Prefeasitbility study for implementing a biomass to electricity chain in Rodrigues island (Mauritius)

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Final Report

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Foreword

This work was carried out by CIRAD within the framework of the COI-Energies program financed by the European Union (10th EDF / European Development Funds).
The authors wish to thank warmly

- The Indian Ocean Commission for the trust granted;
- The National Focal Points of the IOC-Energy Program;
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- All the contributors to this study.

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EXECUTIVE SUMMARY

This study was commissioned by the Indian Ocean Commission as part of the Energies program. The overall objective was to assess the relevance of a bioelectricity production chain from woody resources. The work carried out by CIRAD experts was based on two missions to Rodrigues. Interviews and field visits were conducted with (i) local authorities; (ii) forest services; (iii) actors and stakeholders, especially forest services.

The analysis focused on the following three axes:

- Global context analysis in Rodrigues;
- Analysis of wood resources in the territory and evaluation of the main deposits available for energy recovery;
- Preliminary evaluation of a bioelectricity chain: pre-dimensioning of a power plant and identification of opportunities/constraints concerning its biomass supply and exploitation.

Synthesis of the main findings

Biomass represents a real opportunity for electricity production in Rodrigues, in the context of its energy transition policy towards a more autonomous and less carbon intensive energy mix. The technical potential, evaluated on the basis of rather conservative and sustainable assumptions, represents in short terms:

- 3,000 t of dry wood / year, mainly issued from the exploitation of existing Eucalyptus plantations according to a management plan that has to be implemented, and to a lesser extend by wood issued from mixed forest restoration programs and exploitation of old stands of Acacia Nilotica;
- 13,000 MWh of primary energy (wood energy content), in the form of wood chips;
- 2,600 MWhel of electrical energy produced, which corresponds to a power plant capacity of around 350 kWel.

The potential electrical energy generated would correspond to the average consumption of about 1,700 Rodrigues households. The capacity to install would represent nearly 10% of the electrical consumption threshold power of Rodrigues Island. It could thus potentially be a significant short-term contribution to the electricity mix, with other services provided to the territory (job creation, enhancement of existing forest resources, regional planning, etc.).

A higher capacity can be envisaged (750 kWel) in the longer term through (i) better management of current Eucalyptus plantations which could lead to significant productivity gains; (ii) new energy plantations on land that remains to be identified.

The estimated power ranges correspond to small/medium scale power technologies.

- In these ranges, combustion / steam cycle technologies are uncommon because they are economically unprofitable.
- Gasification might be an interesting technological alternative to combustion, especially on feedstocks such as wood chips. Solutions are available worlwide, though little available yet in IOC region.

A possible organization of the whole chain at the territorial level has been proposed, but still needs to be refined, especially concerning the actors concerned and the technico-economic profitability.

The biomass-energy potential linked to future programs for the control / eradication of Acacia Nilotica massifs has been evaluated and discussed, but the total eradication in the short term is a complex operation for a number of reasons, particularly related to the required means and to uncertainties regarding relevant technical routes. Therefore this resource is currently not considered sustainable for a power plant supply. Nevertheless, experiments are encouraged in order to manage easily accessible spaces.

The first economic estimates lead to feedstock costs as delivered to the power plant, between 3.8 and 4.4 MUR / kg (about 100 Euros / tonne of wood chips), and a cost for electricity production of between 5.5 and 6.5 MUR / kWhel produced.

Recommendations for continuation

As a first step and considering the potential, we recommend the continuation of the project by a feasibility study whose objectives would be to refine and reinforce the estimates on:

1- the technical potential in terms of biomass resources:
   - field expertise to assess the current state of Eucalyptus stands, evaluate their productivity in the short and medium term;
   - co-constructrion with the forest services of a long-term management plan for the Eucalyptus massif and the technical itineraries.

2- the cost of the feedstock as delivered to the power plant:
   - better identify the potential actors in a biomass supply chain, their skills, their investment and action capabilities, their constraints;
   - identify the potential location of the platform, refine the necessary investments, the distribution between actors;
   - consolidate the technical routes and the costs of supply and production.

3- the cost of electricity production by a technical-economic analysis of the plant:
   - Identify potential actors / holder (CEB, independent producer of IPP type);
   - Analyze technological offers, their performances, investment costs, maintenance.

In a second step, based on these feasibility studies, we recommend the implementation of a pilot project scaled and designed to represent the first tranche of a potential future larger power station. The installed power could be between 50 kW and 100 kW and the biomass resource required in the order of 500-1000 tDM / year. The advantage of such pilot project would be to initiate the construction of the whole chain with limited risk, to test technical itineraries, including resource and technical platforms management, and optimize the full costs of electricity production chain.

Introduction – Context and objective of the study

1 Context and objectives of the study

1.1 IOC Energy Program

This study was commissioned by the Indian Ocean Commission as part of the Energies program, "Renewable Energy Development and Energy Efficiency Improvement Program in IOC Member States". This program was funded by the European Union through the 10^{th} EDF (European Development Fund). It aimed to (i) facilitate the conditions of access to development, investment and sustainable management of renewable energies; (ii) increase the energy efficiency of the various economic sectors.

Under Outcome 1 "An IOC regional strategy, which focuses on human resource development and reinforcement of institution, is accepted and implemented", prospective studies were conducted to develop the strategy for developing renewable energies and energy efficiency for several small islands in the sub-region. Following these prospective studies, the stakeholders of each small island selected an illustrative exemplary action regarding Energy issues and inherent to its particular situation.

Power production from woody biomass may contribute to a better energy autonomy of the IOC member states: i) biomass resources, although unequally distributed over the territories, are globally under-exploited; ii) it may be a base or semi-base energy and thus be complementary to intermittent renewable energies such as solar and wind energy; (iii) it is potentially a source of additional income for agriculture and agro-industry / agribusiness sectors.

In line with this context, IOC proposed to finance a preliminary study aiming to evaluate the relevance and the conditions for implementing a bioelectricity production chain in the Islands Rodrigues (Republic of Mauritius) and La Digue (Seychelles).

1.2 Objectives of the study – terms of reference

The present report concerns the study conducted at La Digue. According to the terms of reference, the objectives were to evaluate the relevance of a bioelectricity production chain from woody biomass on the island of Rodrigues (Mauritius).

The expected results in the terms of reference are as follows:

- Inventory of available woody biomass, with particular attention to forest resources, invasive species, green wastes and agricultural residues ;
- Evaluation of possible routes for bioelectricity production through thermochemical conversion of woody species identified.
- Preliminary scaling of a bioelectricity plant, taking into account the available biomass potential;
- Technical and socio-économic analysis of constraints and opportunities related to the supply of the plant associated with plans for the eradication or management of invasive species.

2 General framework and methodology

2.1 Brief description of a bioelectricity production chain

A biomass to electricity system consists of 3 main sections as illustrated in the figure below:

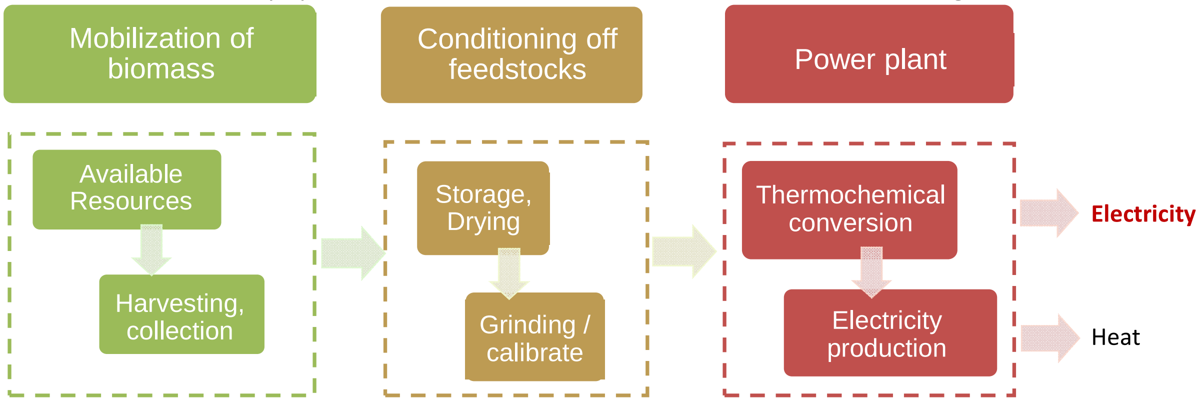


Figure 1 : schematization of a biomass to electricity system

1- Production and mobilization of biomass

This section includes the processes such as harvesting, collecting and transport of the resource to the transformation process. In the context of the present study, the so-called "woody" or "lignocellulosic" biomass is considered: forest biomass, dry agricultural and agro-industrial residues, ligneous fractions of urban waste.

2- Fuel preparation / conditioning

This process includes all of the post-harvest transformations required to provide the fuel with properties (grain size, density) or composition (moisture content) suitable for the selected thermal process.

3- Conversion and energy production (power plant)

The power plant includes processes that make it possible to produce electricity and heat from the fuel. The study will focus specifically on the thermal (or thermochemical) processes that are most relevant producing power from woody biomass.

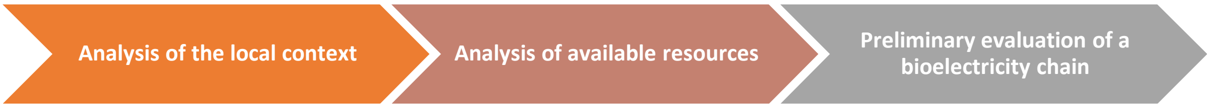
2.2 Methodological approach

The technological choices and the scaling of a bioelectricity production facility (and more generally of a whole production chain) are based on several criteria

- electricity demand (grid connection or decentralized electrification, power ...) but also heat demand in the case of cogeneration systems ;
- performance and reliability of the production technology ;
- regular supply of biomass, with controlled quantity and quality ;
- regulatory framework regarding for biomass supply chain and electricity generation ;
- production costs along the whole chain.

In the context of the present study, the global approach consisted of a "upstream" evaluation, that is to say conditioned by the biomass supply. The major challenge was to identify the territorial possibilities for organizing a biomass energy supply chain for a potential power plant.

The whole methodology for evaluations is described below



1- Global analysis of the context at Rodrigues (public policy, socio-economic, energy and environmental context, regulatory framework, ongoing initiatives ...)
2- Qualitative and, if possible, quantitative assessment of available woody biomass deposits, with available data, taking into account
   a. A first diagnotic on the biomasses produced on the territory, the data available on the deposits, the technical itineraries in place ...
   b. The actual availability in the short / medium term of these resources, taking into account access constraints, competing uses, seasonality, etc.
3- If relevant according to points 1 and 2, proposal and discussion of a possible bioelectricty chain
   a. Preliminary scaling of the power plant and technical orientations
   b. Global analysis of biomass supply chains scenarios.

2.3 Missions to Rodrigues

This work was largely based on two visits of the expert in Rodrigues

- 3-6 décembre 2018 (see annexe 1). The main objective was to dress a first analysis of the context
  - o Meeting local authorities and stakeholders in the following sectors: environment, forest, agriculture, energy;
  - o Analysis of the potential supply of woody biomass (especially forestry biomass, but also agricultural or urban resources), collection of available information on deposits and mobilization constraints, management plans ...;
  - o Analysis of electricity demand - opportunities and constraints for the development of a biomass electricity sector.
- 25-27 février 2019 (see annexe 2). The main objectives were to
  - o share with stakeholders the first trends that emerged from the analysis of biomass resources, scenarios;
  - o explore with the Forest Service the location of forestry resources and the scenarios / technical itineraries that could be envisaged.

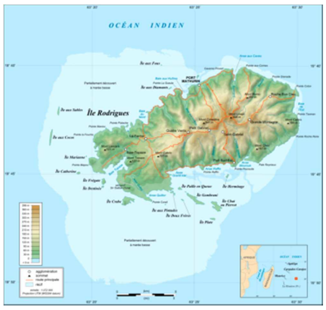
Analysis of Rodrigues island context

1 General overview

Rodrigues Island is the smallest of the main Mascareignes islands and the most isolated in the East, located 583 km east of Mauritius.

It is a volcanic island, its area is 110 km2 (18 km long and 8 km wide). One of its distinction is its lagoon with an area twice that of the land surface. The overall topography is mountainous. The highest peak, Mount Limon, rises to 398 meters.

The climate is tropical, but drier than in Mauritius with a relatively low average annual rainfall for the region, about 1100mm and unevenly distributed over the territory.



The population is about 43,000 inhabitants (Table 1). The main economic activities of the island are fishing, agriculture (mainly corn) and tourism. The agriculture and fishing sectors are the main generators of employment, accounting for just over one third (33.9%) of total employment (source Statistics Mauritius, 2015).

State	Mauritius
Area (km^2)	110
Population (inhab)	42 818
Average pop density (hab/ km^2)	389

Table 1 : Data on Rodrigues island (source Statistics Mauritius, 2017)

Rodrigues is an autonomous region of the Republic of Mauritius. The RRA (Rodrigues Regional Assembly) has 18 members. The Chief Commissioner is appointed by the majority of the assembly and acts as chief of the government, with the support of six other appointed commissioners. Mr. J-Richard Payendee is the Commissioner of the Environment, Agriculture and Forestry.

2 Energy context

2.1 Electricity production highly dependent on fossil fuels

According to the data available to us[1], the electricity generation fleet consists of (i) two diesel-powered thermal power plants at Port Mathurin (6 MW installed, 5.1 MW effective) and Pointe Monnier (6.3 MW); (ii) two wind farms of 1.1 MW (Grenada) and 180 kW (Trefles).

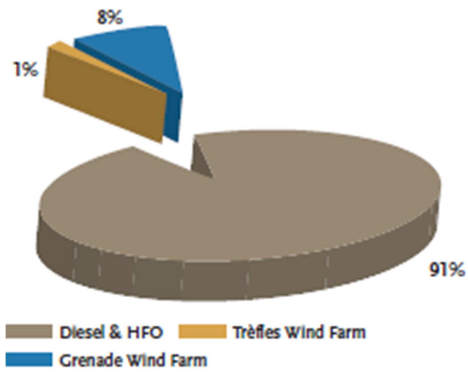


Figure 2 : Electricity mix in Rodrigues Island - 2011 [1]

These data are from 2011 and need to be updated. According to CEB, the rate of renewable energy (ENR) in the electricity mix (consumption) is currently 12%, of wind and solar origin, whose share is likely to increase with photovoltaic projects.

It is important to mention that there is no solid fuel thermal power plant in Rodrigues, neither biomass nor fossil coal, nor even mix of both as is the case in Mauritius with the coal / bagasse power plants.

2.2 Towards the deployment of Renewable Energies in the energy / electricity mix.

The **Rodrigues Regional Assembly (RRA)** has set a target of 100% renewable energies by 2030. This is a vision that still needs to be broken down in terms of phased objectives. A roadmap must be specified next (single electric mix or whike energy balance integrating the fuels, strategy in terms of ENR introduction, calendar ...).

The **Central Electricity Board** (CEB) is responsible for generating, transporting and distributing electricity in Rodrigues and Mauritius. It is the manager of all electrical production facilities in Rodrigues territory. In addition, one of CEB's roles is to propose elements of economic arbitrage concerning the energy strategy, in consultation with URA (Utility Regulatory Autority). CEB has confirmed that the development of renewable energies is a major concern to them, in accordance with the vision of the RRA, on the one hand, and the Long-Term Energy Strategy (LTES) prepared under MEPU's authority. While the current dynamics in terms of ENR mainly concerns the deployment of solar and wind power, a bioelectricity sector could have its place, if guarantees are given in terms of sustainability and cost of production.

In this context, the present study will initiate the debate about the possible rate of bioelectricity in the electricity mix. Some issues and points of attention specific to biomass were shared with the stakeholders met during our missions:

[1] http://ceb.intnet.mu/CorporateInfo/IEP2013/Chapter8_Demand-Supply%20in%20Rodrigues.pdf

- Biomass is a potentially source of base energy, and has a role to play in the stability of the network compared to the intermittent nature of other renewable energies (wind and solar).
- Implementing biomass energy chains requires a solid resource management plan to ensure long-term sustainable use.
- Bioelectricity processes require more technical expertise than other renewable energy sources, which raises the question of the possible operator (CEB or an independent producer "IPP" as it exists in Mauritius).

2.3 Short analysis of electricity demand

The electrification rate in the territory is almost 100%. The 22 kV electricity grid covers the entire territory and is not interconnected with Mauritius (Figure 3). There is therefore a strong challenge to develop grid-connected bioelectricity solutions, in particular to reinforce it and to guarantee stability compared to the intermittent energy productions that are foreseen to develop. In this sense, bioelectricity solutions have the advantage of being based on rotating machines with inertia.

The demand for decentralized production, without connection to the grid (self-consumption, mini-grid), seems to us very limited due in particular to a weak industrial activity.

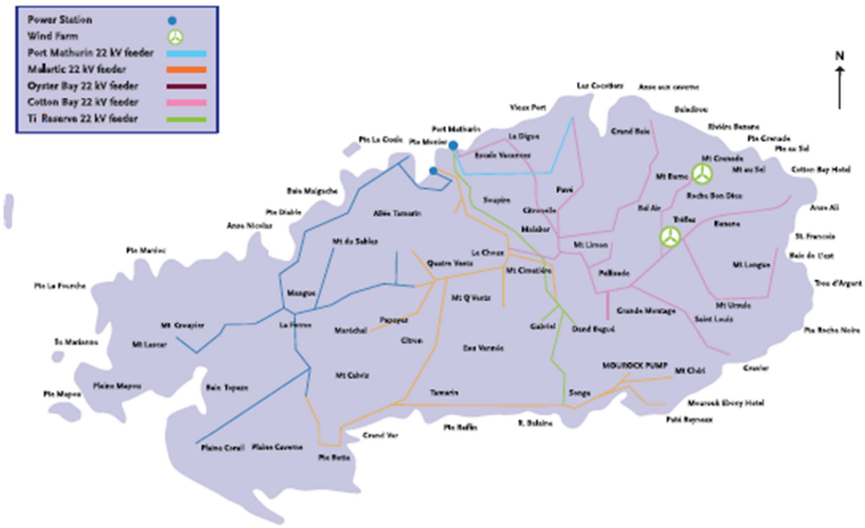


Figure 3 : Electricity grid in Rodrigues – 2011 – source CEB [1]

According to Statistics Mauritius, the annual electricity consumption is in the order of 35,000 MWh in 2017 (Table 2). Households and businesses are the main consumers while industrial needs are quite low.

Class of consumer	2015		2016		2017	
	No. of consumers	Consumption (MWh)	No. of consumers	Consumption (MWh)	No. of consumers	Consumption (MWh)
Domestic	12 223	18 384	12 582	19 190	12 771	19 832
Commercial	1 344	10 117	1 418	10 400	1 490	11 062
Industrial & Others	289	4 196	297	4 306	311	3 829
All consumers	13 856	32 698	14 297	33 896	14 572	34 723

Table 2 : Electricity consumption in Rodrigues per consumer category (source Statistics Mauritius, 2017)

According to an interview with CEB, the daily consumption peak would be of the order of 7 MWel in summer, and the threshold (minimal) power would be of the order of 3.5-4 kW. More detailed information would be needed to refine demand, including the typical daily load curve and economic elements such as the current cost of generating electricity in Rodrigues. This information has not yet been communicated to us.

2.4 Regulatory Framework for the connection of new power plants

In the Republic of Mauritius, including in Rodrigues, electricity production is under the jurisdiction of the Ministry of Energy and Utilities (MEPU). Current regulations and connection authorization procedures are centralized from CEB in Mauritius (Connection Agreement, CEB Corporate Planning).

Grid codes must be respected, depending on the installed capacity:

- Small Scale Distributed Generation (SSDG) for powers <50kW, with connection to the low voltage network.
- Medium Scale Distributed Generation (MSDG) for 50-200 kW or 200 kW-2 MW power, with connection to the medium or high voltage network.

This regulatory framework will have to be explored further, in the case of a possible in-depth feasibility study.

2.5 Limited heat demand in the territory

Identifying a regular demand for heat could allow considering a cogeneration system (electricity + heat) instead of a single electricity production system.

However, there is little agro-food processing in Rodrigues requiring heat (eg drying, distillation of essential oils ...). Currently, solar solutions are preferred for drying systems, but cogeneration can be an opportunity to provide an additional service to electricity production, sould a clear demand be identified and anticipated.

3 Environmental context: control and eradication of invasive species

3.1 Intiatives and programs

The control of invasive species in Rodrigues is a major concern of the RRA, with environmental issues (preservation of biodiversity, control of erosion, impact on water availability…) and socio-economic issues (nuisance to the population, invasion of agricultural land). The major initiatives are:

- "Change the forest" by progressively replacing exotic trees and associated forest formations with native or endemic species

Several restoration projects have been or are being carried out on various sites in Rodrigues. Thus, such restoration processes have already been tested by the forestry services and the NGO Mauritius Wildlife Fundation (MWF) and implemented at three sites on the island: in the Grande Montagne reserve (20 ha have already been restored) ; at Anse Quitor (2 ha); and Cascade Pigeon (15 ha). To date, the wood of exotic trees is mostly left on site and therefore represents a wood resource available for energy production.

- Eradicate invasive species, especially Acacia Nilotica (« piquant loulou ») especially to recover agricultural land that is gradually invaded.

Acacia Nilotica has indeed spread widely in the lower parts of the island, with varying degrees of invasion that are still poorly documented. Several Acacia Nilotica control programs were sponsored by the Environment Commission and MWF, during which various protocols and technical itineraries were tested. The results obtained are variable and these programs require very important (human and financial) resources. The question remains as to the best compromise between the will of eradication and the management of stands to control invasiveness.

3.2 Stakeholders - actors

Two institutions are invoved in implementing forest restoration and Acacia Nilotica management programs in Rodrigues. The Mauritian Wildlife Foundation (MWF) implements dedicated programs at some of the important sites mentioned above for the restoration of native flora, especially strict nature reserves. The Forestry Services of the Rodrigues Regional Assembly have been mobilized for several years in programs against invasive species and aiming to reintroduce native flora.

Both institutions benefit from the close collaboration of the local communities of the island, including through occasional employment contracts with community groups, who work on both state and community lands. The RRA stresses its desire to see long-term programs continued and to involve communities in projects (plant nurseries).

Analysis of available ligneous biomass resources

This section gathers information and data collected during missions or produced by the experts, to estimate ligneous resources available for short to medium-term energy production.

The availability of biomass for energy production is assessed against several criteria of biophysical suitability, accessibility, technical feasibility but also sustainability. The experts tried to take into account the criteria in this assessment within the limits of available information.

1 General inventory of wood (ligneous) resources in the territory

1.1 Forestry resources

Rodrigues' native forest was completely destroyed in the 19th century. However, a vast reforestation program was initiated at the end of the Second World War and today the island has more than 4,000 ha of forest area (out of a total of 10,500 ha). The forest formations are all composed of fast growing "exotic" species: *Acacia nilotica, Casuarina equisetifolia, Eucalyptus tereticornis, Terminalia catappa, Syzygium jambos, Pongamia pinnata*.

The forest inventory carried out in 2002 lists about 1600 ha of forests managed by the State. The Forest Services distinguish two main types of forest: Eucalyptus plantations (Eucalyptus tereticornis) and mature mixed forests. The forest inventory estimated standing stock (log) at 108 m3/ha in Eucalyptus stands and 128 m3/ha in mature forest. These forests are no longer exploited for their timber. Nevertheless a small private production of charcoal and Eucalyptus poles for construction still exists.

In the late 1980s, a program to combat deforestation and erosion of coastal areas created 90 ha of Acacia Nilotica plantation in various parts of the island. Today, due to agricultural abandonment and extensive farming (which disperses seeds), this species has spread widely in the lower parts of the island and it can be estimated that surfaces invaded are about 800 ha, to varying degrees.

Given all these elements (large areas and stocks, little concurrent logging), forest resources may be a priori considered as a major resource for energy production.

1.2 Ligneous fraction of green wastes

Green waste resulting from maintenance of individual or collective green spaces includes a woody fraction (branches, hedge sizes...) that could potentially be used for energy production. In Rodrigues, as in most tropical areas, green waste can represent significant volumes, moreover after cyclonic events such as those recently suffered by the island during the austral summer 2019.

However, to date the woody waste resource actually available for energy recovery seems very limited because of the lack of a suitable collection system. There is so far no appropriate selective sorting and disposal site.

- Individual green wastes are not collected regularly and the practice of individuals is mainly to burn them, to compost them for personal reuse, or to let them degrade in their garden.
- Green waste from the maintenance of public parks and roadsides are transported to a single storage center (not visited) where they should be ground. But at the time of the missions the shredder was out of order.

The green waste resource is not currently known and is rather difficult to assess. It can not be considered as available in the short term because it requires the implementation of a collection / sorting system adapted to ensure a fuel quality and a regular supply for a potential new power plant.

Nevertheless, it could represent in the future a complementary resource.

1.3 Agricultural resources

Agricultural resources from lignocellulosic harvest residues and from agri-food industry are low. The only local production that might provide biomass is maize (Zea mays), which occupies roughly all agricultural land (80% of cultivated area), but on the one hand this production is low and dispersed and on the other hand the totality of the plant is already used for food or feed: grains + leaves + stems. Orchards are usually not pruned and therefore don't provide woody biomass.

There is almost no agri-food processing on the island. The only units identified are, to our knowledge: a small artisanal production unit of coconut oil (200 nuts / year), a unit of extraction of essential oil of Limon, a unit of production of cassava flour. These units, however, do not generate enough dry waste that can feed a bioelectric unit. In addition, agricultural areas in food products tend to decrease, due to a general decrease in rainfall for about 15 years.

Photo 1 : agricultural and forest landscapes of the island

Thus, it appears that the ligneous resource derived from state forests and other wooded land of the State is today the only potential source of biomass likely to supply a biomass power station in the short term.

The following chapter details the production conditions of this biomass and estimates the quantities available.

2 Analysis of forestry resources

The challenge of the present part was

- to inventory and map the typologies of forest formations on the island and to assess their areas (ha);
- to select formations which migh be exploited in the short or longer term for energy uses and to estimate the resources that can be mobilized, within the limits of available information, by hypotheses of technical itineraries.

The results will be expressed at this stage in tDM / year (tonne of dry matter per year). These data will be retranscribed into energy potential (electrical) in the following part.

2.1 Mapping of forest formations

In the present study, a map of the island's forest resources was made by visual interpretation of a SPOT 6 image (December 2013) available on Google Earth. Only this image allowed total coverage of the island without clouds.

The methodology was as follows:

1- The image was first segmented according to the color of the forest cover, its texture and its density.
2- In a second step, more than 50 checking points were taken in the field during the second mission.

This work resulted in discriminating 7 large classes of forest formations:

- Acacia Nilotica formations in almost pure stands
- Eucalyptus plantations in almost pure stands (Eucalyptus tereticornis)
- Mixed formations dominated by Eucalyptus (Eucalyptus tereticornis)
- Filao plantations in almost pure stands (Casuarina equisetifolia)
- Mixed forests, Syzygium jambos (Jambrozoa), Pandanus heterocarpus, Pongammia pinata, Cassine orientalis, Albizia lebbeck, etc. ;
- Riparian mixed forests where Albizia lebbeck is very present.
- Mangroves (Rhizophora microlata)

The areas are given in Table 3.

Formation	Areas (ha)
Acacia Nilotica	1080
Mixed dominated by Eucalyptus	430
Eucalyptus Plantations	679
Filao Plantations	101
Mixed forest	1717
(of which planned restoration areas)	(780)
Riparian mixed forests	204
Mangroves	30
Total	4241

Table 3: surfaces of the forest formations in Rodrigues (source: visual interpretation of 2013 images)

The forest inventory carried out in 2003 recorded 547 ha of eucalyptus plantations and 1025 ha of mixed forests. But the areas surveyed and inventoried did not include private plots, Acacia plantations or Filao plantations.

The forest areas identified in the 2013 image are therefore much higher than those inventoried in 2003. This difference can be explained by the fact that formations on private domain (almost 20% of the total area) is taken into account, but also by natural expansion of forest formations (acacia, eucalyptus, albizia) on certain hillsides, valley bottoms and pastoral areas.

The map (figure 4) reports all the forest formations detected, including the priority restoration areas defined by the Forest Service.

Finally, for each of the forest formations (seized polygons), the following exploitability parameters were calculated:

- Minimum, maximum and average slopes
- Distance closest to the road or practicable track

The maps of these parameters are given in appendix.

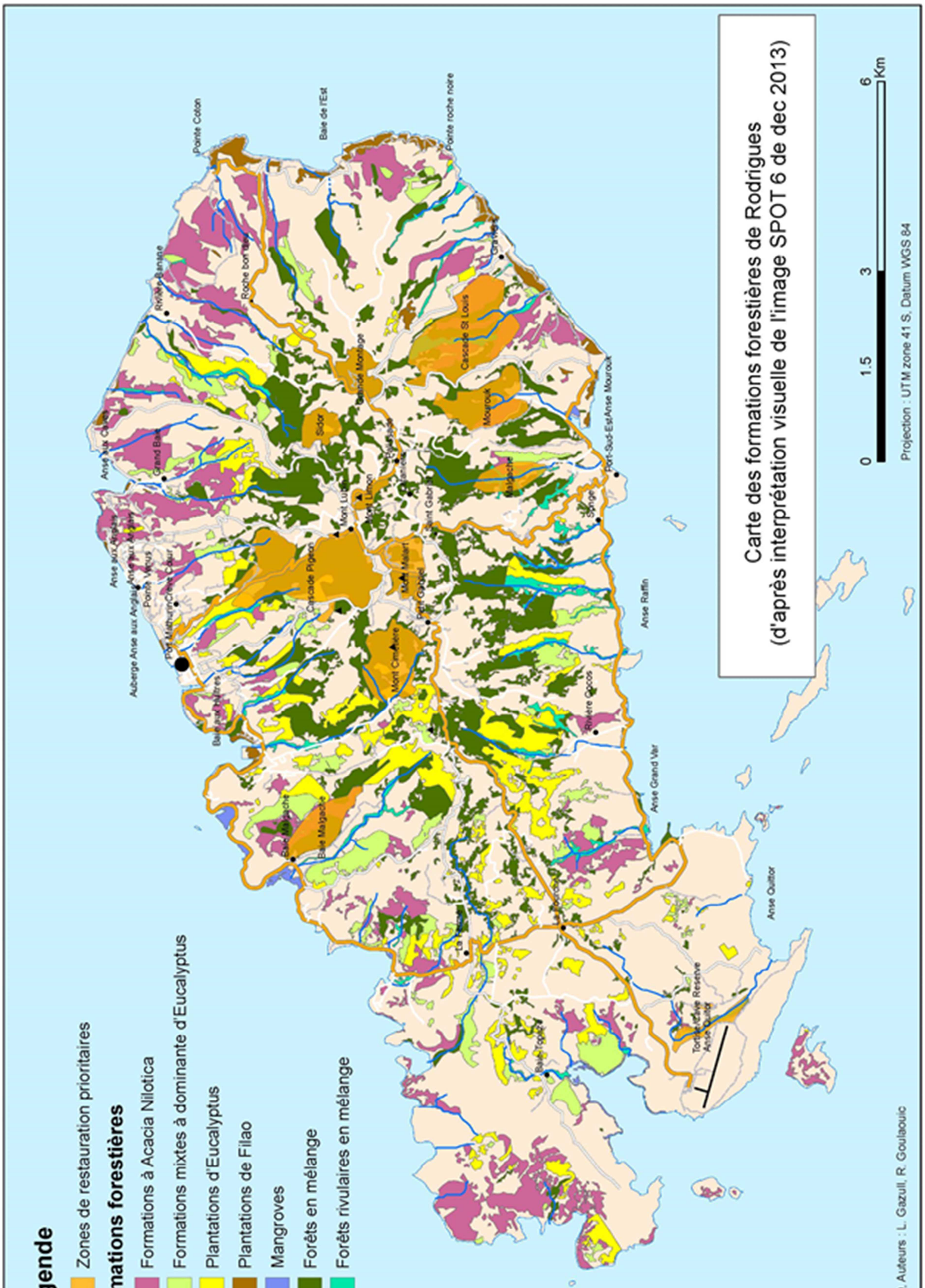


Figure 4 : Map of Rodrigues Forest Formations

2.2 The exploitable resources in the short term

Three types of resources are selected as exploitable in the short and medium term for energy use:

- Eucalyptus plantations
- Residues from exploitation of mixed forest restoration sites
- Acacia Nilotica plantations

2.2.1 'Eucalyptus plantations

Inventory and analysis of exploitation conditions

Eucalyptus was introduced in Mauritius and other Mascareignes Islands in the early 19th century. On Rodrigues, its growth was particularly important from the 1970s (Kueffer and Mauremootoo, 2004). Although *E. grandis* can be found, *E. tereticornis* is largely dominant. This Eucalyptus was chosen for its resistance to drought (annual average rainfall> 500 mm) and to strong winds (up to 160 km/h).

The plantations of *E. tereticornis* represent in Rodrigues about 600 ha almost exclusively on the state domain. The planting density is about 1000 stems/ha (spacing 2m x 2m). On the other hand, it seems that Eucalyptus has naturally colonized some spaces outside the initial plantations where it can be found in formation with *Acacia Nilotica* or *Albizia lebbeck*.

Photo 2 : Eucalyptus stand managed in coppice

1/3 of the plantations is located on slopes less than 30% easily accessible and the remaining 2/3 is situated on slopes between 30% and 60% allowing a manual or mechanized exploitation with dedicated machines.

95% of the plantations are located within 500m of an existing road or pathway.

Today the plantations are very largely under-exploited. They are mainly used for the production of poles for construction (about 15,000 poles/year according to the forest services, the equivalent of 15 ha under exploitation) and the production of honey much sought after by the inhabitants. These uses can easily be reconciled with the potential exploitation of these formations for energy purposes.

➔ In total, it can be considered that all the plantations are exploitable manually and that almost all the logs can be used.

➔ Nevertheless, we stated that 20% of the massif will not be exploited for wood-energy purposes for various reasons: exploitation for poles and timber, inaccessibility, damaged plots, too steep slopes ...)

Estimation of available biomass energy potential

In order to produce wood energy, these plantations can be managed in coppice with very short rotation (rotation of about 5 to 7 years and cycles of 4 to 5 rotations). The regrowth capacity of *E. tereticornis* is excellent, with rapid individualization of 2 to 3 future strands per stump without the need for depressing (Sims et al., 1999).

According to literature, the wood-energy productivity (trunk + branches) of such plantations under conditions close to those encountered in Rodrigues is between 5 tDM/ha/year and 13 tDM/ha/year (with a trial observed at 25 tDM/ha/yr) (Adegbehin et al., 1988; Ahimana and Maghembe, 1987; Chapola et al., 1995; Pima et al., 2016; Ugalde and Pérez, 2001; Verhaegen et al., 2014).

According to the 2003 forest inventory, the average standing roundwood stock of these plantations would be 108 m3/ha, ie about 60 tDM/ha of roundwood (measured density = 0.56 tDM/m3) and 90 tDM/ha of wood energy (with a biomass expansion factor of 1.5 according to literature). This would correspond over 7 years to a harvest rate of about 13 tDM/ha/year without risks concerning the sustainability of the resource.

For our estimates, we will first consider a cautious productivity assumption of about 5 tDM / ha / year that can be exploited because (i) the massif has not been subjected to a long-term monitoring and management plan; (ii) some plots may have been damaged by cyclones, fire or over-exploitation. Given the bioclimatic conditions of Rodrigues, the productivity of the massif can be progressively improved by good management and improvement of the genetic material, which leads us to a hypothesis of roughly 10 tDM / ha / year over the longer term.

Thus, over a period of 30 years (at the end of which it will be necessary to renew the plantations) the quantity of biomass available in the short term would be in the order of 2400 tDM / year (low hypothesis).

This potential could be gradually increased to 4800 tDM / year by improving management of the massif and by replacing old tree material.

2.2.2 Residues from exploitation of mixed forest restoration sites

Inventory and analysis of exploitation conditions

The hypothesis adopted here is the continuation of the restoration program initiated by the Rodrigues Environment Commission, which consists of replacing exotic trees and associated forest formations by endemic or indigenous trees. To date, the wood of exotic trees is left on site and therefore represents a wood resource available for energy production. Only these residues are considered as a potential source of biomass energy. No collection of native / endemic species is considered here.

According to the Forest Service:

- approximately 780 ha should be restored as a priority ;
- the current rate of restoration is in the order of 10-15 ha / year.

Restoration is therefore a very ambitious project that could take some 50 years to complete. Restoration residues could thus represent a significant additional resource.

Photo 3 : Mixed mature forest being restored

Nevertheless, many questions remain about the technical routes for the exploitation and export of wood.

- In order to reduce impacts on soils, runoff and native flora, collection should be done manually. It seems difficult to get out the big woods and work on steep slopes. However some sites (Cascade St Louis, Mourouk, Malagasy) have steep slopes, sometimes beyond 100% and will therefore be difficult to be exploited. Field analysis shows that 20% of the surfaces of these sites have slopes above 60%.

  ➔ By avoiding steep slopes (> 60%) and shallows, the practically exploitable area would be in the order of 500 ha.

- The future of large trees (diameter> 35 cm) does not seem to be clearly defined in the restoration scheme: should they be removed or not according to the risk of opening the forest too widely and causing logging damage? According to the 2003 forest inventory, these large trees mainly concern Eucalyptus tereticornis, Cassine orientalis (olive wood), Mangifera indica (mango trees), Terminalia arjuna, Araucaria, etc. These large trees represent more than 25% of the standing stock.
- Finally, a part of the biomass (leaves, small branches) must remain on the ground after felling the tree, in order to protect the soil from risks of erosion and to contribute to its fertility.

  ➔ Thus it will be assumed that only the main trunk can be exported.

Estimation of available biomass energy potential

The forest inventory estimates that the stock of standing roundwood contained in these forests, excluding crowns, branches and leaves, is 128 m3/ha. Assuming an average dry biomass density of 0.56 tDM/m3 of fresh wood (default setting by FAO in Africa), the total stock would be 70 tDM/ha. Excluding large trees (Diam> 35 cm) this stock is reduced to 50 tDM/ha. However, this figure seems a little overestimated and many areas invaded by Pongammia or Jambrozoa seem to have lower stocks. We will rather keep the figure of 40 tDM / ha as exploitable potential.

Considering the pace indicated by the forestry services (15 ha / year), the restoration residues could represent a biomass supplement of 600 tDM/year for 40 years. However, given the potential hazards: availability of labor, cyclones, financing of restoration projects, we will retain a conservative assumption of 10 ha / year.

Thus in the short term, the complement would be reasonably in the order of 400 tDM/year over 40-50 years.

2.2.3 Acacia Nilotica

Inventory and analysis of exploitation conditions

Acacia Nilotica is a species that was the target of a large planting program in Rodrigues from 1975 to 1989. The objective of this operation was to create a forest cover to fight against soil erosion in the lower and dryer parts of the island which were subjected to agricultural abandonment. In 1975, 83 ha were planted by the forest service at a density of 1600 trees / ha. In 2005, the Forest Service estimated that the area covered was 187 ha. Today, according to the interpretation of the satellite images, the covered surface can be estimated at about 1000 ha. Nevertheless, this figure includes formations with very variable densities: only 100 ha have a high density (initial plantations of the 1980s with more than 1000 trees / ha), 300 ha have an average density (old colonized zones with more than 150 trees / ha) and 600 ha are very sparse (areas being colonized with between 50 and 100 trees / ha).

This tree is very invasive. Its very abundant seeds are propagated mainly by farm animals (cattle, goats, sheep) and the tree easily regrowths from stumps. The Acacia is not appreciated by the local population because it is a very thorny tree and very difficult to control manually. Nevertheless, its foliage is appetized by sheep and goats and is therefore source of forage during dry season. It invades valleys and hills, mainly at altitudes between 0 and 100 m, and forms dense, monospecific clumps, whose dark shading prevents the development of a herbaceous layer.

Thus, if the acacia can represent a source of fodder in its young stage and in low density, in the adult stage its invasion strongly degrades the pastures.

The eradication of acacia, as well as its management, are complex problems for several reasons:

- The stock of seeds scattered by animals and contained in the soil is very important today and its development potential is therefore very strong ;
- Acacia is a highly heliophilic species. Thus the opening of the medium favors its germination and expansion. The destruction of adult individuals thus leads to accelerated germination and colonization of young plants;
- Acacia grows in dry areas, in difficult reliefs and soil conditions, and where alternatives are limited;
- Acacia was planted to protect the soil from erosion and its eradication by leaving bare soil could lead to increased erosion;
- Acacia is a source of dry season forage for sheep and goats and is appreciated by pastoralists in some arid areas of the island, although the vast majority of Rodrigues consider it a pest;
- Acacia is a very thorny plant that requires delicate work during any manual treatment: pruning, thinning, cutting ...

In 2005, the Forest Service had already established a program for the control and progressive eradication of this species. It appeared that this work is very demanding in manpower and that it needs to be differentiated according to the zones and the age of the formations.

In the short term only the exploitation of old stands (1980s plantations) seems possible.

In old, dense plantations (about 100 ha), stands might be exploited by tree pruning and manual thinning at a rate of about 50%. However, a global management and control plan would also be needed at the island scale in order to combine invasiveness control and wood energy production. Some propositions are given in the following chapter.

Photo 4 : An old Acacia Nilotica plantation

Estimation of available biomass energy potential

Estimating available biomass from such management/exploitation is difficult in the absence of in situ measurements and bibliographic references. However, the few existing references report, for plantations of 20 to 25 years under conditions of 500 mm to 800 mm of annual rainfall, growing stocks between 50 m3/ha on the poorest soils and 200 m3/ha on the richest sites and with thinnings after 5 years (Goda, 1986; Indian Council of Forestry Research and Education, 2015; Maguire et al., 1990; Tewari and Singh, 2006).

➔ The figure of 50 m3 / ha for the old Rodrigues plantations will be retained, ie 37 tDM / ha (density of 0.75 kg DM / m3).

The volumes that could be collected during thinning and pruning would be in the order of 3 m3/ha/year, ie 2.2 tDM/ha/year. But these estimates are very uncertain and it would be necessary to carry out a general inventory of planted and invaded areas throughout the island as well as biomass measurements.

The products of the management of old acacia clumps could thus represent in the short term a biomass supplement in the order of 200 tDM/year (100 ha).

2.3 Exploitable resources in longer term

In the context of Rodrigues, two types of resources may be exploited in the longer term:

- Pastoral areas invaded by Acacia Nilotica
- New forest plantations for energy purposes.

2.3.1 Pastoral areas invaded by Acacia Nilotica

As mentioned in the previous section, currently over 900 ha have been invaded between 1990 and 2014 and this figure is certainly underestimated, considering recent field visits. The western part of the island seems particularly affected by this phenomenon.
300 ha have already reached average density (old colonized areas with more than 150 trees / ha) and 600 ha are still sparse (areas undergoing colonization with between 50 and 100 trees / ha).

Photo 5 : Invasive Acacia Nilotica progress in pastoral area

As previously mentioned, the total eradication of Acacia Nilotica would require a lot of time and resources with no guarantee of results. Controlling invasiveness, combining pastoralism and wood energy production seems to us a more reasonable solution.

In the context of the island the main principles of such a management mode are:

- Maintain a tree density that is low enough to allow the herbaceous layer to grow and provide forage for the animals. Acacia Nilotica is a legume, it enriches the soil and improves pasture. The density of trees is maintained by regular thinning and regeneration control, either by animals eating young seedlings, or by human mechanical cleaning (rotary grinding) or manual cleaning;
- Maintain cover in areas of steep slopes that are prone to erosion;
- Allow easy exploitation of the tree resource.

In practice, resource management techniques in space and time can be very variable. There are different solutions around the world that have been tested for this type of silvopastoral space management. Nevertheless, there is no standard solution and such a management plan requires a complementary in-depth study. The solutions depend on the involvement of pastoralists, their grazing practices, the possibilities of mechanization (accessibility, slopes, etc.), the resources allocated to the control of regeneration and the fixed production objectives (in terms of quantity and types of biomass to produce).

In the end, the tree density should not exceed 200 trees/ ha and a cover rate <30%. In such a system, woody productivities could be in the order of 1 m3/ha/year, or 0.75 tDM/ha/year on operating cycles of about 10 years (Audru et al., 1991; Goda, 1986). The surfaces that can be exploited according to this management mode remain to be determined. But by limiting to the easily accessible areas (pastures of slight slopes to the West and East of the island), we can estimate at 400 ha the potential surface. Thus, in theory the exploitation of these silvopastoral spaces could represent in the long term a complement in biomass in the order of 300 tDM / year (400ha).

However to date, the establishment of such stand management seems to be excluded by the Region, which has confirmed to the experts its desire to carry out an eradication program as soon as possible and would invest in technical resources, such as crusher set on excavator. The experts have no visibility as to the possibility of producing wood energy with acceptable quality by these methods of exploitation, which are likely to lead to very heterogeneous shredded grinds.

Therefore, given the very high uncertainty about the management of the trees formations and the Region's willingness to eradicate the Acacia gradually, this resource can not be considerd as a potential and sustainable supply complement for a power plant.

2.3.2 New forest plantations for energy purposes

90% of Rodrigues lands belong to the State which thus owns a large land reserve for new plantations, managed either directly or by delegation of service. Creating energy plantations, in a future to be defined, can be a feasible solution to secure the supply of a plant, increase production and better control the costs.

A recent attempt by the forestry services to create a new forest area of about 100 ha in the west of the island has been unsuccessful, in particular because of the lack of acceptance of such a project by local farmers. Nevertheless, such a failure deserves to draw the necessary lessons to find solutions of plantation and management, probably better adapted to the practices of the breeders and better adapted by the local populations.

Mixed plantings for mixed use: shade, fodder and wood energy should be considered and further studied.

A properly managed 100 ha plantation could bring in the order of 500 tDM / year to 1000 tDM / year at the plant.

2.4 Summary of exploitable resources: estimated potential and constraints

Table 4 gathers the potential estimated by resource type, as well as the strengths and weaknesses to be taken into account.

Resources	Potential estimated (tDM/an)	Strengths	Weaknesses
		Short/medium term	
Eucalyptus Plantations	2400	Known resource Plantations already existing but underutilized No competition with current uses (honey, stems ...)	Old plantations whose condition must be better evaluated Need renewal to consider
Mixed forest restoration	400	Exotic wood not exploited to date	Uncertain technical routes Productivity related to restoration programs
Acacia Nilotica - old plantations	200	Old plantations more exploitable than invaded areas	Current biomass stocks (tDM / ha) to be validated
Total short term	**3000**		
		Longer term complements	
Improvement of Eucalyptus plantations	+ 2400	Genetic material adapted to Rodrigues conditions Durability of the deposit	Forecast Investments
Acacia Nilotica – in silvopastoral spaces	-	Expansion control and compatibility with livestock	High uncertainties about operating techniques Political will to eradicate
Energy plantations	+ 800	Land available Plantations adapted to a low cost operation	Accounting with livestock?
Total long term	**+ 3200**		

Table 4 : Summary of available resources (in tDM/year) estimated by types of exploitable forest resources in Rodrigues

The order of magnitude of the available potential in wood-energy is around 3000 tDM/year in the short- to medium-term, mainly from the exploitation of Eucalyptus plantations and supplemented by wood resources from forest restoration and the exploitation of the oldest stands of Acacia Nilotica.In the longer term, an additional potential estimated at around 3200 tDM/year of woody biomass could be derived from (i) better management of the Eucalyptus plantations, by progressively replacing genetic material and respecting low impact logging rules ; (ii) new forest plantations for energy purposes. The long-term potential may be about double the current potential.

On the other hand, the exploitation of pastoral areas invaded by Acacia Nilotica, in a short-term eradication logic, can not be considered as a sustainable source of biomass energy.

Preliminary evaluation of a bioelectricity chain

This part aims to

- estimate first order of magnitude of capacity for a power station supplied by the resources selected in the previous section;
- propose several technical orientations;
- identify the technical and territorial opportunities / constraints concerning the various parts of the whole chain (Figure 5).

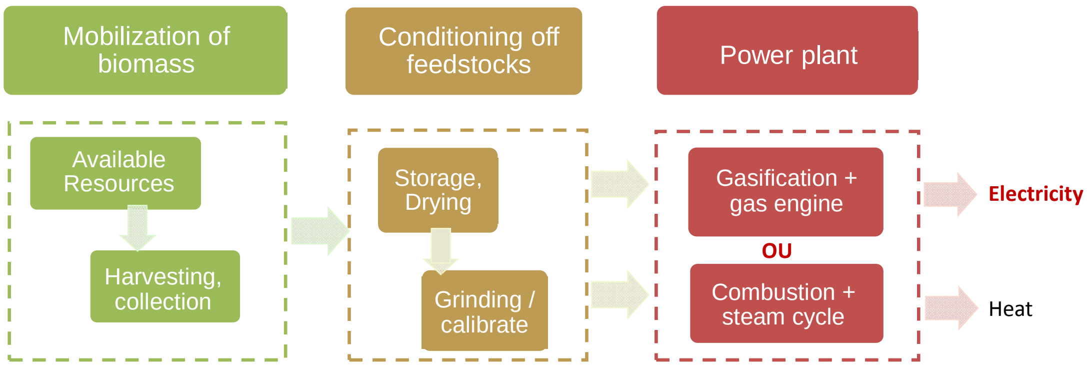


Figure 5 : Gasification and combustion processes in a bioelectricity chain

1 Pre-scaling of a potential power plant

1.1 Primary energy available

1.1.1 Assumptions retained - fuel

The exclusive energy resource for the plant is wood. Its energy content, which corresponds to the Lower Heating Valuer (LHV), depends on its humidity, organic and minerals composition.

Wood LHV is in fact little dependent on the species considered. It is in the order of 5100 kWh/t on a totally anhydrous basis for a hardwood. **LHV of 4350 kWh/t** will be further used as reference in the continuation of the study, for a so-called dry wood at 13% humidity (representative value of wood dried in ambient conditions). Note that the LHV of a wood with higher moisture content would be lower, which would impact energy efficiency.

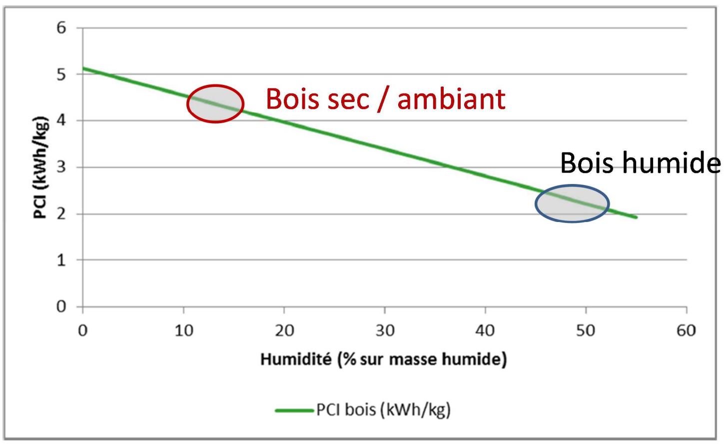


Figure 6 : Wood LHV (=PCI in French) as a function of its humidity (source Valbiom)

1.1.2 Short and long term estimates

The available primary energy corresponds to the energy content of the biomass to be treated annually by the power plant. The values calculated from wood resources estimated in short and long term in previous section are given in the table below.

	Unit	Short term hypothesis	Long term hypothesis
Biomass feedstock	**tDM/an**	**3 000**	**6 200**
LHV (kWh/t)	MWh/t	4,350	
Primary annual energy	**MWh_{LHV}**	**13 050**	**27 000**

Tableau 5 : Annual primary energy corresponding to estimated short and long term wood resources.

1.2 Potential electrical power

1.2.1 Conversion processes and related concepts / definitions

The power plant includes processes that make allow producing electricity from biomass feedstock, and heat that can also be used. Two types of thermal processes are at this stage selected: combustion and gasification (Figure 5), whose principles and technologies will be discussed in more detail later.

Combustion and gasification processes are available in a very wide range of technologies, which are distinguished by several criteria, including: their technical, economic and environmental efficiencies, their availability according to the targeted production capacities, their reliability, the imposed constraints on feedstocks...

The production capacity to be installed is a first decisive element allowing to tighten the range of possible technologies. Assumptions used for this first evaluation phase are fiven below.

The capacity of a power plant is characterized by

- the annual tonnage of biomass treated (tDM/year) and the associated primary energy (kWh_{LHV});
- the electrical energy actually produced over one year of operation (kWh_{el});
- the electrical power produced (kW_{el}) - power rating when operating at full load.

The electrical efficiency is the ratio between the electric power (or energy) produced and that contained in the treated biomass = kW_{el} / kW_{LHV} (%).

1.2.2 Hypothèses de performances/fonctionnement retenues pour la centrale

- The overall availability rate is assumed to be 86%, corresponding to an operation of 7500 h / year of the plant (against 8760 h in a full year). This availability rate includes periods of shutdown, maintenance. This data is of course strongly related to the reliability of the chosen technology. This is a particularly important performance criterion that has to be considered in the analysis of offers on the market.
- The load factor is considered as equal to 1. This hypothesis will be justified a posteriori, since the electric power produced to which one leads is very weak compared to the threshold consumption on Rodrigues electrical grid (in the order of 3.5-4 MWel). It is thus conceivable that the biomass plant is operated at full capacity, without suffering the consequences of variations in power demand.
- The electrical efficiency is conditioned primarily by the technology, but also by many parameters related to the actual operating conditions of the plant (fuel quality, maintenance of equipment, technical skills of operators ...)

➔ In a first stage, reference efficiency will be set to 20%, however with possible variation over a range of 15 to 25%.

1.2.3 Short / long term estimates

Table 6 gathers the results of the estimates made for an average electrical efficiency of 20%, based on the wood resources estimated in the previous section. The capacity of a power station would thus potentially be 350 kW in the short term and 720 kW in the longer term.

These values should only be considered as orders of magnitude, within the limits of the assumptions described above and estimates of available resources. Figure 7 illustrates the sensitivity of the calculations to the efficiency assumption.

	Unit	Short term hypothesis	Long term hypothesis
Biomass input	**tDM/year**	**3000**	**6200**
Annual primary energy	MWh_{LHV}	13046	26961
Electrical efficiency	%	20%	
Feedstock consumption	tDM/MWh_{el}	1,15	
Annual electrical energy	**MWh_{el}**	**2609**	**5392**
Running annual duration	h	7500	
Disponibility rate	%	86%	
Electrical power delivered	**kW_{el}**	**350**	**720**

Table 6 : Calculations of the electrical power of a biomass power plant

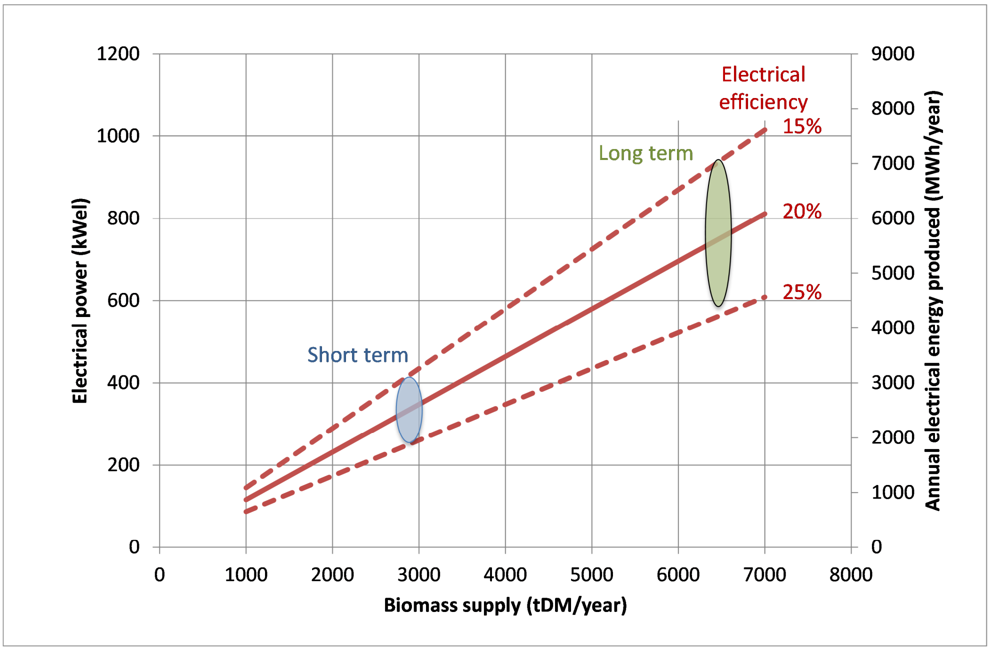


Figure 7 : Electrical power estimation for different electrical efficiency values (15-25%), depending on biomass supply capacities.

Following comments can be made from these estimates.

1- The power plant capacity would be approximately 10-15% of the threshold power consumption in Rodrigues. This confirms that the plant might be operated in base production at full capacity, with no risk of suffering from changes in power demand of the network.

2- The plant can be classified in the category of small / medium powers according to the terminology commonly used in the bioenergy sector (<1 MWel), which allows to propose several initial orientations towards adapted technological solutions (discussion of the next point) .

3- These two points remain valid (i) considering the potential deposits in the short or longer term; (ii) taking into account uncertainties about efficiencies that are dependent on technological choices.

2 Proposals for solutions

2.1 Suggested technology for the power plant

2.1.1 Differences in principles between gasification and combustion

In a very simplified way, Figure 8 illustrates the principle of a biomass combustion plant:

- The fireplace, where the combustion occurs, is supplied with biomass feedstock and air to produce heat.
- In the boiler, pressurized steam is produced from heat and feeds a rotating machine (turbine) coupled to an electricity generator. This set is commonly called "steam cycle".

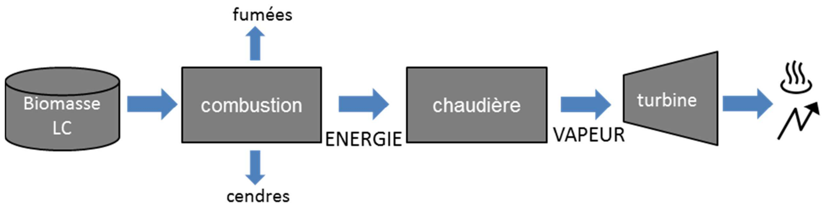


Figure 8 : combustion electricity generation (schematic diagram)

Similarly, Figure 9 illustrates the principle of a gasification plant:

- The gasification reactor (gasifier) converts biomass into combustible gas by thermochemical processes.
- After purification, these gases are burned in an engine coupled to a generator.

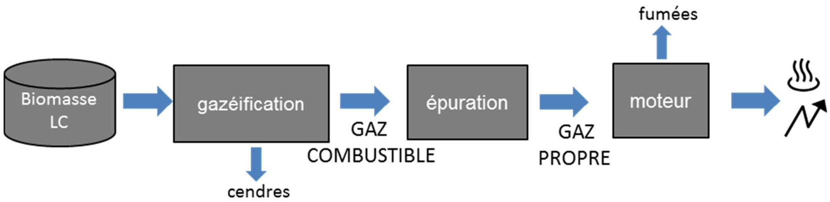


Figure 9 : Gasification electricity generation (schematic diagram)

Combustion and gasification processes are available in a very wide range of technologies, which are distinguished by several criteria, including: their technical, economic and environmental performance levels, their availability according to the targeted production capacities, their reliability, the imposed constraints on feedstocks...

Table 7 summarizes the main features of a selection of technologies that we believe are best adapted to power generation and more fully described in another IOC study [49]. Their strengths and weaknesses are discussed below in the specific context of Rodrigues.

2.1.2 Comparative Analysis in the Context of Rodrigues

Combustion: a proven biomass solution, but with limits for low powers

Biomass combustion power systems are mature and commercial technology around the world. Combustion technologies cover a very wide range of power, from small domestic stoves of a few kilowatts to large CHP plants of several tens of MW.

Stationary or mobile grate fireplaces are both (i) proven technologies; (ii) adapted to a wide range of biomasses; and (iii) affordable in terms of investment cost. They can therefore meet energy needs in a very wide power range, but the energy efficiencies of small power plants are generally lower than those of larger plants.

However, in electricity production the power of reference installations is generally above 1 MWel. A few manufacturers offer lower power technologies, but with much less performance hindsight. The main constraint concerns the power generation module because the technologies are not very profitable for the small powers.

- Steam turbine is the most widespread technology, but only on high power plants. For lower powers, the efficiency is lower and the high maintenance costs are a strong constraint.
- For low-scale installations, steam engine technology can be used when easy and low-cost maintenance (compared to steam turbines) is desired. The technology is not widespread because there are very few manufacturers and the overall electrical yields are low (8 to 15%).
- Finally a last alternative could be ORC (Organic Rankine Cycle) technology but the applications are rather the production of electricity from lost and low temperature heat. Low power technologies for high temperatures are extremely expensive and maintenance constraints too high.

Type	Power (kW_{el})	Electrical efficiency (%)	Constraints on feedtock Moisture content (M) Particle size (PS) Density (D)	Limits
Combustion **Stationary or mobile grate +**			Various feedstocks: wood, agricultural residues, pellets	
- Steam turbine	1 000 - 40 000	20-30 %	M : 5-40 %	Cost - Maintenance at low scale
- ORC	1 000 - 10 000	10-15	PS>10 mm	
- Steam engine	100 - 1 000	5-15 %	Little fine particles Low ash content	Availability and reliability
Gasification **Fixed or staged bed** **+ gaz engine**			Calibrated wood chips Coarse and dense residues	
- « simple » technologies	20-500	10-20 %	M < 20% PS : 30-100 mm	Tars, reliability
- « efficient » technologies	20-300	15-25 %	No fine particles D > 300 kg/m3	Maintenance, Constraints on feedstock

Table 7: Analysis grid for a selection of biomass combustion and gasification processes (adapted from ref [49])

Gasification: a possible alternative to combustion at low scale

Technologies are available and widely distributed at low and medium scales for power generation. In these ranges, the fixed bed technology, relatively simple, is recommended and is particularly suitable for calibrated and previously dried feedstocks, such as wood chips.

Fixed bed technologies can be classified in the following categories:

- The so-called "simple" technologies are the least expensive in terms of investment costs and are generally implemented in Southern countries (Asia in particular). They often require a numerous workforce and are little reliable in the long term.
- The so-called "high performance" technologies are more complex, more expensive but on the other hand more reliable with references rather located in a European context. In particular, this efficiency gain is achieved through a precise control/command which adds a level of complexity to the operation and requires careful equipment maintenance.

Beyond these differentiating characteristics, both technology categories generally have the same specifications regarding feedstocks (Table 7), particularly in terms of moisture content.

A strong limitation of "simple" technologies is the production of liquid co-products (tars) whose management can be problematic from a regulatory and environmental point of view. Their slightly lower energy efficiency may not be limiting in some projects where biomass is available at very low cost, which is unlikely to be the case in Rodrigues.

Finally, it should be noted that some technology providers offer so-called "cascade" solutions consisting in coupling several reactors in parallel to supply synthesis gas to one or more engines. This possibility would make it possible, for example, to plan a gradual increase in capacity over time.

Figure 10 : Examples of power plants on the principle of coupling parallel (cascade) gasification reactors

To summarize, our recommendation for the power plant a technology based on fixed bed gasification, a solution that seems the most adapted to the context of Rodrigues, especially with regards to the potential capacity foreseen. For reasons of reliability and efficienct, robust solutions are recommended, even though they are more expensive to purchase, and provided that technical staff can be trained.

2.2 Feedstock conditioning

The recommended feedstock for these types of process is wood chip, which is a form of shredded wood, made of homogeneous pieces of wood, usually about 3 x 3 x 0.5 cm. It is the most common form of wood energy suitable for many combustion or gasification technologies.

This option seems to us the most relevant, since the resources identified in the short / medium term are exclusively forestry resources, whose sizes (stems, trunk ...) are compatible with the production of chips.

Photo 6 : Examples of wood chips

The preparation / conditioning steps consist mainly of grinding, screening, and drying processes, in order to obtain the size and moisture content specified by the technology provider.

The following assumptions are made:

- The losses of material during the grinding process are assumed to be marginal (in the order of 5% by expert opinion). The grinding can be carried out either with a fixed shredder on a location dedicated to the conditioning, or with a mobile forest shredder.
- Wood chips must be dried to a moisture content of about 15%, which corresponds to the most restrictive specifications (gasification). This drying could be operated in two steps:
    - A natural pre-drying up to a moisture content of 20-30% on a conditioning / storage platform described below.
    - A controlled complementary drying step at the power plant location, by using the heat co-generated by the thermal conversion process, without additional energy requirements.

2.3 Organization of wood chips supply

Rodrigues authorities are willing to create a supply chain upstream the power plant, allowing the creation of a maximum number of jobs in rural areas. As illustrated in Figure 11, this supply chain could be articulated around

- two major circuits of wood harvesting : on the one hand from eucalyptus satnds and on the other hand from forest restoration and acacia management programs;
- a platform supplied by both circuits and dedicated to the drying and preparation of wood chips that will be delivered to the plant.

Wood harvesting circuits

Forest resources can be exploited either directly by the forest service or by private loggers under contract. In particular, the exploitation of Eucalyptus plantations offers the possibility of developing small logging companies.

Once logged, the wood can either be directly delivered or on-site shredded to wood chips thanks to mobile shredders. In particular, the Forest Service could invest one dedicated either to restoration works on the mixed forest or to Acacia Nilotica thining operations.

However, we believe that in Rodrigues context, and in order to avoid large investments by small private loggers, a central shredding and storage platform could be built by local authorities.

Storage / shredding platform

The platform would be equipped with a fixed (or mobile) shredder and would include a sheltered storage / pre-drying area. An estimated dimensioning is provided in the following section. The platform management might be either operated by the region (forestry service or any other service), or entrusted to a private company, accompanied by the forest service. The services provided would be

(i) receiving and unloading raw wood or fresh chips brought by loggers;
(ii) shredding wood;
(iii) storing the wood chips on a concrete floor slab under shelter for 4 to 6 months, until reaching a moisture content to be defined according to the constraints fixed by the plant;
(iv) control the wood chips moisture content;
(v) regularly supply the power plant with 10 m3 trucks.

In terms of location, the platform should ideally be located close to forest areas, for example in the West region to have easy access to land and a drier climate than in the center of the island.

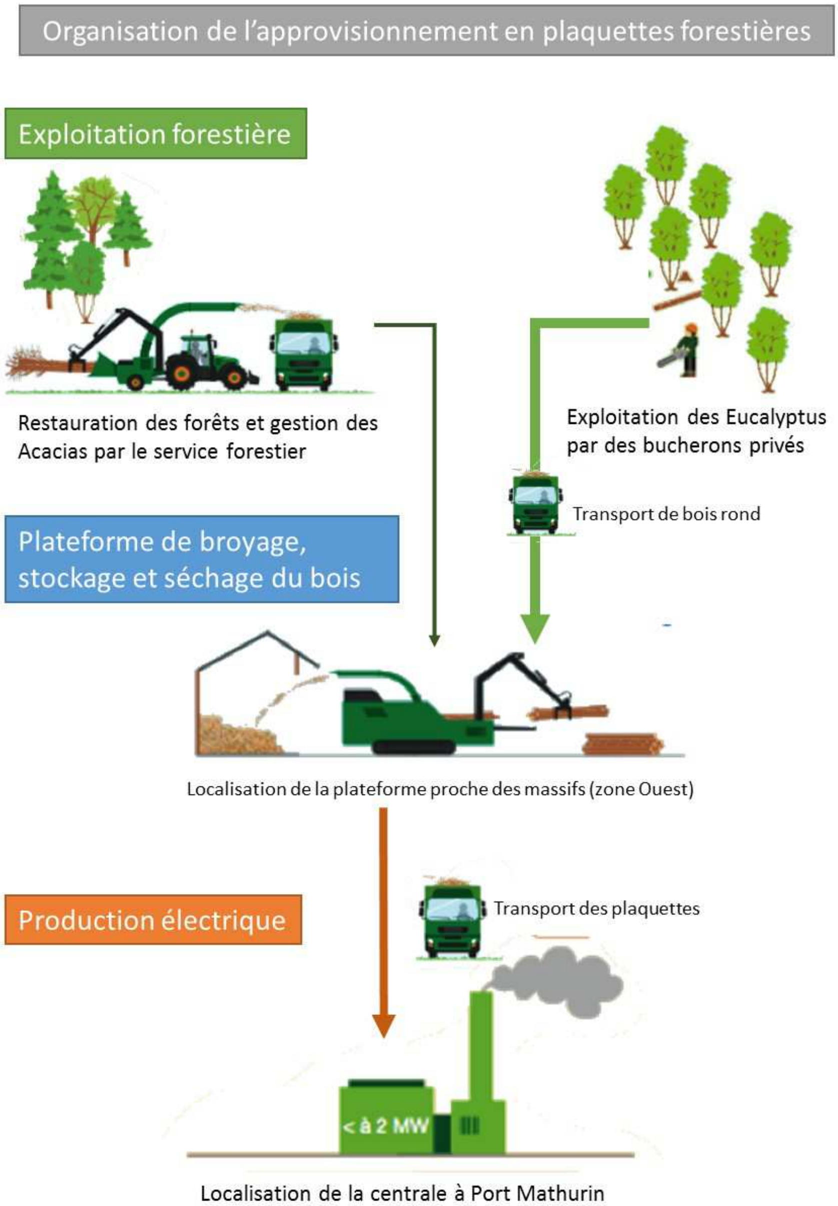


Figure 11 : Illustration of a proposed organization of the wood chips supply chain of a power plant

Wood chips reception on the power plant location

A silo will also be installed to receive the feedstock (wood chips). Its sizing will have to ensure about 30 days of production.

The power plant might be located in Port Mathurin, close to the existing power station, should CEB be interested in operating the plant. But another potential site could be identified according to the biomass supply area and to the platform location, in order to minimize transportation constraints.

2.4 Preliminary cost estimates

In the proposed solution, several points remain to be clarified and evaluated. Nevertheless we present below a first estimate of the investment and production costs in order to fix first orders of magnitude which will have to be refined by a dedicated economic analysis.

2.4.1 Methodology elements

The cost of electricity production includes the following cost categories:

- investment costs, relating (i) to the acquisition of equipment/materials and (ii) to works/infrastructure (power plant or platform sites);
- operating costs, eg for the plant: maintenance (labor and equipment), consumables (purchase of biomass, lubricants, etc.), utilities (water, compressed air, ...) and all the management costs (insurance, accounting, administration, etc ...).

The part of the investment costs to be charged each year is determined by taking into account the amortization period and / or the facility lifetime. The later are added to the annual operating costs, which results in the complete annual cost of the electricity productin, expressed in € (or MUR) / kWhel.

At this stage, only the main cost items will be estimated. The unit figures were selected from various sources:

- Logging and timber transportation costs: scales and tariffs applied to date by the Rodrigues Forest Service;
- Investment and operating costs of the shredding/storage platform: sizing recommended by ADEME (French Agency for the Environment and Energy Management) and average costs observed in France for low-scale installations (between 500 t and 3000 t of chips / year);
- Investment and operating costs of a gasification power plant: average figures observed by IRENA in OECD countries and expert opinion.

The calculations are presented below on the basis of a short-term scaling, ie for a 350 kWel power plant supplied with 3000 tDM / year of wood.

2.4.2 Investment costs

Grinding, drying and storage platform

According to ADEME recommendations, the size of the storage/drying shed for wood chips must be 1m2 per ton of wood chips produced and the size of the whole platform should be at least equal to 2m2 per ton of wood delivered. At least two rotations of the feedstock are envisaged to allow the wood drying between 4 and 6 months. Thus, for a supply of 3000 tDM of wood chips / year, a storage shed of 1500 m2 (1500 tons of chips permanently) will be sufficient. We can certainly consider a slightly smaller size according to the observed drying efficiencies and the management of a greater number of rotations. The total surface of the platform would be in the order of 4000-4500 m2.

The costs observed in France are between 250 €HT / m² and 650 €HT / m² of shed (costs cover the development of the platform and the building). The first estimate is 400 € / m2 of shed, although this figure will obviously have to be readjusted in the context of Rodrigues.

➔ The total investment cost is estimated at € 700,000 including the shredder.

Gasification power plant

The equipments of the power plant include the gasifier coupled to an electric generator, but also all the peripheral equipment (storage of wood chips with possible supplement of drying, transfer of wood chips, grid connection...) and the buildings.

The supplier tariffs vary widely depending on the geographical area and the gasification and engine technologies (cogeneration or production only of electricity, gas engine or dual fuel syngas / diesel) and the associated services. IRENA reports investment costs between 2000 and 6000 Euros / kWel installed. These tariffs theoretically include all the costs (infrastructure, transit of equipment, study, installation and start-up costs on site ...), but an in-depth study is essential to adjust these costs.

For our estimates, we set a figure between 2500 and 4000 euros / kWel installed.

➔ The investment cost for the plant would be between € 0.9M and € 1.4M.

Investments subsidization

These types of investments can be largely subsidized. As an example, we used a credible subsidy rate of 80% given the different mechanisms currently used for financing renewable energies. Thus the rest of the charge for the community would amount to € 140,000 for the platform and between € 175,000 and € 280,000 for the plant, which would represent an annual charge respectively of € 14,800 and between € 18,500 and € 29,700 for a discount rate of 10%. These fixed annual charges will be used in the operating cost estimates.

Grinding, drying and storage platform

Size	*Platform : 4000 m², Shed : 1500 m²*		
Storage capacity	*3000 tDM of wood chips - 2 rotations/year*		
	Unit	**Hypothesis**	**Cost (Euros)**
A1. Investment costs			
Unit cost	€/m2 shed	400	
Platform construction cost	€		600 000
Mobile shredder connected to tractor + other equipments	€		100 000
Total cost for platform			700 000
Subsidization rate	%	80	560 000
Rest of charge to finance	**€**		**140 000**
B1. Annual fixed costs			**14 851**
Lifetime	*Year*	*30*	
discount rate	*%*	*10*	
Annual depreciation	€		4 667
Average annual interest	€		10 184

Table 8 : Estimate of the total and annual investment costs for a conditioning / storage platform. Hypothesis of 80% subsidy

Gasification power plant

Electrical power	*kWél*	*350*			
		Low figure		***High figure***	
	Unit	**Hypothesis**	**Cost (Euros)**	**Hypothesis**	**Cost (Euros)**
A2. Investment costs					
Unit cost	€/kWél	2 500		4 000	
Plant cost	€		875 000		1 400 000
Subsidization rate	%	80	700 000	80	1 120 000
Rest of charge to finance	**€**		**175 000**		**280 000**
B2. Annual fixed costs			**18 564**		**29 702**
Lifetime	*an*	*30*		*30*	
discount rate	*%*	*10*		*10*	
Annual depreciation	€		5 833		9 333
Average annual interest	€		12 731		20 369

Table 9 : Estimate of the total and annual investment costs for a power / gasification plant. Hypothesis of 80% subsidy

2.4.3 Operating and production costs

Estimated cost of biomass delivered to the plant

Taking into account the proposed organization for the supply chain and the elements of operating costs estimated from forestry services, IRENA and ADEME sources, a first estimate of the cost of biomass delivered to the plant would be in the order of 4.4 MUR/kgDM of wood chips (about 100 € / ton of wood chips).

Such order of magnitude is very close to the wood chips production costs in France whereas the labor is cheaper in Rodrigues. Current costs envisaged for logging are likely to decrease. We have thus assumed as high hypothesis the current costs of 1500 MUR/m3 and as low hypothesis a projection at 1200 MUR/m3 (with a density of 560 kg/m3), which would lead to a decrease in the cost of biomass delivered to the central down to 3.8 MUR/kgDM.

Estimated cost for electricity production

From these feedstock costs “delivered to plant” and by integrating assumptions relating to the operating costs of the plant, we estimated a potential cost for electricity production between 5.50 MUR / kWhel and 6.50 MUR / kWhel produced.

It is reminded that these estimates are based on global data assumptions that need to be refined by a more reinforced assessment in the context of Rodrigues and associated with a more targeted technology selection (on which investment and operating costs depend). In addition, we have assumed an 80% investment subsidy that we believe is widely available.

Based on these estimates, it can be noted that biomass “plant gate” costs represent 65% of the total cost of electricity production, which highlights the importance of this item, the costs of which can be optimized should the chain be well managed and organized.

Annual feedsctock inlet	*tDM*	*3000*
Electrical power	*kWel*	*350*
Electricity produced annually	*MWhel / y*	*2610*

	Unit	*Hypothesis Unit figure*	Quantity	*Annual cost HT*		
				Low Hyp	High Hyp	Unit
Forestry exploitation – logging				**242 950**	**284 694**	**€**
Cut	*MUR/t DM*	*Low : 2 143* *High : 2 679*	*3 000*	*166 976*	*208 720*	*€*
Roadside stacking	*MUR/t DM*	*625*	*3 000*	*48 701*	*48 701*	*€*
Transport to plateform	*MUR/t DM*	*350*	*3 000*	*27 273*	*27 273*	*€*
Conditioning on plateform				**55 254**	**55 254**	**€**
Annual fixed costs (B1)				*14 851*	*14 851*	*€*
Operating costs						
Salary 3 operating agents	*MUR/mont*	*15 000*	*36*	*14026*	*14026*	*€*
Maintenance costs	*Euros/year*	*3%*	*100 000*	*3000*	*3000*	*€*
Transport to power plant	*MUR/t DM*	*300,0*	*3 000*	*23 377*	*23 377*	*€*
Complete cost of wood chips delivered to power plant						**Euros**
Feedstock cost per tonne (dry basis) delivered to plant			**3 000**	**99**	**113**	**Euros/tDM**
Feedstock cost per tonne (dry basis) delivered to plant			**3 000**	**3,8**	**4,4**	**MUR/kgDM**
Electricity production				**63 515**	**100 843**	**€**
Annual fixed costs (B2)				*18 564*	*29 702*	*€*
Operating costs						
Salary 4 operating agents	*MUR/mois*	*15 000*	*48,0*	*18701*	*18701*	*€*
Variable maintenance and management costs	*Euros/Mwh*	*4,0*	*2 610*	*10 440*	*10 440*	*€*
Fixed maintenance costs	*MUR/an*	*3%*		*26250*	*42000*	*€*
Complete annual cost for electricity production				**372 159**	**440 791**	**Euros**
Production cost of kWh el			**2 610 000**	**0,14**	**0,17**	**Euros/kWh$_{\text{él}}$**
Production cost of kWh el			**2 610 000**	**5,5**	**6,5**	**MUR/kWh$_{\text{él}}$**

Table 10 : Estimated cost of (i) feedstock as delivered to power plant ; (ii) electricity production

Conclusions and recommandations

Implementing a bioelectricity plant is technically possible in Rodrigues

This study concludes that biomass represents a real opportunity for electricity production in Rodrigues, in the context of its energy transition policy towards a more autonomous and less carbon intensive energy mix.

The short-term technical potential is in the order of 13,000 MWh of primary energy in the form of wood chips (wood energy), mainly issued from the exploitation of existing Eucalyptus plantations, and to a lesser extent from restoration of mixed forests and marginal exploitation of old stands of Acacia Nilotica. In terms of electricity generation, this technical potential would represent around 2600 MWh of electric energy per year, which is equivalent to the average consumption of about 1,700 households in Rodrigues and 7% of the annual electricity consumption of the entire region.

This production could be ensured by setting up a power plant with an estimated capacity of 350 kWel. This could potentially be a significant short-term contribution to the electricity mix, which would represent nearly 10% of the island's electricity threshold power. Such a bioelectricity production system could also constitute a renewable source of base energy and have a technical interest for the stability of the grid compared to the intermittent nature of other renewable energies (wind and solar). Finally, unlike other renewable energies, a bioelectricity chain potentially provides other services to the territory: job creation, resource development, regional planning, etc.

These estimates were made on the basis of rather conservative assumptions about available resources that may be mobilized within short terms. Over the longer term, a higher capacity of around 720 kWel can be envisaged via (i) better management of current Eucalyptus plantations, which could lead to significant productivity gains; (ii) new energy plantations, whose species are still to be selected and on lands that remain to be identified, in consultation with local stakeholders.

Forestry resources are available, but the potential remains to be validated

Existing Eucalyptus plantations are the main source of selected wood energy. The exploitation of the Eucalyptus stands does not represent any major difficulties, except in certain areas of very steep slopes, nor any risk for Rodrigues forest. Simple management rules, under the control of the forest service, would easily make this operation compatible with the services currently provided by these plantations: construction poles, honey production, and erosion control.

Nevertheless, this potential remains to be refined by a more in-depth field-expertise concerning the current state of Eucalyptus stands. Indeed, the massif has not been subjected to monitoring and management plan for a while and some plots may have been damaged by cyclones, fire or over-exploitation. Such a study should lead to a better estimate of the standing stock, the current state of this stock and its productivity, and to a long-term management plan for this massif.

The other available biomass potentials that we have identified as possible complement are exotic woods resulting from (i) continuation of the ongoing restoration of mixed forests and (ii) marginal exploitation of a few old stands of Acacia Nilotica which have been identified. Here again, the biomass stocks and the technical exploitation routes must be better evaluated to refine the potential, but these additional potential resources are far from negligible.

The thorny case of Acacia Nilotica

On the other hand, the exploitation of young stands of Acacia Nilotica, in a logic of control or eradication in the short term, as the RRA wishes to implement, is not retained as a sustainable source of energy biomass. The importance of the invasion of the island and in particular pastoral areas was confirmed by the ground surveys made for the study, and significant measures agains this spread are highly justifies due to socio-economic issues.

However, total eradication in the short term seems complicated to implement and raises many questions about the associated technical itineraries. The biomass generated can not be considered as a long term and sustainable source of feedstock for a power plant.

An alternative solution suggested by the experts would be to manage these spaces in order to control the invasion, through actions combining pastoralism and wood energy production. Experiments are encouraged in this direction to test different operating methods and to see whether it is possible to produce a feedstock adapted to the foreseen type of power plant.

Our technical and structural proposals

Concerning the power plant, for the estimated power ranges and in Rodrigues context, we recommend solutions integrating a gasification process, more specifically fixed bed technologies, coupled to an engine power group. This type of process is technically relevant for low-scale electrical powers and suitable for wood resources conditioned in wood chips. Many experiments are reported around the world, especially in Europe and Asia, but still little in the IOC region. A wide range of technologies with variable efficiencies and cost are available on the market. For reasons of reliability and efficiency, robust solutions are recommended, though potentially more expensive to purchase, and provided that technical staff can be trained. The question of the location and especially of a future manager of the plant remains, and will have to be clarified for a possible project.

A reflection was also conducted on the potential resource supply chain for the plant. We recommend the implementation of a platform for conditioning (grinding and pre-drying) and storage of wood. It would be linked to forest exploitation (logging) routes, and would supplyi the power station with controlled quality wood chips. The surface area of this platform is estimated at about 4000 m2 with a sheltered shed of about 1500 m2 and could be located near the supply basin. It might be managed either directly by the region or by a private company with the support of the forest service, while logging could be largely provided by private loggers.

Such a supply chain structuration would contribute creating jobs in rural areas.

Preliminary cost estimate elements

This study also presents first estimates of production costs that allow a priori to confirm the economic interest of this solution in the Rodrigues context. The costs of the feedstock delivered to the power plant could be between 3.8 and 4.4 MUR/kg (ie 100 Euros/ton of dry wood), and the cost of the electricity, as a first approximation, might be between 5.5 MUR/kWhel and 6.5 MUR/kWhel. In terms of investments, needs are estimated at first approach to around € 700,000 for the storage/conditioning platform and between € 900,000 and € 1.4 million for the plant. These types of investments can largely benefit from subsidies, probably up to 80%, hypotheshis that has been chosen for cost estimates.

These figures are based on average unit costs, which must be refined by an in-depth feasibility study, according to the supply route chosen by Rodrigues authorities and the technical choices concerning the plant.

It is also reminded that beyond the economic profitability of the sector (cost of production of electric kWh), a bioelectricity sector potentially gives the territory other services that must be considered: job creation, resource development, territory development and management…

Opportunity for a pilot project

Beyond the additional and reinforcing studies that should be carried out, it is recommended to consider the opportunity for a pilot project sized and designed to represent the first tranche of a possible future larger power plant. The installed power could be in the order of 70-100 kW and the necessary biomass resource in the order of 600-900 tDM/year. The installations implemented (platform, power plant, generators) would be designed to be further enlarged and thus allow a production capacity increase.

- Storage sheds can easily be enlarged by anticipating and reserving the necessary land area.
- It is technically possible to design gasification power plants in a flexible way provided a sufficiently large building from the outset. Containerized solutions are also available and could be tested frirst on the site of the platform, before considering another site for upscaling.

The investment costs of such a project (excluding studies) are estimated at first approach between € 600,000 and € 800,000 (potentially subsidisable) but must be further refined.

The interests of such a pilot project are multiple:

(i) initiate the construction of a wood supply chain with limited risk;
(ii) test and validate technical resource development routes, including resource management modalities and technical platforms;
(iii) train actors at the various levels of the chain (Eucalyptus exploitation, management of the storage / conditioning platform, management and maintenance of the power plant);
(iv) optimize the full costs of electricity production chain.

The pilot activities might be defined and carried out in a close cooperation with Reunion Island, where 2 projects of gasification platforms on forest resources should start within short terms.

Annex

1 Annexe 1 : Programmes des missions à Rodrigues

1.1 Mission du 04 au 06 décembre 2018

Jour	Objet - Lieu et personnes rencontrées
Lu 03/12 soir	Arrivée Rodrigues FB et LG – installation hébergement
Ma 04/12 **Matin**	Port Mathurin, Commission for Environment M. Azie, Mme Raphael, M. Ravina Présentations, organisation de la mission Problématiques : Gestion des espèces invasives, déchets urbains, biomasses agricoles
Après-midi	Port Mathurin, Commission for Environment M. le Commissaire Payendee (RRA) ; M. Azie, M. Perrine Vision stratégique de la RRA en termes de transition énergétique et de biodiversité ; sites d'intérêts pour visites terrains ------------------- Visites terrain avec M. Azie : repérage de zones envahies par Accacia Nilotica sur le littoral nord autour de Port Mathurin
Me 05/12 **Matin**	La Solitude - Services forestiers M. Perrine et Mme Parmasse Programme de reboisement, gestion du domaine forestier et des espèces invasives, recensement forestier. ------------------- Visites terrain avec M. Perrine et Mme Parmasse : Solitude, Soupir, Cascade Pigeon
Après-midi	Réunion FB / LG – Synthèse et planification
Je 06/12 **Matin**	CEB, Port Mathurin - M. Kevin Waterstone Enjeux de la production électrique à Rodrigues, positionnement de la CEB sur la bioélectricité / ENR, aspects réglementaires ------------------- Visite terrain avec MWF – Réserve de Grande Montagne
Après-midi	Port Mathurin, Commission for Environment Rencontre avec la Commission de l'Agriculture : M. Ravina, M. Gaulbert Activités agricoles générant des résidus potentiels, transformation agroalimentaire à Rodrigues
Je 06/12 et Ve 07/12	Vols retours FB et LG

1.2 Mission du 25 au 27 février 2019

Date	Objet	Lieu
25/02	Echanges sur le planning de mission Visites terrain – repérage avec le service forestier de peuplements d'Acacia Nilotica dans l'Ouest	Port Mathurin La Solitude Terrain
26/02	Matin : présentation des avancées de l'étude et premières tendances + discussion des suites + Rencontre AFD Après-midi : Travail avec le Service forestier sur les données cartographiques collectées	Port Mathurin La Solitude
27/02	Matin: poursuite des échanges avec le service forestier	La Solitude

2 Annexe 2 : Liste de contacts

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	Mme Ramcesse Prosper	FCE Officer	
	Mme Veena Coolen	FCE Officer	
	M. J. Heolen Manvel	Senior FCE Officer	
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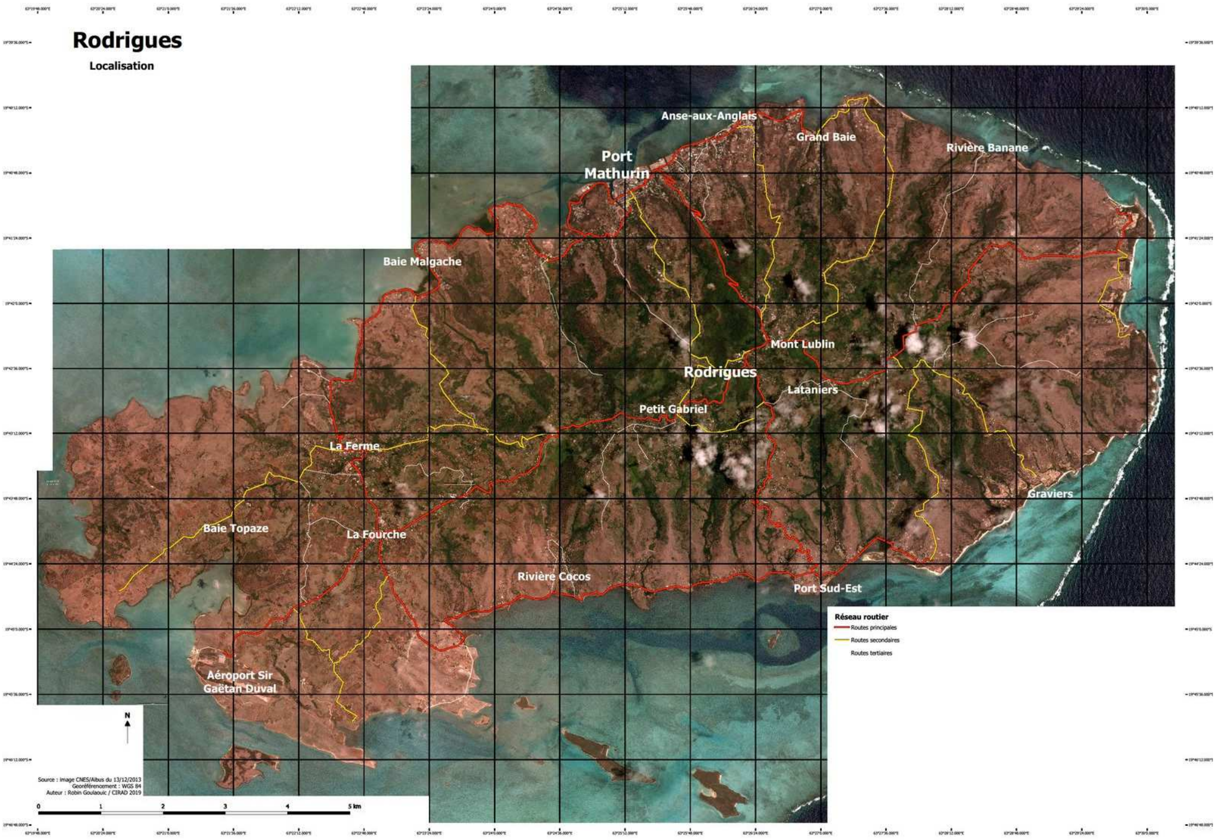
3 Annexe 3 : Cartes

Image SPOT 6 ((C) AirBus) de décembre 2013 ayant servi à la cartoraphie des forêts de Rodrigues.



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