POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Multi-Objective Linear Programming for the cooking energy transition of a Maasai community

TESI DI LAUREA MAGISTRALE IN
ENERGY ENGINEERING
INGEGNERIA ENERGETICA

Author: **Matteo Vegezzi**

Student ID: 953462
Advisor: Prof. Emanuela Colombo
Academic Year: 2021-22

Contents

List of Figures

List of Tables

Abbreviation index

ASAL	Arid and Semi-Arid Land
CRF	Capital Recovery Factor
GDP	Gross Domestic Product
GUI	Graphical User Interface
HH	Households
IAP	Indoor Air Pollution
ICS	Improved Cooking Stoves
IPCC	Intergovernmental Panel on Climate Change
LP	Linear Programming
LPG	Liquefied Petroleum Gas
MOLP	Multi-Objective Linear Programming
OECD	Organisation for Economic Co-operation and Development
SDG	Sustainable Development Goals
WB	World Bank

Abstract in italiano

I cambiamenti climatici in atto stanno già esercitando degli effetti sensibili e irreversibili alle medie latitudini.

La situazione nell'intorno dell'equatore è aggravata e coinvolge quelle popolazioni in via di sviluppo che già vivono in condizioni precarie.

Come ribadito dall' Agenda 2030 delle Nazioni Unite, un punto di svolta è urgente e necessario per consentire a questi paesi di svilupparsi in modo sostenibile.

In particolare l'obbiettivo 7 dell'Agenda persegue l'accesso universale a fonti pulite, economiche e moderne.

Con questa spinta IPSIA ha scritto un progetto rivolto ad una comunità agricola Masai a Laikipia, nelle zone semi-aride del Kenya.

L'idea è quella d'installare alcuni digestori in grado di produrre gas pulito da un lato e dall'altro fermentare l'Opuntia Stricta.

L'Opuntia è una varietà di cactus considerata invasiva che sta danneggiando le attività agro-pastorali dei Masai e la biodiversità della contea di Laikipia.

Il dubbio che ci si è posti in fase di scrittura del progetto, chiamato BeOGas, è se la transizione della Comunità di Twala dal sistema di cottura tradizionale a quello dei fornelli a biogas non abbia un impatto sociale negativo dovuto all'eccessivo onere di tempo.

Si arriva alla questione indagata in questo elaborato, ovvero trovare quel mix di sorgenti (GPL, biogas e legna combusta in stufe migliorate) che oltre a soddisfare la domanda energetica dei fornelli della comunità vada a minimizzare l'impatto sociale, le emissioni di anidride carbonica e il costo di progetto.

Risolto il problema di ottimizzazione si descriverà un tool informatico sviluppato durante lo stage: MakeCH4nge.

Questo programma ha gli stessi obbiettivi del problema appena descritto, ma rende la soluzione scalabile su progetti di Cooperazione in altri paesi e fruibile, tramite un interfaccia grafica, anche da un utente non esperto del linguaggio informatico.

Parole chiave: SDG7, Adattamento ai cambiamenti climatici, Programmazione Lineare Multi-Obbiettivo, Cooperazione allo Sviluppo, Impatto Sociale

Abstract

Ongoing climate changes is already having noticeable and irreversible effects in the mid-latitudes.

The situation around the equator is aggravated and affects those developing populations already living in precarious conditions.

As reiterated in the UN 2030 Agenda, a turning point is urgent and necessary to enable these countries to develop sustainably.

In particular, Goal 7 of the Agenda pursues universal access to clean, affordable and modern energy sources.

With this drive, IPSIA has written a project addressed to a Maasai farming community in Laikipia, in the semi-arid areas of Kenya.

The idea is to install digesters capable of producing clean gas on the one hand and fermenting Opuntia Stricta on the other.

Opuntia is a variety of cactus considered invasive that is damaging the agro-pastoral activities of the Maasai and the biodiversity of Laikipia County.

The question that arose when writing the project, called BeOGas, is whether the transition of the Twala community from the traditional cooking system to biogas stoves will not have a negative social impact due to the excessive time burden.

This leads to the question investigated in this paper, which is to find that mix of sources (LPG, biogas and combusted wood in improved stoves) that not only satisfies the energy demand of the community's but also minimises the social impact, carbon footprint and project cost.

Having solved the optimisation problem, a computer tool developed during the internship will be described: MakeCH4nge.

This programme has the same objectives as the problem just described, but makes the solution scalable to co-operation projects in other countries and usable, via a graphical interface, even by a user who is not computer-literate.

Key-words: SDG7, Climate Change Adaptation, Multi-Objective Linear Programming, Development Cooperation, Social impact

1 Context introduction

1.1. Kenya

Kenya is a country of East Africa with a population of 56 million inhabitants spread over 582,646 km² of land. [1]

Kenyans speak English and Swahili, often declined into dialectal forms such as Kikuyu, Kimeru, and Kimasai.

According to the World Bank (WB) Kenya can be classified as a Low Medium income [1] with a GDP PPP [2] per capita of 5023 USD. [2]

This GDP is supported by agriculture, which is shifting more and more towards monoculture and tourism which accounts for about 9 % (2019 data) [2].

Figure 1.1: Kenya political map

Kenya enjoys a generally stable political situation compared to neighbouring sub-Saharan African states.

However, in recent years there has been a dispute with Somalia over the allocation of (including maritime) borders, which has been brought to the UN Court and relations between Nairobi and Mogadishu are being tightened up.

Also in August 2022 will take place votes for the election of county officials and the new president with the prediction of riots and intertribal protests especially in the capital.

The climate of Kenya is quite varied, from the warm and humid coastal areas becomes milder in the inland areas, in relation to altitude, until becoming semi-desert in the northern areas. [1]

---

[1] The World Bank assigns the world's economies to four income groups—low, lower-middle, upper-middle, and high-income countries.

[2] Purchasing power parities (PPPs) are the rates of currency conversion that equalise the purchasing power of different currencies by eliminating the differences in price levels between countries. In their simplest form, PPPs are simply price relatives which show the ratio of the prices in national currencies of the same good or service in different countries. [3]

1.2. Maasai communities

In the central-southern regions and in the county of Laikipia, some Maasai communities are stabilised.

Originally this nomadic Nilotic tribe survived thanks to pastoralism, in the last century with the arrival of the English settlers and the subsequent redistribution of lands they saw their territory drastically reduced by the creation of national parks [3] such as Masai Mara, Hell's Gate and Samburu. [4]

Thus the history of recent decades is the progressive abandonment of the nomadic pastoral tradition and the consequent approach to sedentary agriculture.

However, this transition is being undermined by certain environmental difficulties.

In particular, the soil occupied in Laikipia is predominantly desert and semi-desert, this means that only permaculture approaches can allow the Maasai to cultivate profitably.

Furthermore, water scarcity has become more acute in recent times as a result of climate change.

As you can see from Figure 1.2 the precipitation historically already scarce (think that in Milan it rains on average 147 mm of water per month) in the last year have further decreased.
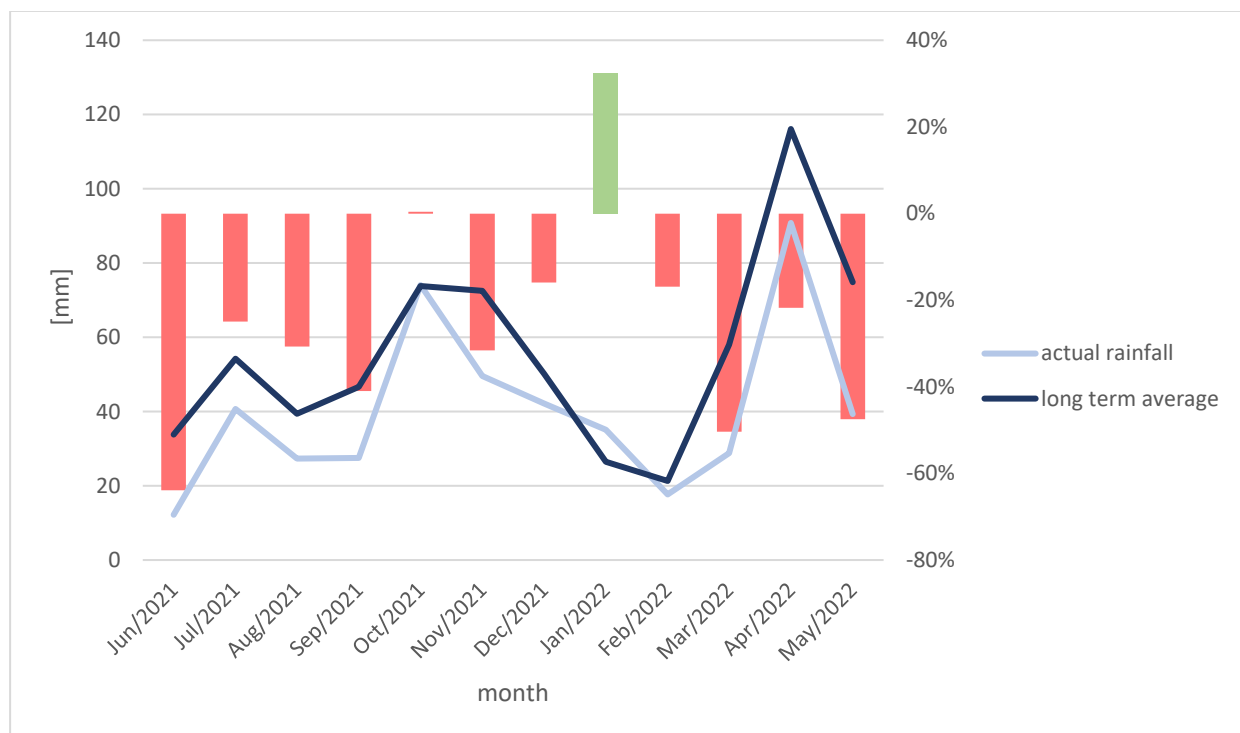
Figure 1.2: systematic decrease of rainfalls during past year. Data adapted from NDMA [5]

---

[3] It must be said, however, that many of these areas are open to grazing for local communities.

The way of life of these populations is mirrored by the diet, composed mostly of farinaceous (such as ugali and chapati) and cooked vegetables (such as sukuma, mukimu and ghideri).

These dishes are cooked with a three-stone system in traditional Maasai houses.

Figure 1.4: Traditional Maasai house (Enkang) made with dung mixed with mud and placed on a structure of flexible branches. The maximum height of the house is about 1,5 m. [6]

Figure 1.3: Maasai woman cooks in the traditional "Three-stone" stove. [7]

1.3. IPSIA

IPSIA is the acronym of Istituto Pace Sviluppo Innovazione ACLI, a non-governmental organization promoted by ACLI with the intention of transforming experiences and values of popular associations into international cooperation initiatives. [8]

Founded in 1985 after the experience of CEPAS, the Center for Peace and Development, since that year IPSIA has articulated its projects in Italy and in 9 countries distributed in the Balkan Peninsula and Africa, as well as an international volunteer project: Terre & Libertà.

IPSIA pursues civic goals, solidarity and social utility and specifically aims to:

1. to promote development cooperation initiatives, understood as Community cooperation, which focus on relations between local international and Italian communities, based on partnership in a constant commitment to access and the promotion of rights and processes of inclusion and social cohesion;

2. promote public awareness of peace and development issues;

3. to promote international voluntary initiatives complementary to development cooperation projects which in turn promote participation and voluntary engagement, relations between the communities involved, be a complementary part to international cooperation projects and offer an organised space to its members, service operators, civil society organisations and the initiatives they promote and citizenship in general to engage in international voluntary activities.

1.3.1. IPSIA Kenya

IPSIA has been operating in Kenya since 2006, although forms of exchange and collaboration between the IPSIA offices in Cuneo and Trentino and organizations in the country were already active in previous years. [8]

After initial projects in support of informal groups in the slums of Nairobi, IPSIA's areas of action focused on agriculture, social entrepreneurship and the environment, with a focus on rural areas.

Since 2015, the IPSIA headquarters in Kenya has been located in Meru with the three-year project at **Meru Herbs**, which aimed to promote the socio-economic development of Tharaka-Nithi County by improving the living conditions of women and young people.

Next, with the "**Maziwa**" project, IPSIA wants to help achieve food security, strengthen nutrition and promote sustainable agriculture, by improving the efficiency of the milk supply chain in Meru County.

Currently IPSIA Kenya collaborates with LPC[4] in the project "**Farming the future"** which aims to increase agricultural production and profitability of business initiatives of 11 target groups.

Figure 1.5: Meru Herbs Karkadè flower post-processing [8]

Figure 1.6: Maziwa project milk transformation [8]

---

[4] Laikipia Permaculture Center is a permaculture organisation founded in 2013 with the aim to teach the local Maasai community about permaculture, land regeneration and sustainable farming methods.

Figure 1.7: Farming the Future seminary at LPC [8]

2   The issue of cooking

2.1.   Urgent transition

In the latest report of the IPCC (Intergovernmental Panel on Climate Change) even in the most optimistic scenario of reducing greenhouse gas emissions from the current 55 $GtCO_2$ to 8-9 $GtCO_2$ by 2050 the probability of remaining below the threshold of 1,5 ºC of global temperature would remain 50%. [9]

So much so that in the same report, four whole chapters are linked to strategies to mitigate the impact of certain irreversible effects on humans and the ecosystem.

The COP26 event in Glasgow provided an opportunity for some developed countries to declare their intention to achieve carbon neutrality.

Examples of this are the European New Green Deal and the declaration of reaching the zero emission threshold for China by 2060.

Objectives that can only be achieved with the diversification of the energy mix, the exploration of new vectors, the improvement of efficiency and international cooperation between countries.

In fact, despite the invasion in Ukraine, Europe is working to make that "just transition" that is mentioned in the text of the Deal, in the developing continents this does not happen. [10]

The WEO 2019 reports that in a continent like Africa where the population is expected to increase by half a billion by 2040 and with it the energy demand and therefore pollution are only exploited 5 GW of photovoltaic energy source (1% of the global). [11]

Since the atmosphere is one for both the Organisation for Economic Co-operation and Development (OECD) [5] countries and the developing ones it is necessary to accompany (economically and with a spill over of knowledge) in the energy choices of the latter to allow them to leapfrog and do not make the same mistakes as ours.

---

[5] It is a forum the members of which are countries describing themselves as committed to democracy and the market economy, providing a platform to compare policy experiences, seek answers to common problems, identify good practices and coordinate domestic and international policies of its members.

2.2.   Agenda 2030

An instrument put in place by the United Nations is an agenda of 17 objectives that aim at a sustainable development of humanity also and especially for future generations. [12]

These goals range from ending poverty to improving health and education for the most disadvantaged countries as well as tackling climate change.

We now want to focus our attention on SDG 7 and SDG 13, which concern more closely the purpose of the project.

Figure 2.1: Goal 13 and Goal 7 logos

SDG 7 specifically wants to ensure access to affordable, reliable, sustainable and modern energy for all, while SDG 13 warns to take urgent action to combat climate change and its impacts.

2.3.   Traditional use of biomass

More than a third of the world's population rely on inefficient cooking systems.

According to the 2021 UN projections, this fraction will remain the same even in 2030 [13] despite the increase in world population. In **Errore. L'origine riferimento non è**
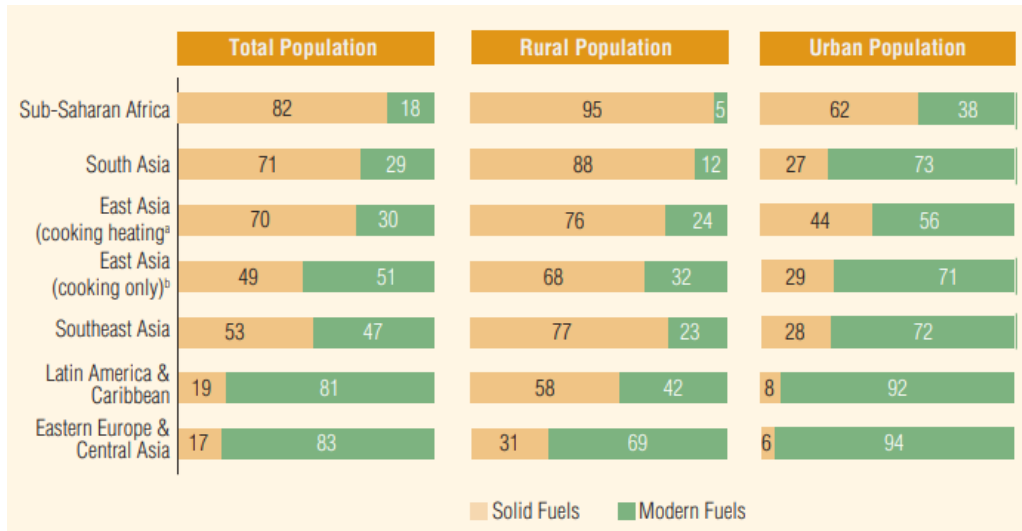
stata trovata. we can appreciate how the

Figure 2.2: Fraction of population still relying on traditional solid fuels. [14]

dependence on traditional cooking systems involves above all the rural populations of sub-Saharan Africa and South Asia.

These considerations are accompanied by the concept of "energy ladder" according to which the efficiency and cleanliness of the cooking system depend on the level of income. From high polluting solid fuels through gaseous ones to electricity that remains at the top.
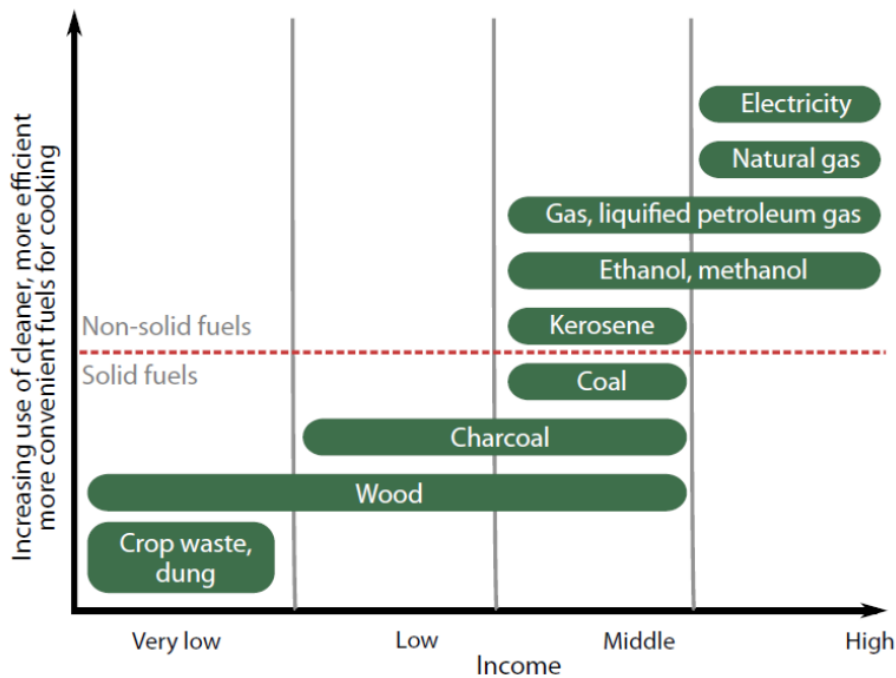
Figure 2.3: The energy ladder [15]

2.3.1. Impact on health

The kitchen with traditional systems, especially indoors, carries serious risks for people.

In fact, incomplete combustion at low flame temperatures leads to a high concentration in the products of harmful substances such as carbon monoxide and nitrogen dioxide that involve pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease and lung cancer. [16]

An impressive figure is the number of annual deaths attributable to Indoor Air Pollution [16] especially when compared to those for malaria [17] , HIV [18], TB [19] and Covid-19 of the same period [20] (Figure 2.4)
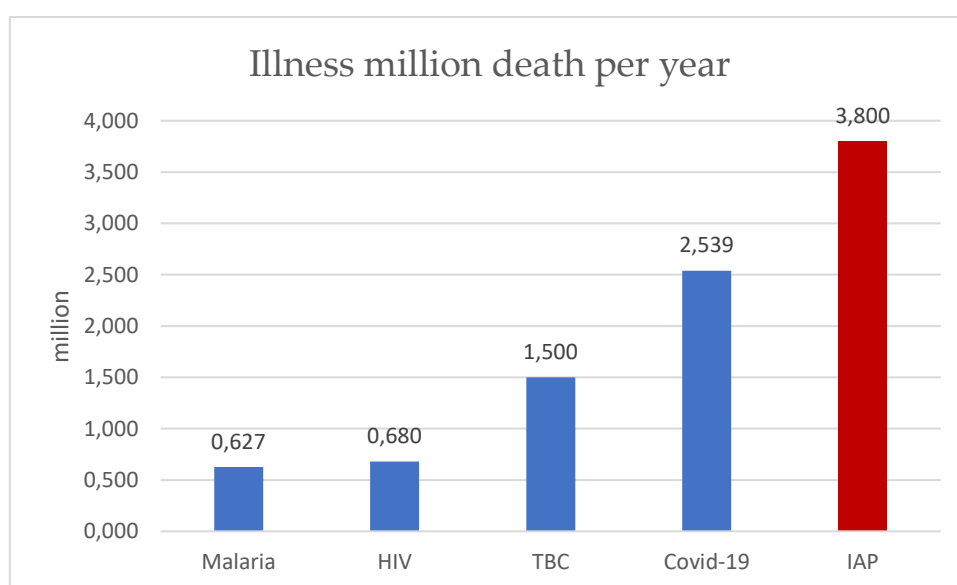
Figure 2.4: Deaths/ year comparison. Adapted from WHO [16] [17] [18] [19] [20]

In addition to the direct impact on health we have several negative externalities directly related to the use of unclean biomass among which the excessive time dedicated to the collection of wood; Burden that falls on women and children who are at risk of being attacked by dangerous animals.

2.3.2. Impact on environment

As already stated, the Environmental Impact that falls on man is not negligible.

The excessive deforestation that involves the supply of fuel- whether firewood or charcoal- adversely affects Biodiversity and increases the number of Mud-slides.

In fact, the harvesting of trees adversely affects the population and the variety of plant and animal species in the forest. The removal of forest cover during deforestation has in some cases led to the scarcity or the outright extinction of many important plant and animal species. Some wild animals have been observed migrating from areas where tree cover has been removed to undisturbed vegetation. [21]

Some plant and animal genetic resources that could be used for the production of new pharmaceuticals or traditional medicine are lost due to the destruction of forest cover.

Last but not least the inefficient combustion of Biomass Involves high gas inputs such as CO_2, CO and NO_2 that contribute to Global Warming.

2.3.3. BeOGas Project

The collection of firewood for domestic use is one of the main traditional activities in Laikipia North: 85,8% of households use firewood as the main type of cooking fuel. [22]

This can be largely attributed to poverty and lack of affordable alternative sources of energy. The burden of collecting firewood usually implies walking for long distances without transportation and falls on women and children.

The project BeOGas (Be zero Gas emission), financed by GIZ [6] , with IPSIA as a project leader aim to contribute to the mitigation of greenhouse gas emission in Laikipia County through an approach potentially scalable in The Arid and Semi-Arid Lands (ASALs) of Kenya.

The project aims to encouraging the transition from traditional to renewable sources of energy for 5 target groups in Laikipia North Sub-County by introducing alternative methods for cooking and promoting community participation to climate change fighting strategies. The project objective will be achieved by installing biogas systems at selected households and by distributing improved cooking stoves which significantly reduce the use of firewood and consequently reduce the greenhouse gas emissions.

The use of Opuntia Stricta to feed the biogas systems brings an added value to the project as it impacts communities on different levels. Aside from being a clean energy source for cooking, the reduction of the plant allows regeneration of the land and the pastures, a critical resource for pastoral communities; the use of the waste from the biodigester is a good biofertilizer promoting kitchen gardens and strengthening food security; women and children's health is also improved by avoiding them to be exposed to pollutants that cause respiratory and eye diseases; finally they will also be less exposed to harassment or attacks by wildlife and people as they collect firewood.

---

[6]Deutsche Gesellschaft für Internationale Zusammenarbeit: main German development agency that provides services in the field of international development cooperation and international education work

The distribution of stoves and the allocation of biogas plants will not be random. The idea is to find an arrangement of the two devices, leaving the possibility of introducing also gas fuel cylinders, which minimizes the cost and environmental impact.

The environmental impact is translated into carbon dioxide emissions that will not exceed half of the baseline.

During the writing of the project there was the doubt that the introduction of the Biogas System does not actually aggravate the time burden, simply shift the community from the task of collecting wood to that of harvesting and grind of the Opuntia. To prevent this risk at the design stage, it was decided to introduce time as a resource to be minimized. The new configuration should therefore not exceed two thirds of the time previously spent on collection and cooking.

At this point the project writing, make a step back leaving room for mathematics. In the next chapter we will see how the problem has been solved.

14

3 Modelling and solving the problem

The aim of the study is to find an optimal mix of technologies for the energy transition in the Maasai community of Twala.

Optimal because the energy matrix of alternative sources researched, not only satisfy the energy demand for the "cooking" task, but also minimise:

1) The total costs linked to the project cycle (from purchase at year 0 to annual running costs).

2) The environmental impact.

3) The social impact.

3.1. System model

As a first step in modelling the problem, system volume is defined. It consists in the summation of the households living in Twala.

Defined the so-called control volume, for now dealt as a black box, is good practice to adopt a sign convention: In our system, incoming flows are considered positive.
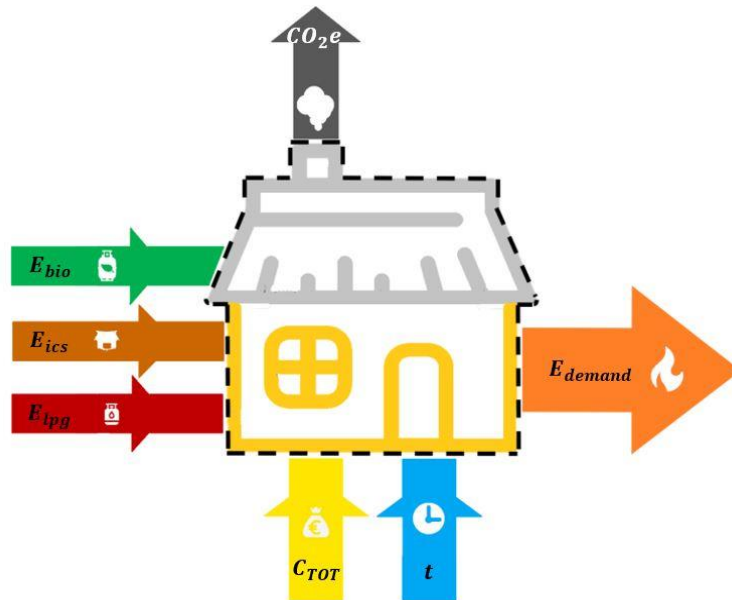
Figure 3.1: Black box model

As shown in Figure 3.1 there are flows of different nature interacting with the system.

In particular,

- E_{demand} is the daily energy demand for cooking meals to be met with the alternative technologies. [MJ].

- E_{lpg} is the thermal energy resulting from the combustion of Liquefied Petroleum Gas (LPG) in stoves net of the various losses, by radiation and convection in the flame-to-pot transition [MJ].

- E_{bio} is the thermal energy resulting from the combustion of biogas in special stoves net of the various losses in the flame-to-pot surface transition. [MJ].

- E_{ics} is the energy released from the combustion of wood in Improved Cooking Stoves (ICS) [7] multiplied by a coefficient that considers the thermal efficiency of the stove. [MJ]

- CO_2e is the mass of carbon dioxide produced by the combustion of fossil fuel or biogas within the control volume [kgCO2]

- C_{TOT} is the total cash flow to support the investment and operating costs for the energy transition. [€]

- t is the time spent by the entire community on the cooking task, from fuel collection to the hours spent cooking the three meals of the day. [min]

In order to define the η_{lpg}, η_{ICS} and η_{bio} thermal efficiency coefficients that characterize the energy actually used for cooking food, we have that:

$$\dot{Q}_{in} = \dot{Q}_{fuel} - \dot{Q}_{rad} - \dot{Q}_{conv} \tag{3.1}$$

$$\eta = \frac{\dot{Q}_{in}}{\dot{Q}_{fuel}} \tag{3.2}$$

Where:

- $\dot{Q}_{in}$ is the power actually entering the pan volume. [kW]
- $\dot{Q}_{fuel}$ is the power released by combustion of the generic fuel. [kW]
- $\dot{Q}_{rad}$ is the power dissipated by radiation. [kW]
- $\dot{Q}_{conv}$ is the power dissipated by convection with the environment. [kW]

---

[7] An improved biomass cookstove (ICS) typically describes a stove which has a higher efficiency or lower level of pollution than a traditional stove, through improvements including a chimney or closed combustion chamber. [23]
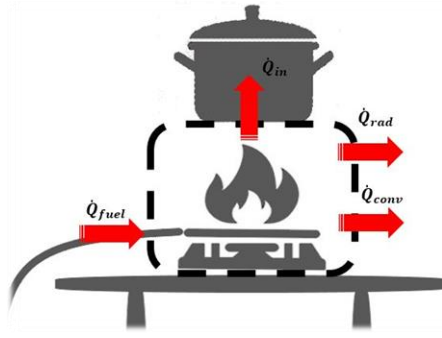
Figure 3.2: Heat exchange scheme

To sketch a mathematical formalism that allows to set up the problem, are defined:

- x_1 independent variable corresponding to the amount of gas mass combusted in LPG stoves. [kg]
- x_2 independent variable corresponding to the amount of firewood combusted in ICS. [kg]
- x_3 independent variable corresponding to the amount of biogas mass combusted in biogas stoves. [kg]
- $C_{TOT}(x_1, x_2, x_3)$ function characterising total project costs. [€]
- $CO_2^e(x_1, x_2, x_3)$ function characterising total project carbon dioxide emissions. [kgCO$_2$]
- $t(x_1, x_2, x_3)$ function characterising total time taken to accomplish the cooking task. [min]
- The spatial domain $\mathbb{P}$ set of all the feasible combinations of x_1, x_2 and x_3.

A Multi-Objective Linear Programming (MOLP) method is used to find a solution that solves this system.

$$
\begin{cases}
\min C_{TOT}(x_1, x_2, x_3) & \text{(3.3a)} \\
\min CO_2^e(x_1, x_2, x_3) & \text{(3.3b)} \\
\quad \min t(x_1, x_2, x_3) & \text{(3.3c)} \\
\quad x_1, x_2, x_3 \in \mathbb{P}
\end{cases}
$$

$$\text{(3.3d)}$$

Therefore, before proceeding to a more complete characterisation of functions and constraints in the next section linear programming is deepened.

3.2. Linear Programming

Linear programming (LP, also called linear optimization) is a technique to achieve the best outcome (such as maximum profit or lowest cost) in a mathematical model whose requirements are represented by linear relationships. [24]

At this point, to give a complete and comprehensive definition of how a LP problem is set up and solved, we proceed by points with the help of a graphic representation of the element to be defined.

1) First of all, we define the **independent variables** x_1, x_2, x_3. Note that the combination of the three can be interpreted as a Cartesian space where each point is represented by a single triplet of values of the three variables.
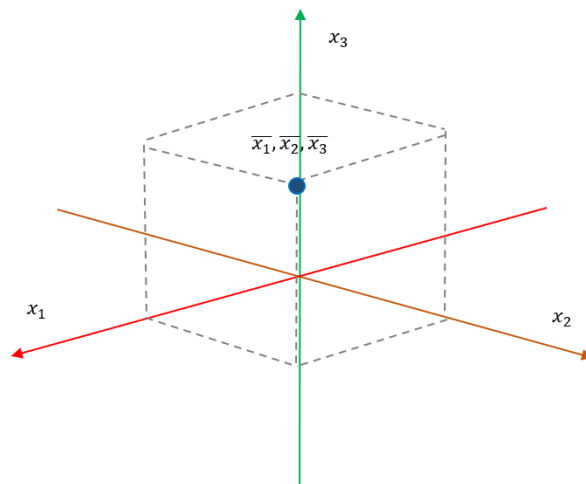
Figure 3.3: Triplet of the variables represents a point in the 3D space.

2) The linear combination of the three independent variables is called **the objective function**. We have that for each point in three-dimensional space.

   Therefore, in addition to the trio of values of the independent variables, we also have a fourth value corresponding to the evaluation of the function $f(x_1, x_2, x_3)$ at point (x_1, x_2, x_3).

   The graphical representation of the objective function is a plan.
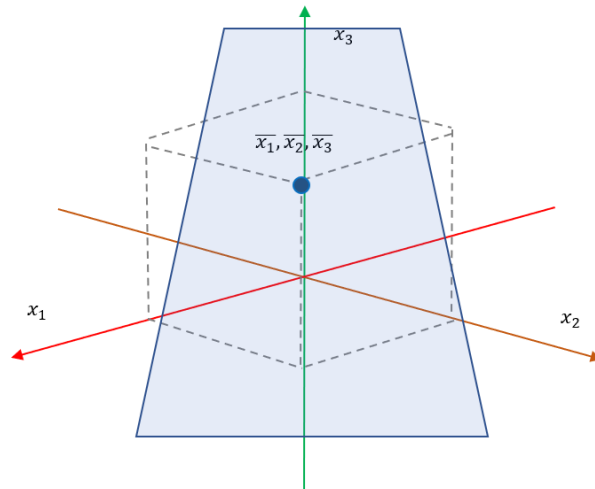
Figure 3.4: Objective function described as a 3D plan

As an optimisation problem, we want to find the minimum value of these functions and the corresponding x_1, x_2, x_3 that satisfy them given certain constraints on the domain.

3) Constraints are inequalities involving at least one variable and constitute the outer surface within which the function can move.
In other words, when we go to define a constraint, all we are doing is drawing a plane beyond which or within which the three variables, and consequently the function, cannot exist. At this point, we obtain the convex polyhedral characteristic of the linear problem $\mathbb{P}$, which in the examined optimizer could have a shape like the one shown in Figure 3.5.
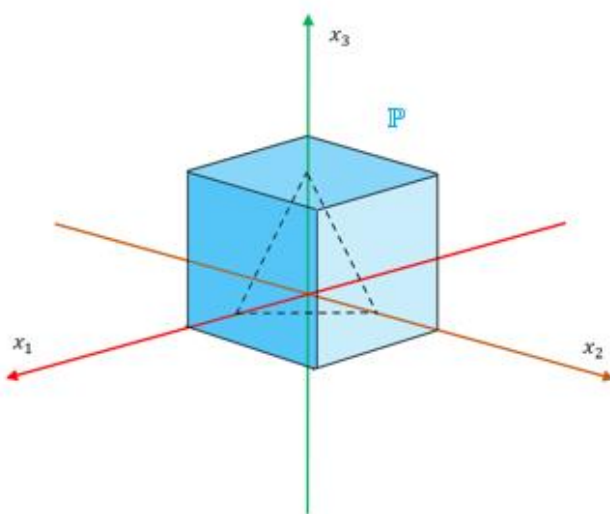
Figure 3.5a: front
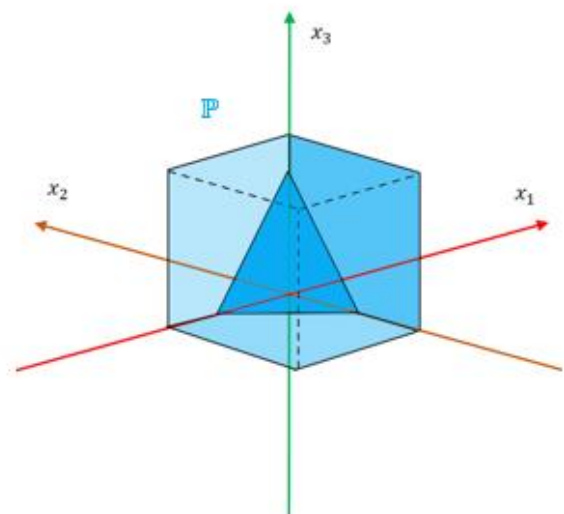
Figure 3.5b: back

3.2.1. Solution existence

Geometrically, the linear constraints define the feasible region, which is a convex polyhedron. A linear function is a convex function, which implies that every local minimum is a global minimum; similarly, a linear function is a concave function, which implies that every local maximum is a global maximum. [25]

An optimal solution need not exist, for two reasons.

Firstly, if the constraints are inconsistent, there is no feasible solution: for example, the constraints $x \geq 2$ and $x \leq 1$ cannot be jointly satisfied; in this case, the LP is said to be inapplicable.

Secondly, when the polytope [8] is unbounded in the direction of the gradient of the objective function (where the gradient of the objective function is the vector of coefficients of the objective function), then no optimal value is reached because it is always possible to do better than any finite value of the objective function.

3.2.2. Multi - Objective Programming

As noted earlier, the optimal mix problem set previously involves finding the minimum of three functions.

To switch from single-objective to multi-objective linear programming, one of two strategies needs to be implemented to return to a standard single-objective situation:

- The first involves converting to a single objective using weights and summation. i.e., determine the importance of each objective function by entering the appropriate weights and then sum all functions.

- The second performs the optimization by considering one objective at a time, according to priority.
  i.e. optimizing one objective results in a constraint (optimal value of the objective) place this objective as a constraint with this optimized constraint and optimize using a second objective. Continue until all objectives are considered. [26]

In this work, the second strategy was chosen.

Having defined the problem, all that remains is to implement a solution algorithm that can bring the independent variables to convergence to the value that minimizes the objective functions.

For simplicity and speed, the **Simplex Method** was chosen.

---

[8] In geometry a polytope is an object with only flat sides.

3.2.3. Simplex Method

Ending point

Starting vertex
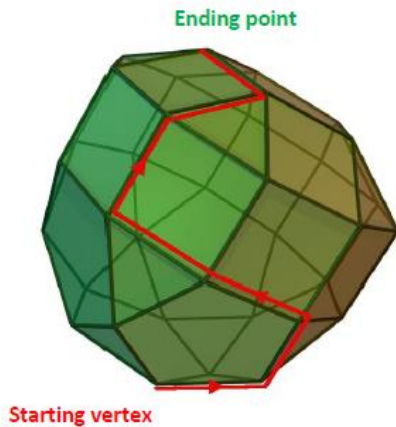
This method is based on the inspection of the vertices of the polyhedron obtained from the graphical definition of the problem, considering that the solution necessarily lies at one of these points. [27]

It starts with a corner point of the feasibility region where all principal variables are zero and then systematically moves from corner point to corner point, improving the value of the objective function at each stage. The process continues until the optimal solution is found.

Figure 3.6: graphical representation of the simplex method.
Adapted from [27]

In particular,

1) Set the problem. That is, write down the objective function and the inequality constraints.

e.g.

$$\max_{x_1, x_2 \in \mathbb{C}} f(x_1, x_2) = 40x_1 + 30x_2$$

$c_a \rightarrow x_1 + x_2 \leq 12$
$c_b \rightarrow 2x_1 + x_2 \leq 16$
$c_c \rightarrow x_1 \geq 0$
$c_d \rightarrow x_2 \geq 0$

2) Convert the inequalities into equations. This is done by adding a slack variable for each inequality.

e.g.

$c_a \rightarrow 2x_1 + x_2 = 16$
$c_b \rightarrow x_1 + x_2 + y_a = 12$
$c_c \rightarrow x_1 = 0$
$c_d \rightarrow x_2 = 0$

$$f(x_1, x_2) \rightarrow 40x_1 + 30x_2 + f = 0$$

3) Construct the initial tableau simplex. Write the objective function as the bottom row.

e.g.

x_1	x_2	y_a	y_b	f	C
1	1	1	0	0	12
2	1	0	1	0	16
−40	−30	0	0	1	0

4) The most negative entry in the bottom row identifies the pivot column.

e.g.

x_1	x_2	y_a	y_b	f	C
1	1	1	0	0	12
2	1	0	1	0	16
-40	-30	0	0	1	0

5) Calculate the quotients. The smallest quotient identifies a row. The item at the intersection of the column identified in step 4 and the row identified in this step is identified as the pivot item. The quotients are calculated by dividing the column on the far right by the column identified in step 4. A quotient that is a zero or a negative number or that has a zero in the denominator is ignored.

e.g.

x_1	x_2	y_a	y_b	f	C
1	1	1	0	0	12
1	1/2	0	1/2	0	8
-40	-30	0	0	1	0

6) Perform pivoting to make all other entries in this column null.

e.g.

x_1	x_2	y_a	y_b	f	C
0	1/2	1	$-1/2$	0	4
1	1/2	0	1/2	0	8
0	-10	0	20	1	320

7) When there are no more negative entries in the bottom row, the calculation is finished; otherwise, start again from step 4.

e.g.

x_1	x_2	y_a	y_b	f	C
0	1	2	−1	0	8
1	0	−1	1	0	4
0	0	20	10	1	400

8) Read the answers. Obtain variables using the columns with 1 and 0. All other variables are zero. All other variables are zero. The maximum value looking for appears in the bottom right-hand corner. [28]

$$x_1 = 4$$

3.3. Objective functions

To comply with the linearity constraint imposed by an LP problem, it is now necessary to enter the black box and trace the linear coefficients that multiplied by the respective independent variables return the three objective functions.

As far as the C_{TOT} function is concerned, the aim is to calculate the Net Present Cost (NPC) of the project, i.e. the total costs incurred to implement the project throughout its lifetime, from investment costs to annually discounted costs.

$$C_{TOT} = NPC = I_0 + \sum_{n=1}^{life} \frac{A\,(1 + i_F)^n}{(1 + i_r)^n} \tag{3.4}$$

Where:

- I_0 is the the initial outlay at year 0. [€]
- A are the total annual cost flows for sustain the project. [€]
- i_F inflation rate fixed at 0,061 [9] [-]
- i_R interest rate fixed at 0,067 [10] [-]
- $life$ is the total lifespan of the project. [years]

---

[9] Data from the World Bank (2021)
[10] Data from the World Bank (2021)

In the Eq. (3.4) the expression of the NPC of a generic investment is given, if we consider the two addends separately, we will have that:

The investment is equal to the cost of each technology times the number of devices purchased for that technology

$$I_0 = n_{lpg}C_{lpg} + n_{ICS}C_{ICS} + n_{bio}C_{bio} \tag{3.5}$$

In the present case,

- n_{lpg} is the number of LPG cylinders purchased brand-new at the project start.

- n_{ICS} is the number of ICS purchased at the project start.

- n_{bio} is the total bio-digesters volume to install at the project beginning. [m³]

- C_{lpg} is the specific cost per gas cylinder. [€]

- C_{ICS} is the specific cost per ICS (including transport costs). [€]

- C_{bio} is the specific cost per cubic meter of digester (including transport and installation costs) [€/m³]

To link the number of devices, just defined, with the three quantities of independent variables throughout the project cycle, the following procedure was followed:

➔ The following formula was used to determine n_{lpg}

$$n_{lpg} = \frac{x_1 \ [kg]}{m_{lpg} \left[\frac{kg}{cylinder}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life \ [year]} \tag{3.6}$$

Where:

- m_{lpg} is the single cylinder size. [kg/cylinder]

- $life$ is the lifetime of one single cylinder. [year]

➔ While to derive n_{ICS}

$$n_{ICS} = \frac{x_2 \ [kg]}{max_{fuel} \left[\frac{kg}{day}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life \ [year]} \tag{3.7a}$$

24

Where:

- max_{fuel} is the maximum quantity of firewood that an average household will adopt to run a single ICS in a day. This value is obtained by multiplying the average quantity of firewood used ante-intervention for the thermal yield of the ICS divided by the thermal yield of the traditional fireplace.

$$max_{fuel} = m_{fw} \left[\frac{kg}{day}\right] \cdot \frac{\eta_{ICS}[-]}{\eta_{fw}\,[-]} \tag{3.7b}$$

- 365 are the number of days in one year.
- $life$ is the expected lifespan of the project.

→ Finally, to derive n_{bio}

$$n_{bio} = \frac{x_3 \cdot V_{dig}\,[m^3]}{max_{gas} \left[\frac{kg}{day}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life\,[year]} \tag{3.8a}$$

- V_{dig} is the volume of one household-based digester. Computation formula in subsection 3.3.3).
- max_{gas} is the maximum biogas that an average household needs to fulfill its energy needs. This value is obtained by multiplying the average quantity of firewood for the lower heating value of the selected wood and the thermal yield of the three-stone fireplace. This three divided by the lower heating value of the biogas and the thermal yield of biogas cookstove.

$$max_{gas} = \frac{m_{fw} \left[\frac{kg}{day}\right] \cdot LHV_{fw} \left[\frac{MJ}{kg}\right] \cdot \eta_{fw}\,[-]}{LHV_{bio} \left[\frac{MJ}{kg}\right] \cdot \eta_{bio}\,[-]} \tag{3.8b}$$

Having eliminated the calculation of investment as a function of quantities x_1, x_2 and x_3 only, it remains to shift attention to the operating cost discounted to the project years. Note that under the assumption that the costs are constant over the useful life, it is possible to take this term out of the summation.

At this point the summation consists of economic constants only and for simplicity of exposition will be called Capital Recovery Factor (CRF).

$$CRF \overset{\text{def}}{=} \sum_{n=1}^{life} \frac{(1 + i_F)^n}{(1 + i_r)^n} \tag{3.9}$$

If one investigates what the total cash flows of the project are, without considering other interventions, the only out-of-pocket expenses are the various fuel costs multiplied by their respective quantities divided by the number of years (to return to an annual expenditure)

$$A = \frac{(x_1 c_{lpg} + x_2 c_{ICS} + x_3 c_{bio})}{life} \tag{3.10}$$

Substituting Eq. (3.6), Eq. (3.7), Eq. (3.8) and Eq. (3.10) into Eq. (3.4) gives:

$$C_{TOT} = \frac{x_1}{m_{lpg} \cdot life} C_{lpg} + \frac{x_2}{max_{fuel} \cdot 365 \cdot life} C_{ICS} + \frac{x_3 \cdot V_{dig}}{max_{gas} \cdot 365 \cdot life} C_{bio} +$$
$$+ \frac{(x_1 c_{lpg} + x_2 c_{ICS} + x_3 c_{bio}) \, CRF}{life} \tag{3.11}$$

With a few algebraic steps and gathering the variables, the following expression is obtained:

$$
\begin{aligned}
C_{TOT} = & \left(\frac{C_{lpg}}{m_{lpg} \cdot life} + c_{lpg} \frac{CRF}{life} \right) x_1 \\
& + \left(\frac{C_{ICS}}{max_{fuel} \cdot 365 \cdot life} + c_{ICS} \frac{CRF}{life} \right) x_2 \\
& + \left(\frac{C_{bio} \cdot V_{dig}}{max_{gas} \cdot 365 \cdot life} + c_{lpg} \frac{CRF}{life} \right) x_3
\end{aligned} \tag{3.12}
$$

For the sake of simplicity, we define the three coefficients of the function C_{TOT} a_1, b_1 and c_1:

$$a_1 \stackrel{\text{def}}{=} \left(\frac{C_{lpg} \, [\text{€}]}{m_{lpg} \left[\frac{kg}{day}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life[year]} + c_{lpg} \left[\frac{\text{€}}{kg}\right] \frac{CRF}{life} \right) \qquad (3.13\text{a})$$

$$b_1 \stackrel{\text{def}}{=} \left(\frac{C_{ICS} \, [\text{€}]}{max_{fuel} \left[\frac{kg}{day}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life[year]} + c_{ICS} \left[\frac{\text{€}}{kg}\right] \frac{CRF}{life} \right) \qquad (3.13\text{b})$$

$$c_1 \stackrel{\text{def}}{=} + \left(\frac{C_{bio} \left[\frac{\text{€}}{m^3}\right] \cdot V_{dig}[m^3]}{max_{gas} \left[\frac{kg}{day}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life[year]} + c_{lpg} \left[\frac{\text{€}}{kg}\right] \frac{CRF}{life} \right) \qquad (3.13\text{c})$$

To derive the total carbon dioxide emissions, the parameter that will constitute the environmental impact of the project, the procedure is more straightforward since it involves adding the quantities of fuel burned, assumed to be equal to the fuel purchased, multiplied by specific emission factors[11] related to the type of fuel.

$$CO_2^e = x_1 e_{lpg} + x_2 e_{ICS} + x_3 \, e_{bio} \qquad (3.14)$$

The linear coefficients will then be:

$$a_2 \stackrel{\text{def}}{=} e_{lpg} \left[\frac{kgCO_2}{kg}\right] \qquad (3.13\text{a})$$

$$b_2 \stackrel{\text{def}}{=} e_{ICS} \left[\frac{kgCO_2}{kg}\right] \qquad (3.13\text{b})$$

$$c_2 \stackrel{\text{def}}{=} e_{bio} \left[\frac{kgCO_2}{kg}\right] \qquad (3.13\text{c})$$

In the very last case, the definition of the coefficients becomes more complicated.

---

[11] A coefficient that quantifies the emissions or removals of a gas per unit activity.
Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions. [29]

First, the notion of social impact must be interpreted quantitatively.

In the case of the elaborate, as seen in paragraph 2.3), the impacts the project aims to trigger are multiple in the sphere of a woman or child in the community:

It is necessary to focus attention on a parameter that can be quantified and directly related to the improvement of the ante-project social condition.

This parameter is the total time spent on the burden of cooking (from the collection of fuel, the estimated time spent at the cooker to the time spent disposing of kitchen waste).

However, each technology needs a separate analysis:

➔ As far as **LPG** technology is concerned, the total time is as follows

$$t_{lpg} = t_{cooking} + t_{change}^{TOT} + t_{refill}^{TOT}$$

(3.14)

Where:

- $t_{cooking}$ is the total time devoted to actually cooking food

$$t_{cooking} = \frac{x_1\,[kg] \cdot LHV_{lpg}\left[\frac{MJ}{kg}\right] \cdot \eta_{lpg}[-] \cdot 1000\left[\frac{kJ}{MJ}\right]}{P_{lpg}[kW] \cdot 60\left[\frac{s}{min}\right]}$$

(3.15)

The numerator gives the total energy released from LPG technology expressed in kJ, dividing this quantity by the cookstove power gives the total seconds of functioning of the gas cooker. Dividing then by 60 gives this parameter in minutes.

- t_{change}^{TOT} is the total time to change unusable cylinders for brand new ones

$$t_{change}^{TOT} = \frac{t_{change}\left[\frac{min}{cylinder}\right] \cdot x_1[kg]}{m_{lpg}\left[\frac{kg}{cylinder}\right] \cdot 365\left[\frac{day}{year}\right] \cdot life[year]}$$

(3.16)

If one divide x_1 by 365, m_{lpg} and $life$, which in this case takes on the meaning of cylinder life, is possible get how many cylinders one will have to completely replace for each project cycle.

It is trivial that by multiplying this by the minutes it takes to replace a cylinder, I get the total minutes for the "cylinder change" task.

- t_{refill}^{TOT} is the total time used to go to the nearest petrol station, fill up one's own cylinder and take it back to the kitchen.

$$t_{refill}^{TOT} = \frac{t_{refill}\left[\frac{min}{cylinder}\right]}{m_{lpg}\left[\frac{kg}{cylinder}\right]} \cdot x_1\,[kg] - \frac{t_{refill}\left[\frac{min}{cylinder}\right] \cdot x_1[kg]}{m_{lpg}\left[\frac{kg}{cylinder}\right] \cdot 365\left[\frac{day}{year}\right] \cdot life[year]} \qquad (3.17)$$

Assuming one go to refill the cylinder once it is completely depleted, from $\frac{x_1}{m_{lpg}}$ you get the total number of fills which, as usual, multiplied by a standard refill time yields the total time for the "cylinder refill" task.

However, from this time must be subtracted the minutes to fill the cylinders purchased at the beginning of the project, which tend to be sold already full.

➔ The time function, on the other hand, for **ICS** technology consists of the following addends:

$$t_{lpg} = t_{cooking} + t_{ignition}^{TOT} + t_{collect}^{TOT} \qquad (3.18)$$

Where:

$$t_{cooking} = \frac{x_2\,[kg] \cdot LHV_{fw}\left[\frac{MJ}{kg}\right] \cdot \eta_{ICS}[-] \cdot 1000\left[\frac{kJ}{MJ}\right]}{P_{ICS}[kW] \cdot 60\left[\frac{s}{min}\right]} \qquad (3.19)$$

- $t_{ignition}^{TOT}$ is the total time devoted to light the ICS fire while the food is not actually cooking.

$$t_{ignition}^{TOT} = \frac{x_2 \, [kg] \, \cdot \, \eta_{ICS} \, [-] \, \cdot \, LHV_{fw} \, \left[\frac{MJ}{kg}\right]}{m_{fw} \, [kg] \cdot \eta_{fw}[-] \, \cdot \, LHV_{fw} \, \left[\frac{MJ}{kg}\right]} \cdot \, 3 \, \cdot t_{ignition} \, [min] \tag{3.20}$$

The first factor gives us the total number of ignitions by dividing the total energy released by all the ICS throughout the project by the daily energy needs of a household.
Assuming 3 daily ignitions, one per main meal, we multiply by the time and get the total.

- $t_{collect}^{TOT}$ total time spent on collecting firewood

$$t_{collect}^{TOT} = \, t_{collect} \left[\frac{min}{kg}\right] \cdot x_2 [kg] \tag{3.21}$$

Since $t_{collect}$ is the time to collect one kg of fuel and assuming that each kg collected ends up in the combustion chamber of the ICS, the product returns the total time spent collecting firewood.

➔ The contribution of time spent on the task of cooking with **biogas** technology can be represented by the following formula

$$t_{bio} = \, t_{cooking} + t_{collect}^{TOT} \tag{3.22}$$

Where:

$$t_{cooking} = \frac{x_3 \, [kg] \cdot \, LHV_{bio} \left[\frac{MJ}{kg}\right] \cdot \, \eta_{lpg}[-] \cdot 1000 \, \left[\frac{kJ}{MJ}\right]}{P_{bio}[kW] \cdot 60 \, \left[\frac{s}{min}\right]} \tag{3.23}$$

- $t_{collect}^{TOT}$ total time spent on collecting and grinding biomass.

$$
\begin{aligned}
&t_{collect}^{TOT} \\
&= \frac{x_3\ [kg_{biogas}]}{GY\ \left[\frac{m_{biogas}^3}{kg_{biomass}}\right] \cdot \rho_{bio}\left[\frac{kg_{biogas}}{m_{biogas}^3}\right] \cdot \rho_{sub}\left[\frac{kg_{biomass}}{m_{biomass}^3}\right] \cdot 0.1\left[\frac{m_{biomass}}{wheelbarrow}\right]}\ t_{collect}^{bio}
\end{aligned}
\tag{3.24}
$$

The first fraction obtains the total number of wheelbarrows to feed the digester. In fact, dividing x_3 by GY gives the mass of substrate and converting it to volume and then dividing by 0.1 m³ (average volume of a wheelbarrow) gives the total number of wheelbarrows. The latter multiplied by the filling time of a wheelbarrow gives the time spent harvesting the substrate.

Similarly to the cost function, we add up the various contributions and collect the variables as shown in the mathematical step below.

$$
\begin{aligned}
t = \ & x_1\left(\frac{LHV_{lpg} \cdot \eta_{lpg} \cdot 1000}{P_{lpg} \cdot 60} + \frac{t_{change} \cdot x_1}{m_{lpg} \cdot 365 \cdot life} + \frac{t_{refill}}{m_{lpg}}\right. \\
& \left. - \frac{t_{refill}}{m_{lpg} \cdot 365 \cdot life}\right) \\
& + x_2\left(\frac{LHV_{fw} \cdot \eta_{ICS} \cdot 1000}{P_{ICS} \cdot 60} + \frac{\eta_{ICS} \cdot LHV_{fw}}{m_{fw} \cdot \eta_{fw} \cdot LHV_{fw}} \cdot 3 \cdot t_{ignition}\right. \\
& \left. + t_{collect}\right) \\
& + x_3\left(\frac{LHV_{bio} \cdot \eta_{lpg} \cdot 1000}{P_{bio} \cdot 60} + \frac{1}{GY \cdot \rho_{bio} \cdot \rho_{sub} \cdot 0.1}\ t_{collect}^{bio}\right)
\end{aligned}
$$

Consequently, the coefficients will be:

$$a_3 \overset{\text{def}}{=} \frac{LHV_{lpg}\left[\frac{MJ}{kg}\right] \cdot \eta_{lpg}[-] \cdot 1000 \left[\frac{kJ}{MJ}\right]}{P_{lpg}[kW] \cdot 60 \left[\frac{s}{min}\right]}$$

$$+ \frac{t_{change}\left[\frac{min}{cylinder}\right]}{m_{lpg}\left[\frac{kg}{cylinder}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life[year]}$$

$$+ \frac{t_{refill}\left[\frac{min}{cylinder}\right]}{m_{lpg}\left[\frac{kg}{cylinder}\right]}$$

$$- \frac{t_{refill}\left[\frac{min}{cylinder}\right]}{m_{lpg}\left[\frac{kg}{cylinder}\right] \cdot 365 \left[\frac{day}{year}\right] \cdot life[year]}$$

(3.25a)

$$b_3 \overset{\text{def}}{=} \frac{LHV_{fw}\left[\frac{MJ}{kg}\right] \cdot \eta_{ICS}[-] \cdot 1000 \left[\frac{kJ}{MJ}\right]}{P_{ICS}[kW] \cdot 60 \left[\frac{s}{min}\right]}$$

$$+ \frac{\eta_{ICS}[-] \cdot LHV_{fw}\left[\frac{MJ}{kg}\right]}{m_{fw}[kg] \cdot \eta_{fw}[-] \cdot LHV_{fw}\left[\frac{MJ}{kg}\right]} \cdot 3 \cdot t_{ignition}[min]$$

$$+ t_{collect}\left[\frac{min}{kg}\right]$$

(3.25b)

$$c_3$$

$$\overset{\text{def}}{=} \frac{LHV_{bio}\left[\frac{MJ}{kg}\right] \cdot \eta_{lpg}[-] \cdot 1000 \left[\frac{kJ}{MJ}\right]}{P_{bio}[kW] \cdot 60 \left[\frac{s}{min}\right]}$$

$$+ \frac{t_{collect}^{bio}}{GY\left[\frac{m_{biogas}^3}{kg_{biomass}}\right] \cdot \rho_{bio}\left[\frac{kg_{biogas}}{m_{biogas}^3}\right] \cdot \rho_{sub}\left[\frac{kg_{biomass}}{m_{biomass}^3}\right] \cdot 0.1 \left[\frac{m_{biomass}}{wheelbarrow}\right]}$$

(3.25c)

It is now possible to explicate the objective functions of the problem, the system of the updated Eq (3.3) thus results:

$$\begin{cases} \min C_{TOT} = a_1\, x_1 + b_1\, x_2 + c_1\, x_3 & \text{(3.26a)} \\[6pt] \min CO_2^e = a_2\, x_1 + b_2\, x_2 + c_2\, x_3 & \text{(3.26b)} \\[6pt] \min t = a_3\, x_1 + b_3\, x_2 + c_3\, x_3 & \text{(3.26c)} \\[6pt] \quad x_1, x_2, x_3 \in \mathbb{P} & \text{(3.26d)} \end{cases}$$

3.3.1. Liquified Petroleum Gas device selection

Having defined the coefficients, all that remains is to assign an appropriate value to all parameters.

In the next three paragraphs, various brand, technology and fuel type alternatives will be evaluated in order to make these variables meaningfully explicit.

For the supply of LPG, the Rubis-K brand in the 6 kg size was chosen for a number of advantages that will be listed below:

- The first is the relative low investment cost compared to the other brands available in the area.
  In fact, as can be seen in Figure 3.7 and Figure 3.8, although the cost of the raw material is fairly constant among the brands, if we compare the cost of the specific cylinder alone per kg of cylinder, the Rubis-K brand is the most advantageous.
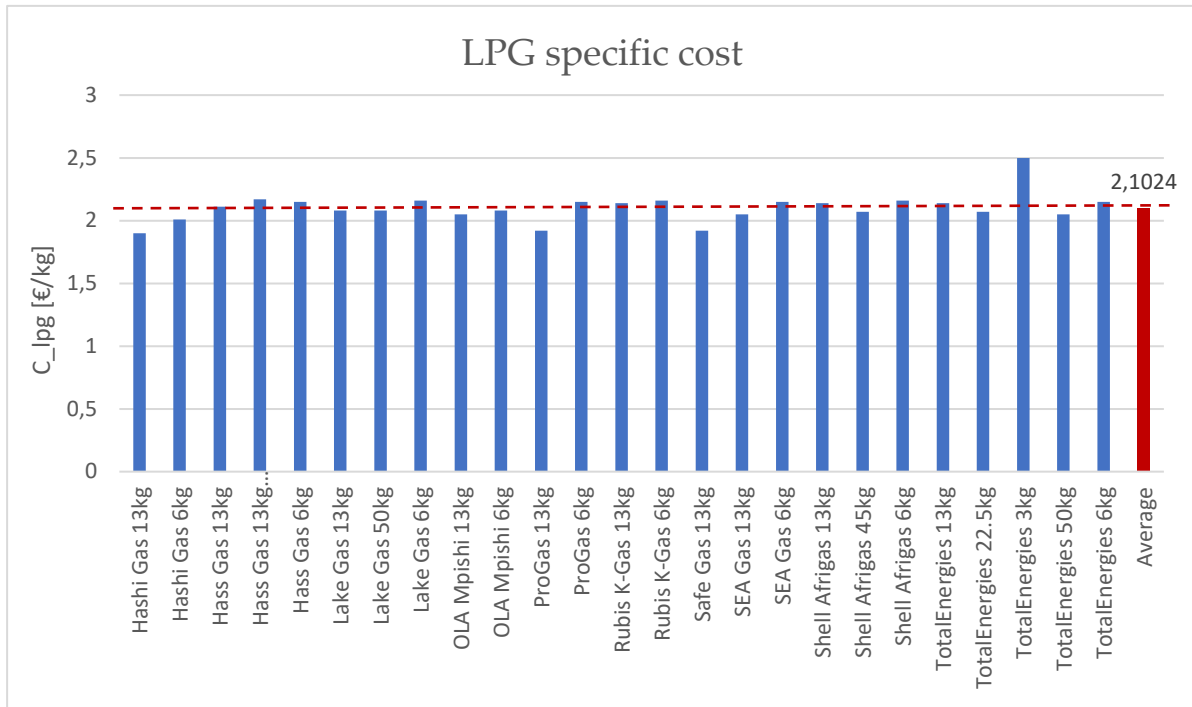
Figure 3.7: LPG specific cost in Kenya Market.
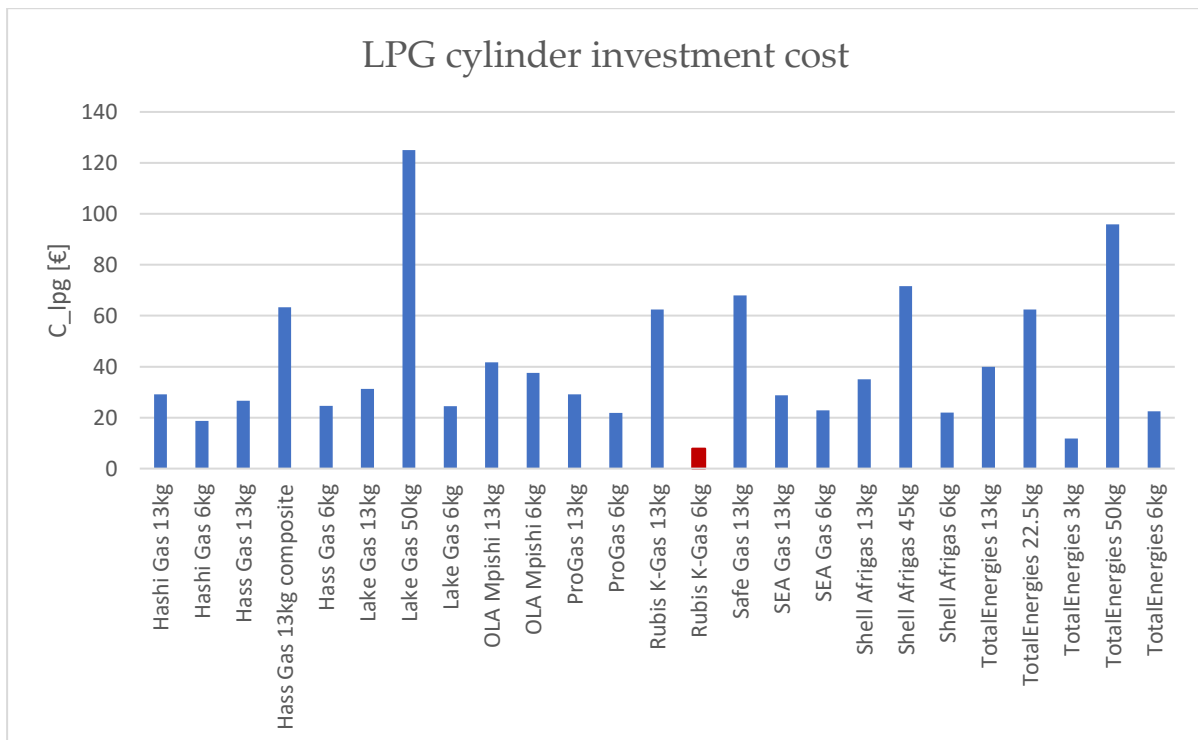
Figure 3.8: LPG cylinder investment costs in Kenya Market [12]

---

[12] References for these values are reported in Appendix B

- The second pro is related to size. In that the nearest buying station is 4 km away from the community and a small to medium cylinder size makes it easy to transport even by more affordable means of transport (Boda-boda)[13].

Figure 3.9: Rubis K-Gas 6 kg

Table 3.1 shows the parameters with attached unit of measurement, value and bibliographic reference.

Table 3.1: Rubis K-Gas parameters

	description	value	UoM	ref
m_{lpg}	Gas mass of a single cylinder.	6	kg	[30]
LHV_{lpg}	Lower Heating Value of LPG.	45.5	MJ/kg	[31]
η_{lpg}	Thermal yield gas combustion.	0.6	$-$	[32]
P_{lpg}	Power released by the cylinder.	6	kW	[32]
C_{lpg}	Investment cost new cylinder.	7.83	€	[30]
c_{lpg}	Gas specific cost.	2.16	€$/kg$	[30]
e_{lpg}	Gas emission factor.	2.871	$kgCO_2/kg$	[34]
t_{change}	Time necessary to change one cylinder.	150	min	14
t_{refill}	Time necessary to refill one cylinder.	170	min	

3.3.2. Improved Cooking Stoves technology selection

In order to select an appropriate ICS device, it is necessary to conduct a small market analysis of the various state-of-the-art models.

Below is a table describing the various technologies available, highlighting the thermal efficiency of each and the retail cost in Kenya.

---

[13] Traditional name for motorbike taxis that transport passengers or objects for a fee.
[14] This value are reasonable estimations

Table 3.2: ICS Market prices[15]

	η_{ICS} [$-$]	C_{ICS} [€]	c_{ICS} [€/kg]
Mud Stoves	0.17	1.66	0
Metal Stoves	0.23	6.66	0
Clay Stoves	0.24	6.66	0
Rocket wood stoves	0.3	37.5	0
Improved Charcoal Stoves	0.32	39.16	1.15
Forced-draft stoves	0.45	60	0
Gasifiers	0.42	23.58	0.1076

It is evident that thermal efficiency and cost are linearly correlated as can be seen in Figure 3.10.
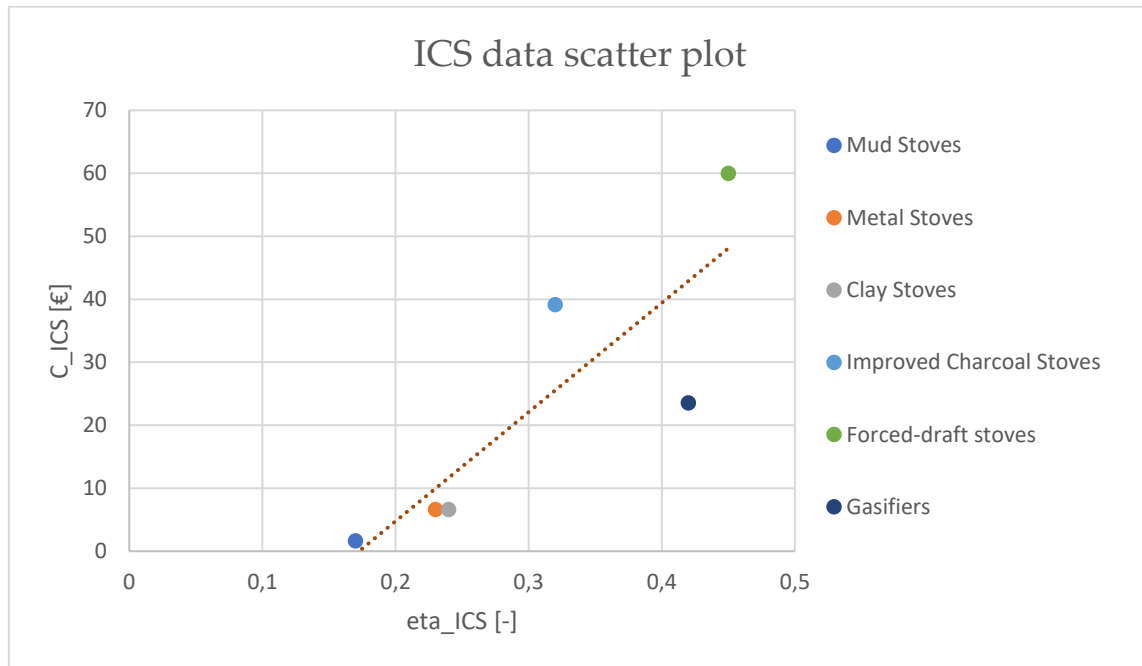
Figure 3.10: ICS techno-economic data scatter plot

As the budget was limited, technology in the low-price range was chosen, specifically the Clay Stove.

This model has other advantages:

---

[15] for complete properties with references see Appendix A

- Firstly, being fueled by wood, a raw material available in the community's surroundings, the cost of fuel is zero (unlike gasifiers and stoves operating with charcoal).

- Secondly, this technology does not require sophisticated materials for production and with a vision to offering the possibility of replication in the future or repair in the event of failure, it permits a certain sustainability that other more complicated technologies cannot offer.

Figure 3.11: Nanyuki new market local retailer selling ICS. Taken by the Author.

However, being a compromise choice, the disadvantages compared to the other options are reported:

- First and foremost, the use of wood, although with improved thermal efficiency, is accompanied by the externalities of traditional technology, in fact the emission factor is higher than for stoves using an alternative fuel (see Figure 3.12)
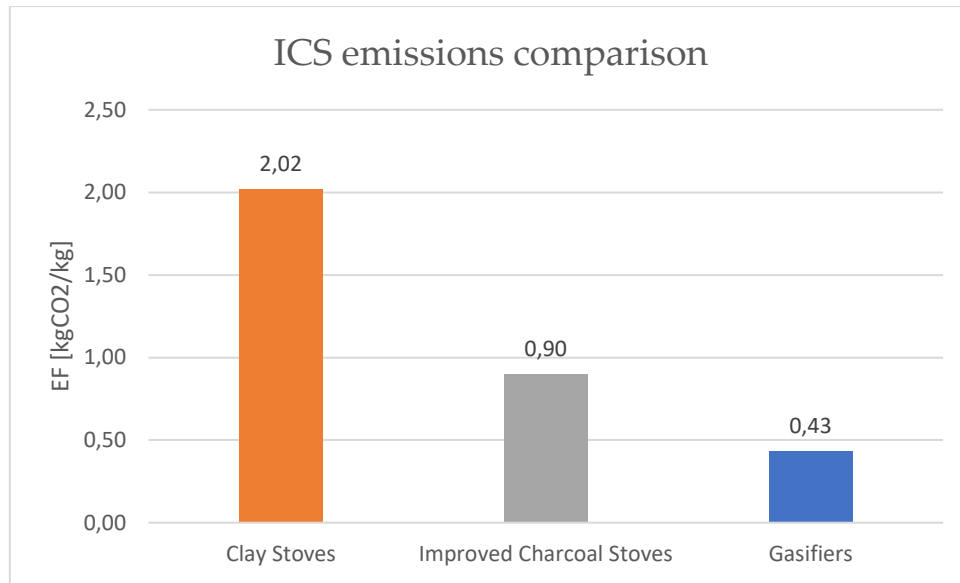
Figure 3.12: ICS emission factor comparison per device

- Furthermore, this technology is more susceptible to failure phenomena, being clay mechanically more fragile compared to metal.

The values of the parameters of interest are shown in Table 3.3 as in the previous paragraph.

Table 3.3: Clay stove parameters

	Description	value	UoM	ref
η_{ICS}	Thermal yield ICS fuel combustion.	0.24	$-$	[33]
P_{ICS}	Power released by the ICS.	2	kW	[33]
C_{ICS}	Investment cost new ICS.	6.66	€	[34]
c_{ICS}	ICS fuel specific cost.	0	€$/kg$	
e_{ICS}	Fuel emission factor.	2.016	$kgCO_2/kg$	[35]
$t_{ignition}$	Time necessary to ignite the fire.	20	min	16
$t_{collect}$	Time necessary to collect 1 kg of fuel.	30	min/kg	

---

[16] Data collected with interviews (see Appendix A)

3.3.3. Biogas technology selection

The definition of parameters for Biogas technology proves to be more complex as there are two degrees of freedom in this case:

The raw biomass that will feed our biodigester from which will derive some specific chemical and physical parameters for biogas production and the type of biodigester that best fits the installation context.

In the first case, the choice is quite unambiguous, as one of the leverage points of the BeOGas project is to eradicate the invasive plant Opuntia Stricta for the reasons already listed in the last paragraph of Chapter 2.

The table with the values for the problem parameters is then given, as usually accompanied the unit of measurement and the corresponding bibliographical reference.

Table 3.4: Opuntia Stricta parameters

	Description	value	UoM	ref
MM_{bio}	Molecular weight Biogas.	25.75	$\dfrac{kg}{kmol}$	[36]
LHV_{bio}	Lower Heating Value Biogas.	31.03	$\dfrac{MJ}{kg}$	[36]
η_{bio}	Thermal efficiency Biogas combustion.	0.6	$-$	[32]
GY	Gas Yield per kg of biomass.	0.0578	$\dfrac{m^3}{kg}$	[36]
TS	Total Solids fraction of the biomass.	7.53	%	[36]
ρ_{sub}	Biomass mass density	975	$\dfrac{kg}{m^3}$	17
c_{bio}	Biomass specific cost.	0	$\dfrac{€}{kg}$	
e_{bio}	Biogas emission factor	0.5559	$\dfrac{kgCO_2}{kg}$	[36]
$t_{collect}$	Time necessary to collect 1 m³ of biomass.	45	min	
HRT	Hydraulic Retention Time[18]	17	day	[36]
OLR	Organic Loading Rate[19]	4	$\dfrac{kg}{m^3 day}$	[36]
C_{org}	Organic fraction of the substrate	0.06969	$\dfrac{kg_{ORG}}{kg_{sub}}$	[36]

[17] Derived from a raw experiment by the author
[18] Average time that a particle of the substrate spent inside the bio-digestor
[19] Organic flowing rate per cubic meter of digester

As can be observed from the chart in Figure 3.13, the Gas Yield is low compared to the average of other biomasses; this defect can be associated with the strong alkalinity of the considered biomass.
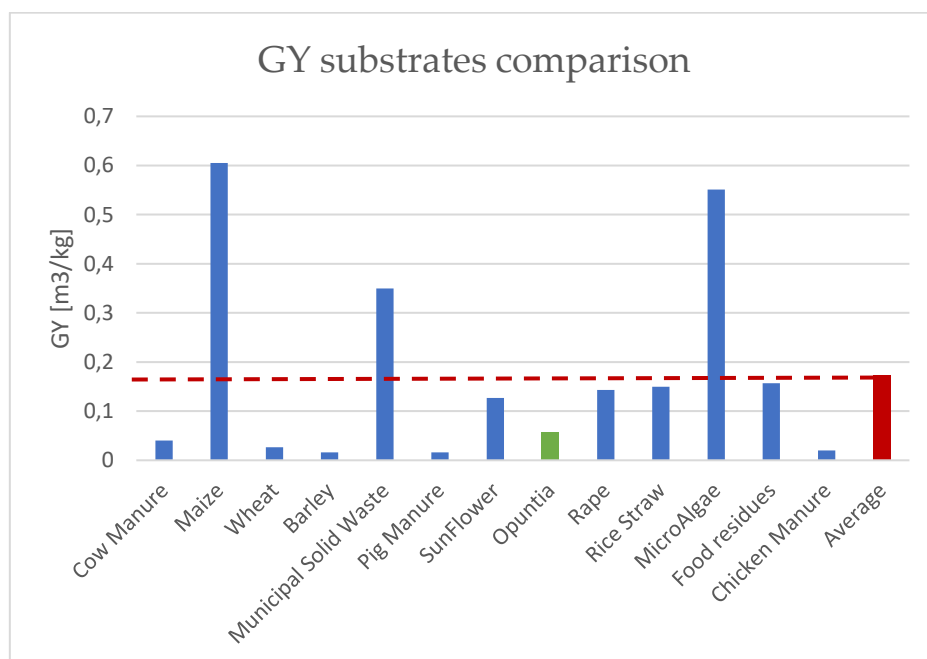
Figure 3.13: Comparison of GY for different inlet biomass

However, a study carried out in 2016 by some Mexican universities, reports that if cow manure is added to this substrate, biogas potential increases and find is optimal in the 60% Opuntia 40% Dairy cattle manure mix (see Figure 3.14) , this benefit is attributable to the acid compensation of the cow manure that stabilises the pH to an optimal value of 6.5.
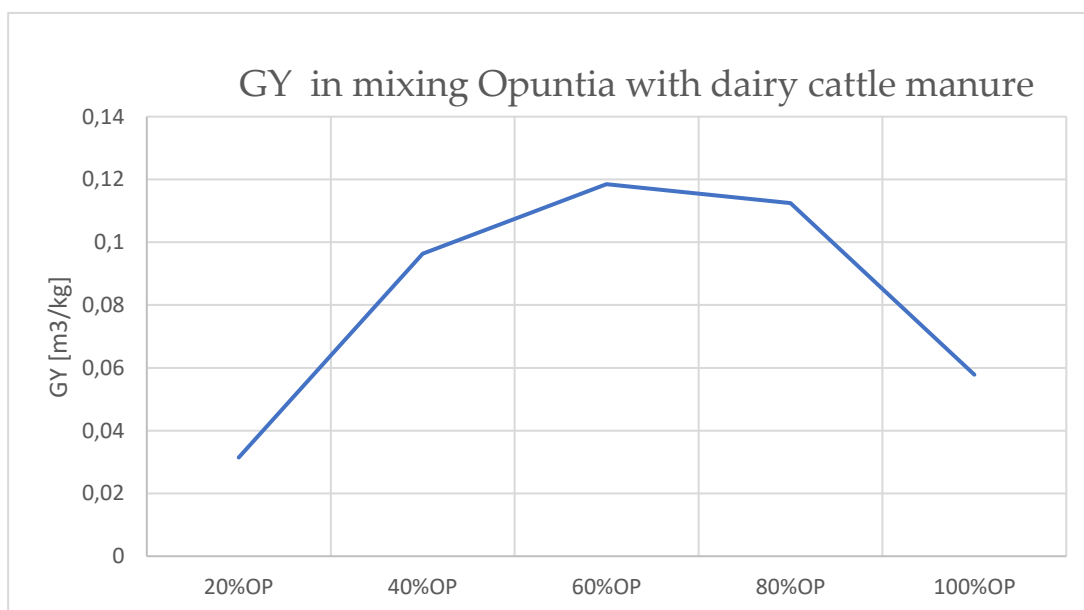
Figure 3.14: Opuntia and dairy cattle optimal mix

The choice of digester model did not prove to be as straight forward.

As a technology that has been widely adopted in the last decades, particularly in rural areas of India and China, the solutions that have been developed over the years have been consolidated, offering pros of different kinds.

To clarify the current situation of the biodigester offer a list follows with the various possibilities and differential technical-economic costs, advantages and disadvantages.

Floating Drum model

It features a variable volume gas storage chamber.
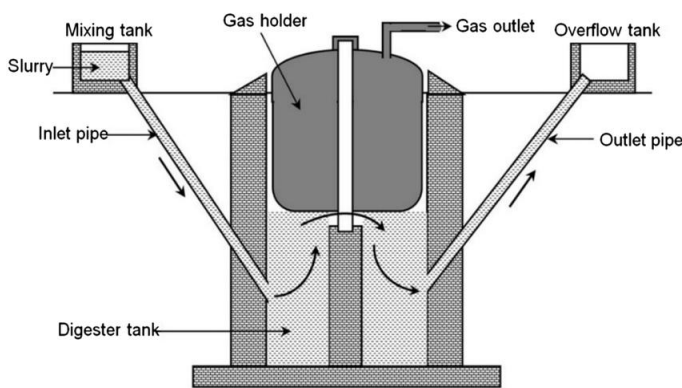
Figure 3.15 Floating Drum drawing

Table 3.5

parameter	UoM	value	reference
lifespan	$year$	10-15	[37]
Installation time	day	20	[37]
Yield	m^3_{gas}/m^3_{dig}	0.35-0.7	[37]
Price	$€/m^3$	250	[37]

Pros:

- Constant gas pressure at the end point of use.
- Quantity of stored gas clearly visible (drum height).

Cons:

- The best biomass to use is animal excrement.
- Specialised labour needed for the installation.
- Steel corrosion problems.
- High Drum expense.

Polyethylene Tubular model

It consists only of a polyethylene bag and two pipes, one inlet and one outlet.

The gas is extracted through a valve at the top of the bag.
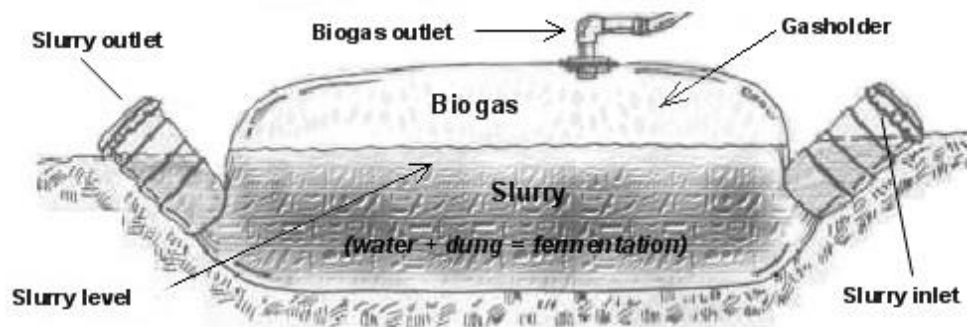
Figure 3.16: PVC tubular drawing

Table 3.6

parameter	UoM	value	reference
lifespan	$year$	2-5	[38]
Installation time	day	5-7	[38]
Yield	m^3_{gas}/m^3_{dig}	0.09-047	[38]
Price	$€/m^3$	100	[38]

Pros:

- Simple construction.
- Fast construction.
- Easily transportable.

Cons:

- Variable gas pressure
- Poor weather resistance.
- Difficult to clean.

Fixed Dome model

The gas is stored in the upper part of the digester and the increase in pressure pushes the digestate into the outlet chamber.

When the gas is extracted, a proportional amount of digestate flows back to the digestion chamber.
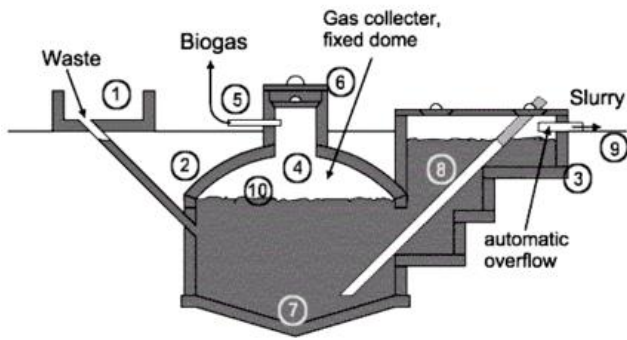
Figure 3.17: Fixed Dome drawing

Table 3.7

parameter	UoM	value	reference
lifespan	$year$	15-20	[37]
Installation time	day	20	[37]
Yield	m^3_{gas}/m^3_{dig}	0.35-0.7	[37]
Price	$€/m^3$	120	[37]

Pros:

- It can be built below ground level thus saving space, isolating and protecting the digester more easily.
- The technology has a low risk of failure.
- Low set-up costs.
- Simple maintenance.

Cons:

- The gas pressure depends on the volume of gas stored and the amount of digestate in the outlet chamber.
- Potential leaks in the mortar if not well constructed.

Having clarified the technological landscape, it was decided to adopt the fixed dome model, which offers a good technical-economic compromise between durability and costs.

In order to define the investment cost for the biodigester, as well as obtaining a crucial design parameter for BeOgas, it is essential to investigate the volume of the fermentation chamber to meet the energy demand of a household.

For this purpose, the data in the Table 3.4 are given and the digester volume is designed following the algorithm in Figure 3.18
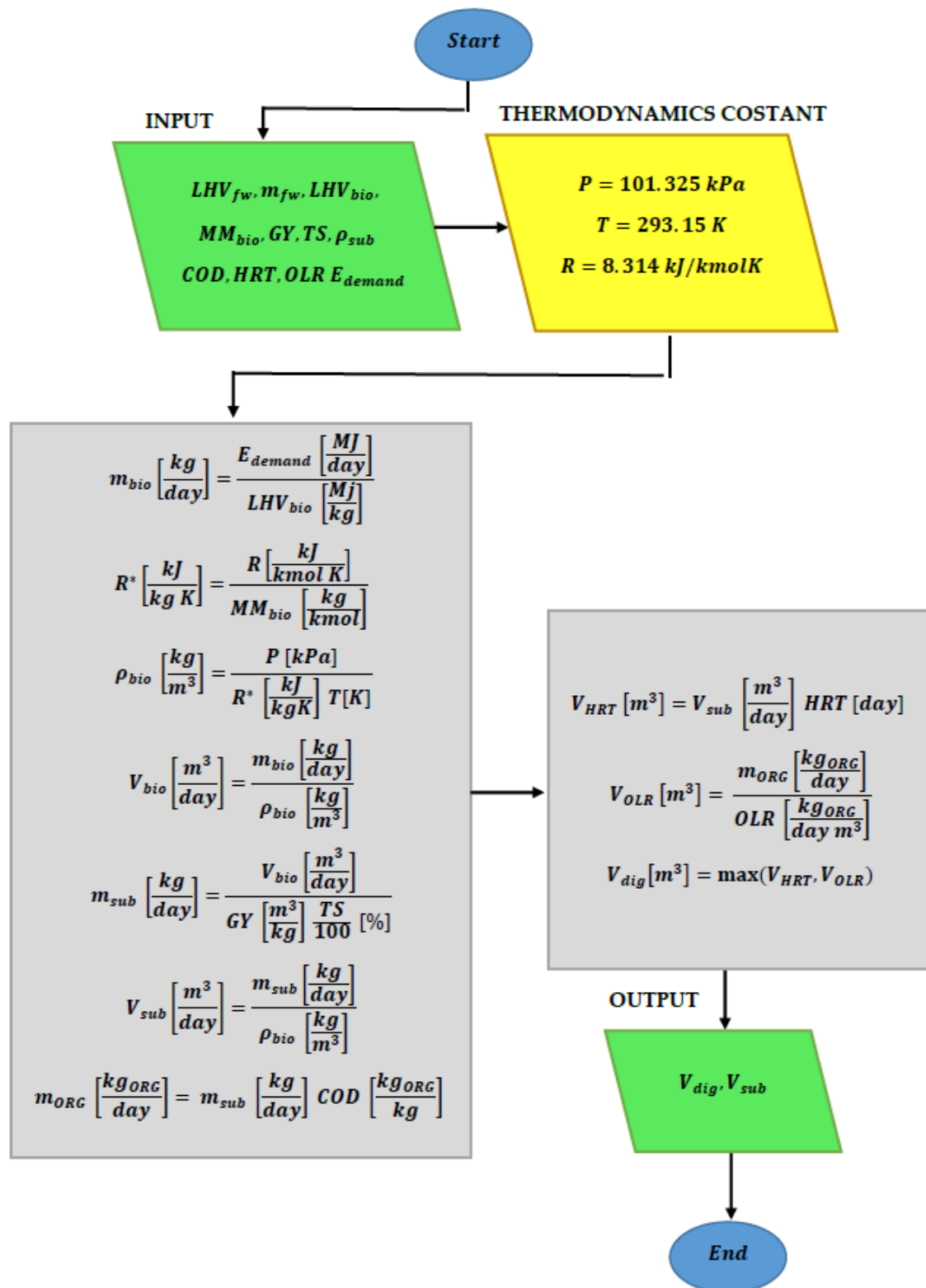
Figure 3.18: Digester volume computation algorithm

3.3.4. Coefficient analysis

In this paragraph we analyze the linear coefficients resulting from the previously obtained data.

The point of this operation is to imagine if and which tradeoffs will be in the optimization phase and if it is possible to simplify the expressions in order to improve the computational speed in solving the problem.

At first it is specified that the coefficients will be analyzed separately according to the objective function because a comparison with the coefficients of the other functions would not make mathematical sense since they are different units of measurement.

At this point, in Figure 3.19 the coefficients for the function $t(x_1, x_2, x_3)$ are reported.
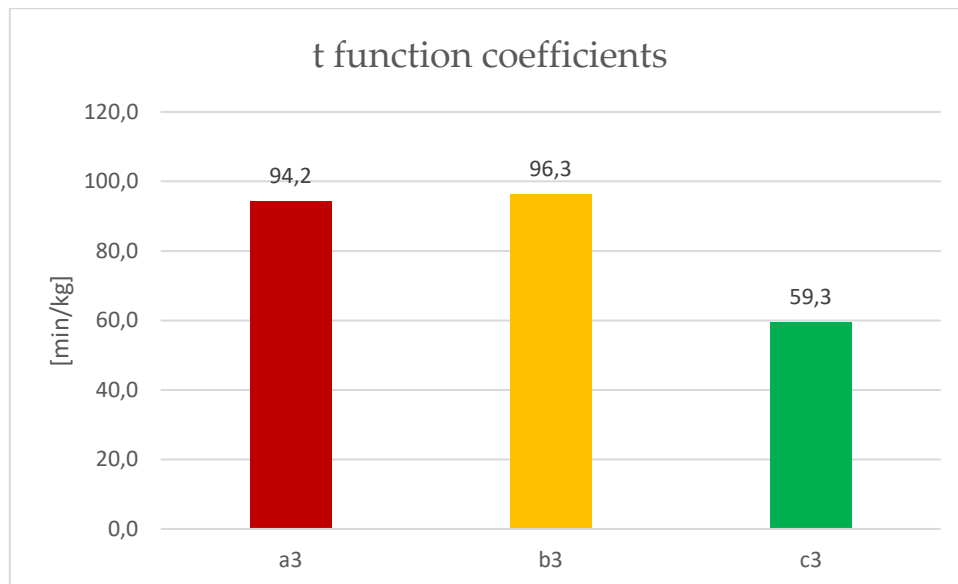
Figure 3.19

The factors are balanced in the various technologies and unsuspected the coefficient b_3, traceable to the time per unit of firewood fueled in ICS, is the highest.

On the other hand, the coefficient c_3 is the lowest: we expect that the only t function privilege the installation of biogas technology.

In an attempt to reduce the specific time for LPG technology, in particular the timing of cylinder supply, the size is increased from 6 to 13 kg.

Nevertheless the coefficient decreases only by 6%. this improvement does not justify the change of input.
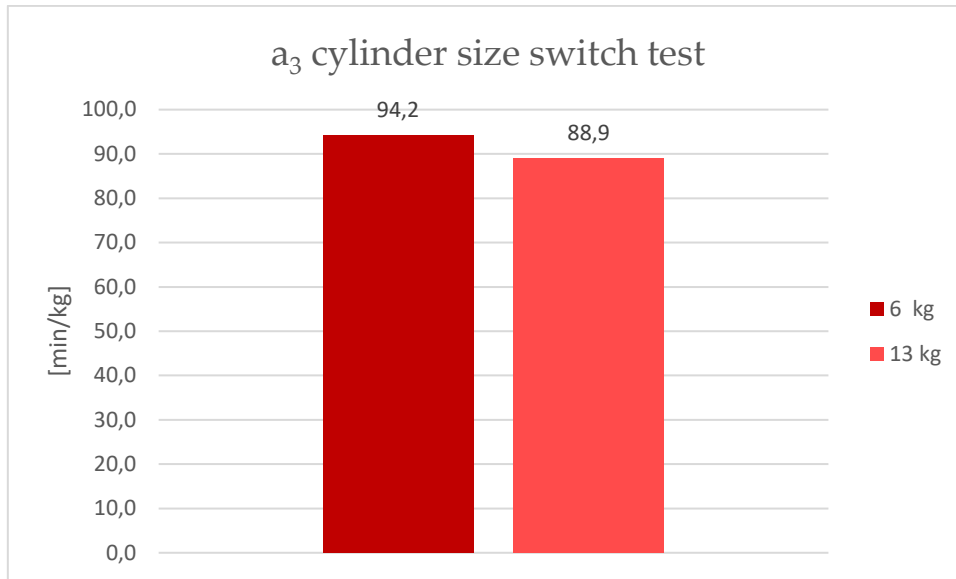
Figure 3.20

Proceeding with the coefficients of the function $C_{tot}(x_1, x_2, x_3)$, Figure 3.21, the ICS turn out to be the most advantageous economically and once again the cylinders remain at the last choice of the algorithm.
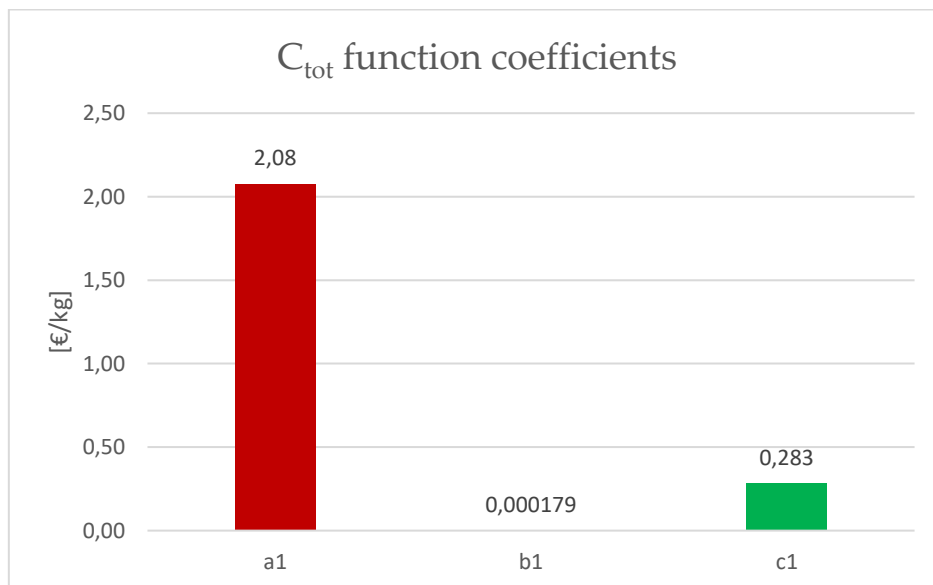
Figure 3.21

In Figure 3.22 are plotted the coefficients of the function $CO_2^e(x_1, x_2, x_3)$ mathematically equal to the emission factors of the various fuels.
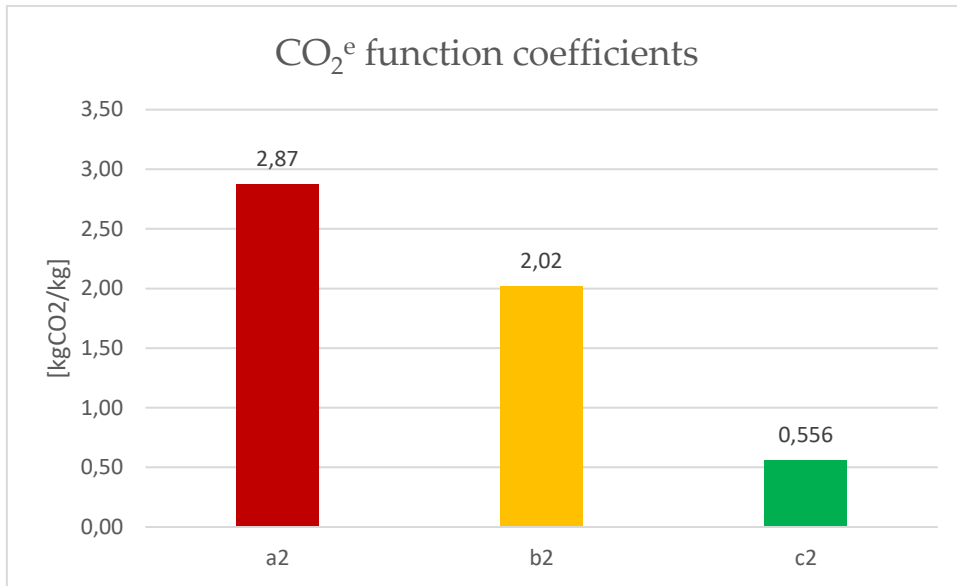
Figure 3.22

Since a fuel like LPG emits more CO_2 per kg than a kg of firewood, but with the same mass the modern gas guarantees a greater amount of energy.

We have obtained the same coefficients but correct in $\frac{kgCO_2}{MJ}$.

$$\left[\frac{kgCO_2}{MJ}\right] = \frac{\left[\frac{kgCO_2}{kg}\right]}{\left[\frac{MJ}{kg}\right]}$$
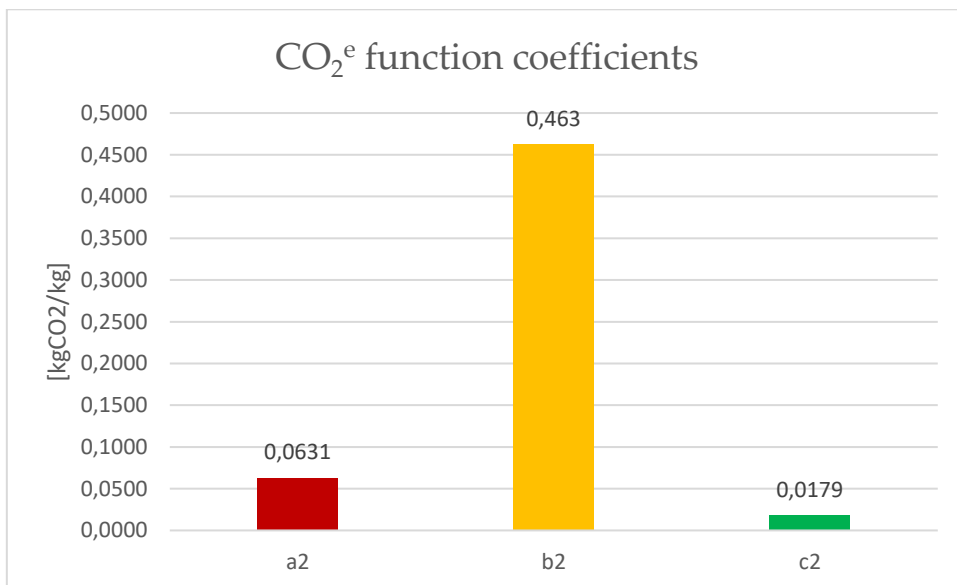
Figure 3.23

Once again biogas dominates the function despite LPG being a viable alternative.

In order to carry out a further critical analysis step, the linear coefficients have been broken down into the various components constituting them. i.e., the addends of the sums Eq. (3.13) and Eq. (3.25).

If the components of operating and investment costs are compared in parallel, it becomes clear how the specific cost of fuel influences factors.

Table 3.8: cost allocation

	UoM	a_1	b_1	c_1
O&M costs	$\frac{€}{kg}$	2,08	0	0
Investment	$\frac{€}{kg}$	0,000238	0,000179	0,283

Downstream of this consideration, the choice to buy ICS designed to operate with traditional wood remains successful (paragraph 3.3.1)

Moving the attention to the time function you can find in the figure the breakup of the three coefficients a_3, b_3, c_3.
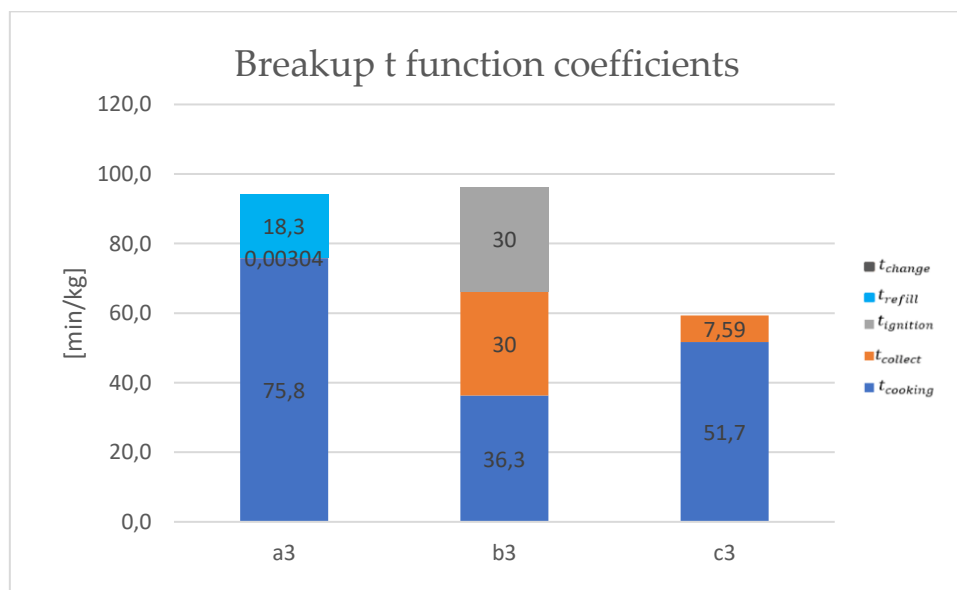
Figure 3.24

It is clear that the specific time to change the cylinders totally is marginal compared to the other contributions: in the resolution phase we neglect it.

Note that although the cost function also has elements with orders of magnitude lower than the specific cost for LPG it was preferred to keep all the factors unchanged to keep a quotation of the costs to be incurred for the project as accurate as possible.

3.4.   Energy demand shaping

Going in order, to obtain the first fundamental input to model the system is required an additional study that explores the customs and eating habits of the Maasai community of Twala.

To do this, the only tool available are interviews and sharing mealtimes with some sample families. In particular, the interviews aim to determine the size of the households (HH), the times, the duration of the meals and the dishes that are cooked more frequently, while the meals together serve to measure the cooking time of the main dishes of the Maasai tradition.

All these raw data can be traced to the end of the thesis in Appendices B and C.

In Figure 3.25 we report the number of people per family distributed in a histogram that allows us to define three class of family nuclei (in Table 3.9) those Small with 15 HH, those Medium with 7 HH and the Big ones with 8 HH.
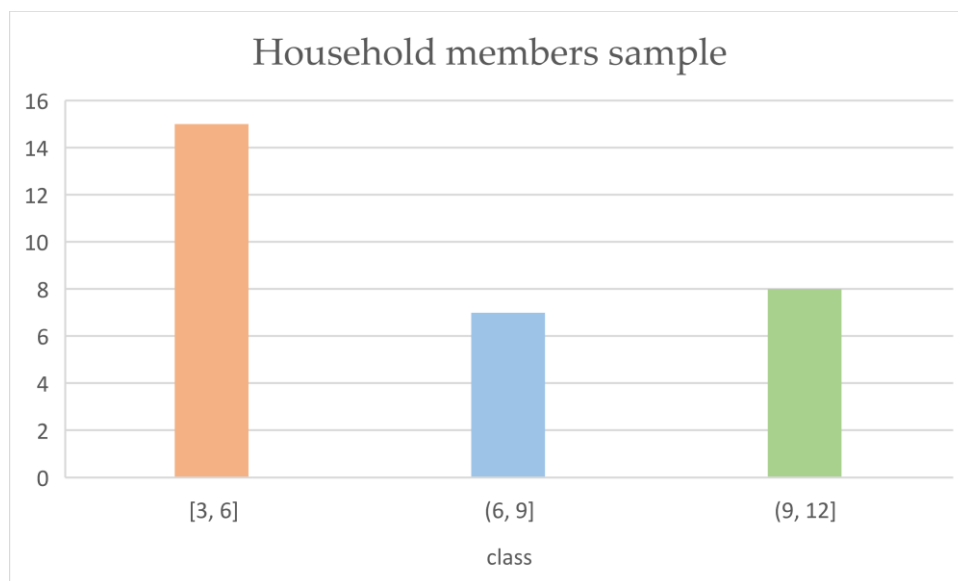
Figure 3.25: Histogram distribution of Household by number of members

Table 3.9: HH distribution estimation

class	range	n° of HH	share [%]	n° of HH (estimation)
Small HH	[3, 6]	15	50	105
Medium HH	[6, 9]	7	23	49
Big HH	(9, 12]	8	27	56
TOT		30	100	210

Note that the real size of only 30 households is reported and will be the statistical sample of the study.

In addition, Table 3.9 gives an estimate of the total number of households per class assessed by making a simple proportion between the sample households and the total number of households in the community.

Once this has been established, the average length of the three main meals (breakfast, lunch and dinner) is evaluate, and a statistic calculation in the Eq. (3.27) takes into account the uncertainty of the percentage of the duration of meals for the three categories of families previously considered.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \qquad (3.27)$$

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad (3.28)$$

Statistical results are transcribed in Table 3.10

Table 3.10

class	$\bar{x}_{breakfast}$ [min]	$\bar{x}_{lunch}$ [min]	$\bar{x}_{dinner}$ [min]	$\sigma_{breakfast}$ [min]	σ_{lunch} [min]	σ_{dinner} [min]
Small HH	36	56	57	11	6	11
Medium HH	35	54	55	6	7	6
Big HH	38	63	70	9	12	17

Always with the study of the results of the interviews a ranking of the most cooked dishes is created and the frequency of appearance can be traced to a probability by category of family to cook that particular dish.

The average cooking time obtained from on-site measurements is then attached to each dish. For the sake of transparency need to be say that the cooking time of some dishes has been estimated according to the times obtained by others.

Table 3.11: Dish frequency

class	dish	$f_{absolute}$	f [%]	rank	cooking time [min]
Big HH	milk	5	16,1	0	30
	sukuma	5	16,1	0	40
	mukimu	5	16,1	0	60
	chapati	5	16,1	0	30
	ugali	4	12,9	1	60
	matoke	4	12,9	1	60
	porridge	2	6,5	2	45
	ghideri	1	3,2	2	60
Medium HH	ugali	5	18,5	0	60
	milk	5	18,5	0	30
	porridge	4	14,8	1	45
	sukuma	3	11,1	1	40
	mukimu	3	11,1	1	60
	chapati	3	11,1	1	30
	ghideri	3	11,1	1	60
	matoke	1	3,7	2	60
Small HH	milk	11	20,8	0	30
	mukimu	10	18,9	0	60
	sukuma	9	17,0	0	40
	ugali	7	13,2	1	60
	chapati	7	13,2	1	30
	matoke	5	9,4	2	60
	ghideri	2	3,8	2	60
	porridge	2	3,8	2	45

It remains only to trace the average power received by the pot during cooking.

Since no thermocouples or transducers were available for direct measurement, an indirect estimate was made.

In fact, note the amount of wood used in the kitchen m_{fw} its calorific value LHV_{fw} an average yield of traditional cuisine η_{fw} and a time dedicated to cook the food you can find the average power delivered by the flames to the surface of the kitchen bowl.

In Eq. (3.29) and in Eq. (3.30) the starting equation is reported and the same reversed to obtain a semi reliable power value.

$$P\, t_{cook}\, 60 = LHV_{fw}\, m_{fw}\, \eta_{fw}\, 1000 \tag{3.29}$$

$$P\,[kW] = \frac{LHV_{fw}\left[\frac{MJ}{kg}\right]\, m_{fw}\,[kg]\, \eta_{fw}\,[-]\, 1000\left[\frac{kJ}{MJ}\right]}{t_{cook}\,[min]\, 60\left[\frac{s}{min}\right]} \cong 1400\, W \tag{3.30}$$

To complete the set of inputs to be set on RAMP, it remains only to assign a certain range of variability of the fire power (0.2) and a ignition time of about 30 minutes.

The recap of inputs can be find in Appendix D.

It reports the simulation of 365 profiles corresponding to the days in a year.

Note that the dark blue line represents the average of the load demand in one typical day of the year.
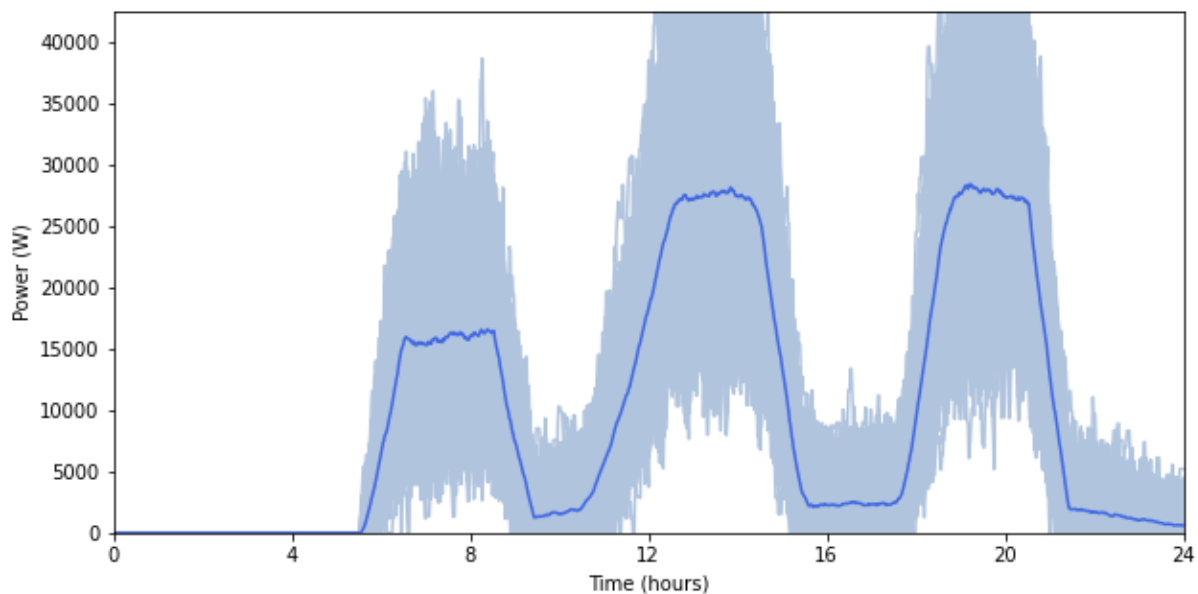
Figure 3.26: RAMP simulation

In the last step to extrapolate the annual energy demand it is necessary to sum the daily contributions multiplied by 60 and divided by 10^6

$$E_{demand} = \sum_{i=1}^{525600} P_i \, [W] \; 60 \left[\frac{s}{min}\right] \frac{1}{10^6} \left[\frac{MW}{W}\right] = 296490 \; MJ \tag{3.31}$$

3.5. Boundary constraints

The purpose of this paragraph is to find the boundary conditions to be subjected to the problem of linear programming justifying them with design choices or physical constraints.

In other words, we will explain those inequalities that will define the domain in which the simplex method will find the three variables x_1, x_2 and x_3 that will minimize the three objective functions C_{tot}, CO_2^e and t.

Non-negativity of independent variables.

Independent variables have been defined as the amount of fuel for each source. This implies that they assume a positive or zero value to be consistent with their physical meaning. The constraints c_1, c_2 and c_3 are defined such that:

$$c_1: \qquad\qquad\qquad\qquad x_1 \geq 0 \qquad\qquad\qquad\qquad \tag{3.32}$$

$$c_2: \qquad\qquad\qquad\qquad x_2 \geq 0 \qquad\qquad\qquad\qquad \tag{3.33}$$

$$c_3: \qquad\qquad\qquad\qquad x_3 \geq 0 \qquad\qquad\qquad\qquad \tag{3.34}$$

Maximum number of improved stoves

As the Twala community consists of 210 families, it is trivial that the number of ICS purchased should not exceed this value.

$$n_{lpg} \leq 210 \tag{3.35}$$

For mathematical consistency it is replaced with the Eq. (3.6) and the constraint c_4 is obtained:

$$c_4 : \qquad\qquad x_1 \le 210 \; m_{lpg} \; 365 \; life \qquad\qquad (3.36)$$

Limits on biogas installation

Biogas technology also has upper and lower limits that correspond to project constraints.

The maximum total volume of biodigesters to be installed is 10 m³ per household.

This is a reasonable maximum value in order to avoid an excessive feeding burden for biodigesters and an aggressive occupation of the community soil.

Remembering the Eq. (3.8a) then defines the constraint c_5

$$c_5 : \qquad\qquad x_3 \le \frac{10 \; \cdot \; 210 \; \cdot \; 365 \; \cdot \; life \; \cdot \; max_{gas}}{V_{dig}} \qquad\qquad (3.37)$$

On the other hand, a minimum of 10 pilot biodigesters are needed to meet the specific objective of the project to introduce biogas technology in Twala and contribute to the disinfestation of Opuntia.

Considering a volume of biodigester equal to 10 m3, we obtain the constraint c6 defined in a manner completely similar to the previous

$$c_6 : \qquad\qquad x_3 \ge \frac{10 \; \cdot \; 10 \; \cdot \; 365 \; \cdot \; life \; \cdot \; max_{gas}}{V_{dig}} \qquad\qquad (3.37)$$

Constraints of objective functions maximum

It is possible to find a reasonable maximum for the 3 objective functions. For the setting of the problem the objectives function tend to the minimum, therefore they do not need a lower limit.

A cost ceiling equal to the project budget is defined: 100.000 €

$$C_{tot} = a_1 x_1 + b_1 x_2 + c_1 \; x_3$$

$$c_7 : \qquad\qquad a_1 x_1 + b_1 x_2 + c_1 \; x_3 \le 100.000 \qquad\qquad (3.38)$$

As for total emissions, a specific objective that has been imposed in the drafting of the project is to reduce the greenhouse gas emissions by half compared to the baseline.

In the first step the total emissions in baseline are calculated.

Note therefore the energy demand is estimated the amount of wood burned dividing it by an average calorific value and the thermal efficiency of the 3-stones system.

$$m_{fw}^{TOT} = \frac{E_{demand}}{LHV_{fw}\, \eta_{fw}} = 137\ Mg \tag{3.39}$$

Then multiply the mass by the emission factor of the firewood obtaining the emissions of CO₂ ante- project: it only remains to divide it in half to obtain the desiderata post-project:

$$CO_2^{MAX} = m_{fw}^{TOT}\, e_{fw} = 137.294\ kgCO_2 \tag{3.40}$$

At this point, note the function CO_2^e is possible to fix the constraint c_8

$$c_8: \qquad a_2 x_1 + b_2 x_2 + c_2\, x_3 \leq 68.647 \tag{3.41}$$

A condition is also specified for the time t function equal to two-thirds of the time spent daily for the kitchen task before the intervention, data assessed by the project manager.

The c_9 constraint will then be:

$$c_9: \qquad a_2 x_1 + b_2 x_2 + c_2\, x_3 \leq \frac{2}{3}\, 8\,[h] \cdot 60\, \left[\frac{min}{h}\right] = 320 \tag{3.42}$$

Satisfaction of energy demand

The last disparity that is specified is the project constraint to meet the energy demand of the Twala community.

Taking Figure 3.1 applying the first law of thermodynamics you get:

$$E_{lpg} + E_{ICS} + E_{bio} - E_{demand} = 0 \tag{3.43}$$

Drawing attention to the formulas for evaluating the three incoming flows, seen at the beginning of this chapter we obtain:

$$x_1 \, LHV_{lpg} \, \eta_{lpg} + x_2 \, LHV_{fw} \, \eta_{ICS} + x_3 LHV_{bio}\eta_{bio} - E_{demand} = 0 \qquad (3.44)$$

c_{10} is characterized:

$$c_{10}: \qquad x_1 \, LHV_{lpg} \, \eta_{lpg} + x_2 \, LHV_{fw} \, \eta_{ICS} + x_3 LHV_{bio}\eta_{bio} \geq 296490 \qquad (3.45)$$

Which assumes this meaning:

The sum of the energy contributions for each source must at least equal the initial demand of the community.

The last constraint completely defined the optimization problem.

To give the reader a comprehensive view of the problem, the system with only unknown the independent variables and all boundary conditions that define the polyhedron for the simplex method.

$$
\begin{cases}
\min C_{TOT} = a_1 \, x_1 + b_1 \, x_2 + c_1 \, x_3 \\
\min CO_2^e = a_2 \, x_1 + b_2 \, x_2 + c_2 \, x_3 \\
\min t = a_3 \, x_1 + b_3 \, x_2 + c_3 \, x_3 \\
x_1 \geq 0 \\
x_2 \geq 0 \\
x_3 \geq 0 \\
x_1 \leq 210 \, m_{lpg} \, 365 \, life \\
x_3 \leq \dfrac{10 \cdot 210 \cdot 365 \cdot life \cdot max_{gas}}{V_{dig}} \\
x_3 \geq \dfrac{10 \cdot 10 \cdot 365 \cdot life \cdot max_{gas}}{V_{dig}} \\
a_1 x_1 + b_1 x_2 + c_1 \, x_3 \leq 100.000 \\
a_2 x_1 + b_2 x_2 + c_2 \, x_3 \leq 137.294 \\
a_2 x_1 + b_2 x_2 + c_2 \, x_3 \leq 320 \\
x_1 \, LHV_{lpg} \, \eta_{lpg} + x_2 \, LHV_{fw} \, \eta_{ICS} + x_3 LHV_{bio}\eta_{bio} \geq 296490
\end{cases}
\qquad (3.46)
$$

56

4 MakeCH4nge

The software stems from the will to extend the mathematical considerations made for the specific problem of Twala to a generic one.

Specifically, it answers to the need to find an optimal energy-mix solution in cooking transition interventions in developing countries.

In fact, when designing a project in the field of international cooperation, economic resources are limited by the available budget, and the project writer tends to rely on local suppliers who obviously try to channel the available cash flow to their own technology.

MakeCH4nge given the boundary conditions of maximum outlay, a limit related to the maximum allowable environmental emissions, and a maximum number of hours/day to devote to the "cooking" task sets the three minimum objectives already exposed in the previous chapter.

Since the software is target to project managers and professionals working in the field of cooperation, it was assumed that they are not keen on the language of computer programming.

Therefore, the system was featured with an intuitive graphic interface that filters the input information to communicate it to the hidden python code that performs the optimization in the background.

For the sake of transparency and in the spirit of open source, the software will be available on the GitHub platform at the link https://github.com/MatteoVegezzi/MakeCH4nge.git to allow free use and the contribution of possible improvements by future software developers.

4.1. Input parameters

The program receives three types of input from the user:

- Variables related to the size of the system.
- The parameters linked to the technologies to be used.
- The constraints to be imposed.

The purpose of the variables linked to the size of the system is to estimate the total annual energy demand of the target community through one of the methodologies chosen by the user:

In the first one asks as input the number of households benefiting from the project **HH**, the amount of wood on average used by a household $\boldsymbol{m_{fw}}$, the thermal efficiency of a traditional stove defined as $\boldsymbol{\eta_{fw}} = \frac{\dot{Q}_{in}}{\dot{Q}_{fuel}}$

The formula for obtaining the energy demand is therefore:

$$E_{demand} = m_{fw} \cdot LHV_{fw} \cdot \eta_{fw} \cdot HH \cdot 365 \tag{4.1}$$

The second involves the input of the heat load profile using a RAMP model.

"RAMP is a bottom-up stochastic model for the generation of high-resolution multi-energy profiles, conceived for application in contexts where only rough information about users' behaviour are obtainable. These may range from remote villages to whole countries." [39]

If one considers the power required by the community at the i-th minute to be P_i, the sum multiplied by the seconds in a minute gives the energy consumption in a year.

In this case, the formula to obtain the energy demand will be:

$$E_{demand} = \sum_{i=1}^{525.600} P_i \ [W] \ 60 \left[\frac{s}{min}\right] \frac{1}{10^6} \left[\frac{MJ}{J}\right] \tag{4.2}$$

Figure 4.1: Change – Firewood page allows the user to choose the typology of firewood that best fits the surroundings of the project place

Figure 4.2: Homepage where the E_{demand} is shaped according the alternatives methodologies

The inputs related to the technologies to be installed are necessary to obtain those multiplicative coefficients that will characterize the objectives functions.

In particular, for cylinders, depending on the brand and size selected by the user, there will be a price, a specific emission per kg of CO_2 fuel and a timespan for recharging the cylinder once it has been used up.

Table 3.1 lists the variables required to model lpg cylinders with their units of measurement.

Figure 4.3: Modify – LPG Page once the brand is selected, clicking the "Fill" button every field is automatic filled, but can be changed according to the user preferences

Similarly for Improved Cooking Stoves, we will have parameters for retail cost, CO_2 emission per kg of fuel (wood), fuel collection time and energy efficiency.

Figure 4.4: Modify – ICS Page

As far as the biogas system is concerned, since a draft sizing of the plant is required (which has been illustrated in section 3.4), in addition to the cost, emission and harvesting time parameters, technical parameters relating to the biomass to be used are also required, such as GY.

Figure 4.5: Modify - Biogas

Note that the values of the variables in the libraries have references taken from the scientific literature: please refer to Appendix B for the complete list and references.

The last variable entry asked of the user, to which an entire window is devoted, is that relating to absolute constraints.

It is possible to define upper and lower mix limits for the various technologies and maximum value of the target functions.

Checking the box on investment includes in the minimum total cost objective function the investment by optimizing the costs for the entire project cycle, conversely it does not include the investment by minimizing only the annual operating costs.

As will be discussed in more detail in the section on multi-objective linear programming, it is necessary to define an order of priority and an absolute weight for each of the three objective functions, to this aim, the last section of the window offers the user the possibility of defining these latter parameters.

A summary of the constraints and their technical significance is given in Table 4.1

Figure 4.6: Constraints page

Table 4.1: Constraints recap.

name	description	UoM
min_{lpg}, max_{l_l}	Set the minimum and the maximum number of LPG cylinders bought at project year 0	−
min_{ICS}, max_{I_l}	Set the minimum and the maximum number of ICS bought at project year 0	−
min_{bio}, max_{b_l}	Set the minimum and the maximum total volume of biodigesters installed at project year 0.	m^3
max_{COST}	Maximum investment cost (upper limit for objective function)	€
max_{CO2}	Maximum carbon dioxide allowed emission (upper limit for objective function)	$t/year$
max_h	Maximum hours per household permitted in the "cooking" task (upper limit for objective function)	h/day
$p1, p2, p3$	Objectives functions priority ranking.	−
$W1, W2, W3$	Relative weight of each objective function.	−

When the module is executed, the very first section is dedicated to the input of the variables seen in the previous paragraph.

Subsequently, depending on how the energy demand is acquired, Eq. (4.1) or Eq. (4.2) will be used alternatively if it is defined by a RAMP model or an estimate.

In any case, the algorithm goes on to calculate the coefficients for the objective functions.

In the case of not considering the investment, this is the mass-specific cost for the respective fuel.

If, on the other hand, investment is also included in the weights for the optimization function, the formula must be distinguished according to the technology considered.

After defining the factors for the three functions, the actual linear programming algorithm begins, which will give us as output the values of x_1, x_2 and x_3 that minimize the three functions.

At this point, a post-processing phase begins, which outputs the technical data useful to the user, which we will see in the next section.

In Figure 4.7 this algorithm is visualized with a flow-chart. The actual python code is attached in Appendix
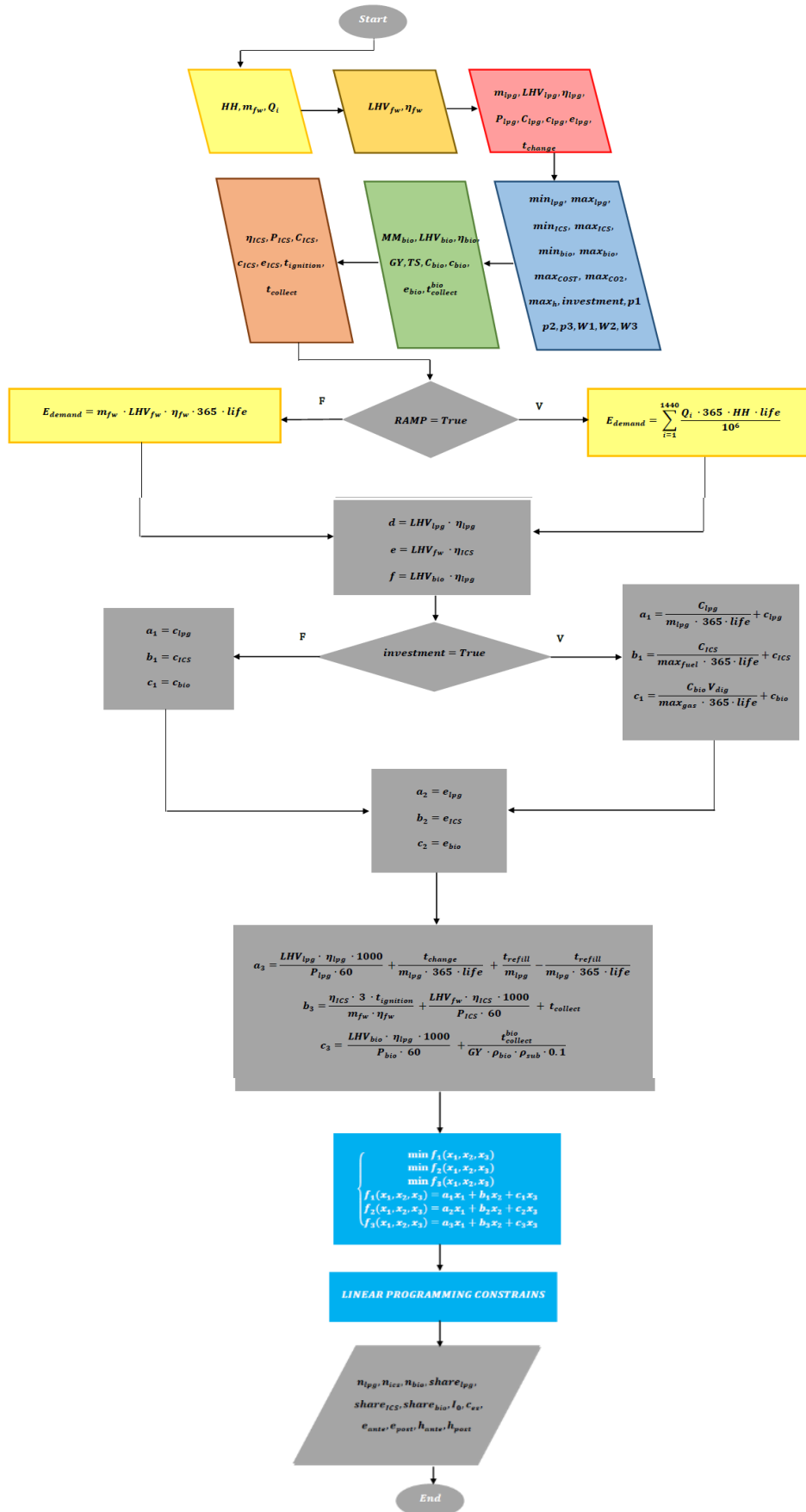
Figure 4.7: Optimizer flow chart

4.2. Output parameters

Again, in pursuit of the user-friendliness of the tool, it was decided to offer the user outputs with a certain graphic readability, as can be seen from the screenshot below.
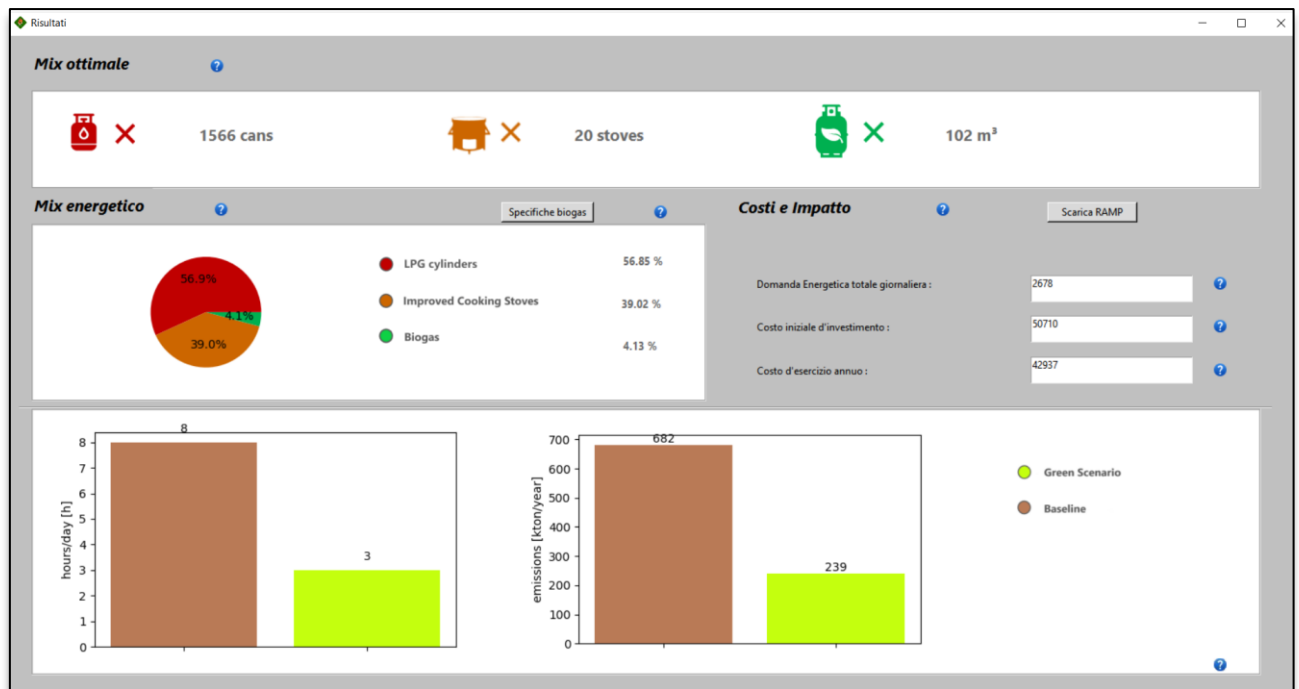
Figure 4.8: Results page

Below instead is the list of outputs, with a brief description, unit of measurement and formula to obtain them

Table 4.2: Output recap

name	description	UoM	formula
n_{lpg}	Number of gas cylinders that the project manager needs to purchase at year 0.	–	$\dfrac{x_1}{m_{lpg} \cdot life}$

n_{ICS}	Number of Improved Cooking Stoves that the project manager need to purchase at year 0.	−	$\dfrac{x_2}{max_{fuel} \cdot 365 \cdot life}$
n_{bio}	Number of m³ of bio-digesters that the project manager needs to install at year 0.	m^3	$\dfrac{x_3 \cdot V_{dig}}{max_{gas} \cdot 365 \cdot life}$
$share_{lpg}$	Share of energy from LPG source in the fulfilled Energy demand.	%	$\dfrac{E_{lpg}}{E_{demand}} \cdot 100$
$share_{ICS}$	Share of energy from ICS in the fulfilled Energy demand.	%	$\dfrac{E_{ICS}}{E_{demand}} \cdot 100$
$share_{bio}$	Share of energy from biogas source in the fulfilled Energy demand.	%	$\dfrac{E_{bio}}{E_{demand}} \cdot 100$
E_{demand}	Daily energy demand of the community.	MJ	$\dfrac{E_{demand}}{life \cdot 365}$
I_0	Project initial expense.	€	$C_{lpg} \cdot n_{lpg} + C_{ICS} \cdot n_{ICS} + C_{bio} \cdot n_{bio}$
c_{es}	Annual expense to sustain the project for 15 years	€/year	$\dfrac{(c_{lpg} \cdot x_1 + c_{ICS} \cdot x_2 + c_{bio} \cdot x_3)\, CRF}{life}$
e_{ante}	Tons of carbon dioxide emitted in the baseline scenario.	$MgCO_2$ /year	$\dfrac{m_{fw} \cdot HH \cdot 365 \cdot e_{fw}}{1000}$

e_{post}	Tons of carbon dioxide emitted in the new green scenario.	$MgCO_2$ /year	$\dfrac{x_1 \cdot a_2 + x_2 \cdot b_2 + x_3 \cdot c_2}{1000 \cdot life}$
h_{ante}	Hours per day per household dedicated to the cooking and fuel harvesting tasks in the baseline scenario.	h/day	$m_{fw} \cdot t_{fw}$
h_{post}	Hours per day per household dedicated to the cooking and fuel harvesting tasks in the new green scenario.	h/day	$\dfrac{x_1 \cdot a_3 + x_2 \cdot b_3 + x_3 \cdot c_3}{365 \cdot HH \cdot 60 \cdot life}$

- n_{lpg} is obtained by dividing the quantity of gas contained in a can by the number of years of design life.

- n_{ICS} on the other hand, is derived from dividing the total quantity by the maximum amount of fuel that can be exploited by a household by the number of years of life for the number of days in a year.

- Similarly, n_{bio} is derived by dividing the quantity of biogas by the same quantities, but multiplying the result by the volume of a biodigester

- To obtain $share_{lpg}, share_{ICS}, share_{bio}$ it is necessary to divide the portion of demand met by LPG, ICS and biogas by the total demand. This value is then multiplied by one hundred to obtain a percentage.

- The investment I_0 is given by the sum of $n_{lpg}, n_{ICS}, n_{bio}$ multiplied by $C_{lpg}, C_{ICS}, C_{bio}$ respectively.

- To obtain c_{es}, the specific costs are multiplied by the quantities x_1, x_2, x_3 and by dividing the whole sum by $life$

- e_{ante} is obtained by multiplying the average daily quantity of wood the number of households and the number of days by the emission factor dividing the whole by 1000 since the unit of measurement of output is ton.

- $e_{post}$is nothing but function 2 with the independent variables replaced divided by the number of years times 1000.

- h_{ante} is obtained by multiplying m_{fw} by the average time spent collecting firewood.

- h_{post} on the other hand is $f2$ with the independent variables substituted divided 365 by HH by 60 as the output is in hours per day.

4.3. Software

4.3.1. Python

The language chosen to code the algorithm just described is Python.

Python is a 'high-level', object-oriented programming language, suitable, among other uses, for developing distributed applications, scripting, numerical computation, and system testing.

The name was chosen because of the passion of the inventor, Guido Van Rossum, for Monty Python and their television series Monty Python's Flying Circus[40].

Figure 4.9: Python logo

The decision to adopt this performer is due to some positive characteristics of Python such as:

- The dynamism.
- The simplicity.
- The flexibility.
- the availability of a large number of free libraries.

- the ease with which the language allows modular software to be written.

According to TIOBE, [41] which is now a standard for this type of comparison/classification, Python is the Language of 2021.

For the sake of transparency, it is reported that Python has a number of weaknesses, including the speed of execution, especially in mathematical calculations.

4.3.2. Gurobi

Rather than rewriting the entire Simplex algorithm, it was decided to use a Python extension that could streamline the entire program.

For this purpose, version 3.4 of Gurobi Optimizer was imported.

Gurobi is a solver for mathematical optimisation problems, which with its algorithms for solving linear programming problems (but also Mixed-integer, Quadratic etc.) has contributed to the search for the optimal mix solution. [42]

Figure 4.10: GUROBI logo

4.3.3. Page GUI builder

As mentioned in the first two paragraphs of this chapter, to achieve better use of the program even by less experienced users, a Graphical User Interface (GUI) was designed in parallel.

Which in computer science is a type of user interface that allows man-machine interaction in a visual manner using graphic representations (e.g. widgets) rather than using the typical commands of a command-line interface.
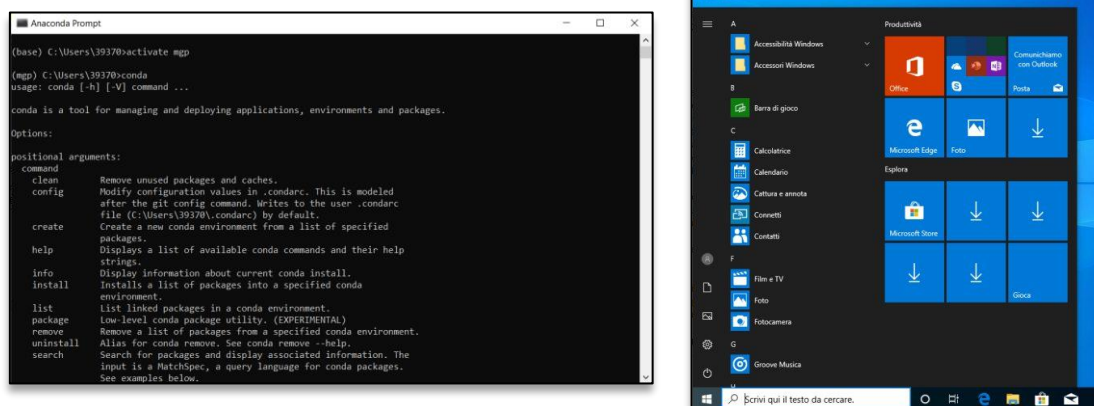
Figure 4.11: command-line vs GUI interface

In order to avoid writing thousands of lines of code by hand, a builder was used to set the graphical appearance of the entire software.

Figure 4.12: PAGE GUI logo

For this purpose, it was decided to use PAGE - Python Automatic GUI Generator - Version 7.4. [43]

PAGE is a cross-platform drag-and-drop GUI generator. It allows you to easily create GUI windows in Python containing a selection of Tkinter [20] widgets. PAGE is written in Tool Command Language [21] (TCL) 8.6, integrated with tkinter. PAGE is born from Virtual Tcl, bifurcated to generate Python modules that realize the desired GUI.

---

[20] Tkinter is a Python module that allows you to build windows and user interface widgets.

[21] TCL (acronym for Tool command language) is a scripting language generally considered easy to learn, but at the same time powerful. It is commonly used to quickly prototype, and test interpreted applications, even with a graphical interface.
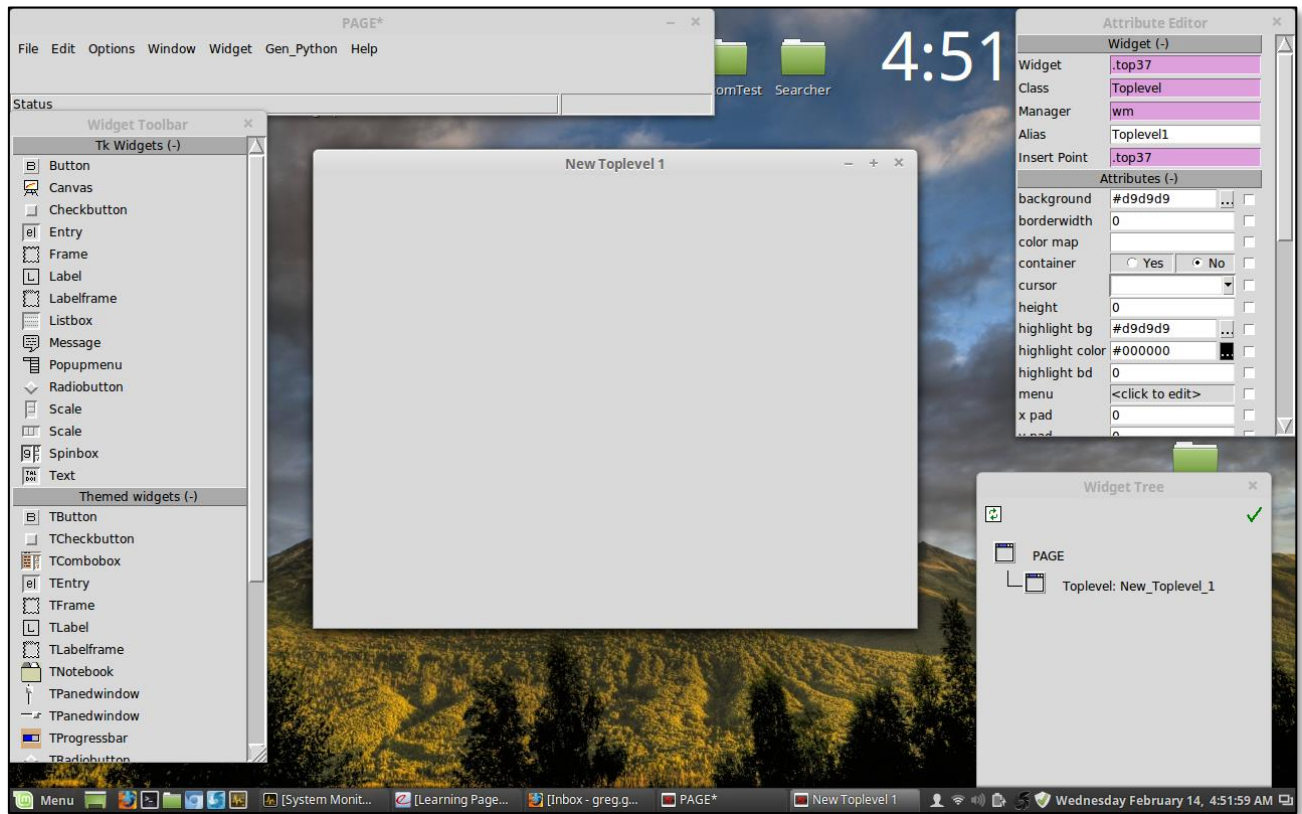
Figure 4.13: PAGE interface

The main widgets that can be implemented from the tkinter library are:

- **Toplevel**

  Toplevel function as windows managed directly by the window manager.

- **Button**

  These buttons can display text or images indicating their purpose. In addition to executing commands such as starting a sub-routine or opening a link to a new Toplevel.

- **Canva**

  The canvas is a rectangular area intended for drawing images or other complex layouts. Graphics, text, widgets or frames can be placed on a canvas.

- **Checkbutton**

  The Checkbutton widget is used to display a series of options to the user in the form of toggle buttons. The user can then select one or more options by clicking on the button corresponding to each option.

- **Entry**

The Entry widget is used to accept one-line text strings from the user.

- **Frame**

  The Frame widget is very important for the process of grouping and organising other widgets in a simple way. It functions as a container, responsible for organising the position of other widgets.

- **Label**

  This widget implements a display box in which text or images can be inserted. The text displayed by this widget can be updated at any time.

- **Combobox**

  A combobox widget allows a value to be selected from a set of values.

- **Message**

  This widget provides a multi-line, non-editable object that displays text, automatically interrupting lines and justifying the content

5   Results analysis and conclusion

5.1.   Optimal solution

As first run you have set the values in chapter 3 leaving the objectives in the following order:

1) Total cost.

2) Environmental impact.

3) Social Impact.

Note that the weights of the functions are equal to allow the software to carry out a search as free as possible.

In Figure we report the results of the first iteration
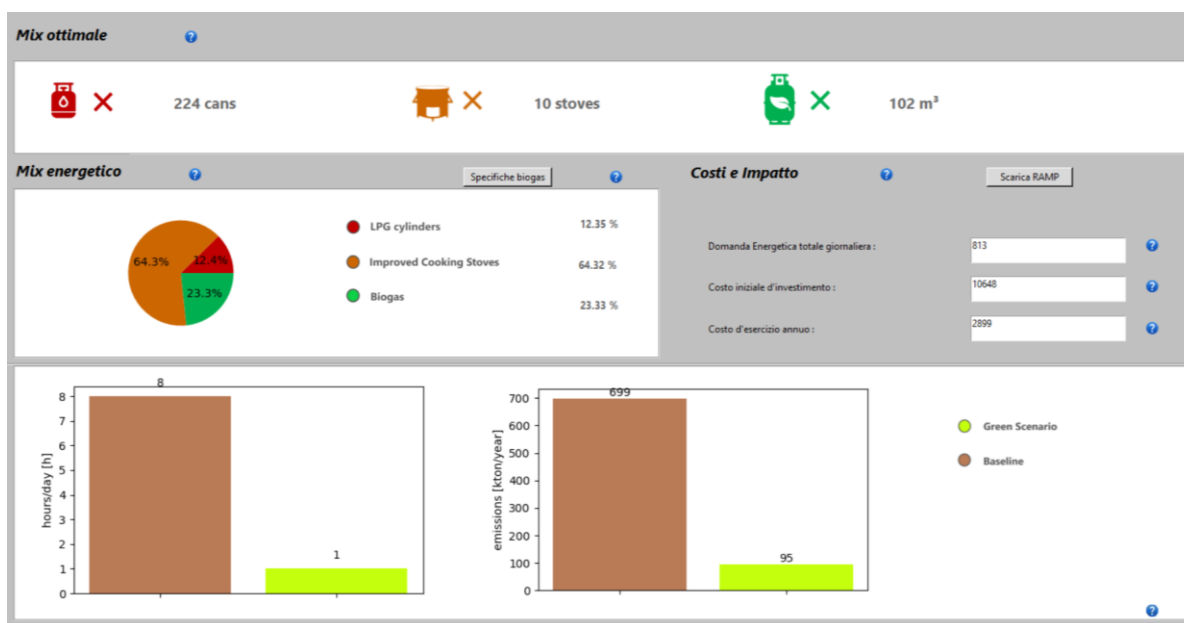
Figura 5.1: First run "free"

It's now clear that the spending budget is far greater than what is actually required for the investment.

Because of this, the system evolves by favoring LPG and inserting ICS and Biogas only thanks to the design constraint.

5.2. Sensitivity Test

Try to limit the budget to extrapolate how the ICS and biogas are distributed in the absence of the first.
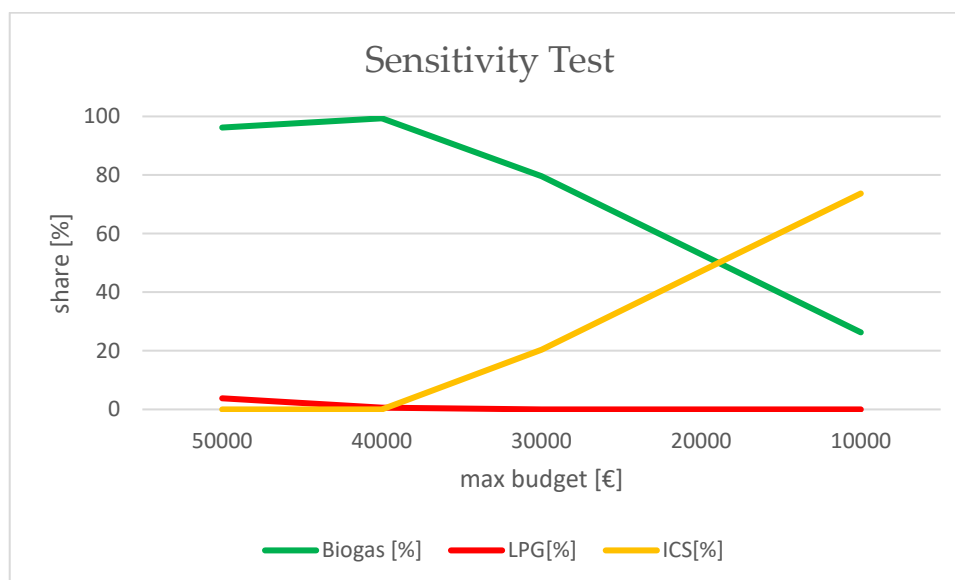
As can be deduced from the graph, limiting the cash flow the LPG give way to Biogas, favored because it emits less, to leave room in turn to the ICS that dominate the low-budget mix, at the expense of emissions and time.

5.3. Software further improvements

In the last measure we report any criticalities found in the code and the possible margins for improvement.

First a limitation of the software is in the definition of biomass for the production of biogas.

In fact, the hypothesis that a family always puts only a type of biomass oversized biodigester and cascade all the coefficients are higher than the current ones.

One idea could be to give the user the opportunity to enter a percentage mix of biomass fed.

In this way all the parameters would be mediated by a sort of weighted sum.

The only critical aspect of this choice is the evaluation of GY which, as seen in the case of Opuntia, is not necessarily proportional.

The second improvement could be the possibility of inserting wood in traditional stoves.

This would be equivalent to the possibility of not satisfying all the energy demand of the system in question.

For reasons of time it was not possible to bring these by the author, but to make the program even more usable you could create a version in English and leave the possibility to the user to select the currency in which he wants to operate.

A Complete surveys

This appendix contains the raw data extrapolated by the interviews of 30 Twala women take in the 29/03/2022

#	How many family memebers your family consist of?	How much time do you dedicate to breakfast?	How much time do you dedicate to lunch?	How much time do you dedicate to dinner?
1	9	30	50	50
2	10	30	50-60	90
3	8	40	60	60
4	6	30	60	60
5	7	40	60	60
6	6	40	60	60
7	10	50	60	60
8	5	45	60	60
9	11	45	60	50
10	3	30	45	60
11	10	45	60	60
12	4	30-45	60	90
13	6	30	60	60
14	10	45	60	60
15	7	30	60	50
16	7	30	60	60
17	6	40	60	60

18	11	30	60	60
19	8	30	45	60
20	8	45	45	45
21	6	45	60	45
22	5	30-45	90	60
23	5	35	60	45
24	4	55	45	45
25	3	30	50	45
26	3	10	60	60
27	5	30	60	60
28	5	40	90	50
29	10	30	60	90
30	12	30	90	90

#	**What kind of dish do you eat more frequently? (1)**	**(2)**	**(3)**	**(4)**
1	matoke	milk	ugali	ghideri
2	matoke	ugali	chapati	
3	ugali	chapati	milk	porridge
4	ugali	sukuma	matoke	ugali
5	chapati	milk	ugali	mukimu
6	chapati	milk	sukuma	
7	chapati	mukimu	matoke	
8	milk	chapati	mukimu	matoke

9	ugali	mukimu	sukuma	milk
10	chapati	sukuma	mukimu	ghideri
11	chapati	matoke	porridge	milk
12	milk	sukuma	mukimu	
13	chapati	ghideri	sukuma	milk
14	milk	mukimu	porridge	sukuma
15	mukimu	milk	ugali	ghideri
16	ghideri	ugali	porridge	sukuma
17	ugali	mukimu	milk	porridge
18	sukuma	ghideri	chapati	milk
19	mukimu	porridge	milk	sukuma
20	sukuma	chapati	ugali	porridge
21	mukimu	matoke	milk	
22	chapati	ugali	sukuma wiki	mukimu
23	matoke	sukuma	milk	
24	sukuma	milk	porridge	
25	milk	mukimu	sukuma	
26	ugali	chapati	matoke	
27	milk	sukuma	mukimu	chapati
28	ugali	milk	mukimu	
29	ugali	milk	sukuma	mukimu
30	milk	mukimu	ugali	chapati

B MakeCH4nge Libraries

This appendix contains the complete list of input data for the different technologies with the bibliography reference.

B.1. Firewood

name	LHV_{fw}	ref
U.o.M	$\frac{MJ}{kg}$	
Acacia	18,14	[44]
Beech	13,68	[45]
Birch	13,80	[45]
Cottonwood	14,4	[45]
DouglasFir	13,68	[46]
Foodwaste	14,76	[47]
Hem-Fir	17,94	[48]
Hybridpoplar	15,09	[49]
Manurecattle	18,06	[50]
Maple	19,59	[51]
Newspaper	19,02	[52]
Oak	16,95	[53]
Orchardprunings	17,25	[54]
Pine	18,39	[44]
Ponderosapine	16,16	[44]

Poplar	17,72	[49]
RedAlder	18,69	[55]
Redwood	19,39	[55]
Ricestraw	16,14	[56]
Spruce	19,54	[55]
Straw	18,61	[57]
Sugarcanebagasse	21,77	[57]
Switchgrass	21,4	[57]
Tire	19,77	[52]
Tobaccoresidue	16,68	[52]
WheatStraw	13,54	[55]
Willow	18,16	[55]

B.2. LPG Technology

name	m_{lpg}	LHV_{lpg}	η_{lpg}	P_{lpg}	C_{lpg}	c_{lpg}	e_{lpg}	t_{change}	t_{refill}
U.o.M	kg	$\dfrac{MJ}{kg}$	$-$	kW	€	$\dfrac{€}{kg}$	$\dfrac{kgCO_2}{kg}$	min	min
Hashi Gas 13kg	13	45,5[31]	0,6[32]	6[32]	29,16[30]	1,9[30]	2,871[35]	150	170
Hashi Gas 6kg	6	45,5	0,6	6	18,75	2,01	2,871	100	110
Hass Gas 13kg	13	45,5	0,6	6	26,66	2,11	2,871	150	170

Hass Gas 13kg composite	13	45,5	0,6	6	63,33	2,17	2,871	150	170
Hass Gas 6kg	6	45,5	0,6	6	24,58	2,15	2,871	100	110
Lake Gas 13kg	13	45,5	0,6	6	31,25	2,08	2,871	150	170
Lake Gas 50kg	50	45,5	0,6	6	125	2,08	2,871	150	170
Lake Gas 6kg	6	45,5	0,6	6	24,5	2,16	2,871	100	110
OLA Mpishi 13kg	13	45,5	0,6	6	41,66	2,05	2,871	150	170
OLA Mpishi 6kg	6	45,5	0,6	6	37,5	2,08	2,871	100	110
ProGas 13kg	13	45,5	0,6	6	29,16	1,92	2,871	150	170
ProGas 6kg	6	45,5	0,6	6	21,81	2,15	2,871	100	110
Rubis K-Gas 13kg	13	45,5	0,6	6	62,5	2,14	2,871	150	170
Rubis K-Gas 6kg	6	45,5	0,6	6	7,83	2,16	2,871	100	110
Safe Gas 13kg	13	45,5	0,6	6	68	1,92	2,871	150	170
SEA Gas 13kg	13	45,5	0,6	6	28,75	2,05	2,871	150	170
SEA Gas 6kg	6	45,5	0,6	6	22,91	2,15	2,871	100	110
Shell Afrigas 13kg	13	45,5	0,6	6	35	2,14	2,871	150	170
Shell Afrigas 45kg	45	45,5	0,6	6	71,66	2,07	2,871	150	170
Shell Afrigas 6kg	6	45,5	0,6	6	22	2,16	2,871	100	110
TotalEnergies 13kg	13	45,5	0,6	6	40	2,14	2,871	150	170
TotalEnergies 22.5kg	22,5	45,5	0,6	6	62,5	2,07	2,871	150	170

B.3. ICS Technology

name	η_{ICS}	P_{ICS}	C_{ICS}	c_{ics}	e_{ICS}	$t_{ignition}$	$t_{collect}^{ICS}$
U.o.M.	–	kW	€	$\frac{€}{kg}$	$\frac{kgCO_2}{kg}$	min	min
Mud Stoves	0,17 [58]	1,44[58]	1,66 [59]	0	2,016 [35]	20	30
Metal Stoves	0,23[60]	1,9 [60]	6,66 [59]	0	2,016	20	30
Clay Stoves	0,24 [33]	2 [33]	6,66 [59]	0	2,02 [35]	20	30
Improved Charcoal Stoves	0,32 [61]	4,4 [61]	39,16 [59]	1,15	0,90 [35]	20	10
Forced-draft stoves	0,45 [62]	3,8 [62]	60 [59]	0	2,02 [35]	20	30
Gasifiers	0,42 [63]	3,5 [63]	23,58 [59]	0,1076	0,43 [35]	20	10

B.4. Biogas Technology

name	MM_{bio}	LHV_{bio}	GY	TS	ρ_{sub}	C_{org}
U.o.M.	$\frac{kg}{kmol}$	$\frac{MJ}{kg}$	$\frac{m^3}{kg}$	%	$\frac{kg}{m^3}$	$\frac{kg_{org}}{kg_{sub}}$
Cow Manure	21,53	38,565	0,04 [64]	21 [65]	1000 [66]	0,7689 [66]
Maize	27,27	28,3	0,6054[64]	90,6 [67]	760 [67]	0,8297 [67]
Wheat	26,42	31,39	0,0267[64]	11,34 [68]	769 [68]	0,1212 [68]
Barley	19,56	35	0,01604 [69]	26,31 [69]	600 [69]	0,2764 [69]

Municipal Solid Waste	22,28	36,384	0,35 [70]	45 [70]	311,73 [70]	0,5 [70]
Pig Manure	26,92	38,565	0,015864[64]	8,2 [71]	1000 [71]	0,37 [71]
SunFlower	27,27	28,3	0,127 [72]	90,5 [72]	885 [72]	0,89 [72]
Opuntia	25,75	31,03	0,0578 [36]	7,53 [36]	975	0,06969 [36]
Rape	26,47	31,3	0,143[64]	90,4[73]	1050[73]	0,225 [73]
Rice Straw	27,27	28,3	0,15[64]	91,4[74]	650[74]	0,003[74]
MicroAlgae	30,5	26,92	0,551[75]	3 [75]	870 [75]	0,000192 [75]
Food residues	27,27	28,3	0,157[64]	28[76]	290[76]	0,003192 [76]
Chicken Manure	26,92	30,5	0,02[64]	32[64]	580 [64]	0,000388 [64]

name	HRT	OLR	C_{bio}	c_{bio}	e_{bio}	$t_{collect}^{bio}$
U.o.M.	day	$\dfrac{kg_{org}}{m^3 day}$	€	$\dfrac{€}{kg}$	$\dfrac{kgCO_2}{kg}$	min
Cow Manure	15 [67]	1,19[67]	86,54	0	2,0032	45
Maize	10 [68]	5,25 [68]	86,54	0	1,5765	45
Wheat	30 [69]	17,1 [69]	86,54	0	1,6651	45
Barley	30 [70]	15 [70]	86,54	0	0,2764	45
Municipal Solid Waste	24 [71]	2,9 [71]	86,54	0	1,7576	45
Pig Manure	15 [72]	1,2 [72]	86,54	0	1,1645	45
SunFlower	25 [73]	0,657 [73]	86,54	0	1,5765	45
Opuntia	17 [74]	4 [74]	86,54	0	0,5559	45
Rape	17 [74]	4 [74]	86,54	0	1,6345	45

Rice Straw	20 [75]	2 [75]	86,54	0	1,5765	45
MicroAlgae	20 [75]	2 [75]	86,54	0	1,7638	45
Food residues	24[76]	5[76]	86,54	0	1,5765	45
Chicken Manure	15[64]	3,14[64]	86,54	0	1,6345	45

C   MakeCH4nge Code

This appendix contains the core code of MakeCH4nge, with the optimizer tool and the source code to calculate the biogas parameters.

Note that the complete code that basically implements the GUI is not attached for the sake of brevity, but can be found at

 https://github.com/MatteoVegezzi/MakeCH4nge.git

C.1.   Optimizer.py

```python
1    '''
2    OPTIMIZER toolkit
3    Author: Matteo Vegezzi - Politecnico di Milano
4    '''
5
6    # LIBRARIES
7
8    from gurobipy import *
9    import numpy as np
10   import math
11   import csv
12
13   def run(filename,HH, m_fw, LHV_fw, eta_fw, stima, ramp, m_lpg, LHV_lpg, eta_lpg, P_lpg
        , C_lpg, c_lpg, e_lpg, t_change, eta_ics, P_ics, C_ics, c_ics, e_ics, t_ignition,
        t_collect_ics, MM_bio, LHV_bio, eta_bio, GY, TS, rho_sub, COD, HRT, OLR, V_dig, C_bio,
        c_bio, e_bio, t_collect_bio, min_lpg, max_lpg, min_ics, max_ics, min_bio, max_bio,
        MAX_inv, MAX_e, MAX_h, investment_is_a_constrain, obb1, obb2, obb3, W1, W2, W3):
14
15       '''INPUT'''
16
17       # ------------------------------------------ TD Constants
18       P = 101.325 # kPa Atmosphere Pressure
19       R = 8.314 #kJ/kmol K
20       T = 25 # °C Ambient Temperature
21       T = T + 273.15 # K
22
23       # ------------------------------------------ System Volume
24
25       HH = int(HH) # number of households
26
27       # ------------------------------------------ Energy Demand
28
29       m_fw = float(m_fw) # kg of firewood daily burned by an household
30       LHV_fw = float(LHV_fw) # MJ/kg
31       eta_fw = float(eta_fw) # yield three- stones technology
32       e_fw = 1.519 # kgCO2/kg
33       t_fw = 8/6 # h/kg
34
35        if stima == True:
36
37            E_demand = m_fw * LHV_fw * eta_fw * HH * 365 * life
38
39        elif ramp == True:
40
41            with open(filename, newline="", encoding="ISO-8859-1") as filecsv:
```

```python
42
43              lettore = csv.reader(filecsv,delimiter=",")
44              matrice = list(lettore)
45              j = 0
46              E_demand = np.zeros(1441)
47              for i in range(1,1438):
48                  E_demand[j] = matrice[i][1]
49                  j = j + 1
50
51              E_demand = (sum(E_demand) * 365 * life)/pow(10,6)
52              m_fw = E_demand / (LHV_fw * eta_fw * HH * 365 * life)
53
54
55          # ------------------------------------------- Economic Data
56
57          life = 15 # years useful life
58          i_f = 0.061 # inflaction rate
59          i_r = 0.067 # interest rate
60          CRF = 0
61
62          for n in range(life):
63              CRF = CRF + (( 1 + i_f )^ n) / (( 1 + i_r )^ n)
64
65
66
67          # --------------------------------------------- Technologies parameters
68
69          #LPG
70
71          #Technical
72
73          LHV_lpg = float(LHV_lpg) # MJ/ kg
74          m_lpg_cylinder = float(m_lpg) #kg
75          eta_lpg = float(eta_lpg) # yield lpg technology
76
77          #Economical
78
79          C_lpg = float(C_lpg) # €/cylinder
80          c_lpg = float(c_lpg) # €/kg
81
82          #Environmental
83
84          e_lpg = float(e_lpg) #kgCO2/kg emission factor
85
86          #Social
87
88          P_lpg = float(P_lpg) # kW power by lpg stove
89          t_change = float(t_change) #min
90          t_refill = 60 #min
91
92          #ICS
93
94          #Technical
95
96          eta_ics = float(eta_ics)# yield ICS technology
97          max_fuel = m_fw * eta_ics / eta_fw
98
99          #Economical
100
101          C_ics = float(C_ics) #€/stove
102          c_ics = float(c_ics) #€/kg
103
104          #Environmental
105
106          e_ics= float(e_ics) #kgCO2/kg emission factor
107
108          #Social
109
110          t_ignition = float(t_ignition) # min
111          P_ics = float(P_ics) # kW power by ics stove
112          t_collect = float(t_collect_ics) # min/kg
113
114          #BIOGAS
115
116          #Technical
```

```python
117
118          MM_bio = float(MM_bio) # kg/kmol
119          LHV_bio = float(LHV_bio) # MJ/kg
120          GY = float(GY) # m3/kg Gas Yield biogas
121          max_gas = m_fw * LHV_fw * eta_fw/ (LHV_bio * eta_lpg ) # kg/day max biogas outlet
             for one household
122          rho_bio = P/(R*T/MM_bio)
123          V_dig = float(V_dig)
124
125          #Economical
126
127          C_bio = float(C_bio) # €/m3
128          c_bio = float(c_bio)# €/kg
129
130          #Environmental
131
132          e_bio= float(e_bio) #kgCO2/kg emission factor
133
134          #Social
135
136          P_bio = 5 #kW
137          TS = float(TS)/100 # % Total Solids
138          t_collect_wheel = float(t_collect_bio) #min
139          rho_sub = float(rho_sub) # kg/m3 Substrate density
140
141          # --------------------------------------------- Constrains
142
143          max_cost = float(MAX_inv)# KSH Investment Cost
144          max_emission = float(MAX_e) # ton of CO2/ year
145          max_hours = float(MAX_h) # h/day HH
146
147          max_cylinders = float(max_lpg)
148          max_ics = float(max_ics)
149          max_biogas = float(max_bio) # m3 of biodigester
150
151          min_cylinders = float(min_lpg)
152          min_ics = float(min_ics)
153          min_biogas = float(min_bio)
154
155          # weight definition
156
157          W1 = float(W1)
158          W2 = float(W2)
159          W3 = float(W3)
160
161          #priority definition
162
163          if obb1 == "Costo Totale":
164              p1 = 1
165              if obb2 == "Impatto Ambientale":
166                  p2 = 2
167                  p3 = 3
168              else:
169                  p2 = 3
170                  Waux = W2
171                  W3 = W2
172                  W3 = Waux
173                  p3 = 2
174
175          elif obb1 == "Impatto Ambientale":
176              p1 = 2
177              Waux = W2
178              W2 = W1
179              if obb2 == "Costo Totale":
180                  p2 = 1
181                  p3 = 3
182                  W1 = Waux
183              else:
184                  p2 = 3
185                  p3 = 1
186                  W1 = W3
187                  W3 = Waux
```

```python
188            else:
189                p1 = 3
190                Waux = W3
191                W3 = W1
192                if obb2 == "Impatto Ambientale":
193                    p2 = 2
194                    p3 = 1
195                    W1 = Waux
196                else:
197                    p2 = 1
198                    p3 = 2
199                    W1 = W2
200                    W2 = Waux
201
202
203        #Energy Demand Constrain coefficients
204
205
206        d = LHV_lpg * eta_lpg
207        e = LHV_fw * eta_ics
208        f = LHV_bio * eta_lpg
209
210        #Cost function coefficients
211
212        if not(investment_is_a_constrain) == True :
213            a1 = c_lpg
214            b1 = c_ics
215            c1 = c_bio
216
217        else:
218            a1 = C_lpg / (m_lpg_cylinder * 365 * life) + c_lpg
219            b1 = C_ics / (max_fuel * 365 * life) + c_ics
220            c1 = V_dig * C_bio / (max_gas * 365 * life) + c_bio
221
222        #Emission function coefficients
223
224        a2 = e_lpg
225        b2 = e_ics
226        c2 = e_bio
227
228        #Time function coefficients
229
230        a3 = (LHV_lpg * eta_lpg * 1000)/(P_lpg*60) + t_change / (m_lpg_cylinder * 365 *
             life) + t_refill * (1/ m_lpg_cylinder - 1 / (m_lpg_cylinder * 365 * life))
231        b3 = eta_ics / (m_fw * eta_fw) * 3 * t_ignition + (LHV_fw * eta_ics * 1000)/(P_ics
              * 60) + t_collect
232        c3 = (LHV_bio * eta_lpg * 1000)/(P_bio * 60) +  t_collect_wheel / (GY * rho_bio *
             rho_sub * 0.1)
233
234
235
236        """
237        PRIORITISATION MODEL:
238        Objective functions are minimised according to a user-defined priority
             classification
239        """
240        m = Model()
241        x1 = m.addVar(vtype = GRB.INTEGER, name = "x1")
242        x2 = m.addVar(vtype = GRB.INTEGER, name = "x2")
243        x3 = m.addVar(vtype = GRB.INTEGER, name = "x3")
244
245        m.setObjectiveN(a1*x1 + b1*x2 + c1*x3, 0, p1, W1)
246        m.setObjectiveN(a2*x1 + b2*x2 + c2*x3, 1, p2, W2)
247        m.setObjectiveN(a3*x1 + b3*x2 + c3*x3, 2, p3, W3)
248
249        # positivity constrains
250
251        constr1 = m.addConstr(x1 >= 0)
252        constr2 = m.addConstr(x2 >= 0)
253        constr3 = m.addConstr(x3 >= 0)
254        # mix constrains
```

```python
255
256         constr4 = m.addConstr(x1 / (m_lpg_cylinder * 365 * life) >= min_cylinders)
257         constr5 = m.addConstr(x2 / (max_fuel * 365 * life) >= min_ics)
258         constr6 = m.addConstr((x3  * V_dig)/ (max_gas * 365 * life) >= min_biogas)
259
260         constr7 = m.addConstr(x1 / (m_lpg_cylinder * 365 *life)  <= max_cylinders)
261         constr8 = m.addConstr(x2 / (max_fuel * 365 * life) <= max_ics)
262         constr9 = m.addConstr((x3  * V_dig)/ (max_gas * 365 * life) <= max_biogas)
263
264         #objective functions constrains
265
266         constr10 = m.addConstr( x1 * a1 + x2 * b1 + x3 * c1 <= max_cost)
267         constr11 = m.addConstr((x1 * a2 + x2 * b2 + x3 * c2)/1000 <= max_emission)
268         constr12 = m.addConstr((x1 * a3 + x2 * b3 + x3 * c3)/(365*HH*60) <= max_hours)
269
270         # Satisfy Energy demand constrain
271
272         constr13 = m.addConstr(d*x1 + e*x2 + f*x3 >= E_demand)
273
274         m.optimize()
275
276         m.printAttr("X")
277
278         X1 = x1.X
279         X2 = x2.X
280
281         X3 = x3.X
281
282         '''OUTPUT'''
283
284         # Quantities for Energy source
285         n_lpg = math.ceil(X1 / (m_lpg_cylinder * life))
286         n_ics = math.ceil(X2 / (max_fuel * 365 * life))
287         n_bio = math.ceil((X3  * V_dig)/ (max_gas * 365 * life))
288
289
290         E_lpg = d * X1
291         E_ics = e * X2
292         E_bio = f * X3
293
294         # Energy share per Energy source
295         share_lpg = abs(round(E_lpg/E_demand * 100, 2))
296         share_ics = abs(round(E_ics/E_demand * 100, 2))
297         share_bio = abs(round(E_bio/E_demand * 100, 2))
298
299         # Energy Demand [MJ]
300         E_demand = E_demand/(life * 365)
301         E_demand = math.ceil(E_demand)
302
303         #Investment cost and annual variable cost
304
305         Io =  C_lpg * n_lpg + C_ics * n_ics + C_bio * n_bio
306         Io = math.ceil(Io)
307         c_es = c_lpg * X1 / life + c_ics * X2 / life + c_bio * X3 / life
308         c_es = math.ceil(c_es)
309
310         #Emission ante/post intervention
311
312         e_ante = m_fw * HH * 365 * e_fw / 1000 # ton/year
313         e_post  = (X1 * a2 + X2 * b2 + X3 * c2) / (1000 * life) # ton/year
314
315         e_ante = math.ceil(e_ante)
316         e_post = math.ceil(e_post)
317
318         #Hours/day ante/post intervention
319
320         h_ante = m_fw * t_fw
321         h_post = (X1 * a3 + X2 * b3 + X3 * c3)/(365*HH*60*life)
322
323         h_ante = math.ceil(h_ante)
324         h_post = math.ceil(h_post)
325


325

326
327         return n_lpg, n_ics, n_bio, share_lpg, share_ics, share_bio, E_demand, Io, c_es,
            e_ante, e_post, h_ante, h_post
328
```

C.2. Biogas.py

```python
'''
BIOGAS toolkit
Author: Matteo Vegezzi - Politecnico di Milano

It calculates the parameters for the biogas homesystem  of one household given the
Energy demand and the selected substrate
'''
# LIBRARIES

import math

'''INPUT'''

#E_demand  [MJ] daily household Energy demand
#LHV_bio  [MJ/kg] Lower Heating Value biogas
#MM_bio [kg/kmol] Molecular Mass biogas
#P = 101.325 # kPa Pressure
#T = 25 + 273.15 # K Temperature
#GY [m3/kg] Gas Yield
#TS Total Solids
#rho_sub  [kg/m3] mass density of the substrate
#COD  [kg_org/kg] Chemical Oxygen Demand Substrate
#HRT [days] Hydraulic Retention Time
#OLR [kg_org/m3 day] Organic Loading Rate

'''SOLUTION'''

def run(LHV_fw, m_fw, LHV_bio, MM_bio, GY, TS, rho_sub, COD, HRT, OLR):


    P = 101.325 # kPa Pressure
    T = 25 + 273.15 # K Temperature

    E_demand = float(m_fw) * float(LHV_fw)
    m_bio = E_demand / float(LHV_bio)
    R = 8.314 / float(MM_bio)
    rho_bio = P / (R * T)
    V_bio = m_bio / rho_bio
    m_sub = V_bio / float(GY) / (float(TS)/100)
    V_sub = m_sub / float(rho_sub)
    m_org = m_sub * float(COD)

    V_HRT = V_sub * float(HRT)
    V_OLR = m_org / float(OLR)



     _       _
    V_dig = max(V_HRT,V_OLR)
    V_dig = min(V_dig, 12)

    '''OUTPUT'''

    V_sub = math.ceil(V_sub)
    V_dig = math.ceil(V_dig)

    return V_dig, V_sub
```

D RAMP model

In this last appendix the complete table of RAMP input attached with the consequently input code is reported.

D.1. RAMP input code

```python
1   # -*- coding: utf-8 -*-
2
3   #%% Definition of the inputs
4   '''
5   Input data definition
6   '''
7
8   from ramp.core.core import User, np, pd
9   User_list = []
10
11
12  '''
13  This example input file represents a single household user whose only loads
14  are the "cooking" activities. The example showcases how to model electric cooking
    loads by means of
15  the Prefence Index and User Preference attributes.
16  '''
17
18  #Create new user classes
19  big_HH = User("Big Households",56,3)
20  User_list.append(big_HH)
21
22  medium_HH = User("Medium Households",49,3)
23  User_list.append(medium_HH)
24
25  small_HH = User("Small Households",105,3)
26  User_list.append(small_HH)
27
28
29
30  #Create Cooking appliances
31  #big HH
32
33  big_HH_milk = big_HH.Appliance(big_HH, P = 1400, w =2, t = 30, r_t =0.215, c = 20,
    occasional_use = 0.161, thermal_P_var = 0.2, pref_index = 0)
34  big_HH_milk.windows([12*60,15*60],[18*60,21*60],0.15)
35
36  big_HH_sukuma = big_HH.Appliance(big_HH, P = 1400, w =2, t = 40, r_t =0.215, c = 20,
    occasional_use = 0.161, thermal_P_var = 0.2, pref_index = 0)
37  big_HH_sukuma.windows([12*60,15*60],[18*60,21*60],0.15)
38
39  big_HH_mukimu = big_HH.Appliance(big_HH, P = 1400, w =2, t = 60, r_t =0.215, c = 20,
    occasional_use = 0.161, thermal_P_var = 0.2, pref_index =0)
40  big_HH_mukimu.windows([11*60,15*60],[18*60,21*60],0.15)
```

```
41
42   big_HH_chapati = big_HH.Appliance(big_HH, P = 1400, w =2, t = 30, r_t =0.215, c = 20,
     occasional_use = 0.161, thermal_P_var = 0.2, pref_index =0)
43   big_HH_chapati.windows([12*60,15*60],[18*60,21*60],0.15)
44
45   big_HH_ugali = big_HH.Appliance(big_HH, P = 1400, w =2, t = 60, r_t =0.215, c = 20,
     occasional_use = 0.129, thermal_P_var = 0.2, pref_index =1)
46   big_HH_ugali.windows([11*60,15*60],[18*60,21*60],0.15)
47
48   big_HH_matoke = big_HH.Appliance(big_HH, P = 1400, w =2, t = 60, r_t =0.215, c = 20,
     occasional_use = 0.129, thermal_P_var = 0.2, pref_index = 1)
49   big_HH_matoke.windows([11*60,15*60],[18*60,21*60],0.15)
50
51   big_HH_porridge = big_HH.Appliance(big_HH, P = 1400, w =2, t = 45, r_t =0.215, c = 20,
      occasional_use = 0.065, thermal_P_var = 0.2, pref_index = 2)
52   big_HH_porridge.windows([12*60,15*60],[18*60,21*60],0.15)
53
54   big_HH_ghideri = big_HH.Appliance(big_HH, P = 1400, w =2, t = 60, r_t =0.215, c = 20,
     occasional_use = 0.032, thermal_P_var = 0.2, pref_index =2)
55   big_HH_ghideri.windows([11*60,15*60],[18*60,21*60],0.15)
56
57   big_HH_breakfast_chai = big_HH.Appliance(big_HH, P = 1400, w =2, t = 10, r_t =0.232, c
      = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
58   big_HH_breakfast_chai.windows([6*60,9*60],[9*60,23*60],0.15)
59
60   big_HH_breakfast_milk = big_HH.Appliance(big_HH, P = 1400, w =1, t = 10, r_t =0.232, c
      = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
61   big_HH_breakfast_milk.windows([6*60,9*60],[0,0],0.15)
62
63   #medium HH
64
65   medium_HH_milk = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 30, r_t =0.126, c
      = 20, occasional_use = 0.185, thermal_P_var = 0.2, pref_index = 0)
66   medium_HH_milk.windows([12*60,15*60],[18*60,21*60],0.15)
67
68   medium_HH_sukuma = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 40, r_t =0.126,
      c = 20, occasional_use = 0.111, thermal_P_var = 0.2, pref_index = 1)
69   medium_HH_sukuma.windows([12*60,15*60],[18*60,21*60],0.15)
70
71   medium_HH_mukimu = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 60, r_t =0.126,
      c = 20, occasional_use = 0.111, thermal_P_var = 0.2, pref_index = 1)
72   medium_HH_mukimu.windows([11*60,15*60],[18*60,21*60],0.15)
73
74   medium_HH_chapati = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 30, r_t =0.126,
      c = 20, occasional_use = 0.111, thermal_P_var = 0.2, pref_index = 1)
75   medium_HH_chapati.windows([12*60,15*60],[18*60,21*60],0.15)
76
77   medium_HH_ugali = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 60, r_t =0.126, c
      = 20, occasional_use = 0.185, thermal_P_var = 0.2, pref_index = 0)
78   medium_HH_ugali.windows([11*60,15*60],[18*60,21*60],0.15)
79
80   medium_HH_matoke = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 60, r_t =0.126,
      c = 20, occasional_use = 0.037, thermal_P_var = 0.2, pref_index = 2)
81   medium_HH_matoke.windows([11*60,15*60],[18*60,21*60],0.15)
82
83   medium_HH_porridge = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 45, r_t =0.126
     , c = 20, occasional_use = 0.148, thermal_P_var = 0.2, pref_index = 1)
84   medium_HH_porridge.windows([12*60,15*60],[18*60,21*60],0.15)
85
86   medium_HH_ghideri = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 60, r_t =0.126,
      c = 20, occasional_use = 0.111, thermal_P_var = 0.2, pref_index = 1)
87   medium_HH_ghideri.windows([11*60,15*60],[18*60,21*60],0.15)
88
89   medium_HH_breakfast_chai = medium_HH.Appliance(medium_HH, P = 1400, w =2, t = 10, r_t
     =0.184, c = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
90   medium_HH_breakfast_chai.windows([6*60,9*60],[9*60,23*60],0.15)
91
92   medium_HH_breakfast_milk = medium_HH.Appliance(medium_HH, P = 1400, w =1, t = 10, r_t
     =0.184, c = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
93   medium_HH_breakfast_milk.windows([6*60,9*60],[0,0],0.15)
94
95   #small HH
```

```
96
97    small_HH_milk = small_HH.Appliance(small_HH, P = 1400, w =2, t = 30, r_t =0.156, c =
      20, occasional_use = 0.208, thermal_P_var = 0.2, pref_index = 0)
98    small_HH_milk.windows([12*60,15*60],[18*60,21*60],0.15)
99
100   small_HH_sukuma = small_HH.Appliance(small_HH, P = 1400, w =2, t = 40, r_t =0.156, c =
       20, occasional_use = 0.170, thermal_P_var = 0.2, pref_index = 0)
101   small_HH_sukuma.windows([12*60,15*60],[18*60,21*60],0.15)
102
103   small_HH_mukimu = small_HH.Appliance(small_HH, P = 1400, w =2, t = 60, r_t =0.156, c =
       20, occasional_use = 0.189, thermal_P_var = 0.2, pref_index = 0)
104   small_HH_mukimu.windows([11*60,15*60],[18*60,21*60],0.15)
105
106   small_HH_chapati = small_HH.Appliance(small_HH, P = 1400, w =2, t = 30, r_t =0.156, c
      = 20, occasional_use = 0.132, thermal_P_var = 0.2, pref_index = 1)
107   small_HH_chapati.windows([12*60,15*60],[18*60,21*60],0.15)
108
109   small_HH_ugali = small_HH.Appliance(small_HH, P = 1400, w =2, t = 60, r_t =0.156, c =
      20, occasional_use = 0.132, thermal_P_var = 0.2, pref_index = 1)
110   small_HH_ugali.windows([11*60,15*60],[18*60,21*60],0.15)
111
112   small_HH_matoke = small_HH.Appliance(small_HH, P = 1400, w =2, t = 60, r_t =0.156, c =
       20, occasional_use = 0.094, thermal_P_var = 0.2, pref_index = 2)
113   small_HH_matoke.windows([11*60,15*60],[18*60,21*60],0.15)
114
115   small_HH_porridge = small_HH.Appliance(small_HH, P = 1400, w =2, t = 45, r_t =0.156, c
       = 20, occasional_use = 0.038, thermal_P_var = 0.2, pref_index = 2)
116   small_HH_porridge.windows([12*60,15*60],[18*60,21*60],0.15)



117
118   small_HH_ghideri = small_HH.Appliance(small_HH, P = 1400, w =2, t = 60, r_t =0.156, c
      = 20, occasional_use = 0.038, thermal_P_var = 0.2, pref_index = 2)
119   small_HH_ghideri.windows([11*60,15*60],[18*60,21*60],0.15)
120
121   small_HH_breakfast_chai = small_HH.Appliance(small_HH, P = 1400, w =2, t = 10, r_t =
      0.314, c = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
122   small_HH_breakfast_chai.windows([6*60,9*60],[9*60,23*60],0.15)
123
124   small_HH_breakfast_milk = small_HH.Appliance(small_HH, P = 1400, w =1, t = 10, r_t =
      0.314, c = 20, occasional_use = 0.8, thermal_P_var = 0.2, pref_index =0)
125   small_HH_breakfast_milk.windows([6*60,9*60],[0,0],0.15)
```

Bibliography

[1] https://it.wikipedia.org/wiki/Kenya [Online]

[2] https://data.worldbank.org/country/KE [Online]

[3] https://www.oecd.org/ [Online]

[4] https://it.wikipedia.org/wiki/Masai [Online]

[5] https://www.ndma.go.ke/ [Online]

[6] https://maasaitribekenya.weebly.com/enkang.html [Online]

[7] https://time.com/5050613/ellie-goulding-clean-air/ [Online]

[8] https://www.ipsia-acli.it/ [Online]

[9] Working Group II, "Climate Change 2022: Impacts, Adaptation and Vulnerability", *IPCC*, 2022.

[10]   https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en [Online]

[11] "World Energy Outlook 2019", *IEA* , November 2019.

[12] https://www.un.org/sustainabledevelopment/development-agenda/ [Online]

[13] "The Sustainable Development Goals Report 2021", *UN*, 2021.

[14] Stoner, O., Lewis, J., Martínez, I.L. et al. Household cooking fuel estimates at global and country level for 1990 to 2030. Nat Commun 12, 5793 (2021).

[15] Paunio, M. (2018). Kicking Away the Energy Ladder: How Environmentalism Destroys Hope of the Poorest.

[16] https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health [Online]

[17] https://www.who.int/news-room/fact-sheets/detail/malaria [Online]

[18]   https://www.who.int/data/gho/data/indicators/indicator-details/GHO/number-of-deaths-due-to-hiv-aids [Online]

[19] https://www.who.int/news-room/fact-sheets/detail/tuberculosis [Online]

[20] https://ourworldindata.org/explorers/coronavirus-data-explorer [Online]

| Errore. Per applicare Heading 1 al
testo da visualizzare in questo punto,
utilizzare la scheda Home.

100

[21] FAO and UNEP. 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Rome.

[22] KNBS, 2021, Laikipia County Statistical abstract 2021.

[23] https://cleancookstoves.org/%7CGlobal [Online]

[24] https://en.wikipedia.org/wiki/Linear_programming [Online]

[25] Rosen, J. B. "Global Minimization of a Linearly Constrained Concave Function by Partition of Feasible Domain." Mathematics of Operations Research 8, no. 2 (1983): 215–30.

[26] Awad, M., Khanna, R. (2015). Multiobjective Optimization. In: Efficient Learning Machines. Apress, Berkeley, CA.

[27] https://en.wikipedia.org/wiki/Simplex_algorithm [Online]

[28] Wright, Stephen J.. "simplex method". *Encyclopedia Britannica*, 2 Aug. 2021,

[29] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_2_Glossary.pdf [Online]

[30] https://gobeba.com/product/rubis-kenol-kobil-k-gas-6kg-refill/ [Online]

[31] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.htm [Online]

[32] https://www.epa.gov/chief [Online]

[33]https://www.researchgate.net/publication/269811863_Performance_of_Clay_Wood_Cook_Stove_An_Analysis_of_Cost_and_Fuel_Savings [Online]

[34] https://www.indiamart.com/proddetail/wayanadan-clay-stove [Online]

[35] https://ghgprotocol.org/Third-Party-Databases/IPCC-Emissions-Factor-Database [Online]

[36] Treviño-Amador, I.A. & Méndez-Llorente, F. & López-Carlos, Marco Antonio & Aguilera-Soto, J. & Ramírez-Lozano, Roque & Núñez-González, M.A. & Zuñiga, E.J.C.. (2013). Biogas production from opuntia ficus-indica and dairy cattle Manure. Acta Horticulturae. 995. 339-342. 10.17660/ActaHortic.2013.995.44.

[37] Ibnu Budiman "The Role of Fixed-Dome and Floating Drum Biogas Digester for Energy Security in Indonesia", Indonesian Journal of Energy. 2020

[38] Pedraza, G. & Chará, Julián & Conde, N. & Giraldo, Sherly & Giraldo, L.. (2002). Evaluation of polyethylene and PVC tubular biodigesters in the treatment of swine wastewater. Livestock Research for Rural Development. 14. 10-28.

[39] https://github.com/SESAM-Polimi/RAMP [Online]

[40] https://www.python.org/doc/essays/blurb/ [Online]

[41] https://www.tiobe.com/tiobe-index/ [Online]

[42] https://www.gurobi.com/ [Online]

[43] http://page.sourceforge.net/ [Online]

[44] Nunes, Leonel & Rodrigues, Abel & Loureiro, Liliana. (2021). Energy Recovery from Invasive Species: Creation of Value Chains to Promote Control and Eradication. 18.

[45] FAO, Wood fuels handbook, 2015 http://large.stanford.edu/courses/2017/ph240/timcheck1/docs/fao-krajnc-2015.pdf

[46] https://www.osti.gov/etdeweb/servlets/purl/642467

[47] F. di Maria , M. Lasagni "Online measurement of the lower heating value of waste"

[48] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8839548/

[49] Gómez-Martín, J & María, Castaño-Díaz & Cámara-Obregón, Asunción & Álvarez-Álvarez, Pedro & Folgueras-Díaz, M. & Díez Díaz-Estébanez, Maria. (2019). On the chemical composition and pyrolytic behavior of hybrid poplar energy crops from northern Spain.

[50] https://lpelc.org/what-are-typical-values-for-the-higher-heating-value-of-manure-scraped-from-cattle-feedyard-surfaces/

[51] Therasme, Obste & Volk, Timothy & Cabrera Ariza, Antonio & Eisenbies, Mark & Amidon, Thomas. (2018). Hot Water Extraction Improves the Characteristics of Willow and Sugar Maple Biomass With Different Amount of Bark. Frontiers in Energy Research. 6. 10.3389/fenrg.2018.00093.

[52] https://h2tools.org/hyarc/calculator-tools/lower-and-higher-heating-values-fuels

[53] Technical, Environmental, and Qualitative Assessment of the Oak Waste Processing and Its Usage for Energy Conversion Algirdas Jasinskas 1,*, Ramunas Mieldažys ̄ 1 , Egle Jotautien ˙ e˙ 1 , Rolandas Domeika 1 , Edvardas Vaiciukeviˇcius 1 and Marek Marks

[54] Article Reusing Pruning Residues for Thermal Energy Production: A Mobile App to Match Biomass Availability with the Heating Energy Balance of Agro-Industrial Buildings Carlo Bisaglia 1 , Massimo Brambilla 1 , Maurizio Cutini 1,* , Antonio Bortolotti 2 , Guido Rota 3 , Giorgio Minuti 3 and Roberto Sargian

[55] https://www.hurstboiler.com/biomass_boiler_systems/heat_values_of_wood

[56] Van Hung, N. et al. (2020). Rice Straw Overview: Availability, Properties, and Management Practices. In: Gummert, M., Hung, N., Chivenge, P., Douthwaite, B. (eds)

| Errore. Per applicare Heading 1 al
testo da visualizzare in questo punto,
utilizzare la scheda Home.

102

Sustainable Rice Straw Management. Springer, Cham. https://doi.org/10.1007/978-3-030-32373-8_1

[57] https://www.reka.com/en/tools/heatingvalues/

[58] Thermal Efficiency of Wood Burning Traditional Mud Cookstoves and Their Impact on Indoor Air Quality in North-Western Himalayas Yashpal Thakur, R K Aggarwal and S K Bhardwaj

[59] https://energypedia.info/wiki/

[60] Bantu, Anthony & Nuwagaba, Gilbert & Kizza-Nkambwe, Sarah & Turinayo, Yonah. (2018). Design of an Improved Cooking Stove Using High Density Heated Rocks and Heat Retaining Techniques. Journal of Renewable Energy. 2018. 10.1155/2018/9620103.

[61] Adeyemi, Kafayat & Lawal, Nasiru & Asere, Abraham. (2017). Thermal Performance of Improved Charcoal Stove as A Clean Development Mechanism Project – A Case Study of Bauchi. FUOYE Journal of Engineering and Technology. 2. 10.46792/fuoyejet.v2i1.62.

[62] P. Raman, J. Murali, D. Sakthivadivel, V.S. Vigneswaran, Performance evaluation of three types of forced draft cook stoves using fuel wood and coconut shell, Biomass and Bioenergy, Volume 49, 2013, Pages 333-340, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2012.12.028.

[63] https://www.chinabiomasspower.com/products?gclid=CjwKCAjwiJqWBhBdEiwAtESPaOCNFU1aAXywfpqFJtSqHHhlfOOx1_26bH6ychumpdKq5EPpsM4hOhoC0WUQAvD_BwE

[64] https://energypedia.info/wiki/Gas_Yields_and_Methane_Contents_for_Various_Substrates

[65] Rosenberg, Logan & Kornelius, Gerrit. (2017). Experimental investigation of biogas production from feedlot cattle manure. Journal of Energy in Southern Africa. 28. 10.17159/2413-3051/2017/v28i4a1753.

[66] younoussa Moussa Baldé, Kanté Cellou, Sette Diop, Sihem Tebbani. An experimental study for the characterization of biogas production from cow dung and droppings. Ecological Engineering and Environment Protection, National Society of Ecological Engineering and Environment Protection, 2019, 2019 (1), pp.54-61. ⟨10.32006/eeep.2019.1.5461⟩. ⟨hal-02413804⟩

[67] https://www.researchgate.net/figure/Total-solids-of-the-maize-parts-at-harvest_tbl1_343815203

| Errore. Per applicare Heading 1 al testo da visualizzare in questo punto, utilizzare la scheda Home.

103

[68] Momayez, Forough & Karimi, Keikhosro & Sárvári Horváth, Ilona. (2019). Sustainable and efficient sugar production from wheat straw by pretreatment with biogas digestate. RSC Advances. 9. 27692-27701. 10.1039/C9RA05285B.

[69] Bioconversion Process of Barley Crop Residues into Biogas—Energetic-Environmental Potential in Spain Carlos Morales-Polo 1,2,3,* , María del Mar Cledera-Castro 1,2,3 , Marta Revuelta-Aramburu 2 and Katia Hueso-Kortekaas

[70]   https://www.globalmethane.org/documents/news-item-438/16-Frankiewicz-GMI-Notes.pdf

[71] Makara, Agnieszka & Kowalski, Z. (2015). Pig manure treatment and purification by filtration. Journal of environmental management. 161. 317-324. 10.1016/j.jenvman.2015.07.022.

[72] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6982727/

[73] Eid S. Gaballah, Abd El-Fatah Abomohra, Chao Xu, Mahdy Elsayed, Tarek Kh. Abdelkader, Jiacong Lin, Qiaoxia Yuan, Enhancement of biogas production from rape straw using different co-pretreatment techniques and anaerobic co-digestion with cattle manure, Bioresource Technology, Volume 309, 2020, 123311, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2020.123311.

[74] Jingqing Ye, Dong Li, Yongming Sun, Guohui Wang, Zhenhong Yuan, Feng Zhen, Yao Wang, Improved biogas production from rice straw by co-digestion with kitchen waste and pig manure, Waste Management, Volume 33, Issue 12, 2013, Pages 2653-2658, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2013.05.014.

[75] Hossain M. Zabed, Suely Akter, Junhua Yun, Guoyan Zhang, Yufei Zhang, Xianghui Qi, Biogas from microalgae: Technologies, challenges and opportunities, Renewable and Sustainable Energy Reviews, Volume 117, 2020, 109503, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109503.

[76] Safoora Mirmohamadsadeghi, Keikhosro Karimi, Meisam Tabatabaei, Mortaza Aghbashlo, Biogas production from food wastes: A review on recent developments and future perspectives, Bioresource Technology Reports, Volume 7, 2019, 100202, ISSN 2589-014X, https://doi.org/10.1016/j.biteb.2019.100202.