UNIVERSIDADE DE LISBOA
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Cost reduction strategies for the Rural Village Energy concept

VERSÃO PÚBLICA

Henrique Maria Costa Garrido da Silva

Dissertação

Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de

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2013

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Resumo

A agência internacional de energia estima que cerca de um quinto da população mundial não tem, acesso a eletricidade, particularmente em zonas rurais, maioritariamente na África Subsaariana e no Sudeste Asiático. A taxa de eletrificação rural na África Subsaariana era, em 2009, cerca de 14 % - consideravelmente abaixo da média mundial de 68%. As Nações Unidas apontam que a disponibilidade de energia (em especial energia elétrica) sustentável com baixo custo, tem o potencial de promover a educação, o acesso a água potável, a igualdade de géneros, diminuição da pobreza, e sustentabilidade ambiental – assim, a disponibilidade de energia pode ter um impacto direto e considerável na realização dos oito Objetivos de Desenvolvimento do Milénio. Os sistemas descentralizados de energia como o KUDURA podem providenciar energia limpa e água potável a comunidades rurais ou remotas. Apesar disso, este tipo de abordagens requerem um maior atual desenvolvimento, de modo a que se consiga aumentar a sua competitividade tecnológica e económica, e assim, a sua flexibilidade em ser distribuído em zonas rurais.

O presente trabalho estuda duas tecnologias e *case-studies* em específico: Gaseificação de biomassa de pequena dimensão para a geração de eletricidade no Norte de Moçambique, utilizando casca de caju como combustível; e micro-hídrica para geração e armazenamento de eletricidade no litoral do Quénia – estas aplicações foram contempladas como possíveis formas de reduzir os atuais custos do KUDURA. Estas tecnologias são comparadas e analisadas com recurso ao *software* HOMER – uma ferramenta de análise para a avaliação de diferentes tecnologias e recursos energéticos e sua otimização com base em critérios económicos.

O custo de energia para o sistema híbrido de gaseificação a biomassa é de 0.46 €/kWh, em oposição aos 0.53 €/kWh do sistema KUDURA. Estes resultados mostraram ser sensíveis a variáveis como o preço do caju, a potência do sistema solar fotovoltaico e, mais importante, sensíveis ao custo de operação e manutenção – em particular, o salário dos técnicos locais.

Em relação ao sistema hídrico de fio-de-água proposto, é mostrado nesta análise que o custo de energia situa-se na gama de 0.17-0.27 €/kWh, tornando este sistema particularmente adequado a regiões com um recurso hídrico abundante. Por outro lado, como opção de armazenamento hídrico de energia através de bombagem de água, os resultados simulados sugerem que pode não tornar-se economicamente competitivo com as formas tradicionais de armazenamento de energia eletroquímica.

Palavras-chave: gaseificação, caju, micro-hídrica, Africa Subsariana, custo de energia

Abstract

The International Energy Agency estimates that about one-fifth of the world's population does not have access to electricity in particular in rural areas, mainly in sub-Saharan Africa and South Asia. In 2009, the rate of rural electrification in sub-Saharan Africa was 14%, considerably below the global average of 68%. The United Nations has found that access to affordable and sustainable energy, particularly electricity, can promote education, access to potable and safe water, gender equity, poverty's end and environmental sustainability, thus electricity can have a direct impact on achieving the eight Millennium Development Goals. Decentralised energy systems, like the KUDURA concept, have the ability to provide clean energy and potable water to rural or remote communities. Nevertheless, these approaches require further development to increase its cost-effectiveness and deployment flexibility.

The present work looks at two specific technologies and case-studies: small-scale biomass gasification for power generation using cashew nut shells as feedstock for the northern region of Mozambique; and micro hydro-power for power generation and energy storage for coastal Kenya – which were seen as possible cost reduction routes. These technologies are compared and analysed through the use of the HOMER software, an analytic tool for evaluating different energy technologies and resources and optimization based on economic criteria.

The levelised cost of energy (LCOE) of the optimized hybrid biomass gasification system may reach €0.46/kWh, significantly below the KUDURA baseline cost of €0.53/kWh. These results are sensitive to variables such as the feedstock cost, the photovoltaic array required and, most importantly, to the costs associated to operation and maintenance, in particular the salaries of the local technicians.

Regarding the proposed run-of-the-river-type hydro system, it is shown that it may achieve a LCOE in the range of €0.17-0.27/kWh, making it particularly suitable for regions with an abundant hydro resource. On the other hand, as a form of energy storage via pumped water storage, the simulation results suggested it cannot become competitive with standard electrochemical energy storage.

Key-words: biomass gasification, cashew, micro-hydro, sub-Saharan Africa, LCOE

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List of Acronyms

AC	Alternating Current
APL	All Power Labs
BB	Battery Bank
CAPEX	Capital Expenditure
CC	Cycle Charging
CO_2	Carbon Dioxide
DC	Direct Current
DOD	Depth of Discharge
ELC	Electronic Load Controller
GHG	Green House Gases
HOMER	Hybrid Optimisation Model for Electric Renewables
IC	Internal Combustion
LAB	Lead-Acid Battery
LF	Load Following
LCOE	Levelised Cost of Energy
kW	Kilowatt
kW_e	Kilowatt electric
kWh	Kilowatt hour
kWp	Kilowatt peak
MDGs	Millennium Development Goals
MJ	Mega Joule
MWh	Megawatt hour
NASA	North American Space Agency
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance

OPEX	Operation Expenditure
PAT	Pump as Turbine
PV	Photovoltaics
PVC	Poly-Vinyl Chloride
PVGIS	Photovoltaic Geographic Information System
PWS	Pumped Water Storage
RVE.Sol	Rural Village Energy Solutions
SHS	Solar Home System
SOC	State of Charge
SSA	Sub-Saharan Africa
SPH	Solar-Peak Hours
UN	United Nations

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1. Introduction

1.1 Energy context in rural areas

In an ever more economically-linked and globalised world, access to electric energy is an important factor in creating the necessary conditions for encouraging economic development in remote or rural communities. The United Nations (UN) has found that access to affordable and sustainable energy, particularly electricity, is necessary to achieve all eight of its *Millennium Development Goals* (MDGs). Thereby, it finds that energy services contribute directly to meeting the MDGs by improving economic conditions and indirectly by improving education, health, gender equality, and even environmental sustainability [1]. The International Energy Agency estimates that about one fifth of the world's population still does not have access to electricity, about 85% of which live in rural areas in developing countries, in particular in sub-Saharan Africa (SSA) and South Asia. As of 2009, the rate of rural electrification in sub-Saharan was 14%, far below the global average of 68% for rural areas [2]. Figure1 illustrates the electrification rate of SSA countries, of which Kenya and Mozambique have electrification rates under the 20% mark and their share of people without electricity was about 85% of the total population in 2009 [3].

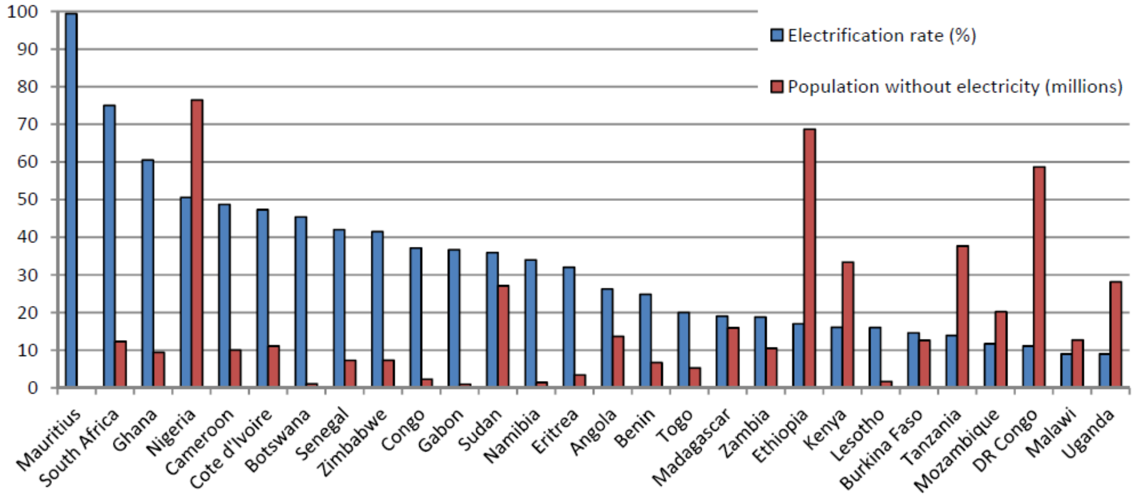

Figure 1 - Electrification rates of sub-Saharan Africa, IEA 2009 data, adapted from [4]

Remote or rural communities are often characterised by being highly dispersed with a low population density and a low load density, generally concentrated at evening-peak hours which tends to make national grid extension economically unreliable, by low level of education, and low income. This has been hampering the efforts of eradicating poverty in rural areas with a strong linkage to the *energy-water nexus*. The lack of access to safe and potable water makes health and sanitation almost impossible to achieve as well as education conditions, gender equality, reducing child mortality or combat malaria and other diseases, which entail the first seven MGDs. In SSA, malaria kills an estimated 1 million people per year which the large majority are children under five [5]. Electric energy could provide new solutions for water extraction in areas where water is already scarce, purification techniques through inverse osmosis and UV-light treatment, power medical equipment, chilling power to store vital vaccines, etc, and therefore enhancing health and sanitation conditions.

In addition, electric energy can also provide access to information, communication and improve health care by powering computers in schools, radios or cell-phones as well as lighting. The relative brightness of the light bulb as opposed to candle lights or kerosene lamps allows children to read or study in the later hours of the day bringing obvious education and leisure benefits as well as less exposure to pollutants from kerosene indoor-combustion. Businesses and agriculture activities can be created or significantly improved, promoting income-generating revenues that can have a significant impact of the welfare of a particular rural community [6].

The benefits of rural electrification have the potential to cover social, economic and environmental grounds. However, some experts [7] warn that the necessary conditions for such benefits, especially economic, lie in the parallel or complementary development programmes for the newly electrified communities and the adequate local conditions such as organised rural markets and sufficient credit in order for such niches to grow, without hindering the true potential of the latter benefits.

The pool of potential energy technologies for rural electrification is quite large and each technology naturally varies in its generation techniques, initial capital expenditure (CAPEX), operating expenditures (OPEX), and in the quality of the service it delivers. Diesel generators are characterised by having a relative low CAPEX, which rendered them as the main technology in rural areas, but have high OPEX, mainly due to high fuel and operation and maintenance (O&M) expenses. Nowadays, sustainability considerations are encouraging the deployment of cleaner and ever-more competitive renewable technologies such as photovoltaic (PV) systems, wind turbines, small-scale hydro turbines and small-scale biomass gasification as a means of providing notable economic and environmental advantages over conventional fossil-fuel technologies.

PV systems are relatively high in CAPEX but this tendency has been greatly decreasing for the past 5 years [8], they are very low in OPEX and are highly scalable allowing the ability to meet the desired load of a particular application, whether an individual solar home system (SHS) or a larger system powering a decentralised mini-grid, which usually makes use of a diesel generator to cope with higher load requirement when solar energy is not available. This configuration is normally coined as solar-diesel hybrid system. Wind turbines are also similar to PV systems in the sense they also have a relatively high CAPEX but its OPEX is a bit higher since it has moving parts, although they have the potential to be more cost-effective than PV where solar irradiation is low and wind resource is high, as in the prime example of the Atlantic islands of Azores [6]. Small-scale biomass gasifiers produce a combustible gas known as *producer gas* or *syngas* from the gasification of solid biomass, such as wood or agro-forestry residues. It may be used in diesel generators to produce electricity, offering an affordable and cleaner alternative to diesel.

There is a wide spectrum of local and clean energy production technologies for decentralised rural electrification today, although the process of determining the 'right' energy technology or mix of technologies to use depends on a multitude of factors such as local resource availability, the end-use of electric power, scale of the system, benefit of usage, local acceptance, etc. But it is clear though that decentralised renewable-based (or partially) have the potential to provide social, economic and environmental benefits to remote or rural communities in developing countries.

1.2 The Rural Village Energy concept

The Rural Village Energy concept was originally defined by RVE.Sol, a social enterprise working towards the development and distribution of sustainable and market-ready energy solutions to rural communities in developing countries. It can be perceived as a holistic sustainable solution with the main purpose of ending rural poverty by tackling three major issues in developing countries: Provide access to clean and reliable energy, potable water and modern cooking techniques through biogas.

In order to meet that end, RVE.Sol developed the KUDURA[1], a containerised stand-alone system designed as a hub, to provide energy services based on a solar-diesel hybrid system, potable water through a 2-stage purification unit, and biogas through the use of a biodigestor as an alternative to biomass traditional combustion for cooking purposes, which in the process generates an organic fluent rich in micronutrients to be applied to agriculture to improve the quality and yield of crops. In addition, all the 3 sub-systems that entail KUDURA can be monitored and controlled remotely providing telemetry data on battery condition, load demand and equipments power curves, filters state of the water purification unit or biogas inner pressure, etc, to ensure the maximum reliability and longevity of the system. The integration of KUDURA is illustrated in Figure 2.

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[1] **i.e. "the power to change" in Swahili language.**

Figure 2 - Schematic of KUDURA concept, adapted from [9]

KUDURA is about empowering communities with a sustainable, community-owned and run, clean energy and water solution. As a result, communities control their own destiny and their practices protect the environment from degradation as well as their own welfare.

Nonetheless, this “one-solution-fits-all” does not optimised the harnessing of local energy resources since every project has specific requirements and conditions that need to be taken into account in order to provide the most cost-effective solution. At present date, KUDURA is limited to solar PV energy and diesel generators to provide electric power, which also limits its deployment flexibility is terms of making the most out of different locally-available resources and ultimately increase its cost-effectiveness. Hence, this urges for a techno-economic assessment of different energy technologies suitable to integrate in KUDURA.

1.3 Introducing to HOMER

Throughout the 1990's, the National Renewable Energy Laboratory (NREL) of the USA was very active on helping developing countries incorporate renewable power into their rural electrification program. NREL needed a model for its internal use to understand the design trade-offs between different system configurations. To that end, the Hybrid Optimisation Model for Electric Renewables (HOMER) was created for designing and analysing energy systems which may contain, or not, a mix of conventional diesel generators, biomass power gasifiers, wind turbines, solar photovoltaic, hydropower, LAB batteries, flow batteries, hydrogen, electric grid and other inputs, as illustrated in Figure 3.

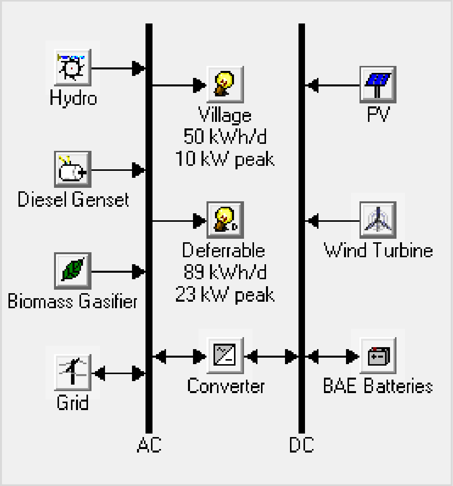

Figure 3 - Example of several power sources and loads displayed by HOMER

Additionally, HOMER allows co-firing of two different fuels, thermal loads, co-generation and model electricity excess to serve thermal loads and efficiency measures.

HOMER simulates the operation of a system by making energy balance calculations in each time step of the year. For each time step, HOMER compares the electric and thermal demand in that time step to the energy that the system can supply in that time step, and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides in each time step how to operate the generators and whether to charge or discharge the batteries. It performs these energy balance calculations for each system configuration. It then determines whether a configuration is feasible, i.e., whether it can meet the electric demand under the conditions that one specifies, and estimates the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as CAPEX, replacement, O&M, fuel expenses, and interest.

When defining sensitivity variables as inputs, HOMER repeats the optimisation process for each sensitivity variable that one specifies. For example, if one defines wind speed as a sensitivity variable, HOMER will simulate system configurations for the range of wind speeds specified. This sensitivity analysis is very useful in terms of understanding how an input variable can impact a certain output variable such as the LCOE. Figure 4 illustrates the HOMER model structure.

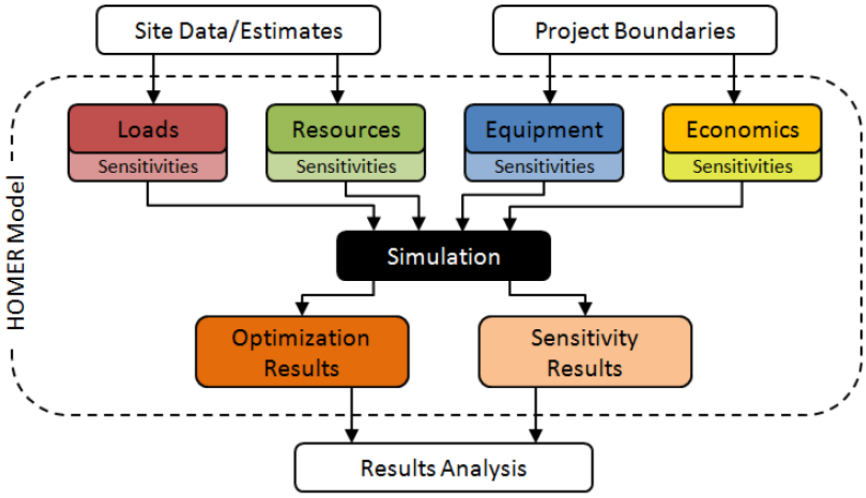

Figure 4 - Schematic of HOMER modeling methodology and structure, adapted from [4]

After simulating all of the possible system configurations, HOMER displays a list of configurations sorted by *net present cost* (NPC), and not by LCOE, under the assumption that the determination of the LCOE throughout the simulations is somewhat arbitrary and disputable whereas the NPC is a simple mathematical concept, according to [10].

1.4 Objectives

The main objective of the present thesis is to evaluate alternative energy technologies for the rural stand-alone KUDURA system developed by the Portuguese-based RVE.Sol Company in order to promote cost reduction routes propitious to increase its cost-effectiveness. In this thesis, biomass gasification and small-scale hydro power were considered as the technologies to evaluate.

Therefore, the objectives of the present thesis are to analyse and optimise the following system configurations for remote electrification:

- *status quo* of the stand-alone system for energy generation in rural applications, in particular the KUDURA concept;
- stand-alone system with a biomass gasification unit;
- stand-alone system with an hydro energy generation and storage unit.

The back-bone of this analysis is based on use of HOMER v2.81, a software tool for analysing and optimising micro energy systems that simplifies the task of evaluating the large number of technology options and the variation in technology costs and availability of energy resources, when designing new system configurations.

Section 2.2 elucidates the main aspects of the gasification technology. A characterisation of the corresponding case study is carried out in section 2.3, whereas section 2.4 portraits the proposed system configuration and operation and describes a thorough methodology in creating a HOMER model, the benchmark further simulations. Section 2.5 reflects the results of the proposed system in which a preliminary analysis is preceded by the optimal system configuration, and a sensitivity analysis is performed to evaluate the impact on the *levelised cost of energy* (LCOE). Conclusions of the integration of the proposed gasification system are drawn in section 2.6.

Section 3.2 and 3.3 characterise the hydro-power technologies and the corresponding case study. Section 3.4 depicts the configuration and HOMER model set for the two proposed systems – one with hydro-power exclusively and one with *pumped water storage* (PWS), which is compared with a traditional *lead-acid battery* (LAB) storage application in section 3.5. Final conclusions of the proposed hydro systems are discussed in section 3.6.

2. Gasification

2.1 Motivation

Biomass has been used to produce a wide variety of energy vectors through different and well-established techniques such as the fermentation of corn or sugarcane due to its high content of carbon hydrates[2] – like starch and saccharose respectively – then followed by a distillation process which ends up yielding biofuel products normally known as bioethanol, or, through the transesterification[3] of oily seeds as palm or colza seeds to produce biodiesel. These so called first generation biofuels yet lack on some sustainability issues at environmental, economic and technological level which make them sometimes difficult to compete with traditional fossil fuels, especially for small-scale energy projects. For instance, they require dedicated crops commonly known as energy crops as its primary feedstock which need vast and good quality soil areas to grow hence directly competing with food crops, sometimes inflating the latter end-user price and/or perpetuating the environmental pollution of intensive monocropping practices such as soil degradation, intensive use of fresh water, destruction of pristine ecosystems through deforestation and subsequent loss of habitat, water courses or reservoirs contamination due to over-fertilization, amongst many others environmental issues [11].

Thus first generation biofuels should not be a privileged option for biomass energy production, and ought to be replaced by second generation biofuels, which use as primary feedstock lignocellulosic material (e.g. the plant's fibre or cellular wall of plants) or vegetable oils and animals fats to produce second generation biodiesel. Table 1 summarises the main features of both first and second generation biofuels.

Table 1 - Material and process of first and second generation biofuels; [a] Urban Solid Residues; [b] Biomass-to-liquid;

Raw material	*Process*	*Biofuel*
High hydrocarbons content material: Corn, wheat, sugarcane	Hydrolysis/fermentation/distillation	Bioethanol
Vegetable oils, animal fats or used oils	Transesterification	Biodiesel
Agro-industrial effluents, USR[a], manure	Anaerobic Digestion	Biogas
Lignocellulosic material	Acid or enzymatic hydrolysis/fermentation	Bioethanol
Lignocellulosic material	Gasification	Producer gas, syngas, BTL[b]
Vegetable oils, animal fats	Hydrogenation/ isomerisation	Biodiesel (H-Bio)

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[2] Any of the group of organic compounds consisting of carbon, hydrogen, and oxygen, usually in the ratio of 1:2:1, hence the general formula: Cn(H2O)n. Examples include sugar, starch or cellulose.

[3] The process reacts an alcohol with the triglyceride oils contained in vegetable oils, animal fats, or recycled greases, forming fatty acid alkyl esters (or biodiesel) and glycerine.

There are two possible conversion routes to transform lignocellulosic material (essentially a complex polymer made of three main sub-polymers: cellulose, hemicellulose and lignin of which are made of monomers, the building blocks of organic matter, in this case, such as glucose or fructose (carbohydrates)) into energy vectors: bio-chemical and thermal-chemical conversion processes. The scope of this work will be focusing on the thermal-chemical or gasification conversion process due to the main advantages summarised below, which apply in the context of rural electrification:

- Lignocellulosic material can range from energy crops to a wide variety of residues from agriculture, wood-processing industry, food-processing industry and forestry which are usually associated in rural areas;
- Relatively good readiness to generate power;
- Fully mature and small size turn-key power solutions already available in the market;
- Straight forward operation and maintenance;
- Low cost per kWh_e produced;
- Due to its high temperature process, combined heat and power generation is possible, increasing efficiency of the system and/or feed other thermal loads;
- An 80% fuel substitution can be achieved in already existing diesel generators;
- Lower GHG emissions compare to gasoline or diesel generators in which CO_2 emissions are neutral in the sense that biomass withdraws CO_2 from the atmosphere over its growing period and releases it back into the atmosphere when burnt;

Examples of lignocellulosic materials suitable as feedstock for a gasification unit are hardwoods (usually angiosperm trees e.g. oak, aspen or walnut), softwoods (usually gymnosperm trees e.g. pine, cedar or other conifers), hard shells (e.g. from hazelnuts, walnuts, coconuts or caju nuts), agriculture residues (e.g. corn cobs, rice husks, sugarcane bagasse or cotton stalks), forestry residues (usually material cleared from forests to protect them from forest fires e.g. branches, dead trees or sawdust from logging activities), etc.

In the context of the present work, biomass resources are refer to as residues from forests, agriculture residues and any other wastes generated during the processing of industrial wood products.

Agriculture and cattle waste are interesting feedstock sources for a gasification power unit since they are relatively abundant in rural areas, where agriculture and cattle raising are intrinsically linked to most of peasants’ main activities making it a valuable energy source. Food processing residues are also a possible energy pool because most of the food processing plants are located within or near rural areas (most cases do in order to increase their process efficiency by shorting the distance between the place where crops grow and where they are processed – bio-refinery concept [11]) and sometimes these residues are not given a proper termination, ending up in land/waste fields not harvesting its full energy potential, most of which ends up incinerated or consumed by a small fraction of household.

Thus food processing industry is a suitable source of feedstock for power generation in rural areas in terms of environmental sustainability, by providing a new use to residues which otherwise would be incorrectly disposed of or incinerated as means of residue management but also in terms of micro-economic sustainability where residues can generate revenues for the processing industries at the same time providing a solution to residues' disposal which ultimately will produce cheaper energy for the rural communities.

Finally, it is worth mentioning that forestry residues could work at some point if it was to follow a strict and multi-disciplinary programme e.g. forest cleaning to prevent wildfires, in which the rate of retrieving biomass from the forest floor would not pose problems within the ecosystem, making it a relatively hard-to-assess source in terms of impacts upon the ecosystem.

2.2 Gasification technology

2.2.1 Principles of Gasification

The gasification process is the thermal-chemical conversion of high lignocellulosic content biomass in which oxygen is supplied in sub-stoichiometrically conditions or in partial air conditions – required for complete combustion – and the resulting thermal-chemical breakdown of the biomass and internal reactions results in a combustible gas usually called *producer gas* (sometimes as synthesis gas, syngas or wood gas) whose composition – depending upon the feedstock biomass fuel and type of gasifier used – consists always of a mixture of combustible gases such as hydrogen (H_2), carbon monoxide (CO) and methane (CH_4) and incombustible gases carbon dioxide (CO_2), and nitrogen (N_2), as illustrated in Table 2. The different types of gasifiers shown in this table are discussed in next section. Since it contains CO, the producer gas is toxic and in its raw form tends to be extremely dirty, containing significant quantities of tars, soot, ash and water without proper a cleaning procedure. The heating value of this gas varies between 4.0 and 6.0 MJ/m^3 which amounts to about 10 to 15% of the heating value of natural gas [12], although its value depends greatly on the feedstock used.

Table 2 – Typical gas composition for different fuels and gasifier types, adapted from [12]

Gasifier type (moisture in feed - % wet basis)	*Updraft: wood (10-20)*	*Downdraft: wood (10-20)*	*Cross-draft: charcoal (5-10)*
Hydrogen	8 - 14	12 - 20	5 – 10
Carbon monoxide	20 - 30	15 - 22	20 – 30
Methane	2 - 3	1 – 3	0.5 - 2
Carbon dioxide	5 - 10	8 - 15	2 – 8
Nitrogen	45 - 55	45 - 55	55 - 60
Oxygen	1 – 3	1 – 3	1 – 3
Moisture in gas (Nm^3 H_2O/Nm^3 dry gas)	0.20 - 0.30	0.06 - 0.12	< 0.3
Tar in gas g/Nm^3 dry gas	2 - 10	0.1 – 3	< 0.3
Lower heating value (MJ/Nm^3 dry gas)	5.3 - 6.0	4.5 - 5.5	4.0 - 5.2

The gasification process itself can be divide in four major stages which are drying, pyrolysis distillation, combustion and reduction, not necessarily in that order [12]:

- **Drying:** biomass feedstock is firstly dried up to remove most of liquid water content i in order to prevent temperature drop at the entry of the reactor, especially upon cold-start when temperature has to increase rapidly during a short period; temperature ranges from 100-400ºC; the biomass does not experience any kind of decomposition at this stage.
- **Pyrolysis:** actual breaking down (*lysis* from the Greek) of biomass material by heat (*pyro* from the Greek) takes place at about 400-600ºC in the absence of air and it is the first step in the gasification and combustion stages. It is when charcoal, gases and tar vapours are formed which require an external heat source to do so.

$$Biomass\ + Heat \rightarrow Charcoal +\ Oil +\ Gases$$ Eq. 1

- **Combustion (or oxidation):** At this point, air (oxygen and nitrogen) is supplied in limited amounts oxidising the carbon present in the charcoal, producing carbon dioxide and water vapour as described in the following reactions which release heat therefore increasing the temperature to around 1,000ºC.

$$C + O2\ \leftrightarrow\ CO2\quad \Delta H = -394 \text{ MJ/kmol}$$ Eq. 2

$$H + \frac{1}{2}O2\,.H20\quad \Delta H = -241 \text{ MJ/kmol}$$ Eq. 3

- **Reduction:** Lastly, the carbon dioxide and water vapour are converted (reduced) to form CO, hydrogen and methane. The net enthalpy balance of these main four reactions is positive, hence decreasing the temperature to around 750ºC; the remains are ash and unburned carbon or char.

$$C + CO2\ \leftrightarrow\ 2CO\quad \Delta H = +173 \text{ MJ/kmol}$$ Eq. 4

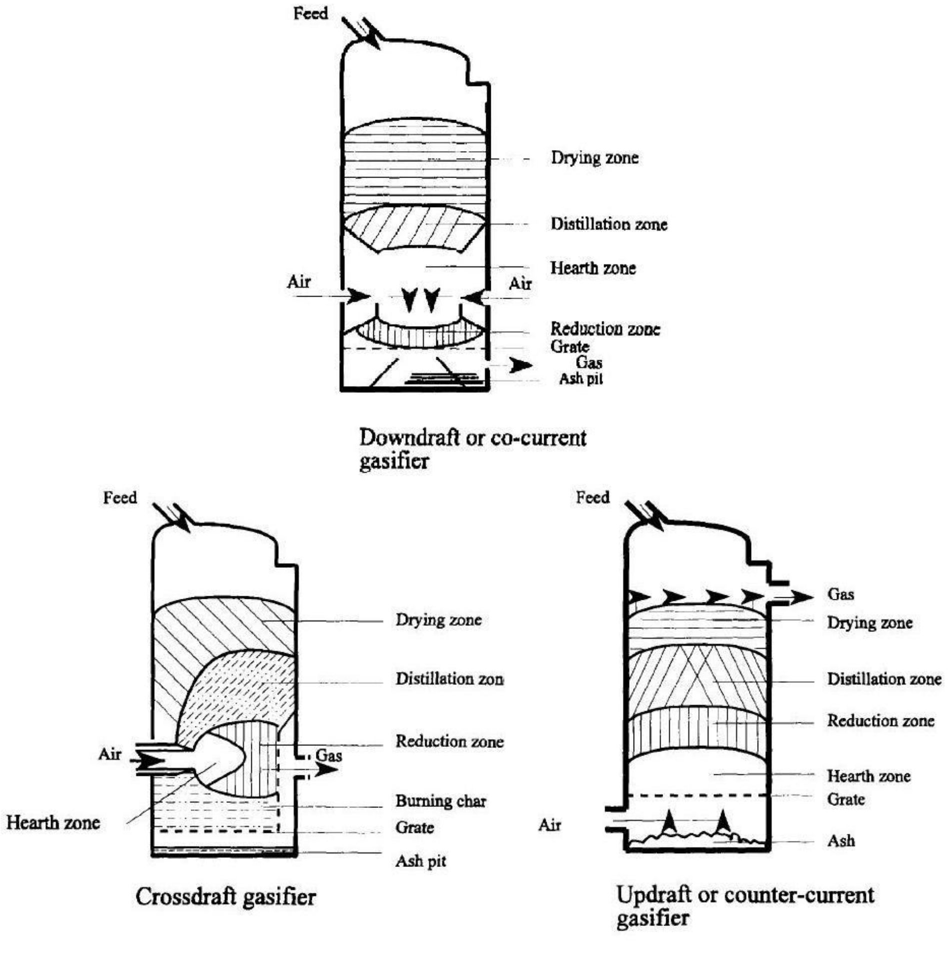
$$C + H2O \leftrightarrow CO + H2 \quad \Delta H = +131\text{MJ/mol} \qquad \text{Eq. 5}$$

$$CO + H2O \leftrightarrow CO2 + H2 \quad \Delta H = -41\text{MJ/kmol} \qquad \text{Eq. 6}$$

$$C + 2H2 \leftrightarrow CH4 \quad \Delta H = -75\text{MJ/kmol} \qquad \text{Eq. 7}$$

2.2.2 Types of Gasifiers

For a review of the different types of gasifiers see [12]. There are three main types of gasifiers: fixed bed (the scope of this study), fluidised or bubbling bed and entrained flow. In the former category, three different configurations can be distinguished: down-draft, up-draft and cross-draft (Figure 5).



Downdraft or co-current gasifier

Crossdraft gasifier

Updraft or counter-current gasifier

Figure 5 - Three types of fixed-bed gasifiers, adapted from [12]

These categories are characterised by the direction of the gas flow through the gasifier/reactor itself – upward, downward or horizontal – or by the direction of the solid flow – co-current, counter-current or cross-current. Gasification efficiencies for any type of modern gasifiers are between 80-90%.

In up-draft gasifiers, the resulting hot gas (~500ºC) normally contains large amounts of tars as well as ash and soot, suitable for direct combustion in a gas burner for thermal applications whereas in internal combustion (IC) engines applications the gas has to be thoroughly cleaned in order to avoid major engine wear (such as manifold obstruction due to soot deposits or tar corrosion). Conversion efficiency is usually higher. Down-draft gasifiers produce a hot (~700ºC) almost tar-free gas which after cooling and cleaning from soot and ash is suitable for use in IC engines but its conversion efficiency is a bit lower than the up-draft. Cross-draft gasifiers produce a tar-free gas normally if fuelled with good-quality charcoal i.e. a low content of volatile matter. Differences in gas composition can be seen in previous Table 2.

2.2.3 Power Gasifiers and Heat Gasifiers

In spite of its relatively low heating value, fuelling IC engines to produce shaft power to generate electricity, water pumping or grain milling with producer gas can be very effective in rural environments. In this context, gasification systems are often called *power gasifiers* whereas when producer gas is used to fuel gas burners to produce heat for thermal loads such as boilers, dryers or ovens these are called *heat gasifiers*. In many technical and operational aspects, these two types of gasifiers are rather different technologies since power gasifiers have to produce a very clean gas because of the strict-quality demands for an IC engine, and therefore the cleaning apparatus and operation is more complex and expensive. In contrast, heat gasifiers require little or no gas conditioning and are therefore simple to operate and less costly. However, since this study focus on the generation of electricity, the latter will not be discussed.

Spark-ignition engines (e.g. gasoline) can operated exclusively on producer gas while compression ignition (diesel) engines require mixtures of diesel and producer gas; a maximum of 80% of diesel replacement has been achieved in dual-fuel mode [13]. For this purpose, engines have to be properly modified to run on gaseous fuels since they have a significant lower energy content than liquid fuels e.g. the ignition system has to be able to provide stronger sparks or the ignition timing has to be adjusted accordingly because gaseous fuel have lower flame front speed etc. [14].

The temperature of the producer gas impacts the power output of an engine; the highest power output is achieved at the lowest temperature. This is due to the fundamental ideal gas law, gas volume increases with the gas temperature i.e. cooler gases have less volume and vice-versa, which means that for a constant gas flow rate, one can burn more fuel with a cooler gas than a warmer gas. It is therefore advantageous to cool down the gas before the engine intake. However, this cooling allows vaporized tars in the gas to condense on the engine inlet manifolds and valves and soot and ash can form deposits. Thus in power applications it is absolutely mandatory to filter and clean the gas properly in order to prevent excessive engine wear [12].

2.3 Case study - Rural community in Nampula, Mozambique

In order to explore the potential of biomass for the generation of electricity within the KUDURA concept, a case study was analysed. This case study was developed within the framework of a techno-economic assessment of the gasification of cashew nut shells in the already existing KUDURA solution to generate power in a small rural community located in the northern region of Mozambique.

Site location & climate characterisation

The Republic of Mozambique is located in the Southern Hemisphere covering latitudes from 11º to 27º south, in Southeast Africa, bordered by the Indian Ocean to the east, Tanzania to the north, Malawi and Zambia to the northwest, Zimbabwe to the west and Swaziland and South Africa to the southwest as illustrated in Figure 6. As of 2012, the total population was about 23.5 million [15] and the capital is Maputo (formerly known as Lourenço Marques) and it is the largest city. Based on the projections of [16], the country has a land are of 78,638,000 hectares of which 64% is considered to be agricultural area (sum of areas under arable land, permanent crops and permanent meadows and pastures).

Figure 6 - Location of Mozambique within African continent a) and province division b), adapted from [17]

The site of the project is located near the 15º7’S, 39º16’E coordinates close to Nampula city within the province of Nampula where the cashew industry is concentrated.

Mozambique has a tropical climate has a tropical climate with two seasons, a wet season from October to March and a dry season from April to September. For the region of Nampula, the average monthly temperatures and precipitation are presented in Table 3 and illustrated in Figure 7, based on about 30 years of historical record [18]. It is important to know the average temperature of the particular site since HOMER can introduce the effect of ambient temperature on power performance of a photovoltaic module.

Table 3 - High, low and mean temperatures and precipitation in the province of Nampula, adapted from [18]

	JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AGU*	*SEP*	*OCT*	*NOV*	*DEZ*
High T (ºC)	32	32	31	30	29	27	27	27	32	34	34	33
Low T (ºC)	21	22	21	20	18	16	15	16	17	19	21	22
Mean T (ºC)	27	27	26	25	24	22	21	22	25	27	28	28
Mean Precipitation (mm)	234	220	183	79	20	16	21	8	7	24	85	182

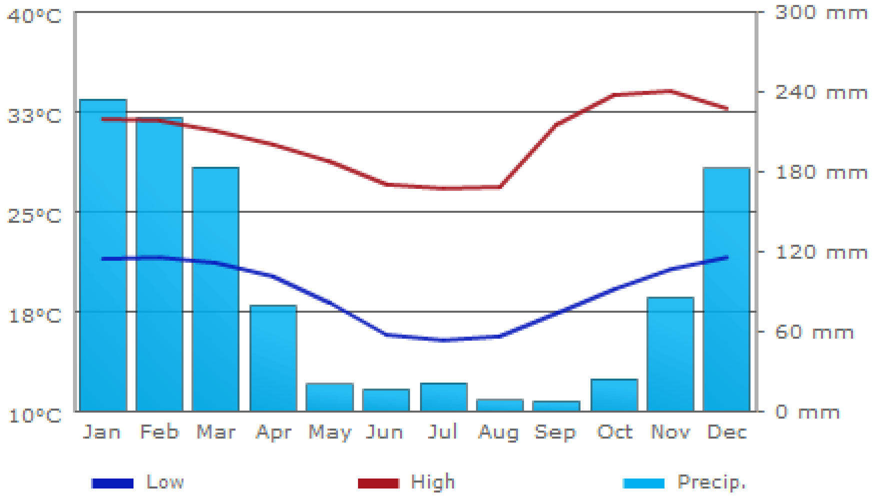


Figure 7 - Annual high and low temperatures and mean precipitation profiles for the province of Nampula, adapted from [18]

2.4 Proposed System

Gasification solution – APL's 10kW Power Pallet

The chosen gasification-based solution for this study is the 10kW Power Pallet model illustrated in Figure 15 from All Power Labs, a company specialised in small-scale gasifiers for both power and thermal applications. It comprises the following main features[4] [19]:

- Stainless steel hopper which holds up to 10 hours of fuel;
- GEK Gasifier: Compact multi-stage downdraft gasifier which consumes about 1.2kg of biomass per $1kWh_e$ produced;
- Gas filter with washable foam elements;

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[4] Technical details available at Annex 1

- Waste heat recovery and recirculation system for improved tar conversion and up to 30% moisture tolerance (TOTTI[5]);
- Internal combustion gas engine Kubota 962cc fully modified;
- Synchronous electric generator with automatic voltage regulation and $10kW_e$ of rated power;
- The process control unit (PCU) monitors and responds to all internal reactor, engine and filter conditions with a LCD display.

Figure 8 - Power Pallet 10kW model, adapted from [20]

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[5] Tower of Total Thermal Integration: It combines recovering waste heat from the hot output producer gas and IC engine exhaust to enhance tar conversion, increase tolerance of the fuel’s moisture and efficiency on the gasifier.

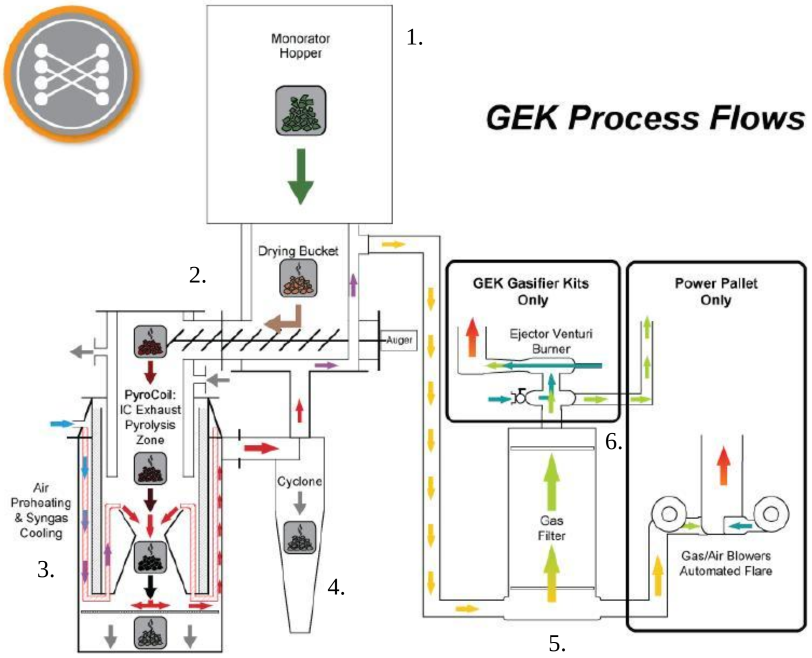

Figure 9 - Flow schematic of the GEK gasifier from APL, adapted from [20]

The sequence of its operation is relatively straightforward as shown in Figure 16 and goes as follows:

1. The feedstock enters the hopper after being properly chipped and dried according to APL specifications for the particular feedstock used;
2. Feedstock enters the drying bucket and passes through an auger where is conveyed into the GEK reactor (it is at this stage that TOTTI system supplies the recovered waste heat);
3. Feedstock fills the GEK reactor where it is submitted to four stages of gasification;
4. The hot producer gas exits the reactor and passes through a cyclone filter to separate particulate matter, heating the drying bucket as it exits the cyclone filter;
5. At this stage, the gas by-passes the gas filter on start-up and the blower system provides gas and air for the flare in order to promote the downstream circulation inside the reactor; after start-up, the flare is shut-off and the engine sucks the gas through the gas filter made of washable foam (dry filtration);
6. Finally, the gas is pre-mixed with air before entering into engine where excess gas produced is burnt in a Venturi burner.

A series of pressure, temperature and oxygen sensors controlled by the process control unit allow it to perform physical functions such as grate shaking, conveying the feedstock or adjusting the air-fuel mixture the ensure complete combustion inside the reactor, enabling it to be a turn-key system without the need of a technician standing at “all times”. But since it is not a fully automated solution (unlike diesel genset) e.g. it needs to warm up through a series of manual procedures or to remove the ash tray and clean the gas filter after every 8 hours run [20], a technician will be required to start-up/shut-down the gasifier and engine.

In usual applications, the feedstock has to be processed before entering the hopper of the gasifier; this drying and chopping requires an electric chopping unit. In our application, though, since the feedstock (cashew nuts shells) is within the size tolerance specified by the manufacturer (20-50mm), they do not require such preparation and a drying unit is not necessary.

3. Hydro-power

3.1 Motivation

Small-scale hydro-power is a promising energy technologies for providing energy to rural areas beyond the reach of a national grid in developing countries due to its simplicity, robustness and straightforward O&M, promoting cost-effective solutions when properly managed locally [21]. For example, pico hydro schemes (<5kW) have been successfully deployed in Kenya [22] along with micro hydro schemes (5<kW<100) in Nepal [23]. In most instances, small-scale hydro-plants are in the run-of-the-river configuration, which means that there is no need for a dam or barrage, and little or no water is stored. Hence, the civil works only purpose is to serve the function of regulating the water level at the intake to the hydro-plant. As a result, and unlike large hydro plants, run-of-the-river installations do not have the adverse effect on the local environment, making it almost impact-free on the environment during construction and operation periods.

The hydro resource is a much more concentrated energy resource than either solar or wind, its availability is predictable and today's commercial technologies convert potential energy into useful energy at efficiencies in the range of 50% to 90%, whereas wind turbines are limited to around 80% of the theoretical Betz limit[6] and most crystalline silicon-based PV modules can convert around 15-20% of the total incoming solar energy reaching the Earth's surface, making hydropower one of the most efficient energy technologies [24].

Another advantage of hydro-power is the ability of continuously generate energy without the need of some sort of storage; however, since river flows often vary considerably with the seasons, especially where there are monsoon-type climates, this can limit the power output to a small fraction of the maximum annual capacity factor. One other limitation is the fact that it is a highly site-specific technology, depending critically on the local features as e.g. available head, annual flow-duration curve, terrain characteristics or the distance between the well-suited site for harnessing of water-power and the actual location where power can be exploited etc. This fact confines each analysis to a given hydro-power site whereas solar PV systems are not so site-dependent and are highly scalable [21].

Another major hindrance to the exploitation of small-scale hydro-plants in developing countries is the relatively high initial CAPEX, which limits its deployment without leveraging through funding programmes and other mechanisms [21]. Most of the total CAPEX comes from the civil work expenses and electro-mechanic equipment as shown in Figure 38 [25]. There are several ways of decrease these expenses – civil work can be carried out by local enterprises using locally sourced

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[6] Defined by Albert Betz in 1919 based on the fundamental law of conservation of mass and energy, wind turbines cannot capture more than 59.3% of the total potential kinetic energy in wind.

materials and expertise. Also, given the right conditions, the *pumps as turbines* (PAT) concept can be used instead [26] since they are mass-produced for a wide range of heads and flows and their corresponding spare parts are easily available, and easy to install and maintain, they can be made into an affordable “off-the-shelf” solution, which has already made an important contribution to village development for certain remote areas [27]. The main problem of using a PAT is the difficulty of predicting accurately the turbine performance and the de-rating effect on the overall efficiency.

In spite of having a relatively high initial CAPEX, micro hydro-plants also have the lowest pay-back period among renewable energy resources as illustrated in Figure 39 according to [25].

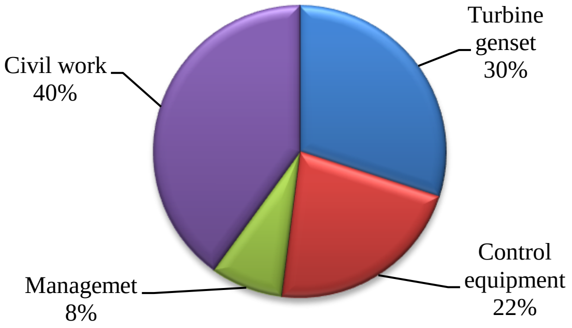

Figure 10 - Small-scale hydro plant cost break-down, adapted from [27]

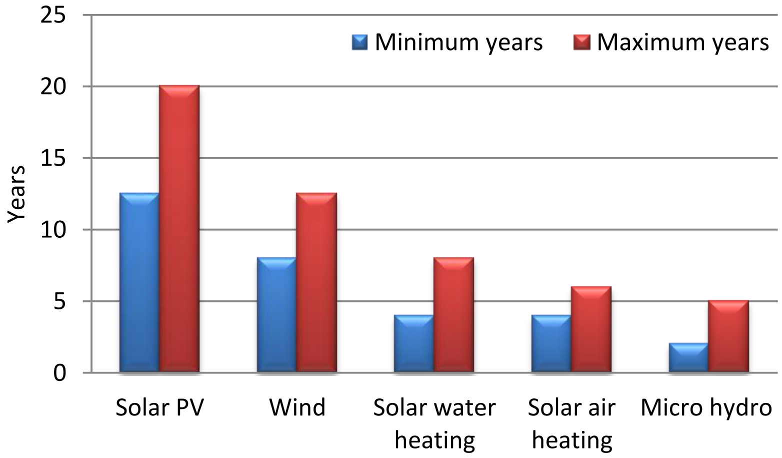

Figure 11 - Pay-back period of different renewable energy systems, adapted from [25]

Other purposes than electric power (lightning, radio, TV) can have great impact upon the community development, such as shaft-power for driving machinery for e.g. crop-processing, woodworking or power looms. Studies in Nepal have shown that rural electrification alone has had minimal impact on agriculture or industrial production, and the most cost-effective local use of hydropower has been through mechanical end-uses [28]. In Kenya, a major energy demand sector in rural areas is agroprocessing services, such as corn milling and coffee bean pulping, hence a service can be provided to local households at a lower cost than alternatives such as diesel [21]. In summary, where hydropower resource exists, experience as shown that there is no more cost-effective, reliable, and low impact on the environment than a small-scale hydropower system. There are many mountainous regions of the world where the national grid will probably never reach, but which have sufficient hydro resources to meet basic household and cottage industry needs of local communities. It has been successfully achieved in a few selected countries.

3.2 Hydro-power technology

3.2.1 Principles of Hydro-energy

The hydro-electricity production is an energy conversion process in which the water is the vehicle of transmission and transformation of its gravity potential energy into mechanical and electric energy by the turbine genset. The water is led through pipes and/or canals to the turbine, which turns the shaft of the generator to produce electric energy, based on the fundamental equation below [23]:

$$E = m \times g \times H \times \gamma \qquad \text{Eq. 8}$$

In which m represents water mass (kilograms), g the gravitational constant (9.8 J/(kg.m)), H the useful height (commonly known as useful *head* in meters) and γ represents the hydraulic, mechanical and electrical efficiencies of the turbine, which for micro-hydro turbines it typically ranges from 70 to 90% for steady-state conditions.

The useful head is defined as the difference between the available gross head (Hg) and hydraulic loses (HL) expressed in meters (Eq. 9) that may occur inside the penstock; these hydraulic losses depend on water flow (Q), penstock hydraulic diameter (Dh) as well as penstock length (L) and penstock material (C) as described in Eq. 10 and 11.

$$H = Hg - HL \qquad \text{Eq. 9}$$

$$HL = \left(\frac{0.2083}{100} \times \left(\frac{100}{C}\right)^{1.85} \times (Q \times 15{,}85)^{1.85} \times \frac{1}{Dh^{4.87}} \times 208.25\right) \times L \qquad \text{Eq. 10}$$

$$Dh = 4 \times \frac{A}{P} \qquad \text{Eq. 11}$$

The quoted HL are based on the Hazen-Williams equation for pressure losses inside pipes and they can be negligible depending on water flow and penstock diameter. Also HL parameters may differ whether the penstock system is a pipe or tunnel and if it is pressurised or not. The parameter C is a constant that depends solely on penstock material (internal friction). A list of several materials' parameters is presented in Annex 2.

The typical schematic of run-of-the-river micro hydro-plant is illustrated in Figure 40. Water flow is deviated from the main waterway and is submitted to several stages until it actually produces useful work by the following order [29]:

1. It is conveyed either through a canal or pipe into the intake reservoir which constitutes a small storage form of the available potential energy and sets the gross head of the hydro scheme.
2. Then enters the intake penstock down to the power house where the turbine genset is located; some kinetic energy gets degraded due to internal friction of the penstock.
3. The turbine genset transforms water-falling kinetic energy into mechanical rotating kinetic energy which turns the shaft of an electric generator.
4. Electric power is then controlled by an electronic load controller (ELC) to provide a stable voltage frequency to the AC micro distribution grid and ultimately to the end-user.
5. Finally, water flows out through a pipe onto the tailrace where it returns back to the main waterway.

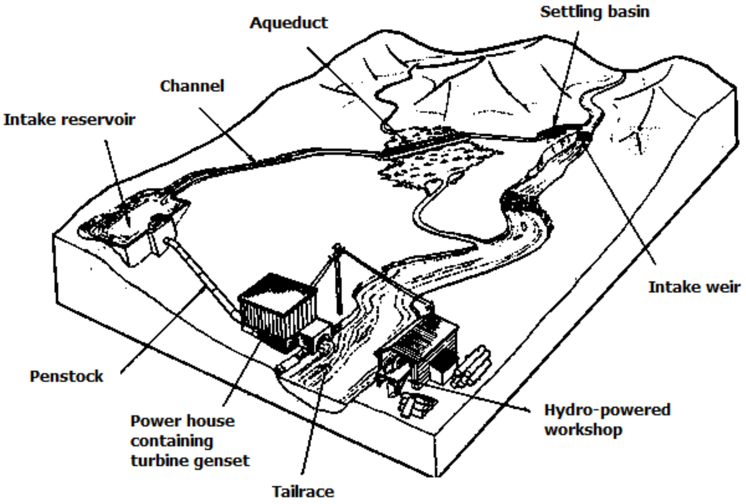

Figure 12 - Typical micro hydro-plant layout scheme, adapted from [23]

3.2.2 Flow-duration curve

The flow-duration curve is a cumulative curve that shows, for a given period, the fraction of time when the specified flows were equalled or exceeded. It combines in one curve the flow characteristics of a stream throughout the range of flow, without regard to the sequence of occurrence. If the period represents the long-term flow of the stream, this curve may be used to predict the distribution of future flows and it is a useful assessment of water-flow resource for energy generation in a hydro-power project.

Figure 41 illustrates an example of a flow-duration curve for a specific site in Northern Portugal [30]. In a hydro-power application, hypothetically assuming that the project's turbine flow is 10 m^3/s and that it runs during 16% of the time, the rectangular area limited by these two values gives the theoretical amount of annual energy produced by the turbine.

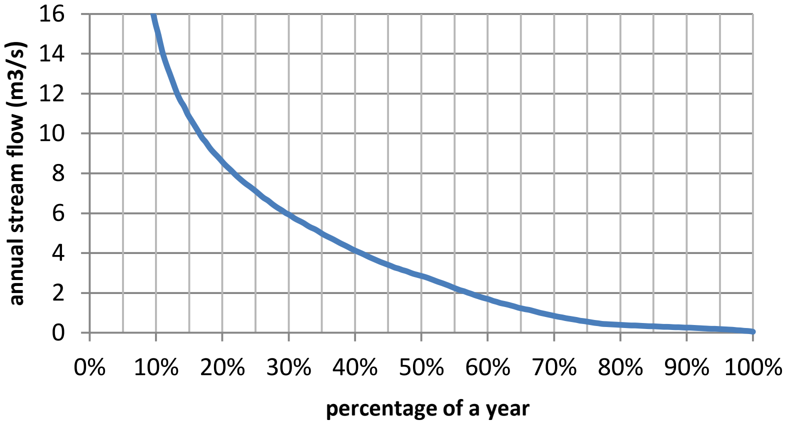

Figure 13 - Annual flow-duration curve for a particular site in the Northern region of Portugal [30]

At locations where the season variation of water flow of a particular waterway is very pronounced (e.g. monsoon-type) or limited by external factors (e.g. irrigation purposes) and thus water supply gets constrained during a certain period of the year, a scheme of two turbines gensets of different sizes is a possible strategy to cope with seasonal/daily variation while maintaining a high capacity factor throughout the year. Figure 42 shows the hypothetical use of two Pelton turbines – Pelton turbines can decrease water flow to about 60% of its nominal flow while maintaining high efficiency (Figure 45) – the larger (red) runs during the period of greater water flow (e.g. rainy season) for 30% of the time in a year, and the smaller (green) during periods of less intense water flow. This way, it is possible to maximise the annual power output of the hydro-plant and its flexibility upon water flow constrain.

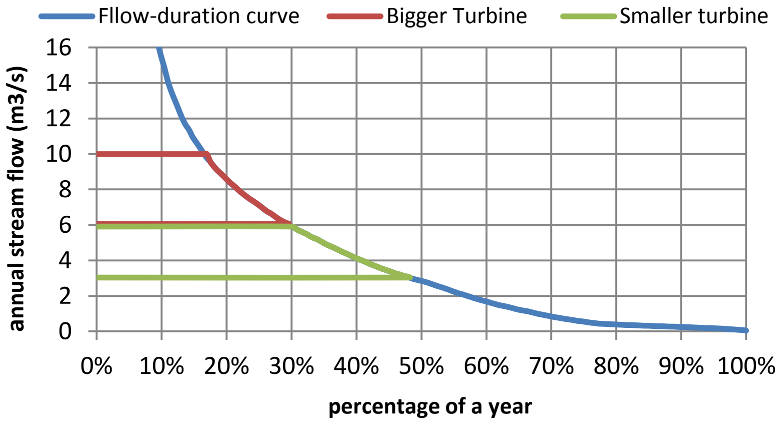

Figure 14 - Annual energy production of two Pelton turbines, a bigger and smaller one, in a constrained water flow scenario

3.2.3 Types of Turbines

The selection of the best turbine for any particular hydro site depends mainly upon the site characteristics, in particular the available head and flow. Selection also depends on the desired running speed of the generator or other device loading the turbine. All turbines have a power-speed characteristic and an efficiency-speed characteristic. They will run most efficiently at a particular speed, head and flow. Table 4 differentiate the two main types of hydro turbines according to head classification for a micro-scale scheme.

Table 4 - Head classification of different types of micro hydro-turbines, adapted from [21]

Turbine type	***Head classification***		
	High (>50m)	***Medium (10-50m)***	***Low (<10m)***
Impulse	Pelton Turgo Multi-jet Pelton	Cross-flow or Banki Turgo Multi-jet Pelton	Cross-flow or Banki
Reaction	PAT	Francis PAT	Francis PAT Kaplan or Propeller

The *Pelton*, the *Turgo*, and the *Cross-flow* or *Bank*i may be grouped as *impulse* or free-jet turbines at atmospheric pressure (Figure 43). The Pelton turbine consists of a wheel with a series of split-buckets set around its rim; a high velocity jet of water is directed tangentially at the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through 180°. The Turgo is similar to the Pelton but the jet is designed to strike the plane of the runner at an angle (typically 20°) so that the water hits the runner on one side and exits on the other. Therefore the flow rate is not limited by the discharged fluid interfering with the incoming jet (as in Pelton turbines). As a consequence, for an equivalent power, a Turgo turbine can have a smaller diameter runner than a Pelton. The Cross-flow has a drum-like rotor with a solid disk at each end and gutter-shaped ‘slats’ joining the two disks. A jet of water enters the top of the rotor through the curved blades, emerging on the far side of the rotor by passing through the blades a 2nd time. The shape of the blades is such that on each passage through the periphery of the rotor the water transfers some of its momentum, before falling away with little residual energy.

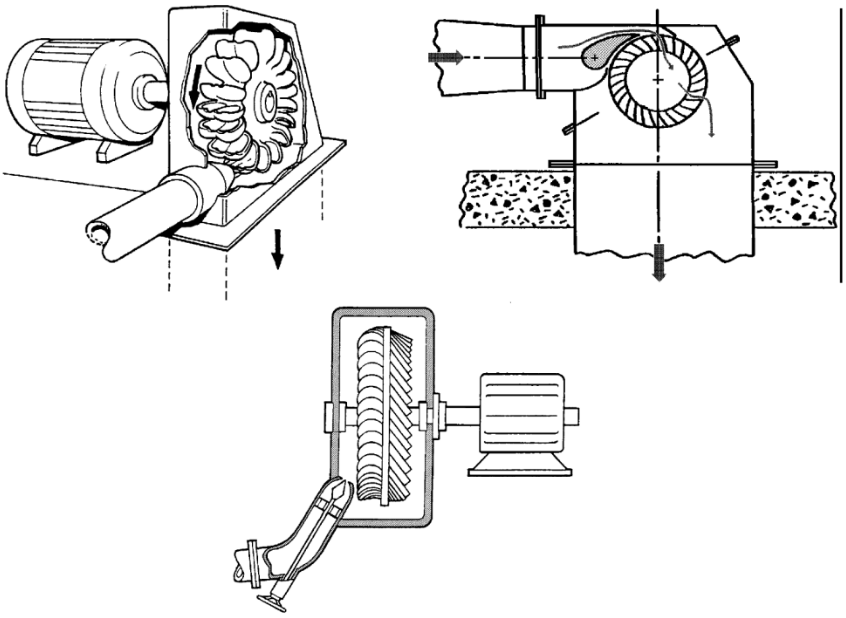

Figure 15 - Impulse turbines: a) Pelton; b)Cross-flow or Banki; c) Turgo, adapted from [23]

Reaction or pressurised flow turbines are distinguished from impulse turbines by having a runner that always functions within a completely water-filled casing or pressurized (Figure 44). All reaction turbines have a diffuser known as the *draft tube* below the runner through which the water discharges. The draft tube slows the velocity of the discharged water and reduces the static pressure below the runner (as in aircraft wings) and thereby increases the effective head. The two main types of reaction turbine are the *Propeller* (*Kaplan* variant with adjustable pitch blades) and *Francis* turbines. A propeller turbine is similar to the propeller of a ship, but operating in reversed mode. The Francis is essentially a modified form of propeller turbine in which water flows axially inwards into the runner and is turned to emerge axially. The runner is most commonly mounted in a spiral casing with internal adjustable guide vanes.

Reaction turbines require more sophisticated fabrication than impulse turbines because they involve the use of more intricately profiled blades together with carefully profiled casings. Fabrication constraints as well as difficult access to inner components such as bearings and runner make these turbines less attractive for use in micro hydro in developing countries. However, because low head sites are far more numerous and closer to where the power is needed, work is being undertaken to develop propeller machines which are simpler to construct [21].

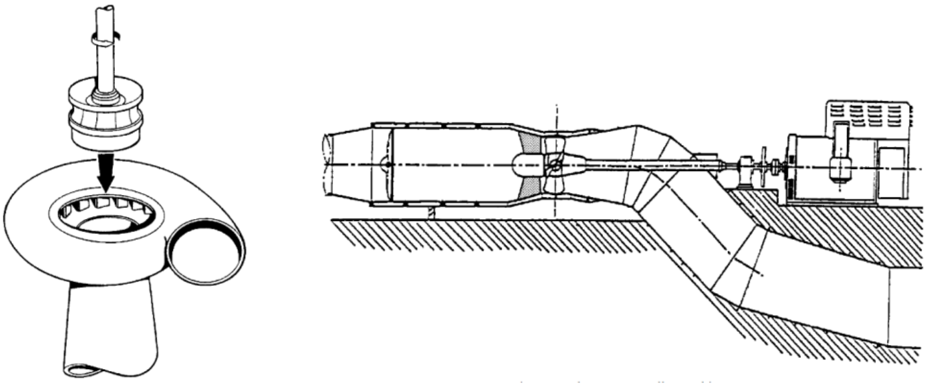

Figure 16 - Reaction turbines: a) Francis; b) Propeller (fixed blades) or Kaplan (adjustable pitch blades), adapted from [23]

A significant factor in the comparison of different turbine types is their relative efficiencies both at their design point and at reduced flows. Typical efficiency curves are shown in Figure 45. An important point to note is that the Pelton, Cross-flow and Kaplan turbines retain very high efficiencies when running below design flow; in contrast the efficiency of Francis and Propeller turbines fall away considerably if run at below half its normal flow.

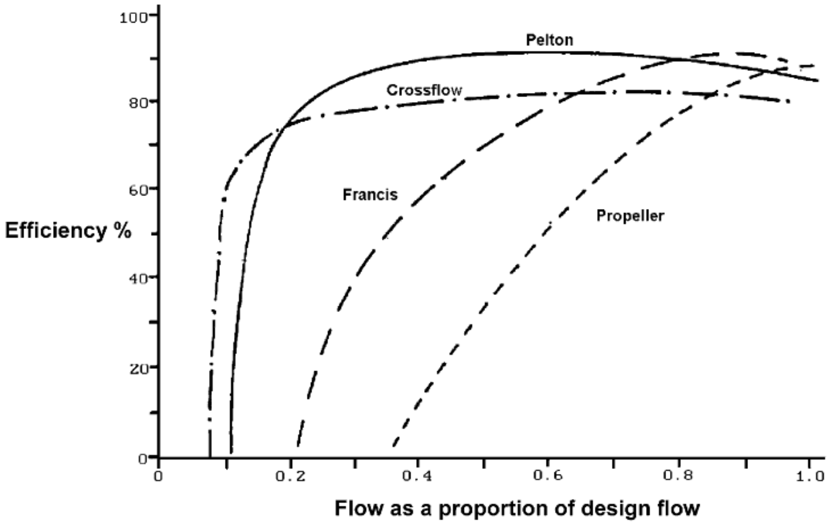

Figure 17 - Relative efficiency of impulse and reaction turbines [21]

For micro-hydro, turbine selection is relatively easy. For high heads and low flow, Pelton and Turgo turbines are the best option; for low heads and high flow, Propeller and Francis are the most indicated; for medium and low heads and high flow, Cross-flow and multi-jet Pelton turbines usually suit best.

Figure 46 illustrates the selection chart for an overall efficiency from water to mechanical power of 75%.

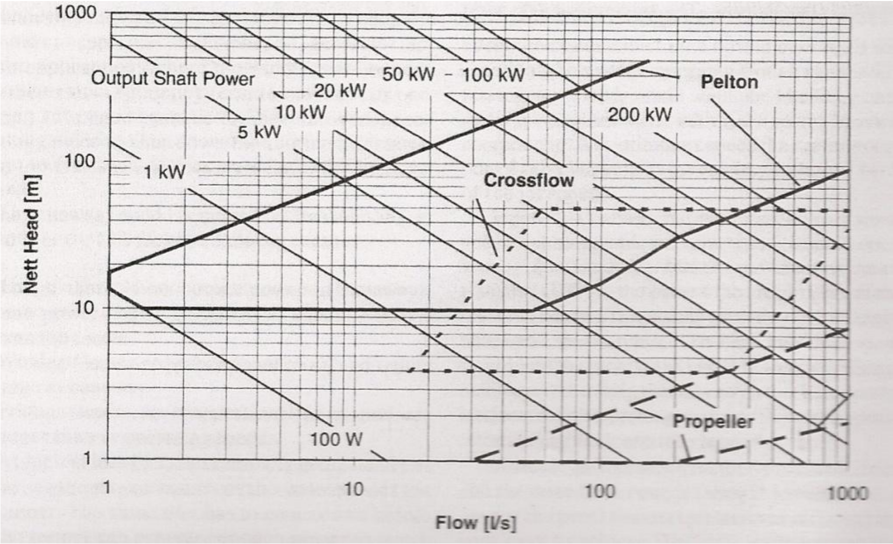

Figure 18 - Application ranges of different types of turbine for micro-hydro(power lines are drawn for an overall efficiency from water to mechanical power of 75%, adapted from [23]

Also an important note is whether the turbine and the electric generator (or other shaft loads) are coupled on the same shaft or not. If it is not direct-drive, belts and pulleys will be necessary and with it an extra bearing since it uses two shafts, thus lateral forces may lead to faster wearing; this design is necessary when the synchronous speed of the electric generator is different from the turbine designed speed. In order to select a direct-drive set, which is definitely wiser regarding maintenance issues, the number of poles on the electric generator's rotor has to increase/decrease depending on the turbine used and desire voltage frequency.

3.2.4 Governors and controllers

Governing is the control of the speed and power output of a turbine. Instead of relying in one operator to manually govern valves to stabilise frequency or turbine speed when villagers turn on and off their appliances, an automatic system can be fitted. There are two main types. Those which control the flow – they sense the turbine speed and adjusts the flow accordingly. As more loads are switched on, the speed starts to drop, and the governor opens up the valves to increase flow and vice-versa. And those which control the load – load controllers also sense the speed but they allocate power to a dummy or ballast load when load is lower than turbine output power, restoring the equilibrium.

Flow controllers have the advantage that they only use the water they require. This is particularly important for storage applications where stored water is used to meet peak demand. The main disadvantage is its mechanical complexity, as the governor has to be able to accurately control valves against quite large forces; most systems use pressurized hydraulic oil for this purpose which can introduce many other components such as actuators, tanks, hoses that are expensive and require some engineering expertise.

Load controllers are more appropriate for micro-hydro applications and have been widely used. The controller is usually an electronic device (*Electronic Load Controller* or ELC) which senses the frequency and adjusts the load by solid-state switching, usually using thyristors. ELCs can react very quickly to changes in the load and they can cope with switched loads, which constitute a high proportion of the total load (e.g. sawmill in a small village scheme), something flow control governors find difficult. Also they are relatively cheap, being much cheaper than flow control governors for most micro-hydro applications and usually makes it the best solution for governing a micro hydro-turbine in developing countries.

3.2.5 Types of Pumps

There is a wide multitude of electro-pumps available in the market today, with specific features that vary accordingly to the type of application. They can be divided as *surface pumps*, which can be a single stage or horizontal/vertical multi-stage centrifugal pumps as illustrated in Figure 47a) and b) respectively and, as *submersible pumps,* which have with a hermetically sealed motor coupled to the pump; these can be a regular single-stage centrifugal-type usually used in sewage pumping, or multi-stage fitted with an elongated induction motor typically used in boreholes of water-wells as illustrated in Figure 48a) and b) respectively [31].

Figure 19 - Surface pumps: a) Single-stage and b) Multistage, adapted from [32]

Figure 20 - Submersible pumps: a) single-stage and b) multi-stage, adapted from [32]

The main difference of single and multi-stage pumps is the ability of the latter to pump to higher heads for equivalent flow figures. Single-stage and multi-stage surface pumps along with single-stage submersible pumps have relatively medium flow capacities ($20\ m^3/s < Q < 60\ m^3/s$) but their maximum pumping head is medium to high ($30\ m < H < 200\ m$) whereas multi-stage submersible pumps can pump to greater heads (up to 450 m) as well as flow capacities (up to $120 m^3/s$) since they are used in deep water-wells and oil extraction [32].

Efficiency ranges from 60% up to 85% depending on the manufacturer building quality, as well as designed head and flow. Exchanged feedback from Portuguese manufacturers and dealers has suggested that multi-stage pumps are more efficient but also the most expensive as well [32, 33].

There is wide multitude of pumps available and each solution can be easily tailored to meet the necessary project specifications to achieve either the maximum pumping efficiency at the best CAPEX.

3.3 Case study - Rural village in Lamu, Kenya

To assess the potential of integrating micro hydro-power within the KUDURA concept, the coastal Lamu province in Kenya was chosen to conduct the study.

Site location and climate characterisation

The Republic of Kenya lies between latitudes 5^oN and 5^oS, and longitudes 34^o and 42^oE and its population was 43 million in 2012 [34]. It borders with the Indian Ocean and Somalia on the east, South Sudan to the north-west, Uganda on the west and with Ethiopia and Tanzania on the north and south respectively (Figure 49). The capital city is Nairobi located in the high lands, home to the north-south-running Great Rift Valley and the second highest point in Africa, the Mount Kenya (5,199m). To the west, land descents towards coastal and north-east regions. Climate in Kenya varies from tropical along the coast to temperate inland to arid in the north and north-east parts of the country. The country's orographic map is presented in Figure 50. About 75% percent of Kenyans work in agriculture, most as subsistence farmers. [35].

Figure 21 - Administrative map of Kenya [35]

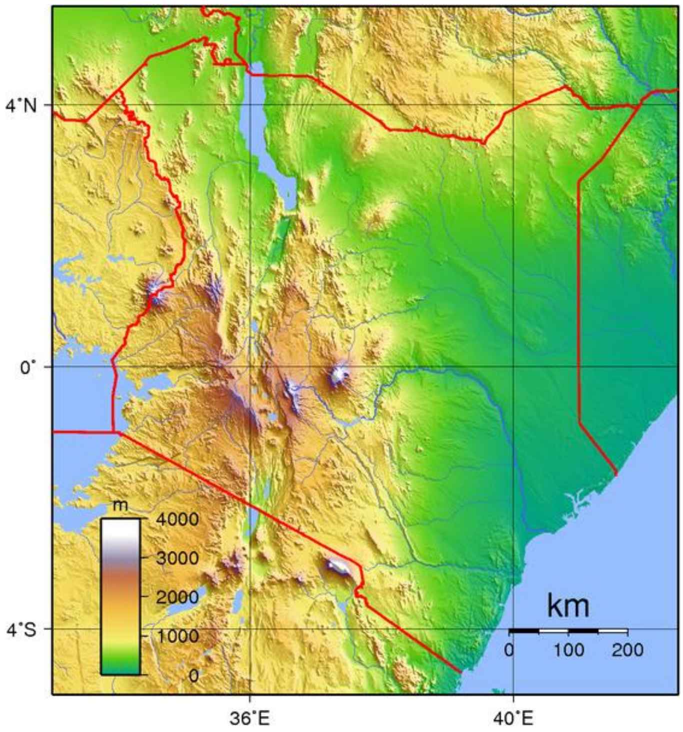

Figure 22 - Orographic map of Kenya [35]

The site of the village is located somewhere within 2º21'S, 40º19'E in the province of Lamu located on the ocean coast of Kenya. Local climate is characterised by a strong and steady daily variation of temperature throughout the year with a tropical climate mainly influenced by moisture from the Indian Ocean and the large extension of mangrove swamps whereas in the highlands, although Kenya is located near the equator, the climate is more temperate, with a typical winter season due to altitude. Wet season in Lamu occurs usually from April to July. In Table 15 and Figure 51 the annual profile of temperature and precipitation are presented [18].

Table 4 – Average high, low and mean temperatures, in ºC, for the province of Lamu, adapted from [18]

	JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AGU*	*SEP*	*OCT*	*NOV*	*DEZ*
High T (ºC)	42	43	44	43	41	39	38	38	40	41	42	42
Low T (ºC)	14	14	15	14	14	13	13	13	13	14	14	14
Mean T (ºC)	28	29	30	29	28	26	26	26	27	28	28	28
Mean Precipitation (mm)	6	4	38	128	295	167	86	46	56	43	57	30

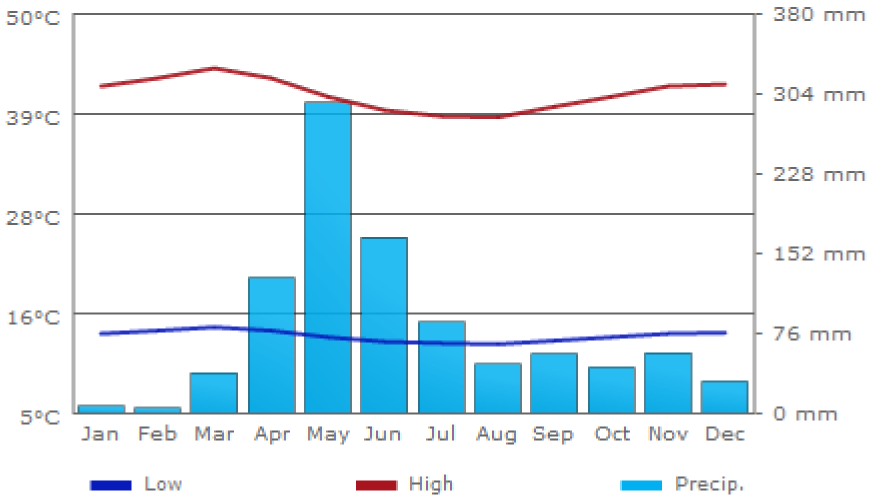

Figure 23 - Annual high and low temperatures and mean precipitation profiles for the province of Lamu, adapted from [18]

3.4 Proposed system

Two different micro hydro-systems are presented in this section. The first is a typical run-of-the-river micro hydro-plant with a simple configuration; the second includes energy storage, and is more complex in the sense it is a “regular” PV system but without the typical lead-acid battery (LAB); instead it uses *pumped water storage* (PWS) as a means of storing energy.

Hydro-power scheme

This system configuration is somewhat very similar to the one presented in Figure 40 and its operation is suggested in Section 3.2.1. It comprises a turbine-AC genset, an ELC unit, penstock, hydraulic miscellaneous such as intake manifold, valves, pressure gauges etc., and electric miscellaneous such as panel board, protections, cables and switches. Every component is to be fitted and shipped inside a single 6x2.5x2.5m container (except for the penstock) which works as power-house structure as well.

For determining the turbine rated power and water flow, it is assumed that 90% of the daily energy demand is within the evening-night peak (Figure 52) thus energy has to be provided in a 5 hour-period. Therefore, the turbine rated power will be 9kW in steady-state conditions. Assuming a global efficiency of 85%, a gross head of 50 m and Eq. 12, it is possible to calculate the turbine rated flow Q_t. Therefore, the necessary water flow is 22L per second or 78m^3 per hour.

$$P_t = Q_t \times Hg \times g \times \gamma_t \qquad \text{Eq. 12}$$

A Pelton turbine was considered to be the turbine suitable for a high available head of 50m due to its high efficiency and simple maintenance. Since no quote was obtained from any manufacturer/dealer, the cost of a Pelton turbine genset was estimated using Eq. 13 from the literature [36] in which a 1.2 factor was added to approximately convert the cost in British pound to Euro currency. Estimates lie within ±15% of the quoted value.

$$C_t = 2{,}600 \times {P_t}^{0.54} \times 1.2 \qquad \text{Eq. 13}$$

It is assumed that the penstock is tilted at a 45º angle between the point where it is connected to the turbine intake manifold and the reservoir located at 50m up in the vertical. Therefore, the total length of the penstock is about 71 m.

Penstocks can be installed over or under the ground, depending on factors such as the nature of the ground itself, the penstock material, the ambient temperatures and the environmental requirements. A flexible and small diameter PVC penstock for instance, can be laid on the ground, following its outline. Small pipes installed this way do not need anchor blocks. A simple criterion for penstock diameter selection is to limit the head losses to a certain percentage. Loss in power of 4% is usually acceptable [29]. Hence, the hydraulic losses inside the penstock were calculated assuming the penstock is made of PVC (C=150) and with an inner diameter of 130mm. The total hydraulic losses are 1.22 m or 3.3% of the total penstock length. For cast-iron, hydraulic losses would be of 2.7 m or 5.1%. Additionally, PVC is a less expensive material than cast-iron or steel and easier to transport and to work with. The PVC material cost was estimated at €10 per meter.

The civil work i.e. construction of the concrete intake reservoir, diversion way, foundations for the container and spillways, to be done locally – no expenses on the construction of the powerhouse is assumed since the container serves that purpose.

The electric components comprise electric miscellaneous such as the ELC unit, AC protection boards, cables, ground protections, cable paths, etc.

PV with PWS

The system comprises a PV array and an alternative form of energy storage based on *pumped water storage* (PWS). The PWS system is comprised of a turbine-AC genset, a hydraulic pump and an upstream and downstream reservoir. Carrying out an analogy of a lead-acid battery (LAB), the turbine genset works as an inverter converting gravity potential energy (DC energy) into useful kinetic energy (AC energy); the pump works as a regulator charging the “battery” when there is a surplus of PV production or hydro-power production from the ELC unit, pumping water from the downstream reservoir up to the upstream reservoir until the desired water level is reached if power is available. Hence, water acts as an energy vector, like the electrolyte of a LAB. Simple schematic of the proposed system is shown in Figure 58.

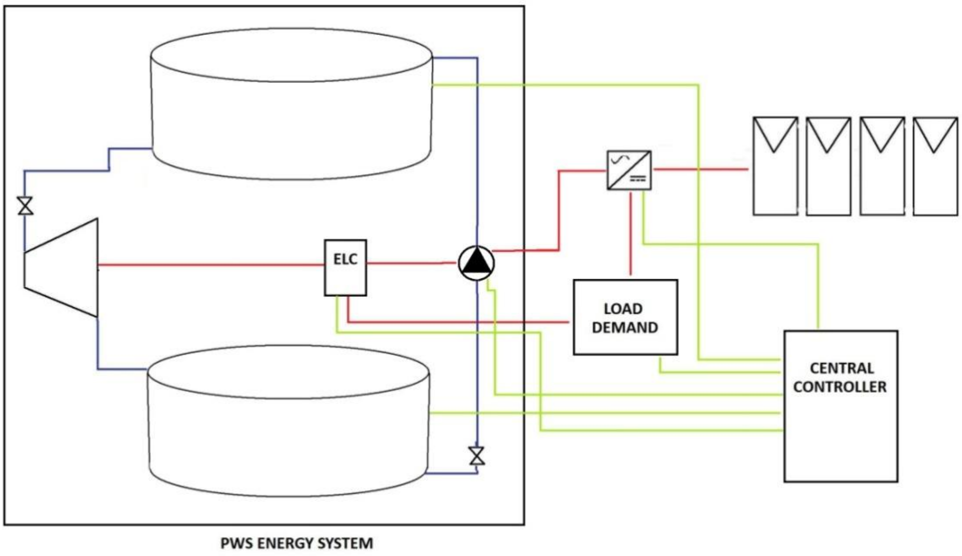

Figure 24 - Simple schematic of the PV system with PWS: red lines represent electric power; blue lines represent water flow; and green lines represent sensors and actuators

In order to determine the pump rated power and flow, PV array capacity and reservoirs sizes, the following assumptions are considered:

- Figure 59 plots the gross head as a function of water volume for 50 kWh$_e$ per day demand considering a global efficiency of 85%. Thus, for a 50m head, the total volume that flows through the turbine runner each day is about 432,000 L. One day of autonomy requires a 432m^3 capacity reservoir.

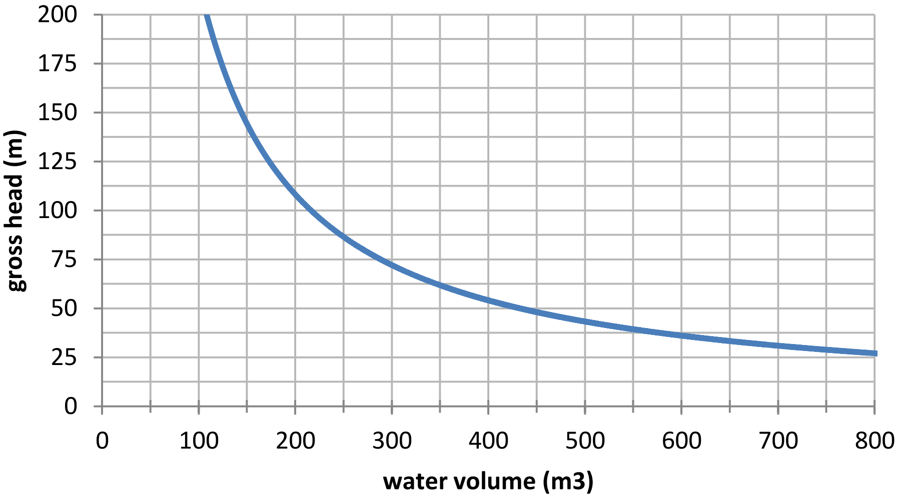

Figure 25 - 50kWh$_e$ hydro energy for a global efficiency of 85%

- Autonomy days are set as two thus each of the reservoirs has to have 864 m^3 of volume capacity.

- Pump efficiency is set to 75% and the pumping head is 60 m, because the pump is located lower than the turbine and also it has to pump over the top of the upstream reservoir.
- An average of 4 solar peak-hours (SPH) is assumed for the site which is the period for pumping 432 m^3 of water each day at nominal conditions.

Thus taking into account the latter assumptions, the following is also assumed:

- Daily pumping energy is $89kWh_e$.
- Dividing 89kWh by 4 SPH leads to a PV array rated power of $23.5kW_p$ thus, the pump rated power is 23.5kW.
- Therefore pump rated pumping capacity is 108 m^3/h or 30 L/s.
- The PV array is comprised of 95 modules of 250Wp each.

Reservoirs can be made of concrete or metal. The first option is assumed to be more expensive either in terms of cost per m^3 as well as in logistics of construction equipment and personal allocation to the site, especially in remote sites; in addition, concrete structures usually have a significant impact on the surrounding environment during the construction period due to cement washout during cleaning and rain, formation of solid residues, sound pollution, etc., [37] which in turn can also impact the rural community. Metal reservoirs, as the name implies, are made of several metal sheets which can be stacked to fit inside a container, along with a plastic *geo-membrane* for water tightness; this makes metal reservoir easy to assemble/disassemble and transport and very flexible in terms of desired volume capacity and highly scalable with minor interventions. Therefore, metal reservoirs were selected as the best solution for water storage of the case study. Figure 60 illustrates the specific metal reservoir considered for the water storage application.

Figure 26 - Examples of Genap water reservoir, adapted from [38]

This type of reservoir is commonly known as *Genap* reservoir, derived from the Dutch manufacturing company Genap. They have a circular shape outlined by wavy galvanised steel sheets that can last between 25-30 years; the geo-membrane is composed of a plastic material with good tolerance to UV chemical-degradation with a serviceable lifetime of 7-14 years; additionally a top cover can be add to prevent evaporation losses, debris entering the reservoir and shade protection from UV rays [38]. Main drawbacks are the geo-membrane replacement, installation by qualified personnel and, depending on the size and terrain characteristics, a concrete foundation may be required for proper base fitting of the reservoirs.

Since the nominal volume capacity required for 2 days-autonomy is 864m^3, from the size spectrum available, the reservoir has to have 21.85m of diameter and 2.36m height, thus a total capacity of 884m^3.

4. Conclusions

The potential of rural electrification in SSA is enormous since less than 15% of its rural inhabitants do not have access to electricity; Kenya and Mozambique are no exceptions. The challenge of providing energy services to rural areas, either through grid extension or decentralised energy systems is very significant. High infrastructure costs, financial constraints and relatively low electrical demand make connecting the large number of rural communities to the grid unattractive to national utilities. On the other hand, decentralised generation has the potential to offer a medium- and long-term solution for rural electrification but the CAPEX for these off-grid systems can be high, and therefore securing financing can be challenging, and the lack of national policy mechanisms to support the development of off-grid systems or complementary programmes to ensure the maximum benefit of this kind of systems, has often hinder their successful deployment.

The proposed biomass system was analysed in this thesis due to the potential of biomass gasification technology on providing sustainable energy services to rural areas and is expected to be part of the RVE.Sol’s technology portfolio in a not far future. The analysis showed that the energy dispatch strategy of a generator, whether on biomass or diesel, can have a significant impact on several factors such as fuel consumption, O&M costs, BB lifetime and the system’s ability to serve energy demand – LF strategy limits the generator to produce only the necessary power to meet load demand thus consuming less fuel but increasing the usage frequency and DOD of the BB whereas CC strategy forces the generator to operate at nominal power capacity whenever it is requested with the energy surplus being allocated to charge the BB and keep its SOC up, thereby promoting less often and deeper DODs, increasing its lifetime and the system´s readiness to serve load demand (although at a cost of consuming more fuel which can be problematic if fuel supply is somehow constrained).

The proposed biomass system still faces a number of technical and economic challenges in order to be competitive over other energy solutions, in particular diesel gensets which can operate automatically on optimised mode whenever power is needed, and without the need of a technician. This is a particular important feature in stand-alone hybrid systems because it can lead to potential fuel and O&M costs savings, especially when allied with highly scalable PV power. Small-scale gasification systems lag in this technical ground, requiring an on-hand technician at all-time, significantly increasing the O&M costs. The simulation results show, however, that the baseline diesel system did not outperform the biomass system at the standard case-study conditions. While the biomass CAPEX was k€12 more, its OPEX was €4,620 per year leading to an LCOE of €0.46/kWh (to be compared with €7,750 and €0.53/kWh for the baseline system, respectively). The sensitivity analysis has shown that the biomass system was forced to operate during the evening-nigh peak on a yearly basis and therefore becomes more competitive for higher energy loads, whilst the diesel system, running on optimised mode, was more favourable at a lower load demand because only then its relative low PV capacity enable it to be more competitive than biomass although making a much greater use of the BB.

Increasing the PV array capacity from 15kW to 21kWp, as initially proposed, although it costs k€2 more, the diesel system outperforms the biomass by a moderate margin in terms of LCOE (0.40€/kWh) due to a lower OPEX (€2,860). We can conclude that the diesel genset leads to a more cost-effective solution than power gasifiers whenever PV capacity expansion is allowed (i.e. higher initial investment). Gasification solutions can only become real competitive alternatives to diesel if, or when, they are able to meet high automation standards, achieved without critical increase of CAPEX.

Nevertheless, for the particular case study of the province of Nampula, in the northern region of Mozambique, with a large production of cashew shells, the power gasifier has the potential to be a competitive renewable resource.

A hybrid energy system based on biomass gasification is certainly technically feasible and has some advantages over other small-scale technologies. It allows a relatively wide range of feedstock to be used, which can come in handy during supply shortages. Another important advantage, as a renewable energy source, is that biomass resource can be easily stored and the generation can be dispatched depending on demand. Also, and although it is a recently-commercialised technology, it has already proven to be a decisive technology in remote areas e.g. power production through coco nut shells in isolated Pacific islands or through rice-husks in Uganda[7]. Finally, if managed in a sustainable way, the use of food-processing or agriculture residues have lower potential environmental impacts by giving a different end-use to residues rather than direct environment disposal or incineration. Of course, if the biomass supply chain is not controlled to ensure a steady output, this could potentially contribute to deforestation by creating an additional market for woody biomass in areas where the demand already exceeds the supply.

The second case study deals with the small scale use of hydropower in Lamu, a coastal village in Kenya. The results of the proposed micro hydro scheme proved that micro hydro is the most cost-effective solution of all the technologies evaluated in this work, with a relatively low initial CAPEX and OPEX, and therefore low LCOE. For the standard case study conditions, the hydro systems costs just 30% of the initial CAPEX of the baseline KUDURA system (which is the optimised HOMER solution) and it leads to a 25% decrease of the OPEX. The LCOE is €0.23/kWh, less than half of the standard's solution (€0.53/kWh). Even for a pessimistic scenario where both hydro CAPEX and OPEX are increased by 40%, by shortening the replacement period of several components, the hydro based system's LCOE is €0.36/kWh, although the OPEX is 25% more than the baseline KUDURA. Assuming that the CAPEX of the hydro system is within a ± k€5 of the estimated cost, and yearly O&M within the €500-1.500 range, the LCOE lies between €0.17 and €0.27/kWh.

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[7] Until the time of writing, and in the author's knowledge, there are no known examples of cashew as feedstock for power gasifiers.

The daily load demand is that of a typical load diagram shape for rural villages, much of it is concentrated at evening- and night-time for lighting and low power appliances. Since the governing system is through an ELC device, the hydro system wastes 75% of its yearly electricity production. This means that the results presented above do not reflect the true potential in terms of cost-effectiveness, which could be significantly increased by spreading the daily demand throughout the day or adding more day-time loads for income-generating activities e.g. increasing the productivity of local labour through commercial and cottage industry activities, thus increasing the social benefit as well.

Lamu landscape characteristics suggests the 50 m of head initially assigned for a Pelton turbine type can be excessive since the region is mainly flat (actually, part of it is under sea level). However, this can be overcome by using a cross-flow turbine instead, which can operate with heads as low as 5m and for a wide range of power ratings at acceptable peak-efficiencies. Also the fact that this type of turbine is simple and cheap to make, allowing its local manufacturing, is an important feature for deployment in developing countries. Nevertheless, it is also manifest that the feasibility of deploying micro hydro schemes in Kenya would certainly increase as one goes inland, where landscape gets more mountainous-like in the highlands.

Either way, the positive results are quite clear strongly suggesting that micro-hydro schemes have a significant cost reduction potential, therefore increasing the cost-effectiveness of the KUDURA. The advantage can be even greater when opting for even smaller schemes, like pico-hydro, which do not require much civil work (typically 40% of the total CAPEX for micro schemes), the equipment is smaller and cheaper, and the overall configuration is simpler.

As far as energy storage is concerned, and in general, the PWS HOMER model and CAPEX function model proved to be unreliable. The limited capacity of the HOMER software for modelling PWS applications did not enable to model a precise “charging” (pumping) process, thus rendering a misleading LCOE value, which makes the comparison with the LCOE of the baseline LAB system impossible. Notice that these limitations lead to the underestimation of the OPEX, and thus the underestimation of the LCOE. The CAPEX function model designed for the PWS system has several limitations such as the fact that the specific costs of the reservoirs and the pump are based on the quote provided for the particular case study conditions and are not linear with head. Furthermore, there is lack of sensitivity to penstock diameter and material to variations of the diameter, and evaporations losses of the reservoirs are not taken into account. From the academic point of view, it would be interesting to develop a small-hydro add-on to the HOMER software to include all these recommendations.

Having this notice in mind, the PWS marginally outperformed the baseline system in terms of CAPEX (less €2.500) for 160 m of head (which is three times the specified head) for a very favourable solar irradiation scenario (5 SPH). At standard condition (50 m head and 4 SPH radiation), the PWS costs

20% more and its OPEX is almost doubled, leading to a LCOE of €0.671/kWh (was €0.563/kWh of the baseline system).

It is also interesting to notice that the PWS system has a much lower energy density than the baseline system using LABs, requiring about 245 times more volume to meet the same energy capacity, which considerably increases the amount of space require to place the system. The LAB is limited to an area footprint of just 6.25 m^2. In addition, it is a more complex system to deploy and install, with a lot of moving parts, hence prone to regular maintenance, and a more complicated operation. Therefore, the cost-effectiveness of a system using PWS as a means of storing energy would have to outweigh these limitations by a significant margin in order to opt for a system with that kind of configuration. It can then be concluded that the PWS system is not a suitable option for integrating in KUDURA.

In a general appreciation of the objectives delineated for this thesis, micro hydro power and biomass gasification have an indubitable potential on setting cost reduction strategies for the RVE concept, thus promoting its flexibility as an energy system based on locally-sourced resources and help more rural communities to achieve self-sufficient sustainable development.

One final note remembering that rural electrification can have very positive impacts indeed but there also issues and challenges that require one’s attention. Access to energy services enabled by electrification generally results in improvements in education, gender equity, health and overall economic conditions in a community but increased reliance on technology and increased per capita energy consumption can be seen either positive or negative depending on how they fit within the definition of sustainable development.

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Annex 1 – Power Pallet Specifications

ALL Power Labs offers downdraft gasifier systems in various sizes: 10kW, 20kW, and 100kW. These kWe ratings reference the potential of electrical power capable in a gasifier/ICE/generator system at the gasifier's maximum gas flow capacity. The GEK Power Pallet integrates an internal combustion engine and a generator with automated controls with the ability to utilize the gas for other purposes, while the GEK Gasifier comes as an assemble-yourself kit that provides stand-alone wood gas for a variety of end uses. Below are the specifications of the systems provided by ALL Power Labs.

GEK Gasifier System Sizes provided by ALL Power Labs

	10kW GEK	*20kW GEK*	*100kW GEK*
electrical capacity range (kW)	2 - 10	4 - 20	20 - 100
gas flow range (m^2/hr)	5 -27	11 - 53	53 - 267
gas heat flow at max (BTU/hr)	168,993	331,727	8,355,765
biomass consumption rate (kg/day)	160 - 320	320 - 640	640 - 3200
gasifier system footprint (excluding hopper) (ft)	2 x 4	2 x 4	4 x 7

The GEK Systems are offered at various integration stages as well as at different kit levels to make the equipment accessible at various price points. The kit 'Levels' refer to the completeness of the offered product. The levels are as follows:

- Level I: free CAD files available online
- Level III: Weld-It-Yourself kit (mild steel only)
- Level IV: Assemble-It-Yourself kit (stainless steel only)
- Level V: Completely Assembled and Integrated

GEK Gasifier Models, Levels and Features Offered

Model	*Sizes (kW)*	*Levels Available*	*Included Features*
Basic GEK	10, 20	I, III, IV	Reactor, gas filter only. Gas drive system: ejector
GEK TOTTI	10, 20, 100	III, IV	Basic GEK with Pyrocoil and Drying Bucket. Gas drive system: ejector
GEK Power Pallet	10, 20	V	GEK TOTTI, PCU, logic and components for automation, engine and generator. Gas drive system: blowers. Integrated on a 4x4 pallet. Available in 120V/208/240V AC, 60/50Hz, and in single, split, or three phase configurations.

Biomass Requirements of the GEK Gasifier Systems

Most downdraft gasifier systems require specified feedstock characteristics and can be sensitive to feed stocks that lie outside of the required specifications for the given equipment. Across all of the GEK Models above, ALL Power Labs has implemented designs in both the reactor and the bulk handling systems that broaden the allowed feedstock characteristic requirements of typical systems of its size. Below are the suggested ranges for given feedstock characteristics to be used in the GEK systems.

Biomass requirements

particle size (in)	.5 - 1.5
moisture content (% by dry weight)	<25
fixed to volatile ratio	>0.25
ash content (%)	>5

Annex 2 – Penstock internal friction coefficients

Table 6 - Hazen-Williams Coefficient of several materials for calculating hydraulic losses

Material	**Hazen-Williams Coefficient, C**
ABS - Acrylonite Butadiene Styrene	130
Aluminum	130 - 150
Asbestos Cement	140
Asphalt Lining	130 - 140
Brass	130 - 140
Brick sewer	90 - 100
Cast-Iron - new unlined (CIP)	130
Cast-Iron 10 years old	107 - 113
Cast-Iron 20 years old	89 - 100
Cast-Iron 30 years old	75 - 90
Cast-Iron 40 years old	64-83
Cast-Iron, asphalt coated	100
Cast-Iron, cement lined	140
Cast-Iron, bituminous lined	140
Cast-Iron, sea-coated	120
Cast-Iron, wrought plain	100
Cement lining	130 - 140
Concrete	100 - 140
Concrete lined, steel forms	140
Concrete lined, wooden forms	120
Concrete, old	100 - 110
Copper	130 - 140
Corrugated Metal	60
Ductile Iron Pipe (DIP)	140
Ductile Iron, cement lined	120
Fiber	140
Fiber Glass Pipe - FRP	150
Galvanized iron	120
Glass	130
Lead	130 - 140
Metal Pipes - Very to extremely smooth	130 - 140
Plastic	130 - 150
Polyethylene, PE, PEH	140
Polyvinyl chloride, PVC, CPVC	150
Smooth Pipes	140
Steel new unlined	140 - 150
Steel, corrugated	60
Steel, welded and seamless	100
Steel, interior riveted, no projecting rivets	110
Steel, projecting girth and horizontal rivets	100
Steel, vitrified, spiral-riveted	90 - 110
Steel, welded and seamless	100
Tin	130