MWh/year	686	3,009	-	-
Output	i_corn_stover	MWh/year	660	2,896	-	-
Operating Unit	**o_ethanol_plant_sc**		-	-	**132,904**	**17,814**
Input	i_sugar_cane	MWh/year	5,739	29,665	-	-
Output	i_ethanol	MWh/year	285	2,363	-	-
Output	i_vinasse	ton/year	3,421	-	-	-
Output	i_cake_filter	ton/year	181	-	-	-
Operating Unit	**o_ethanol_plant_co**		-	-	**43,809**	**35,206**
Input	r_corn_harvest	MWh/year	1,892	8,739	-	-
Output	i_ethanol	MWh/year	563	4,671	-	-
Output	i_fraction_products	ton/year	329	-		
Operating Unit	**o_gas_turbine**		-	-	**399,078**	**9,764**
Input	i_ethanol	MWh/year	848	7,034	-	-
Output	i_electricity	MWh/year	-	2,152	-	-
Operating Unit	**o_steam_turbine**		-	-	**263,391**	**4**
Input	i_sugar_cane_trash	MWh/year	432	1,718	-	-
Input	i_corn_stover	MWh/year	660	2,896	-	-
Output	i_electricity	MWh/year	-	2,709	-	-

The table above presents all investment and operational costs considered in the simulation. Also, it shows the inputs and outputs used in each one of the operating units. It was decided not to present here the all the physical operating units. All units that were created for conversion or selling products are not presented since they do not possess investment or operational costs. The detailed information about the definition of the operating units is presented in Appendix 2. It is noteworthy that the investment costs of the ethanol production plant were split between two ethanol operating units. This was done to consider the fact that the different crops result in distinct products. Therefore, although this is physically one installation, it is considered as two in the optimization and the cost is split considering the mass flow of biomass.

RESULTS

On this chapter the main results of the optimization will be presented. In section 5.1, the results from RegiOpt are presented briefly discussed to provide a connection to the base scenario presented in section 5.2 together with a discussion of the implications of the optimum technological network. In section 5.3, the hypothesis for the other scenarios will be presented. Finally, in section 5.4 the results of the different scenarios will be compared with the base one regarding impacts on the costs and electricity production.

5.1. RegiOpt results

As discussed beforehand, the main goal of using RegiOpt is to obtain a first estimation of the technological network of the region and to assess its applicability to help in making sustainable energy projects more attractive. Due to that, not all results will be presented here. The tool proved to be focused on the European market, and due to the lack of flexibility, does not provide fruitful results in the Brazilian content. To illustrate that, the following graph is presented:

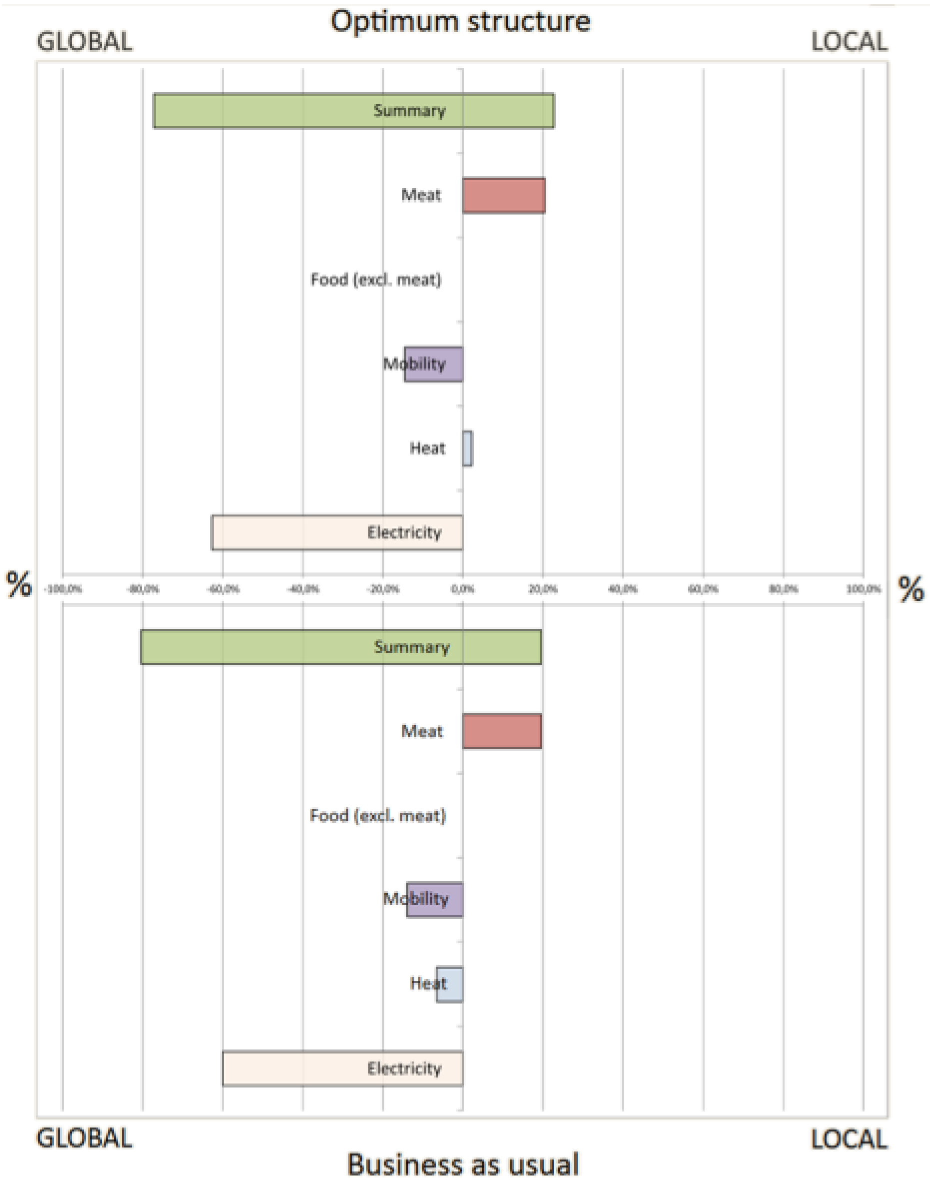

Figure 15 Comparison Optimum structure vs Business as usual – RegiOpt

This diagram shows the distribution of the ecological footprint between global and local impacts of the provision of energy services and food. The upper part again refers to the optimal technology system calculated by RegiOpt, the lower part shows the ecological footprint of the business as usual situation. It is possible to see that the optimum system has very little impact in the total ecological footprint; it is only marginally shifted to local. This means that the region continues to be dependent of resources from outside its borders.

Two main results can be derived from the distribution above. First, the only significant relative impact of the optimum network is in heat. But, as mentioned before, the correct situation would be no heat requirement; heat generation optimization is not among the goals of this project. Therefore, the fact that the tool only provides improvements in this area shows that it is not adequate for simulations in contexts without heat demand. Second, the tool only provided a minor improvement in the electricity generation. If significant impact is needed in this area more attention must be given to the modelling and the optimum technological network found is not adequate for the purposes of this case study, which is to make the region electricity neutral. No information about the technological network is carried to the next steps due to the arguments discussed.

5.2. *Base scenario results*

Based on the information of the previous chapter, several solutions are provided by the software. One criterion to determine if the solution would be considered is the profit. If the solution does not give, at least, the same profit obtained by selling the crops it is not suitable for the region. Therefore, the minimum profit required is the € 243,679 per year. This value was calculated by considering the revenue of selling the total production based on their market price and subtracted the production costs of the same crops. The only solution that surpasses the threshold and considers the use of all resources available is also the one that maximizes the profit. The table below presents the composition of the profit obtained by the region per year.

Table 14 Financial information

Item	Energy flow [MWh/year]	Cost[5] [euro/year]
Sugar cane harvested	33,478	93,404
Corn harvested	8,739	123,045
Corn stover harvested	3,009	30,421
Investment costs	-	138,699
Variable costs	-	38,639
Corn sell	8,739	-357,949
Sugar cane sell	29,665	-91,368
Electricity sell	2,709	-173,891
Subsidies	-	-130,906
Total	**-**	**-329,907**

Appendix 3 shows the maximal structure optimum structures in a graphic way. The optimized network represents a huge simplification of the system described beforehand. The first remark about this solution is that no ethanol is produced. It is considered more efficient to use the corn stover and sugar cane trash in the steam turbine system to produce electricity and sell the crops. Therefore, there are three sources of revenue for the region presented in this solution. The first is the harvesting and trade of corn and sugar cane. The second is selling the electricity and the third is the subsidies associated with the electricity produced from biomass. It is important to notice that selling these crops and using the leftover biomass to produce electricity demand the use of treatment installations.

[5] The negative sign indicates revenue while the positive represents cost.

The route for sugar cane involves the harvest, transportation and trash separation in a centralized location. After the trash is separated it is fed to a high efficiency boiler to generate the steam for electricity generation. The sugar cane is sold at this step. The corn grain route is direct; there is no need to separate it from the stover due to harvest technology choice. Therefore, it is sold straight after harvest and transportation. The corn stover left in the field after the grain harvest is collected, transported, milled and fed to the same high efficiency boiler used for the sugar cane trash to produce electricity.

The yearly revenue from this solution for the region is € 329,907. When compared to the revenue of selling the crops it is possible to know that there is an improvement. Below a diagram of the optimized network considering the flow of materials and prices:

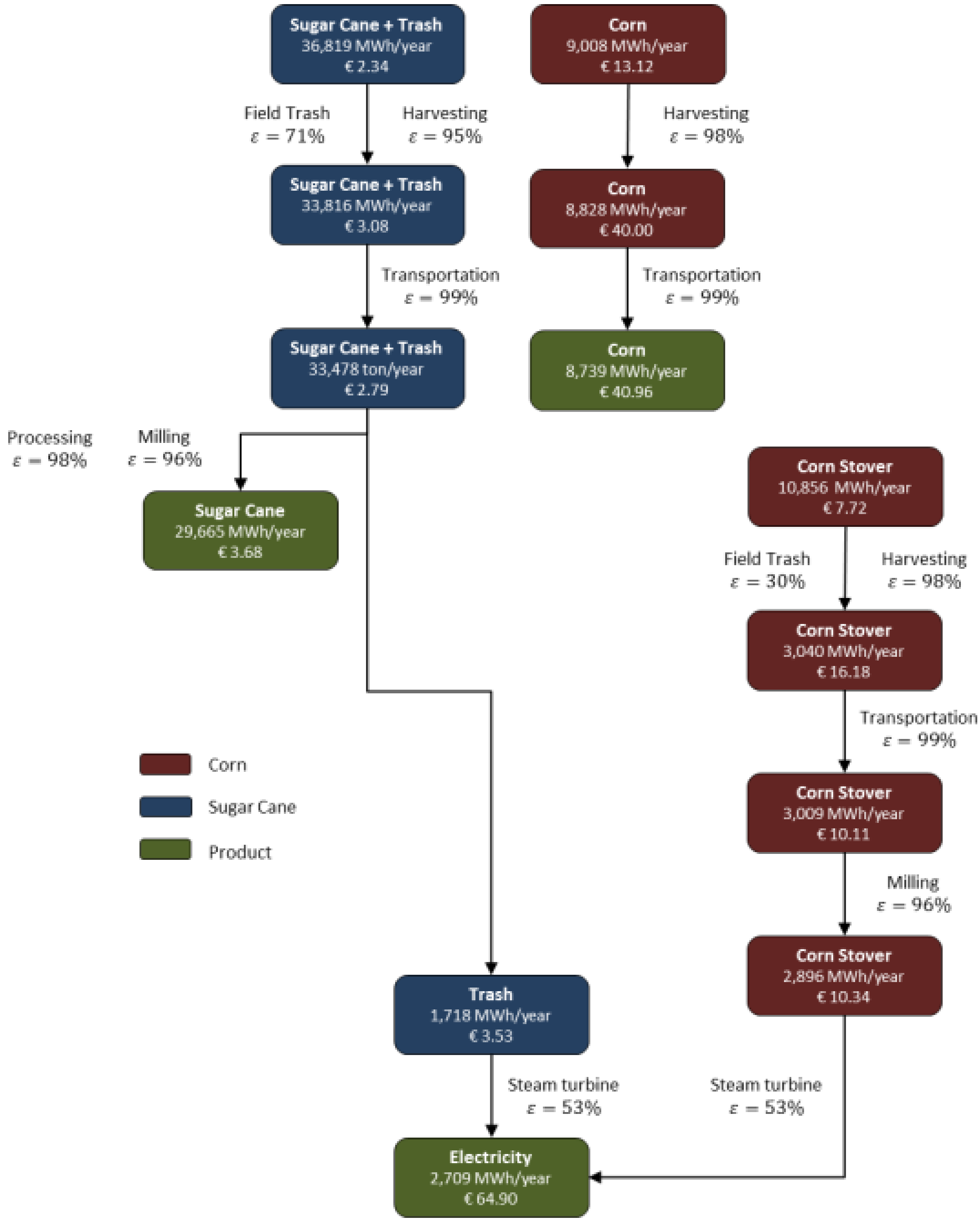

Figure 16 Optimum technology network

As can be seen in the diagram, $2,709\ MWh$ of electricity is produced per year. All the electricity is produced by the use of second generation biomass. This is one important result of this optimization; the use of waste biomass is not only better due to the fact that it does not compete with the food chain, but also, it is more cost efficient in regional scale. This is partially explained considering that the use of sugar cane and corn for electricity production demands the conversion of the raw materials. This implies that more installations need to be built, which results in more investment and operation costs, and also more losses due to conversion. A direct use of the waste biomass in a steam turbine system requires a minimum amount of treatment, mostly drying and grinding. Furthermore, steam turbines are a well-established technology and are usually cheaper than gas turbines for the same capacity.

Furthermore, it is possible to see that around € $300,000$ of the revenue is referent to the electricity production. Therefore, selling electricity is almost in the same level of revenue as selling corn. But it is not as cost efficient as selling the agricultural products due to the investment and operation costs of the installations. One alternative to spread the profit margin is to enhance the size of the installations since the investment costs vary logarithmically with the capacity of the plant. This means that the growth in the in the costs is not as expressive as the cost in the capacity. So, the revenue from selling electricity would grow more than the costs to build the technological network. Another point of interest is that more than 40% of the electricity income comes from the subsidies. Therefore, it is important to understand how changes in subsidy policy can impact the region. The graph below shows the representability of each of the components of the system in the final revenue composition[6].

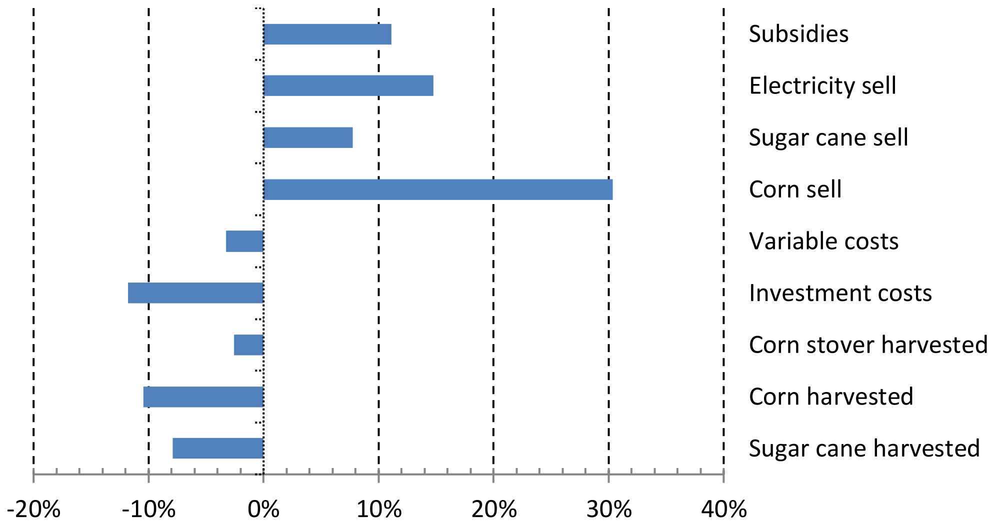

Figure 17 Profit composition

5.3. *Scenario definition*

As stated previously, the base scenario was built based on the current crop distribution of the region. The main goal was to use these resources to produce electricity locally. The system obtained is sensible to several variables. Therefore, it is reasonable to assess its stability when faced with changes. Also, the electricity production is not sufficient to fulfill the region demand. So, it is important to assess the possibility to fulfil the demand by using other technologies or by expanding the area harvested.

Based on the previous discussion, two types of scenarios will be discussed. The first are *demand scenarios*; the goal of these is to find out if it is possible and feasible to fulfill the electricity demand locally. The second are

[6] The values are calculated over the total amount of money flow in the production chain.

stability scenarios; these are based in changing variables in the technological regime to assess the system's stability.

1. *Demand scenarios:*

Four main scenarios are discussed here. The two first ones aim to understand why the ethanol production chain is not active and if there is any possibility to reverse the situation. This is relevant since the production of electricity is coming only from the steam turbine. If the gas turbine can also be used the remaining electricity potential can be reached, what will increase the total electricity production of the region. These scenarios are based in the following assumptions:

> **Scenario D1**: The electricity production in the gas turbine is supposed to be deactivated due to the *low yield of ethanol production*. Simulation of several ethanol yields, to assess which is the breaking point for the activation of the gas turbine, is performed. All other parameters of the system are kept constant.
>
> **Scenario D2**: The electricity production in the gas turbine is supposed to be deactivated due to the *low efficiency of small scale gas turbines*. The same base system is ran but considering a higher efficiency of the gas turbine. The highest possible value is the record in efficiency for a combined cycle gas turbine.

The other two *demand scenarios* consider what can be expanded in order to fulfil the regional demand. There is potential for the production of electricity using other technological sources, like wind or solar power. Also, the expansion of the area harvested is a possibility, since there is a huge grassland area that can have part of its use shift to agriculture. Therefore:

> **Scenario D3**: The solution for the demand problem is to enhance the area harvested. Removing the limitation over the crop flows and fixating the electricity production to the regional demand enables the algorithm to determine if it is reasonable to expand the area harvested and, if so, which crop with dominate the agricultural landscape. An assessment of the required area for this expansion is also made.
>
> **Scenario D4**: The solution for the demand problem is to introduce other technologies. PV panels are chosen due to the high irradiance in the location and the fact that, since the region is located in a very forestry and mountainous area, the roughness is likely to be high and discourage the use of wind turbines. The modelling is done fixating the electricity demand and assessing the area of the solar panels that need to be installed to fulfil the demand.

2. *Stability scenarios:*

The *stability scenarios* aim to consider how possible changes in the market can influence the design of the base scenario. The market prices that influence the most the regional revenue is the corn and electricity ones, combined these products represent 88% of the money inflow. Since changes in these can impact significantly the situation in the region, the two next scenarios are based on changes in the prices of the two commodities.

> **Scenario S5**: An analysis of the market price of corn is performed in order to propose different probable prices and assess their impact in the region. Another goal is to determine the lowest possible price that can be reached by corn for the solution to be feasible.
>
> **Scenario S6**: An analysis of the market price of electricity is performed in order to propose different probable prices and assess their impact in the region. Another goal is to determine the lowest possible price that can be reached by electricity for the solution to be feasible.

As stated previously, around 40% of the regional electricity revenue comes from subsidies. Therefore, the next scenario intends to assess what happens to the design if the subsidies are removed.

Scenario S7: Subsidies are related to the level of electricity production and are given in €/MWh. Therefore, it is interesting to asses if removing the subsidies impact the structure of the network and, if so, what is the minimum value per MWh that guarantees the proper functioning of the base scenario solution.

Another interesting point is to consider coupling the aforementioned effects. Instead of looking at the limits from the proper functioning of the system use the minimum values in the past years to build a stressed scenario.

Scenario S8: To build a stressed scenario the minimum values of the aforementioned variables historical series, in the past ten years, are used simultaneously. The result is analyzed to understand if there is a solution for the situation and how big is the impact of the combined effect in the region.

These are the main assumption of the 8 scenarios that will be discussed further.

5.4. *Scenario results*

The discussion of the results is also structured into demand and stability scenarios, using the assumptions established beforehand. After all scenarios are discussed individually a summary is presented, in a table, with the main information regarding each one.

D1: Low ethanol yield

In order to enhance the local electricity production, the ethanol yield was investigated. It is clear, while looking at the production chain the highest losses are located at this step. Mass conversion and energy efficiencies are 5% and 8%, respectively. The low mass efficiency is mostly due to the conversion of the sugar cane to vinasse; this byproduct represents 81% of the mass flow and has a very low market price. The low energy efficiency is associated with the fact that the bagasse is used to power the production, which reduces external energy demand to virtually zero but takes out a considerable part of the energy of the byproducts of ethanol production.

Ethanol is produced from both corn and sugar cane. Therefore, both yields were modified from the current values up to 100%. This is not realistic. But the goal is to identify what range of conversion would be needed to start producing electricity using ethanol in the region. Varying one yield at a time, the system was optimized using the higher yield and for **no conversion efficiency the gas turbine was activated**. This is an indication that although the conversion efficiency is low it is not the factor that disables the electricity production using the gas turbine.

D2: Low efficiency gas turbine

Another factor that could impact the activation of the gas turbine is its efficiency. Gas turbines are usually and expensive investment and are more common in systems that supply higher demands. The smallest gas turbine found has an efficiency of 30.60%, which is low compared with bigger systems. This scenario was motivated by the possibility to couple the demand of neighboring cities and built a bigger system that could supply both locations. This would assure high efficiency gas turbine due to the higher mass flow. As a first assessment, it is decided to simulate a system with the same size but with the record efficiency that can be achieved by a combined cycle gas turbine, 61.5% [57].

Again, the results are not positive considering the electricity production of the region. Even considering the record efficiency the **gas turbine is not considered a feasible alternative**. Also, although a bigger system would have higher efficiency, this demonstrates that coupling the demand with other city would not make the gas turbine significantly more attractive. Obviously this coupling would have benefits since the investment costs would be lower, but it would be better to upscale the base scenario system, without the gas turbine.

D3: Expansion of area harvested

In this scenario all parameters were kept constant and fixed, except for the maximum flow of the crops. Simultaneously, the electricity demand was fixed to the value that fulfils the regional demand, $24{,}897\ MWh$. It is desired to maintain the production of the crops at least to the same level they are nowadays and the main questions is whether it is relevant or not to expand the area harvested. Also, if the area should be expanded, it is important to know which distribution of crops should be employed.

The values obtained in the base scenarios for the production of were used to set the minimum flow for harvesting. This was done to assure that the software was not going to recommend shifting completely the agriculture to one of the crops. When this was done both crops were harvested to the limit but only sugar cane trash was used to produce electricity. Therefore, **sugar cane was considered more efficient for electricity generation**.

Due to that, a second situation is considered. This time, the corn production is fixed to the current one and the sugar cane flow is left free in order to determine the area needed to fulfill the demand. When this is done the following results are obtained:

Table 15 Scenario D3 - Results

Item	Energy flow [MWh/year]	Cost[7] [euro/year]
Sugar cane harvested	769,894	2,148,004
Corn harvested	8,739	123,045
Corn stover harvested	3,009	30,421
Investment costs	-	138,699
Variable costs	-	38,639
Corn sell	8,739	-357,949
Sugar cane sell	682,206	-2,101,194
Electricity sell	24,897	-1,598,138
Subsidies	-	-1,203,090
Total	**-**	**-874,378**

It is possible to see that this system improves considerably the revenue of the region. But, it demands the expansion of the area harvested. $769{,}894\ \mathrm{MWh}$ of sugar cane is translated into $1{,}740\ \mathrm{ha}$ considering the yield of sugar cane in the region. Águas da Prata has $8{,}719\ \mathrm{ha}$ of grassland; if 20% area can be used for the expansion of crops it would be possible to fulfill the electricity demand and elevate the profit of the region more than 3 times when compared with the current situation.

D4: Introduction of solar PV

The last *demand scenario* is based on the introduction of solar PV in the region. To do that, solar irradiation was introduced as a raw material and it is an input for an operating unit the convert it electricity, a PV panel. There are no subsidies for solar power, although the selling price of electricity is usually higher. In this scenario both crops and electricity generated by biomass are fixed in order to avoid shifting all electricity production to solar energy. This needs to be done because the biomass route is considerably more expensive than the solar one.

First, solar irradiation is free, while the crops have considerable production costs. Furthermore, the conversion of the raw material to electricity is direct, which means that no conversion steps are needed and this translates

[7] The negative sign indicates revenue while the positive represents cost.

into less losses. A first run of the software shifted all electricity production to solar energy. But, this is not considered the best solution even if it is the most profitable one. The production of biomass, as obtained in the base scenario, uses waste resources and integrates electricity production with the local economy. Due to that, it was decided to force the code to produce electricity using this route and use the solar panels as a complement. In the table below a summary of the information used to introduce solar panels in the mix:

Table 16 Scenario D4 – Extra information

Variable	Value
Solar irradiation [30]	$3.42\ MWh/m^2 \cdot year$
Capacity factor [30]	50.43%
Solar panel efficiency [58]	18%
Investment costs[8] [58]	€ 4.44
Project lifetime	$25\ years$

Solar irradiation was determined by the average value of the daily irradiation, converted into megawatt-hour. The capacity factor was calculated based on the same data, considering the number of sunlight in that year. Detailed information on the structure used to simulate this scenario is available in Appendix 4 since some other changes were needed in order to introduce other type of electricity source in the mix. Considering the information provided beforehand, the following results were obtained considering the revenue of the region.

Table 17 Scenario D4 - Results

Item	Energy flow [MWh/year]	Cost[9] [euro/year]
Sugar cane harvested	33,478	93,403
Corn harvested	8,739	123,045
Corn stover harvested	3,009	30,421
Investment costs	-	1,137
Variable costs	-	38,639
Corn sell	8,739	-357,949
Sugar cane sell	29,665	-91,368
Electricity biomass sell	2,709	-173,891
Subsidies	-	-130,906
Electricity solar sell	22,188	-1,838,275
Total	**-**	**-1,718,700**

This result demands $71{,}574\ m^2$ of solar panels. To assess the area needed for such a system it was decided to determine the optimum inclination angle of the solar panels that maximizes electricity production over the year. To do that, a simple tool was developed and the details are included in Appendix 5. The optimum tilt angle was found to be $18°$. It was assumed that the solar panels are stacked together and shadow effects due to the proximity can be neglected due to the low tilt angle. Therefore, the land area needed for solar panels is the projection of the solar panel in the ground:

$$A = Area\ of\ solar\ panels \cdot \cos(18°) \tag{2}$$

This results in a land requirement of $6.81\ ha$, which is considerably lower than the one from the *Expansion of area harvested* (D3) scenario.

[8] Cost of a 1 m^2 module.

[9] The negative sign indicates revenue while the positive represents cost.

S5: Corn price change

All stability scenarios will be built over the base scenario. This choice was made because both scenarios D3 and D4, which are able to fulfil the regional electricity consumption, demand changes in the land use of the region. Even though this is reasonable, these scenarios are proposed as alternatives. The base scenario is the one used for stability check since it does not demand significant change in the regional economy. The land use is kept constant; all farmers can keep their activities unaltered while electricity production is added.

The graph below represents the corn price per ton from 2007 to 2017 [59]. By looking at this temporal series it is clear that the current moment is good for selling corn. The year of 2016 shows elevated prices, but the trend for the future is a drop of almost 30 € up to Jul/17. Also, based on the graph below it is possible to see that the values have been oscillating around the average, with the exception of the last year. Therefore, one reasonable assumption is that the prices are going to come back to previous levels. Thus, it was assumed that the most probable corn price for the next years is the average value of the 10-year series, $€\,129.06\,per\,ton$ or $€\,27.94\,per\,MWh$. Also, the lowest value during the time period, $€\,72.85\,per\,ton$, was used in order to identify the worst foreseeable situation.

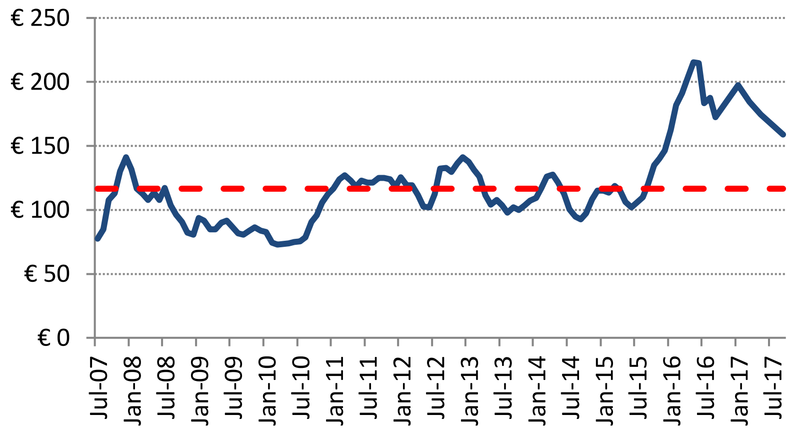

Figure 18 Temporal series - Corn price oscillation related to the average

Neither simulations change the technological structure of the system. Nevertheless, they impact the profit due to the lower revenue from selling the corn. It is important to notice that even if the price of the corn is lower the region suffers less when electricity is produced. Considering that no electricity is produced and the two possible corn prices, the revenues[10] of the region were calculated for comparison. The results are presented in the table below:

Table 18 Scenario D5 – Results

	Corn Price [€/ton]	Revenue [€]
Current Price – Producing electricity	184.79	-329,907
Average Price – Producing electricity	129.06	-216,038
Lowest Price – Producing electricity	72.85	-109,772
Current Price – No electricity	184.79	-243,679
Average Price – No electricity	129.06	-125,910
Lowest Price – No electricity	72.85	-19,664

[10] It is important to remember that the revenue here is calculated only with the use of the crops used in this study, sugar cane and corn.

As posited beforehand, electricity production is a way to mitigate fluctuation of corn prices. Therefore, the production of electricity is advised even in adverse corn price scenarios.

S6: Electricity price change

By looking at the revenue of the base scenario, it is possible to see that the other relevant source of income is electricity. Therefore, changes in this price can also impact the region significantly. The electricity prices, in Brazil, are determined in the electricity auctions. The following graph represents the annual average price of electricity produced from biomass in the state of São Paulo. The date is the year when the auction took place.

The values for the electricity price present a significant variation throughout the years [34]. Because of that, it was chosen to present also the hired capacity of the same year. Thus, it is possible to see that the volume of the biomass plants hired oscillates considerably during the years. And this helps to explain such a high change in the prices from one year to the other. Due to that, in order to assess the average price of electricity it is chosen to calculate a weighted average, in order to consider these fluctuations in capacity hired. The current electricity price, used in this project is very close to the average value obtained € $66.14\ per\ MWh$.

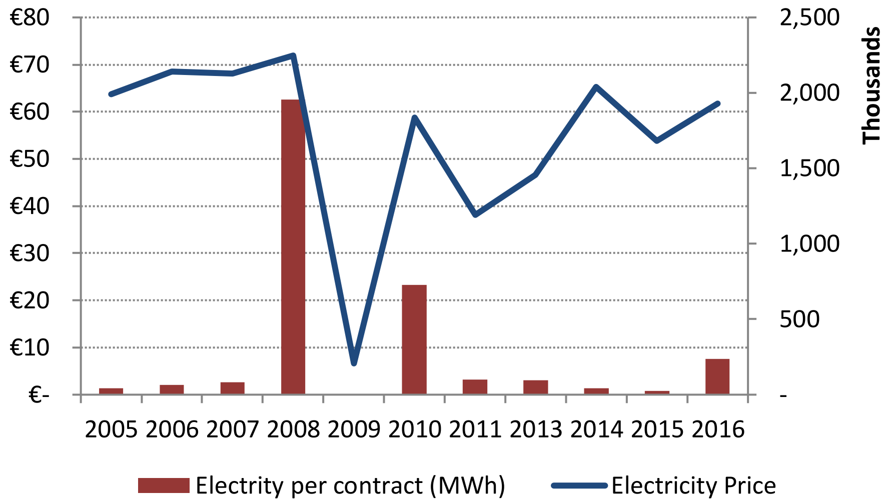

Figure 19 Electricity prices

The year of 2009 is the one that represents the lowest possible price. Since the volume of electricity installed this year, $2{,}087\ MWh$, is negligible when compared to the others and is clearly an outlier, it was decided to consider the second lowest value for the simulation of the impact in the region. This was achieved in 2011 and the electricity hired was $99{,}537 MWh$. A summary of the values used and the revenue obtained by the region is presented in the table below:

Table 19 Scenario D6 – Results

	Electricity Price [€]	Revenue [€]
Current Price	64.19	-329,907
Average Price	66.14	-335,189
Lowest Price	38.14	-269,901

For the lowest price, € $38.14\ per\ MWh$, the technological network was not affected but it was considered more financially efficient to use only the corn stover for electricity production and sell the sugar cane directly. Therefore, the electricity production of the region is lowered to $1{,}700\ MWh\ per\ year$. The threshold was found to be € $40\ per\ MWh$; for electricity prices below this sugar cane production should be sold directly to the market after harvesting (without harvesting the sugar cane trash).

S7: Subsidies removal

As discussed beforehand, a considerable part of the profit obtained by the region from selling electricity comes from subsidies. The assumption that the prices are going to be static through the years is not reasonable. In this case, it was decided to assess turning points for the functioning of the technological network. The main goal is to identify for which subsidy levels there will be changes in the operation of the system.

With up to 50% reduction in the subsidies the system operates normally, although with a much lower profit margin, € 264,454. When the subsidies are lower the first change in operation occurs. The sugar cane is not used for electricity production anymore; all the production is sold directly in the market without harvesting the sugar cane trash. This new situation is maintained up to 63% reduction and the profit margin at this level of subsidy is € 262,432. Finally, below this level, no electricity is produced. Also, the profit is maximized when no sugar cane trash is sold. From 64% to 100% reduction the revenue is fixed and equal to € 262,209.

Table 20 Scenario D7 – Results

Up to % reduction	Subsidy (€/MWh)	Revenue [€]	Status
0%	48.32	-329,907	Base scenario
50%	24.16	-264,454	Normal operation
63%	17.40	-262,432	No sugar cane for electricity production
100%	00.00	-262,209	No electricity production

It is clear that below 50%, by changing the operation of the system, it is possible to keep the profit margin almost at the same level. This strategy mitigates the impact of the changes in subsidy policy.

S8: Stressed scenario

The stability scenarios discussed above aimed to understand the impacts of individual variables in the system proposed in the base scenario. In reality these effects may happen simultaneously. Therefore, the worse values found during the previous analysis are used as inputs to the simulation of a *worst case scenario*. The table below presents a summary of the information used:

Table 21 Scenario S8 – Input information

Variable	Value
Electricity price per MWh	€ 38.14
Corn Price per ton	€ 72.85
Subsidy per MWh	€ 00.00

As expected, no electricity is produced, and that is mostly to the absence of subsidies. The region would still be able to keep profiting even in an adverse situation like this. One important remark is that, when no electricity is produced, the software does not assume the use of the operating units. Therefore, if this scenario becomes a reality after the installations are already built there still need to pay for investment costs. This is not contemplated in the modelling and a solution should be found outside this analysis. Some examples are renting the plants for other municipalities in moments like this, or use other fuels to keep the system working to pay for the investment costs. The revenue obtained with this information is € 42,073.

5.5. Summary

This section presents a summary of the results discussed in the chapter. The indicator presented in order to compare solutions is revenue and electricity production. A brief explanation of the most significant characteristics for each scenario is presented. This is focused in what crop is used, what is the impact of each scenario in the basic situation.

Table 22 Summary Results

Scenario	Revenue [€]	Electricity Production [MWh]	Comments
Current	-243,269	-	▪ Both crops are sold directly in the market.
Base	-329,907	2,709	▪ Corn and SC[11] are used for electricity production; ▪ No ethanol production; ▪ SC trash and corn stover are burned for steam turbine.
D1	-329,907	2,709	▪ Low conversion is not the reason for no ethanol production; ▪ Enhancing ethanol conversion does not elevate electricity production.
D2	-329,907	2,709	▪ A gas turbine is not a feasible solution for this chain; ▪ Elevating gas turbine efficiency is not a solution to enhance electricity production.
D3	-874,378	24,897	▪ Sugar cane is the best crop when looking for expansion of area harvested; ▪ Around 20% of the pasture area would be needed to fulfil the regional electricity demand (1,740 ha).
D4	-1,718,700	24,897	▪ Even without subsidies PV represents a good alternative due to high electricity prices; ▪ Only 6.81 ha are needed to fulfill the demand.
S5	-109,772	2,709	▪ Calculated with the lowest corn price of the last 10 years; ▪ Electricity production mitigates oscillation in corn prices.
S6	-269,901	1,700	▪ Calculated with the lowest energy price for biomass; ▪ Only corn stover is used for electricity production.
S7	-264,454	2,709	▪ Up to 50% reduction in subsidies the operation of the system is maintained unaltered; ▪ Using only corn stover or selling the crops directly mitigates impacts of subsidy policy changes. But lower electricity production.
S8	-42,073	2,709	▪ Without subsidies no electricity is produced and the region has to rely on the crops; ▪ With low corn prices the revenue of the region is extremely low, but it still higher than zero.

[11] SC = sugar cane

DISCUSSION

During the development of this project, it was assumed that the best approach for energy planning is to make it locally. Due to that, a small city in Brazil was chosen as an experiment for energy planning. Also, it was considered that there is need to make energy planning project more attractive to stakeholders. Assessing the characteristics of the city it was clear that the focus of the planning should be in electricity. The region does not require heat and, due to the high production of ethanol as fuel in Brazil and the small size of the region, the mobility issue was not considered as relevant as electricity.

In order to make a solution attractive there is need for it to be sustainable. We defined being sustainable based on the TBL framework. Shifting to renewable energy is already a step towards the environmental dimension and in order to make it more attractive to stakeholders it is necessary to include the other two dimensions as well. The social dimension is included qualitatively; during the design decisions should be made trying to impact the least the local economy. The financial dimension was included quantitatively by looking for solutions that maximizes the regional revenue.

The first approach was to use the ReiOpt tool. The tool proved itself inadequate to simulate energy systems in the Brazilian market due to the lack of flexibility considering heat requirement. Because of that, the tool was dismissed and the project was developed almost exclusively with the use of PNS Studio.

In PNS Studio, the social dimension was considered by assessing which crops are already produced in the region and have potential for electricity generation. By doing this, there is no need for farmers to change their practices significantly. The crops chosen were sugar cane and corn. Although the option to produce ethanol, both to be used as vehicle and gas turbine fuel, was contemplated it was not considerable feasible. More importantly, the use of the crops for energy purposes elevated the regional revenue:

Table 23 Financial results for the base scenario

Item	Energy flow [MWh/year]	Cost[12] [euro/year]
Sugar cane harvested	33,478	93,404
Corn harvested	8,739	123,045
Corn stover harvested	3,009	30,421
Investment costs	-	138,699
Variable costs	-	38,639
Corn sell	8,739	-357,949
Sugar cane sell	29,665	-91,368
Electricity sell	2,709	-173,891
Subsidies	-	-130,906
Total	**-**	**-329,907**

Selling the harvest directly, but considering its use for electricity production, elevated the revenue by € 86,228. An interesting fact is that only second generation biomass is used in the base scenario, corn stover and sugar cane trash. The use of waste biomass is not only better due to the fact that it does not compete with the food chain, but also, it is more cost efficient in regional scale. This is partially explained considering that the use of sugar cane and corn for electricity production demands the conversion of the raw materials to ethanol. A direct use of the waste biomass in a steam turbine system requires a minimum amount of treatment. Furthermore,

[12] The negative sign indicates revenue while the positive represents cost.

steam turbines are a well-established technology and are usually cheaper than gas turbines, needed for ethanol use, for the same capacity.

At the same time that this scenario enhances the regional revenue it is not sufficient to fulfil the electricity demand of Águas da Prata. In order to do that some alternatives were considered. Two of them were successful, one that considers the expansion of the sugar cane crop and another that contemplates the installation of PV panels.

Table 24 Scenarios to fulfil electricity demand

Item	D3 Sugar Cane	D4 PV Panels
Electricity Production [MWh(year]	24,897	24,897
Area Needed) [ha]	1,740	7
Revenue [€/year]	-874,378	-1,718,700

As can be seen, solar PV demands less area and gives higher annual revenue. The fact that the high revenue impacts positively the financial dimension of sustainability is obvious, but less area impacts both other dimensions. A low area requirement means that fewer hectares will have to be moved from another activity to electricity generation, which fits better the local economy. Expanding the sugar cane crop would demand almost 20.0% of the grassland area to be shifted to sugar cane production. This means that there would be less area available for cattle. Also, it would require more effort from all stakeholders to find a common ground when compared with the 0.1% needed for solar. A smaller area implies in a smaller environmental footprint, since this is calculated on the land used. On the other hand, solar has higher net CO_2 emissions when compared to biomass. Therefore, a more careful analysis of the environmental dimension of the system is needed to make a final statement. Nevertheless, based on the information at hand, and the fact that adding solar to the mix contributes to the diversification of the energy matrix, scenario D4 is considered the best option for the fulfillment of the electricity demand.

Nevertheless, solar energy is not currently subsidized by the government. One of the arguments is that it is an expensive source of electricity, as can be seen by the prices used in this project, and do not represent a decrease in CO_2 emissions, since in Brazil hydro power is very established. Based on the PROINFA project, that finances biomass, wind and small hydro systems, it is possible to notice that solar is not a priority for the government.

One possible option to make the project also interesting for the people that lives in the region is to build the solar panels in a multi-purpose solar park. The biggest trait of multi-purpose solar parks is that they combine other activities with energy generation. This is an interesting strategy to mitigate the one of the most important problems for LEI's, which is NIMBY behavior. But, if the installation of solar panels proves to be overly complex, scenario D3 presents guidelines on how the expansion of the crop should be done in order to fulfill the demand.

On one hand there is solar energy. It is more profitable, requires less area and do not depend on subsidies for revenue but have higher CO_2 emissions and NIMBY problems. On the other, there is biomass based electricity production. It is still profitable for the region and have a closed carbon cycle but is much more dependent on subsidies. The highest risk for solar in this context is possible NIMBY factors and for biomass the removal of subsides, but also the combination of the interests of different stakeholders due to the high land requirement.

Considering the stability of the system, the scenario without PV panels was considered. That is because solar is an alternative to achieve electricity sufficiency, but the initial idea would be based only the use of waste biomass to produce electricity locally. This basic system has proven to be reliable in different market scenarios.

Reducing corn or electricity prices, or removing up to 50% of the subsidies directed to biomass the system is still able to provide revenue in higher levels when compared to the current situation.

When the prices of corn are down the region would suffer a huge impact since a considerable part of the economy revolves around it. But, when producing electricity using corn stover the impacts are mitigated; there are two more sources of revenue, the electricity and the subsidies. If electricity prices are down, sugar cane is not used anymore for electricity production, only corn stover. This is the case because in order to use the sugar cane trash there is need to consume the profit margin of the sugar cane crop. When the electricity price is low this is just not financially interesting. But to stop using the sugar cane trash is a good alternative to keep the revenue level above the current levels.

A very interesting remark at this stage is that part of the subsidies are paying for the opportunity cost of sugar cane trash for electricity production. Due to the choice in harvesting, sugar cane costs right after the pre-treatment step are higher than the market selling price. It was found that from 50% reduction in the subsidies the solution recommends to stop using the trash for electricity production. It means that at least half of the subsidies are needed to finance the treatment of the sugar cane in order to make the use of the trash feasible. When the subsidies are totally removed the electricity project is no longer feasible.

Furthermore, since the technological network is based on the use of a high efficiency boiler to produce electricity in a steam turbine, it is possible to assess if other crops also have residues that can be burned together with corn stover and sugar cane trash. This is not considered in the beginning of this project because it was desired to define a clear boundary and focus on more important crops. The stream of other residues will be low when compared with corn due to the size of the area harvested and the fact that most of them are permanent crops. Nevertheless, a further study could be developed in order to expand the use of the utilities.

CONCLUSIONS

This chapter is organized as follows. In section 7.1 the main conclusion that can be drawn from this study will be presented. In section 7.2, the most significant limitations of the research are discussed with possible solutions. Finally, in section 7.3, some recommendations for further research are presented.

7.1. Conclusions

In search for a way to tackle the climate change challenge by using sustainable energy technologies the question of how to make projects more attractive to stakeholders appeared. This question was formulated in terms of a process network problem:

Given an amount of natural resources and a demand that needs to be met; what is the technological network that will maximize the revenue function for a certain region, while respecting the local economy?

To answer this question several assumptions were made. The focus was on how to make the projects and proposals more sustainable. It was posited that choosing renewable energies already considers the environmental dimension of sustainability, but there was need to include the financial and social dimensions. The financial was included by maximizing the revenue and the social by considering the local habits and looking for a synergy between the new and old economic setting.

By applying this concept to a region it was possible to assess if the results given by the tool enable the proposal of more sustainable projects. It can be seen that the results obtained showed that it is possible to elevate regional revenue by the use of sustainable energies using currently available resources. The strategy employed proved to be an interesting alternative for energy planning.

Usually, sustainable energy projects are designed in the technical point of view and then the financial impact is calculated. By incorporating the revenue in the technology choice process it is possible to assure that the financial dimension is considered since the beginning of the project. Also, this approach guarantees that the best technology network is chosen. It is hard for a designer to consider the right combination of technologies and ratios of materials that will maximize revenue, due to the interconnected nature of such systems.

Moreover, although the social dimension was inserted qualitatively, the results showed that the impact of the designed systems is low on the local habits. Which indicates that even by inserting the dimension qualitatively it is possible to taken it successfully into account. The final system enabled the exact same crops to be planted and harvested, and is based in the use of waste biomass for electricity production. This means that the crops can still be sold in the market but there is value added due to electricity production; providing a win-win situation.

Also, the social dimension has a very subjective facet. Each community will have different demands and problems. The social constraints should be defined specifically for each project. Therefore, to consider this dimension qualitatively, as guidance for decision making, is considered the best approach.

Therefore, it can be concluded that the tool used in this project can be used to answer the research question proposed above. But, climate change is a huge challenge and there is no attempt to find a unique solution for it. Nevertheless, the broad question presented in the beginning of this work still needs to be answered

How is it possible to make renewable energy solutions more attractive to stakeholders?

The answer found in this work is that it is possible to make solutions more attractive by coupling the design of an energy system with the maximization of the regional revenue. Instead of looking at a renewable energy solution as an isolated system, it is important to position it in the local economy and identify how it can make a better use of the local resources. It is advised to perform a similar study as the one in this report in order to assure that the system has a higher probability to leave stakeholders satisfied. The decision makers will appreciate the higher revenue and the community will appreciate to have their needs to be considered in the decision making process.

Also, another aspect of crucial important is that this analysis can provide critical insights that are not obvious at first sight. For example, by analyzing the results of this work, it was possible to realize that sugar cane is the most indicated crop for electricity production but, at the same time, the importance of subsidies. In reality, the subsidies are paying the opportunity cost of using the sugar cane trash for electricity production and, without them, corn is a better crop due to the easiness of harvesting. The different harvesting methods impact which crop is more adequate for the region, and this is not a trivial outcome.

Furthermore, the data collection step is the most time consuming. The implementation of the information collected and the optimization of the technology represented around 30% while data collection was responsible for the rest. Therefore, if the information about possible solutions in the regional context is already known the application of this framework to optimize the network does not demand a lot of time. The implementation and scenario simulation could be done under a week for a system of the same size (same amount of operating units), if the tools are known and the information of the production chain is easily available. For research purposes this is not indicated, but it is ideal if there is need for a fast assessment of each combination of technology would fit the region better.

7.2. Limitations

This research, due to its purpose, has several limitations. One of the most significant ones is that no proper literature review was made. Instead of scouting literature to find the best method to answer the research question it was assumed that being more sustainable makes a project more attractive for stakeholders. Furthermore, the tool used was the same used by the group where the work was conducted. This means that even if other tools were already developed and would provide a more complete solution they would not be identified due to the lack of a comprehensive literature review.

Another limitation is that the information was collected from internet; no contact with the region was attempted. This limits the quality and reliability of data. Also, some assumptions for the decision making could have been better assessed with direct contact. It was assumed that no change in the land use is desired and that this would make farmers more satisfied, but this may not be the case.

Also, due to the time limitation of the project, the boundaries of the systems were set around two crops; others could also be used for electricity production even if most of the flows are covered by the two crops chosen. Also, it was considered that the city is completely isolated, which means that no heat requirement exists. Considering the neighboring cities could give raise to heat demand and this could also be a source of revenue for the region.

7.3. Aspects for further research

Further research could be conducted in several different subjects. One straight forward follow up research would be the further development of the system designed for the region. As stated before, the crops used were limited to the most relevant for energy generation due to the ethanol production potential. Expanding the use for the other crops of the region and also considering the existence of neighboring cities may enhance the city revenue. So, expanding the boundaries of the system may lead to benefits for the region.

Also, there may be attempts to include the social dimension of sustainability quantitatively. Although, society has a subjective facet there may be variables that when maximized could lead to higher people engagement or acceptance of the solution. The identification of these variables and inclusion in the model could make energy planning projects even more sustainable and attractive. Although this should not replace the social considerations during the decision making process.

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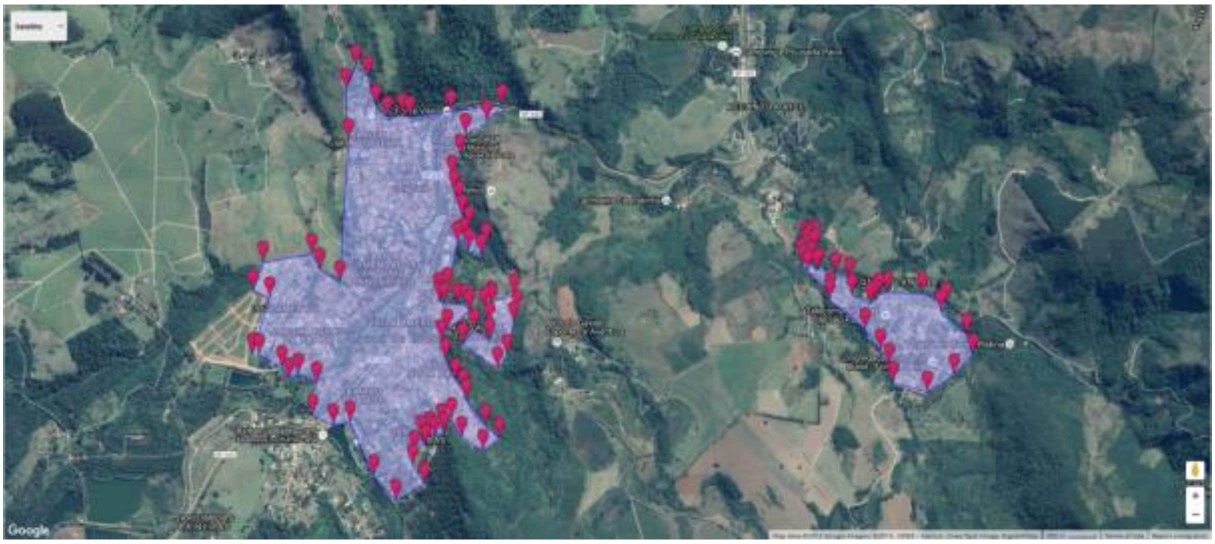
APPENDIX 1 – MAP WITH URBAN AREA BOUNDARIES

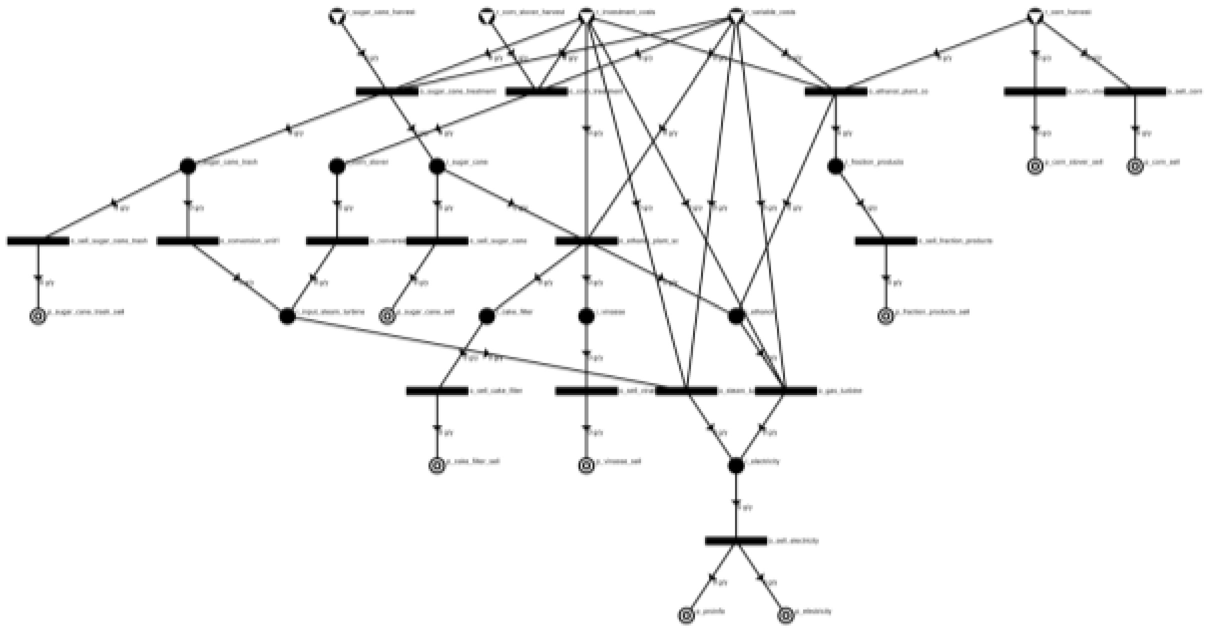


APPENDIX 2 – DEATAILED OPERATING UNIT DEFINITIONS

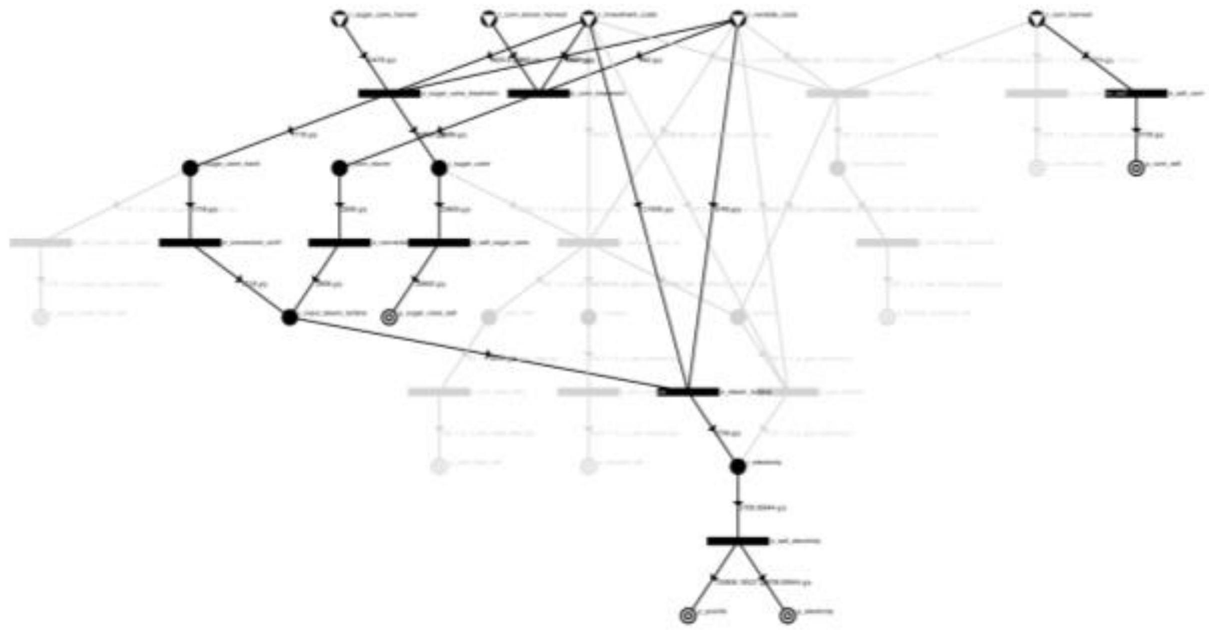
- Operating Units
  - o_sugar_cane_treatment
    - Input Materials
      - r_variable_costs: 28201 €/yr
      - r_investment_costs: 5835,9 €/yr
      - r_sugar_cane_harvest: 33478 MWh/yr
    - Output Materials
      - i_sugar_cane: 29665 MWh/yr
      - i_sugar_cane_trash: 1718 MWh/yr
  - o_corn_treatment
    - Input Materials
      - r_corn_stover_harvest: 3009 MWh/yr
      - r_variable_costs: 692 €/yr
      - r_investment_costs: 1167 €/yr
    - Output Materials
      - i_corn_stover: 2896 MWh/yr
  - o_ethanol_plant_sc
    - Input Materials
      - r_investment_costs: 66452 €/yr
      - r_variable_costs: 17814 €/yr
      - i_sugar_cane: 29665 MWh/yr
    - Output Materials
      - i_ethanol: 2363 MWh/yr
      - i_cake_filter: 182 t/yr
      - i_vinasse: 3421 t/yr
  - o_ethanol_plant_co
    - Input Materials
      - r_investment_costs: 21205 €/yr
      - r_variable_costs: 35206 €/yr
      - r_corn_harvest: 8739 MWh/yr
    - Output Materials
      - i_fraction_products: 329 t/yr
      - i_ethanol: 4671 MWh/yr
  - o_gas_turbine
    - Input Materials
      - r_investment_costs: 199539 €/yr
      - r_variable_costs: 9764 €/yr
      - i_ethanol: 7034 MWh/yr
    - Output Materials
      - i_electricity: 2152 MWh/yr
  - o_steam_turbine
    - Input Materials
      - r_investment_costs: 131696 €/yr
      - r_variable_costs: 9746 €/yr
      - i_input_steam_turbine: 4614 MWh/yr
    - Output Materials
      - i_electricity: 2709 MWh/yr
  - o_sell_corn
    - Input Materials
      - r_corn_harvest: 8739 MWh/yr
    - Output Materials
      - p_corn_sell: 8739 MWh/yr
  - o_sell_sugar_cane
    - Input Materials
      - i_sugar_cane: 29665 MWh/yr
    - Output Materials
      - p_sugar_cane_sell: 29665 MWh/yr
  - o_sell_sugar_cane_trash
    - Input Materials
      - i_sugar_cane_trash: 1718 MWh/yr
    - Output Materials
      - p_sugar_cane_trash_sell: 1718 MWh/yr
  - o_sell_fraction_products
    - Input Materials
      - i_fraction_products: 329 t/yr
    - Output Materials
      - p_fraction_products_sell: 329 t/yr
  - o_sell_cake_filter
    - Input Materials
      - i_cake_filter: 182 t/yr
    - Output Materials
      - p_cake_filter_sell: 182 t/yr
  - o_sell_vinasse
    - Input Materials
      - i_vinasse: 3421 t/yr
    - Output Materials
      - p_vinasse_sell: 3421 t/yr
  - o_sell_electricity
    - Input Materials
      - i_electricity: 4862 MWh/yr
    - Output Materials
      - p_proinfa: 234945 €/yr
      - p_electricity: 4862 MWh/yr
  - o_corn_stover_sell
    - Input Materials
      - r_corn_harvest: 3009 MWh/yr
    - Output Materials
      - p_corn_stover_sell: 3009 MWh/yr
  - o_conversion_unit1
    - Input Materials
      - i_sugar_cane_trash: 1718 MWh/yr
    - Output Materials
      - i_input_steam_turbine: 1718 MWh/yr
  - o_conversion_unit2
    - Input Materials
      - i_corn_stover: 2896 MWh/yr
    - Output Materials
      - i_input_steam_turbine: 2896 MWh/yr

APPENDIX 3 – MAXIMAL AND OPTMUM STRUCTURE

Maximal Structure:



Optimum Structure:



APPENDIX 4 – SOLAR PV SCENARIO PROBLEM DEFINITION

- Operating Units
  - o_sugar_cane_treatment
    - Input Materials
      - r_variable_costs: 28201 €/yr
      - r_investment_costs: 5835,9 €/yr
      - r_sugar_cane_harvest: 33478 MWh/yr
    - Output Materials
      - i_sugar_cane: 29665 MWh/yr
      - i_sugar_cane_trash: 1718 MWh/yr
  - o_corn_treatment
    - Input Materials
      - r_corn_stover_harvest: 3009 MWh/yr
      - r_variable_costs: 692 €/yr
      - r_investment_costs: 1167 €/yr
    - Output Materials
      - i_corn_stover: 2896 MWh/yr
  - o_ethanol_plant_sc
    - Input Materials
      - r_investment_costs: 66452 €/yr
      - r_variable_costs: 17814 €/yr
      - i_sugar_cane: 29665 MWh/yr
    - Output Materials
      - i_ethanol: 5000 MWh/yr
      - i_cake_filter: 182 t/yr
      - i_vinasse: 3421 t/yr
  - o_ethanol_plant_co
    - Input Materials
      - r_investment_costs: 21205 €/yr
      - r_variable_costs: 35206 €/yr
      - r_corn_harvest: 8739 MWh/yr
    - Output Materials
      - i_fraction_products: 329 t/yr
      - i_ethanol: 7000 MWh/yr
  - o_gas_turbine
    - Input Materials
      - r_investment_costs: 199539 €/yr
      - r_variable_costs: 9764 €/yr
      - i_ethanol: 7034 MWh/yr
    - Output Materials
      - i_electricity_biomass: 2152 MWh/yr
  - o_steam_turbine
    - Input Materials
      - r_investment_costs: 131696 €/yr
      - r_variable_costs: 9746 €/yr
      - i_input_steam_turbine: 4614 MWh/yr
    - Output Materials
      - p_steam_on: 1 €/yr
      - i_electricity_biomass: 2709 MWh/yr
  - o_sell_corn
    - Input Materials
      - r_corn_harvest: 8739 MWh/yr
    - Output Materials
      - p_corn_sell: 8739 MWh/yr
  - o_sell_sugar_cane
    - Input Materials
      - i_sugar_cane: 29665 MWh/yr
    - Output Materials
      - p_sugar_cane_sell: 29665 MWh/yr
  - o_sell_sugar_cane_trash
    - Input Materials
      - i_sugar_cane_trash: 1718 MWh/yr
    - Output Materials
      - p_sugar_cane_trash_sell: 1718 MWh/yr
  - o_sell_fraction_products
    - Input Materials
      - i_fraction_products: 329 t/yr
    - Output Materials
      - p_fraction_products_sell: 329 t/yr
  - o_sell_cake_filter
    - Input Materials
      - i_cake_filter: 182 t/yr
    - Output Materials
      - p_cake_filter_sell: 182 t/yr
  - o_sell_vinasse
    - Input Materials
      - i_vinasse: 3421 t/yr
    - Output Materials
      - p_vinasse_sell: 3421 t/yr
  - o_corn_stover_sell
    - Input Materials
      - r_corn_stover_harvest: 3009 MWh/yr
    - Output Materials
      - p_corn_stover_sell: 3009 MWh/yr
  - o_conversion_unit1
    - Input Materials
      - i_sugar_cane_trash: 1718 MWh/yr
    - Output Materials
      - i_input_steam_turbine: 1718 MWh/yr
  - o_conversion_unit2
    - Input Materials
      - i_corn_stover: 2896 MWh/yr
    - Output Materials
      - i_input_steam_turbine: 2896 MWh/yr
  - o_solar_panel
    - Input Materials
      - r_solar_irradiation: 1,723 MWh/yr
      - r_investment_costs: 6,28 €/yr
    - Output Materials
      - i_electricity_solar: 0,31 MWh/yr
  - o_sell_electricity_biomass
    - Input Materials
      - i_electricity_biomass: 4862 MWh/yr
    - Output Materials
      - p_proinfa: 234945 €/yr
      - p_electricity_biomass: 4862 MWh/yr
  - o_sell_electricity_solar
    - Input Materials
      - i_electricity_solar: 0,31 MWh/yr
    - Output Materials
      - p_electricity_solar: 0,31 MWh/yr

APPENDIX 5 – OPTIMUM TILT ANGLE TOOL

In order to use this tool the user needs to input the latitude of the location and at least two irradiation points with measurement date half a year apart. Basically, there is need for the highest and the lowest irradiance values in the year of interest.

With these two points, the tool is able to simulate the incident ($S_{incident}$), horizontal ($S_{horizontal}$) and module (S_{module}) irradiation. The scheme below shows how to calculate the irradiation incident on a tilted surface given either the solar irradiation measured on horizontal surface or the solar irradiation measured perpendicular to the sun. Where α is the elevation angle of the sun; and β is the tilt angle of the module measured from the horizontal.

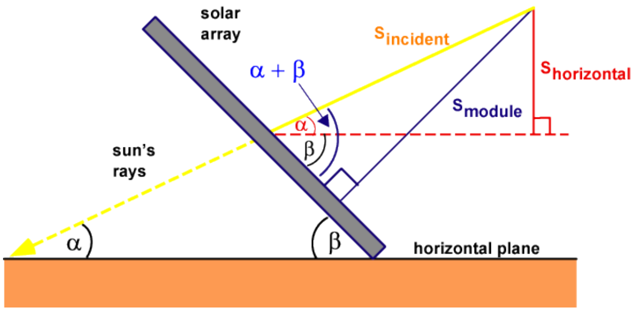


Figure 20: Angles of the irradiation on the several planes

Since both triangles are right triangles with a hypotenuse in common it is possible to use the definition of the sines in both cases and use the hypotenuse to find the relationship. Based on the diagram above:

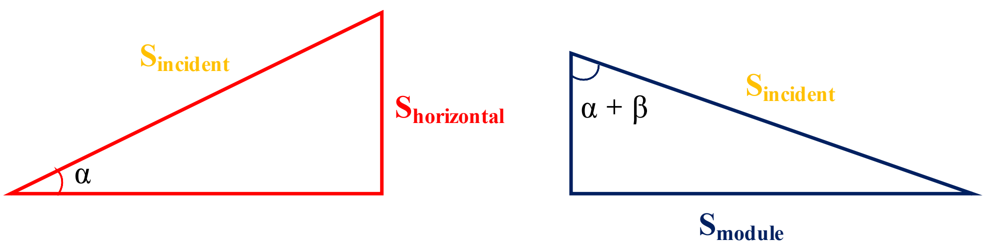


Figure 21: Triangles for the horizontal en module irradiation

Therefore:

$$\sin(\alpha) = \frac{S_{horizontal}}{S_{incident}} \quad , \quad \sin(\alpha + \beta) = \frac{S_{module}}{S_{incident}}$$

$$\frac{S_{module}}{\sin(\alpha + \beta)} = \frac{S_{horizontal}}{\sin(\alpha)} \quad \therefore \quad S_{module} = \frac{\sin(\alpha + \beta)}{\sin(\alpha)} \cdot S_{horizontal} \quad \blacksquare$$

First, it is necessary to calculate the declination angle (δ) in order to define the elevation angle (α), both expressions are presented bellow:

$$\delta = 23.45^o \cdot \sin\left[\frac{360}{365}(284 + d)\right]$$

$$\alpha = 90 - \phi + \delta$$

In order to estimate the $S_{incident}$ it is assumed that the irradiation during the year oscillates as a perfect **sine function**. This is reasonable if no environment factors are considered, like clouds or wind, since the only oscillation will be due to the change in the declination angle throughout the year. Considering this is also reasonable to assume the same phase angle of the declination angle. Thus:

$$S_{incident}(d) = \overline{S_{incident}} + A \cdot \sin(\frac{360}{365} \cdot (284 + d))$$

The average of the irradiation is taken since the oscillation does not happen around the zero, but around the middle point of the sine curve, which is the average of two symmetrical values. Considering that usually the maximum and minimum points in irradiance are half a period apart in a sine curve they can be used to calculate the average:

$$\overline{S_{incident}} = \frac{S_{incident}(max) + S_{incident}(min)}{2}$$

To calculate the amplitude of the oscillation, it is only needed to use one of the two points known for the irradiation, for example, the value and day of the year with minimum irradiance:

$$A = \frac{S_{incident}(min) - \overline{S_{incident}}}{\sin\left(\frac{360}{365} \cdot (284 + day(min))\right)}$$

After calculating these values it is possible to simulate $S_{incident}$ and, consequently, $S_{horizontal}$ and S_{module}. The tool was parametrized using the expressions derived above. As an input the user has to insert the latitude of the region of interest and some initial irradiation point with the corresponding date. After that the tool will inform for which day of the year another irradiation point is needed. Therefore, if the user possesses the information for that specific date they can input it, otherwise it is also possible to input maximum and minimum points, with no regard to the date of the data collection.

2				
3	Latitude	49	°	
4				
5		*Irradiance*	*Date of Irradiation Point*	
6	Initial Point	493.1	01.01.2016	
7	Mid Point	267.6	**01.07.2016**	
8	**Period**	**365.0**		
9	**Center**	**380.3**		
10	**Amplitude**	**-146.5**		

Figure 22 Input information – Tilt angle tool

It is important to know that the Initial point is the irradiation in the beginning of the year and the Middle point in the middle of the year. Therefore, if the user is using only maximum and minimum points they should consider when the maximum occurs in the hemisphere their region of interest is located.

Nevertheless, with this information it is possible to calculate all the variables needed to simulate the irradiation throughout the year. More importantly, the optimization of the tilt angle goes as follows.

1. $S_{incident}$ and $S_{horizontal}$ are simulated once using the user input and the expressions derived;
2. S_{module} is calculated for tilt angles ranging from 0 to 90°;
3. The yearly sum of S_{module} is calculated for each tilt angle in order to assess which maximizes the irradiation in the module;

4. The value that maximizes S_{module} through the year is then used to calculate the optimum S_{module}.

The figure below represents an example of the tool output:

2			
3	Latitude	49	°
4			
5		*Irradiance*	*Date of Irradiation Point*
6	Initial Point	493.1	01.01.2016
7	Mid Point	267.6	01.07.2016
8	**Period**	**365.0**	
9	**Center**	**380.3**	
10	**Amplitude**	**-146.5**	
11			
12	**Maximum Irradiance**	**133,697**	**W/m2*year**
13	**Optimum Tilt Angle**	**44**	**°**
14			
15			
16			
17			
18			

Day	Delta	Elevation (alpha)	Elevation (rad)	Sincident	Shorizontal	Smodule Opt
0	-23.1	17.9	0.313	236.05	72.61	208.249
1	-23.0	18.0	0.314	236.51	73.04	208.803
2	-22.9	18.1	0.315	237.02	73.52	209.408
3	-22.8	18.2	0.317	237.57	74.03	210.063
4	-22.7	18.3	0.319	238.16	74.59	210.770
5	-22.6	18.4	0.320	238.79	75.19	211.527
6	-22.5	18.5	0.322	239.47	75.83	212.335
7	-22.4	18.6	0.324	240.18	76.51	213.193
8	-22.3	18.7	0.326	240.94	77.24	214.101
9	-22.2	18.8	0.329	241.74	78.01	215.059
10	-22.0	19.0	0.331	242.58	78.82	216.067
11	-21.9	19.1	0.333	243.47	79.67	217.125
12	-21.8	19.2	0.336	244.39	80.57	218.232
13	-21.6	19.4	0.339	245.35	81.51	219.388
14	-21.4	19.6	0.341	246.35	82.49	220.592
15	-21.3	19.7	0.344	247.40	83.52	221.846

Figure 23 Output optimum tilt angle tool