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IMPROVING ACCESS TO MODERN ENERGY SERVICES IN RURAL AREAS OF DEVELOPING COUNTRIES. TOWARDS A COMPREHENSIVE ACCESS STRATEGY

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Dedication

To my dear mother, Philomena Akum

I remember in 1993, when my education seemed to come to a stop, my sweet mother wept about it.

I assured her that, by the grace of God, I shall study to the highest academic level.

Mama, THANK YOU,

You were my source of motivation to attain this academic level

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This Thesis was successful because of the moral, spiritual and financial support of some people and institutions. I would like to take this opportunity to acknowledge all the support I received. Any person or institution that supported me in anyway and is not mentioned herein should not take offence as such omissions were not deliberate.

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My greatest gratitude goes to the Supreme Being, GOD, ALLAH, YAWEH... for his favor, providence and protection.

Summary

This thesis was realized as part of the research activities of the UNESCO Chair in Energy for Sustainable Development, Department of Energy. The thesis addressed the issue of energy access in DC with focus on the development of a "comprehensive energy access strategy" to improve access to modern energy services, especially energy for cooking. The context within which this issue was addressed is households in rural areas of SSA.

The situation of access to modern energy services may be more challenging in SSA where little has been done on sustainable rural energy planning, coupled with the reality that 80% of the population, of which 75% live in rural areas, still rely on the traditional use of biomass. The production of modern energy carriers, such as electricity, Natural Gas, LPG and other petroleum products, which could be used to ameliorate the energy situation of rural areas in DC are available in a few countries and are often far away from the consumers requiring dedicated infrastructure and well-functioning service chain. There is a growing trend towards the production of energy carriers closer to consumption centers both in developed and developing countries. Furthermore, it has been identified that in developing countries, especially rural areas, the use of distributed renewable sources is a primary tool for increasing energy access towards targets set in the recently adopted Sustainable Development Goals (SDG).

With regards to the above context, improving access to modern energy services, especially for cooking in rural households in DC, cannot be resolved through individual technology dissemination or fuel switching in isolated energy projects or programs as it is the existing practice. A comprehensive energy access strategy is envisaged in order to intensify research, development and dissemination of small scale technologies to improve access to modern energy services. Increasing access to energy in DC may entails innovative business models, increase investment, policies and a comprehensive access strategy etc. This thesis contribute to the development of a comprehensive access strategy which comprise of a more sustainable rural energy planning, selection and optimization of appropriate small scale sustainable energy technologies, such as biogas technology, to increase the energy carrier alternatives within the rural energy supply package. A review of rural energy planning revealed that most rural energy planning procedure often lack systematic data set and do not quantify energy consumptions to level required at the modelling stage of the procedure. Furthermore, most of the planning procedures do not consider the sustainability of rural energy systems. A sustainable rural energy system should integrate the theme of sustainable energization (SE). The Nissing et al six-step procedure integrated SE theme and could provide systematic data and quantify energy consumptions to levels required for modelling. However, it did not take into account the existing rural energy supply system, and its 4-steps ESSN model did not allow for a flexible and more cost-effective way to identify

appropriate end-use devices to meet the energy services demanded. Thus, it did not resolve the issue of technology stacking. Furthermore, it is yet to be applied within the rural context, especially in SSA.

Small scale technologies, such as biogas technology, could be a more sustainable solution to the issue of improving access to modern fuels in rural areas of SSA. However, a selection strategy, research and development of such small scale technologies within the intended application environment, especially in SSA, is required.

Considering the above mentioned gaps identified in the literature, this thesis had as overall objective to contribute to the development of a comprehensive energy access strategy in DC, with a focus on access to clean energy for cooking in rural areas of SSA.

The specific objectives of the thesis were:

- To propose a comprehensive procedure for the sustainable energization of rural areas of DC.
- To develop and apply a Decision Support Tool for the selection of an appropriate small scale technology to improve access to modern energy services in rural areas.
- To elaborate a procedure for the optimization of the performance of the selected technology within the local context.

The general methodology adopted to achieve these objectives included: a review of the relevant literature in order to have a general understanding of issues discussed in the thesis. In the development of a more comprehensive sustainable rural energy planning procedure, desk study was used. This was followed by field case study to test the validity of the developed procedure. A decision support system was selected, elaborated and applied in the selection of an appropriate digester design for mass dissemination in rural context of Cameroon. Field experimentation of the selected technology at full-scale was used to investigate its performance within the application environment in order to identify parameters which led to the improvement of the technology. Numerical analysis was used in the laboratory investigations of different technology designs configuration during the optimization process. CFD techniques and the OpenFoam software was adopted to investigate design structure modifications to improve mixing in the Nepali GGC2047 digester design. Qualitative and quantitative analysis were used to discriminate for an improved inlet configuration from eight candidates which modified the engineering structure of the digester design. Further field experimentation were carried out to investigate the performance of the improved technology at full scale within the local context for subsequent dissemination. Furthermore, specific methods and tools

were applied as appropriate at different stages of the development of the comprehensive energy access tool.

The following results were achieved:

- The Nissing et al six-step planning procedure for a sustainable rural energy planning was adopted and modified in two ways: (i) it was extended to account for the existing energy situation in the planning procedure. Including this step allowed for the creation of a systematic database and quantification of energy consumptions to levels that permitted a more realistic energy system modelling (ii) energy drivers were integrated in the ESSN model. This allowed for a flexible and a more cost-effective way to identify appropriate end-use devices to meet the energy services demanded and thus resolved the issue of "technology stacking" at the level of households. Furthermore, the validity of the modified procedure was demonstrated in a rural context through a case study in Cameroon. The results showed an improved, reliable, affordable and diversified PES based on local energy resources, a 85% increase in FC by the rural community and a 50% improvement in energy efficiency. Alternative and more sustainable energy sources, such as biogas, hydropower and solar featured in the new energy mix of the community. Some of these sources, especially biogas could be exploited as a modern energy carrier to improve access to modern energy carriers for cooking at the level of rural households.
- The Analytic Hierarchical Process (AHP) was elaborated and applied in the selection of an appropriate technology. The selection of an appropriate biogas digester design for dissemination in Cameroon as used to demonstrate the application of the selection strategy. Technical, economic, social and environmental criteria were used together with appropriate sustainable indicators according to the approach of EISD. Amongst the five identified candidate digesters, the Nepali GGC2047 design emerged as the appropriate design for the context of Cameroon.
- Field experimentation was carried out on a full scale unit of the Nepali GGC2047 digester installed and operated within the local socio-economic and environmental context of a rural village in Cameroon. Two crucial issues affected the performance of the design within the local context, namely: water scarcity, which led to the digester being operated at 16%TS which was higher than the designed 10 %TS concentration in the influent. The average operating temperature inside the digester was 26 °C, which was below the 30-35°C optimal range for mesophilic digestion. The digester design operated between upper psychrophilic and lower mesophilic range of temperature, away from its design mesophilic operation. The technical performance of the design in terms of biogas

production rate and productivity were 0.16 $m^3_{biogas}/m^3_{digester}$ per day and 0.18 $m^3_{biogas}/kgVS$ respectively. These values were lower than the expected values of 0.34 $m^3_{biogas}/m^3_{digester}$ per day and 0.25 $m^3/kgVS$ respectively. Also the energy recovery efficiency was only 20%. This low technical performance of the design could be related to poor mixing of the digester content and low temperatures. This thesis focused on improving mixing of the digester content in order to optimize the technical performance of the design within the context.

- Laboratory investigations were carried out on eight candidate inlet configurations which were suspected to improve mixing of the digester content. Numerical analysis with the application of CFD techniques and the OpenFoam software were used in the analysis. The results were evaluated qualitatively in terms of velocity field flows and quantitatively in terms of the volume integral of the tracer in the digester volume. The funnel-shaped inlet configuration which opens into the digester seemed to improve mixing of the slurry in the digester. The effect of this inlet configuration on the performance of the digester was further investigated through a field experimentation.
- A field experimentation to validate the effect of the modified inlet configuration on the performance of the selected Nepali GGC2047 design was carried out in Cameroon. The hypothesis investigated was:
 - H₀: $\mu_m \leq \mu_c$ i.e. modified digester is not better than the control
 - $H_1: \mu_m > \mu_c$ i.e. modified digester is better than the control

After a first experimentation carried out between August 2015 and January 2016 it was realized that the modified inlet was poorly produced due to insufficient local technology and know-how. An improved version of the modified inlet was produced and installed. A second experimentation was carried out between January and September 2016. The modified digester and the control digester in both experimentation were operated under the same essential operating conditions. During the first experimentation, the mean biogas production from the modified digester was 159.10 litres with a standard deviation of 98.76 while the control digester had a mean production of 267.88 litres with a standard deviation of 171.00. A t-test of the hypothesis produced a p value of 3E-05. During the second experimentation, the mean biogas production from the modified digester was 239.67 litres with a standard deviation of 134 while the control digester had a mean production of 296.83 litres with a standard deviation of 67. A t-test of the hypothesis produced a p value of 0.005. The two versions of the modified inlet produced statistically significant results which demonstrate that the modification seem to improved mixing of the digester content. The second version produced better results than the first. This demonstrate that, translating, high-tech laboratory results into locally produced technology was a challenge. This is often the case in DC, especially SSA, where technological development was still in the embryo stages. Thus optimization of small scale technology to improve access to energy in the context of DC would require coupling laboratory analysis with local capacity building in manufacturing know-how.

An alternative design operated on DAD and based on the leaching bed principle with the integration of a Green House to influence digester operating temperature was investigated. The objective was to characterize it for application in DC. The operational volume of this experimental digester was 2.6 m³. Co-digester of a variety of biomass residues widely available in DC were digested by the design with a good process stability; operating temperatures were stabilized at about 28 °C; the SRT and HRT time were 139 and 10 days respectively. The design operated in three phases within what was termed a cycle. These phases were start-up, stable and saturation phases. A cycle lasted 3-4 months, after which the digester had to be re-loaded. The average biogas production was $1.0 \text{ m}^3/\text{day}$; the production rate was 0.36 m³_{biogas}/m³_{digester} per day and average methane content of the biogas was 63.5 %volume/volume which were comparable to the $0.34 - 0.7 \text{ m}^3_{\text{biogas}}/\text{m}^3_{\text{digester}}$ per day and 55 - 65 % volume/volume ranges respectively reported for digesters commonly disseminated in DC. The use of the Green House concept improved on the thermal performance of the digester. It may be concluded from this investigations that the design demonstrated suitability for application in DC, however challenges in feeding the digester due to the inlet configuration and the re-loading of the digester every 3-4 months required further investigations.

The overall results of the activities of this thesis were consolidated into a threestage strategy to improve energy access in rural areas of DC. This strategy was named "*Towards* a *comprehensive energy access strategy for DC*" The stages in this strategy are described herein below.

An improved rural energy planning procedure: This stage consisted of seven steps, namely: (i) integration of the goals of sustainable energization into the decision making process,(ii) assessment of the existing energy balance situation of the target rural community,(iii) identification and prioritization of the energy services demanded according to energy drivers,(iv) local resource assessment with focus on renewable energy sources, (v) design of an integrated renewable energy system, (vi) set up of energy services supply network and (vii) control and adaptation of the energy services supply network.

Technology selection strategy: The steps in this stage are: analysis of the energy conversion technology, identification of the appropriate alternatives and

implementation of a decision support system for the selection of an appropriate design for a particular context.

Technology optimization process: The steps in this stage are: identification of local performance parameters of the selected technology, laboratory investigations to improve local performance of the technology and, full scale field validation of the improved technology design.

Conclusion

The challenge to access to modern energy services for cooking in DC could be better approached through the integration of the concept of sustainable energization (SE) within a comprehensive energy access strategy. This study fulfilled the set specific objectives, namely:

- An improved rural energy planning procedure was developed and applied in the context of a rural area; the results demonstrated a decrease PES, an improved FC and energy efficiency.
- The AHP decision support system was elaborated and applied in the selection of an appropriate small scale technology to improve energy access in rural areas of DC. The Nepali GGC2047 design was selected as an appropriate small scale biogas digester design to improve access to clean fuel for cooking in the context of Cameroon.
- A framework for a procedure for the optimization of small scale technology was developed. This procedure consisted of three steps, namely: field investigation of the technology at full scale to identify critical parameters which could be researched to improve the performance of the technology; laboratory investigations to improve the technology based on the identified critical local context parameters, and full scale field validation of the improved technology.

The outcomes of this thesis were consolidated into a three-stage energy access strategy named "*Towards a comprehensive energy access strategy for DC*". This outcome makes a great contribution to the search for a comprehensive energy access strategy in order to intensify research, development and dissemination of small scale technologies to improve access to modern energy services, especially rural areas, as highlighted in the REN21 Global Status Report 2016.

Sommario

Questa tesi è stata realizzata nell'ambito delle attività di ricerca della Cattedra UNESCO di Energia per lo Sviluppo Sostenibile, Dipartimento di Energia. La tesi ha affrontato due questioni principali, ovvero: l'accesso all'energia nei Paesi in via di sviluppo (PVS) ed una strategia comprensiva per migliorare l'accesso a servizi energetici moderni, in particolare dedicati alla cottura di cibi. Il contesto all'interno del quale tali questioni sono state affrontate è quello delle famiglie delle zone rurali dell'Africa Sub-Sahariana (ASS).

La situazione relativa all'accesso a servizi energetici moderni può essere più difficile in ASS dove poco o nulla è stato fatto in materia di pianificazione energetica rurale; inoltre, l'80% della popolazione – di cui il 75% vive in zone rurali – si basa ancora su un uso tradizionale della biomassa. La produzione di vettori energetici moderni – quali l'elettricità, il gas naturale, l'LPG ed altri prodotti petroliferi –, che potrebbero essere usati per migliorare la situazione energetica delle aree rurali nei PVS, è presente solo in pochi Paesi e spesso a grande distanza dai consumatori, poiché sarebbero necessarie infrastrutture dedicate ed una efficiente catena di distribuzione. C'è pertanto una tendenza crescente verso la produzione di vettori energetici più prossimi ai centri di consumo, sia nei Paesi sviluppati che in quelli in via di sviluppo. È stato inoltre stato rilevato come nei PVS, e soprattutto nelle aree rurali, l'utilizzo di risorse rinnovabili distribuite sia uno strumento primario per l'incremento dell'accesso all'energia, in un'ottica di raggiungimento dei Sustainable Development Goals (SDG) recentemente adottati.

Nel contesto di cui sopra, l'accesso a servizi energetici moderni per cucinare, non può essere risolto semplicemente tramite la disseminazione di singole tecnologie o la sostituzione del combustibile in progetti o programmi isolati, come si fa attualmente. Una strategia comprensiva di accesso all'energia è necessaria al fine di intensificare la ricerca, lo sviluppo e la disseminazione di tecnologie di piccola taglia volte al miglioramento dell'accesso a servizi energetici moderni. Migliorare l'accesso all'energia nei PVS potrebbe determinare l'affermazione di modelli di business innovativi, un aumento degli investimenti, lo sviluppo di politiche specifiche, ecc. Questa tesi contribuisce allo sviluppo di una strategia comprensiva per l'accesso all'energia, che comprende una pianificazione rurale più sostenibile e la selezione e l'ottimizzazione di tecnologie di piccola taglia appropriate – come il biogas – per incrementare il ventaglio di alternative per la scelta di vettori energetici in ambito rurale. Una revisione delle strategie di pianificazione energetica rurale ha rivelato che la maggior parte della pianificazione è spesso carente di banche dati sistematiche e non quantifica il consumo di energia al livello di dettaglio richiesto per una modellazione realistica. Inoltre, la maggior parte delle procedure di pianificazione non considera la sostenibilità dei sistemi energetici rurali. Un sistema energetico rurale sostenibile dovrebbe contemplare il concetto di "sustainable energisation" (SE). La procedura di Nissing et al. a sei-step includeva il concetto di

SE ed era in grado di fornire banche dati sistematiche e di quantificare i livelli di consumo con un grado di dettaglio adeguato. Tuttavia, non prendeva in considerazione il sistema di approvvigionamento energetico rurale già esistente, e il suo modello ESSN a quattro-step non garantiva un modo flessibile ed economico per identificare strumenti d'uso-finale adeguati al soddisfacimento della domanda energetica. Pertanto, non forniva soluzioni al problema del "technology stacking". Inoltre, non è ancora stato applicato ad un contesto rurale, specialmente in ASS.

Tecnologie di piccola taglia, come il biogas, potrebbero rappresentare una soluzione più sostenibile al problema dell'accesso a combustibili moderni nelle zone rurali dell'ASS. Tuttavia, è necessaria una strategia per la selezione, la ricerca e lo sviluppo di tali tecnologie all'interno del contesto di applicazione specifico, soprattutto in ASS.

Considerando le mancanze sopracitate identificate nella letteratura, questa tesi si è posta l'obiettivo generale di contribuire allo sviluppo di una strategia comprensiva per l'accesso all'energia nei PVS, con una particolare attenzione per l'accesso ad energie pulite per la cottura di cibi nelle aree rurali dell'ASS.

Gli obiettivi specifici di questa dissertazione sono stati:

- proporre una procedura comprensiva per l'energizzazione sostenibile delle aree rurali dei PVS;
- sviluppare ed applicare un Decision Support Tool per la selezione di tecnologie di piccola taglia appropriate per migliorare l'accesso a servizi energetici moderni nelle aree rurali;
- elaborare una procedura per l'ottimizzazione delle prestazioni della tecnologia selezionata, all'interno del contesto locale.

La metodologia generale adottata per raggiungere questi obiettivi ha incluso: una revisione della letteratura finalizzata ad una comprensione generale dei problemi discussi nella tesi. Un "desk study" utilizzato per lo sviluppo di una procedura comprensiva di pianificazione energetica rurale sostenibile. A seguire, un caso di studio sul campo finalizzato a testare la validità della procedura sviluppata. L'elaborazione di un "Decision Support System" applicato poi nella selezione di un design appropriato per un digestore da disseminare su larga scala nelle aree rurali del Camerun. La sperimentazione sul campo della tecnologia prescelta, usata per valutare le sue prestazioni all'interno del contesto di applicazione e per identificare eventuali parametri da ottimizzare. L'analisi numerica è stata utilizzata in studi di laboratorio relativi a differenti configurazioni tecnologiche, nel corso del processo di ottimizzazine. Tecniche CFD e il software OpenFoam sono stati adottati per valutare modifiche strutturali al design tecnologico, in particolare per migliorare il miscelamento del digestore Nepali GGC2047. Analisi qualitative e quantitative sono state usate per selezionare fra otto opzioni la miglior configurazione di "inlet"

del digestore, che è andata a modificare la struttura ingegneristica dello stesso. Ulteriori studi sul campo sono stati effettuati per valutare le prestazioni della tecnologia migliorata all'interno del contesto locale per una successiva disseminazione. Inoltre, metodi e strumenti specifici sono stati applicati nei vari stadi del processo di sviluppo dello strumento comprensivo per l'accesso energetico.

Sono stati raggiunti i seguenti risultati:

- La procedura di pianificazione Nissing et al. a sei-step per lo sviluppo energetico rurale sostenibile è stata adottata e modificata in due modi: (i) è stata estesa per tenere conto della situazione energetica esistente nella procedura di pianificazione. L'inclusione di questa fase ha permesso la creazione di una banca dati sistematica e la quantificazione dei consumi energetici a livelli che hanno permesso una modellazione più realistica del sistema energetico. (ii) Sono stati integrati nel modello ESSN dei driver energetici. Questo ha permesso un modo più flessibile e conveniente per identificare opportuni dispositivi di uso-finale per soddisfare i servizi energetici richiesti, e ha permesso di risolvere il problema del "technology stacking" a livello delle famiglie. Inoltre, la procedura modificata è stata applicata in un contesto rurale attraverso un caso di studio in Camerun. I risultati hanno dimostrato una migliore, affidabile e diversificata PES sulla base di risorse energetiche locali, un aumento dell'85% nel FC da parte della comunità rurale, e un miglioramento del 50% nell'efficienza energetica. Fonti energetiche alternative e più sostenibili, come il biogas, l'idroelettrico e il solare, sono state incluse nel mix energetico della comunità. Alcune di queste fonti, soprattutto il biogas, potrebbero essere sfruttare come vettori energetici moderni per migliorare l'accesso all'energia per la cottura di cibi a livello di famiglie rurali.
- Il processo gerarchico analitico (AHP) è stato applicato per la selezione di una tecnologia appropriata. La selezione di un digestore a biogas appropriato per la diffusione in Camerun ha consentito una successiva validazione sperimentale della tecnologia. Criteri tecnici, economici, sociali e ambientali sono stati utilizzati insieme ad indicatori di sostenibilità appropriati, secondo l'approccio degli EISD. Tra i cinque candidati individuati, vale a dire: Il design Nepali GGC2047 è emerso come il design appropriato per il contesto del Camerun.
- Sperimentazione sul campo è stata condotta su un prototipo in scala del digestore nepalese GGC2047 installato in un villaggio rurale del Camerun, gestito nel contesto socio-economico e ambientale locale. Due problemi

principali hanno influenzato le prestazioni della soluzione nel contesto locale: la scarsità d'acqua, che ha fatto sì che il digestore operasse al 16% della TS che è più alta della TS di progettazione pari al 10%. La temperatura operativa dentro il digestore era di 26°C, al di sotto del range ottimale 30-35°C per la digestione mesofilica. Il digestore operava quindi in un range di temperatura tra il psicrofilico e mesofilico, al di fuori del range mesofilico ottimale. In termini di tasso di produzione di biogas, la produttività è stata di 0.16 m³_{biogas}/m³_{digester} al giorno e 0.18 m³_{biogas}/kgVS. Questi valori sono risultati più bassi di quelli attesi di 0.34 m³_{biogas}/m³_{digester} al giorno e 0.25 m³/kgVS. Anche l'efficienza di ricovero è stata di soli 20%. Queste basse prestazioni sono da attribuirsi allo scarso miscelamento della miscela e alle basse temperature. Questa tesi si è focalizzata sul miglioramento della fase di miscelamento del contenuto nel digestore in modo da ottimizzarne le performance tecniche nel contesto operativo.

- Indagini di laboratorio sono state condotte su 8 configurazioni e tipologie di "inlet" nel digestore, sospette di poter migliorare il miscelamento interno. Sono state impiegate l'analisi numerica con applicazione CFD e software OpenFoam. I risultati sono stati valutati qualitativamente in termini di flusso di velocità e di volume integrale del liquido tracciante nel volume del digestore. La configurazione di ingresso a "funnel" è sembrata migliorare il miscelamento della fanghiglia nel digestore. L'effetto di questa configurazione sulle performance del digestore è stata investigata ulteriormente tramite sperimentazione sul campo.
- La sperimentazione sul campo per validare l'effetto della nuova configurazione del tubo di ingresso sulle performance del modello Nepalese GGC2047 è stata condotta in Camerun. L'ipotesi investigata è stata:
 - H₀ : $\mu_m \le \mu_c$ i.e. il digestore modificato non è migliore di quello base
 - H₁: $\mu_m > \mu_c$ i.e. il digestore modificato è migliore di quello base

Dopo una prima fase di sperimentazione condotta tra agosto 2015 e gennaio 2016, si è realizzato che l'ingresso "modificato" è stato prodotto non correttamente a causa di tecnologia inadeguata e scarse conoscenze tecniche. Una versione migliorata è stata dunque prodotta e installata nuovamente. Una seconda campagna sperimentale è stata condotta tra gennaio e settembre 2016. Il digestore modificato e quello base sono stati testati alle stesse condizioni operative. Durante la prima fase di prove, la media della produzione di biogas è stata di 159.10 litri con deviazione standard pari a 98,76, il digestore base ha rivelato una produzione di 267.88 litri con una deviazione standard di 171,00. Un'analisi t-test al 95% di confidenza dell'ipotesi ha generato un p-value di 3E-05. Durante la seconda fase sperimentale, la media della produzione di biogas è stata di 239.67 litri con una

deviazione standard di 67, mentre il digestore base ha rivelato una produzione di 296.83 litri con deviazione standard di 134. Un'analisi t-test dell'ipotesi al 95% di confidenza ha generato un p-value di 0.005. I risultati dei test statistici hanno verificato che è possibile rifiutare l'ipotesi nulla, e che quindi non è possibile affermare che il digestore modificato non sia migliore di quello base. La seconda versione ha prodotto risultati migliori del primo. Questo dimostra che riprodurre localmente tecnologie costruite in laboratorio è stata una sfida. Questo è un caso frequente nei PVS, specialmente in Africa sub-Sahariana, dove lo sviluppo tecnologico è ancora in fase embrionale. Quindi l'ottimizzazione di tecnologie di piccola taglia per garantire accesso all'energia nei paesi in via di sviluppo deve considerare sia un'analisi di laboratorio che tenga in conto le capacità locali in termini di manifattura.

È stato investigato un design alternativo basato sul principio "leaching bed" tramite integrazione di una serra per aumentare la temperatura operativa nel digestore. L'obiettivo era quello di caratterizzare tale modello per eventuali applicazioni nei PVS. Il volume del digestore era di 2.6 m³. Una grande varietà di biomassa residua largamente disponibile nei PVS è stata digerita dal modello con grande stabilità di processo; le temperature operative si sono stabilizzare a circa 28°C; il tempo di SRT e HRT sono stati rispettivamente di 139 e 10 giorni. La produzione media di biogas è stata di 1.0 m³/giorno, il tasso di produzione di 0.36 m³_{biogas}/m³_{digester} al giorno e la produttività di 1.52 m³/kgVS al giorno. Il contenuto medio di metano è stato valutato circa pari a 0.34 - 0.7 $m_{biogas}^3/m_{digester}^3$ al giorno e la qualità di gas tra 55 – 65 % volume / volume riportato per i digestori comunemente distribuiti nei PVS. L'uso del concetto di serra ha migliorato le performance termiche del digestore. Da questa analisi si può concludere che il design ha dimostrato di essere idoneo per applicazione nei PVS, nonostante le difficoltà derivanti dall'alimentazione del digestore, a causa della configurazione del tubo di ingresso, e dal carico di materia da digerire ogni 3-4 mesi richiedano ulteriori indagini.

I risultati generali delle attività della tesi sono stati consolidati all'interno di una strategia a 3 fasi per migliorare l'accesso all'energia nelle aree rurali dei PVS, nominata "Verso una strategia per un completo accesso". Le fasi della strategia sono qui descritti:

Una procedura completa per la pianificazione energetica rurale: questa ha considerato 7 ulteriori steps, ovvero: (i) integrazione degli obiettivi sostenibili di energizzazione all'interno del processo decisionale, (ii) valutazione della situazione energetica delle comunità rurali, (iii) identificazione e assegnazione delle priorità dei servizi energetici domandati in accordo con i vettori energetici, (iv) valutazione delle risorse energetiche locali con attenzione verso le risorse rinnovabili, (v) progetto di un sistema energetico integrato, (vi) configurazione di una rete di approvvigionamento di servizi energetici.

Strategia di selezione della tecnologia: gli steps in questa fase sono: analisi delle tecnologie di conversione energetica, identificazione di appropriate alternative e implementazione di un sistema di supporto decisionale per la selezione di un modello appropriato dato un contesto specifico.

Processo di ottimizzazione tecnologica: gli steps in questa fase sono: identificazione dei parametri di performance della tecnologia selezionata, campagna sperimentale per migliorare le performance locali della tecnologia e, validazione sul campo della tecnologia migliorata in scala.

Conclusione

La sfida per garantire accesso ai moderni servizi energetici per la cottura nei PVS dovrebbe essere approcciata in maniera più appropriata tramite integrazione del concetto di *energizzazione sostenibile (SE)* in strategie più comprensive per garantire accesso all'energia. Questo studio ha raggiunto gli obiettivi specifici che si è prefissato inizialmente, ovvero:

- una procedura di pianificazione energetica comprensiva è stata sviluppata e applicata in contesti rurali; i risultati hanno dimostrato una diminuzione di PES, un FC migliorato ed efficienza migliore;
- è stato elaborato un sistema di supporto decisionale basato sul metodo AHP e applicato per la selezione di una tecnologia di piccola scala per migliorare l'accesso all'energia nelle zone rurali dei PVS. Il modello di bio-digestore Nepali GGC2047 è stato selezionato per migliorare l'accesso ai combustibili puliti per la cottura nel contesto camerunense.
- è stata sviluppata una struttura procedurale per l'ottimizzazione di una tecnologia di piccola taglia. Questa procedura consiste in 3 fasi, ovvero: ricerca sul campo della tecnologia in scala per identificare i parametri critici da investigare per migliorare le performance della tecnologia; valutazioni di laboratorio per migliorare la tecnologia basata sull'identificazione dei parametri critici dovuti al contesto, la validazione delle miglior performance della tecnologia migliorata.

I risultati di questa tesi sono stati consolidati in una strategia a tre fasi chiamata "Verso una strategia comprensiva per garantire accesso all'energia nei PVS". Questo risultato ha fornito un grande contributo alla ricerca in corso sui metodi per garantire accesso all'energia, con lo scopo di intensificare la ricerca, sviluppo e disseminazione di tecnologie su piccola scala per migliorare l'accesso ai servizi energetici moderni, specialmente nelle aree rurali, come sottolineato nel REN21 Global Status Report 2016.

• L'obiettivo era quello di identificare i parametri fondamentali che influenzano le sue prestazioni tecniche. Co-digestione di una varietà di feedstock disponibili locale era fattibile nel disegno. Tuttavia, la scarsità

d'acqua ha portato al digestore essere operato ad un superiore progettato% TS nel influente. Il disegno operato tra psicrofila superiore e inferiore gamma mesofilo della temperatura, dalla sua progettazione funzionamento mesofili. L'andamento tecnico del progetto in termini di produzione di biogas e il tasso di produzione è stata inferiore al previsto e l'efficienza energetica è stato solo il recupero del 20% .Il basso prestazioni tecniche del disegno potrebbe essere correlato alla scarsa miscelazione del contenuto del digestore e basse temperature. Pertanto, ottimizzazione del progetto potrebbe essere basata sul miglioramento miscelazione e / o temperature del digestore operativo.

- Il processo di digestione e disegni di digestivo per applicazioni in DC • presenta i seguenti: (i) tipo limitato di biomassa come influente. (ii) un limite% TS dell'affluente con un elevato contenuto di acqua (fino al 90% del volume del digestore) imposto dai disegni che portano a costi elevati di installazione e bassa produttività (iii) i sistemi operano a temperature inferiori ottimali. Un design alternativo operato DAD e basata sul principio base lisciviazione con l'integrazione di una casa verde di influenzare la temperatura di esercizio del digestore è stata sperimentata. L'obiettivo è stato quello di caratterizzare per applicazioni in corrente continua. Codigestore di una varietà di residui di biomassa ampiamente disponibili in DC sono stati digeriti dal disegno con una buona stabilità di processo; temperature di funzionamento sono stati stabilizzati a 25 ° C; il tempo SRT e HRT erano rispettivamente 139 e 10 giorni. Produttività era 1,52m3 / kgVS al giorno e contenuto di metano del biogas era 63,5% v / v in media. L'uso del concetto Green House potrebbe essere integrato funzionamento dei digestori comuni SSA. Sebbene il disegno dimostrato idoneità per applicazioni in corrente continua, sfide alimentazione del digestore causa della configurazione di ingresso e la ri-caricamento del digestore ogni 3-4 mesi richiesti ulteriori indagini.
- Povero miscelazione è stato identificato come uno dei parametri che hanno contribuito al basso rendimento del progetto nepalese GGC2047 nel contesto rurale Camerun. È stato adottato l'approccio numerico con l'applicazione di tecniche CFD utilizzando il software OpenFOAM per indagare la miscelazione nel disegno digestore. Attraverso l'analisi qualitativa e quantitativa di una configurazione di ingresso che ha prodotto migliore miscelazione del contenuto digestore è stato individuato tra 8 configurazioni candidati. Una campagna sperimentale è stata condotta in Camerun per convalidare l'impatto della configurazione di ingresso modifica la produzione di biogas. Alle stesse condizioni operative essenziali, digestore con l'entrata modificato prodotto circa il 18% di biogas al giorno rispetto al disegno originale. Così la modifica engineering dell'ingresso migliore miscelazione del contenuto digestore.

• I risultati di questa tesi sono stati capitalizzati in una strategia di accesso energetica globale a tre stadi per migliorare l'accesso ai servizi energetici moderni in DC. Queste fasi e le azioni principali sono state:

• Modificato rurale procedura pianificazione energetica. Questa fase consiste di sette passi, tuttavia, le fasi principali sono: la valutazione delle risorse locali, hanno bisogno di un documento d'identità e delle priorità e locali di pianificazione soluzione risorse-necessità.

• Tecnologia strategia di selezione. Fasi principali sono: analisi della tecnologia di conversione di energia, l'identificazione delle alternative e l'attuazione di un sistema di supporto decisionale.

• Tecnologia processo di ottimizzazione. Passaggi principali sono: indagini di laboratorio di prestazioni della tecnologia in un contesto, ottimizzazione laboratorio della progettazione della tecnologia, la convalida campo del design migliorato.

• Questa ricerca ha raggiunto gli obiettivi prefissati, in particolare:

• Una procedura di pianificazione energia rurale modificato è stato proposto e applicato nel contesto di una zona rurale; risultati hanno dimostrato una migliore PES e FEC.

• Il design nepalese GGC2047 è stato selezionato come un design appropriato per il contesto del Camerun attraverso l'applicazione del sistema di supporto decisionale AHP.

• miscelazione e la temperatura del digestore sono stati identificati come parametri locali che hanno condizionato l'andamento del progetto nepalese GGC2047 nel contesto del Camerun.

• Le prestazioni di questo disegno è stato ottimizzato attraverso una configurazione di ingresso modificato che migliorato la miscelazione del contenuto del digestore.

Inoltre, un approccio globale a 3 stadi per migliorare l'accesso all'energia nelle zone rurali della DC è stato proposto.

List of Abbreviations

AD	Anaerobic Digestion			
ALEP	Advanced Local Energy Planning			
BP	British Petroleum			
CH_4	Methane			
CO_2	Carbon dioxide			
DAD	Dry Anaerobic Digestion			
DECC	Department of Energy and Climate Change UK			
DC	Developing Country			
ESSN	Energy Services Supply Network			
EHV	Energy Heating Value			
FNR	Fachagentur Nachwaschsende Rohstoffe			
FC	Final Energy Consumption			
GGC	Globar Gas Company			
HOMER	Hybrid Optimization of Multiple Energy Resources			
H_2S	Hydrogen Sulphide			
HRT	Hydraulic Retention Time			
IEA	International Energy Agency			
LCOE	Levelized Cost of Energy			
LHV	Lower Heat Value			
LPG	Liquefied Petroleum Gas			
IREPP	Improved Rural Energy Planning Procedure			
NPC	Net Present Cost			
OLR	Organic Loading Rate			
PES	Primary Energy Supply			
REP	Rural Energy Planning			
RES	Renewable Energy Source			
RT	Retention Time			
SDG	Sustainable Development Goals			
SE	Sustainable Energization			
SRT	Solid Retention Time			
SSBT	Small Scale Biogas Technology			
SSA	Sub Sahara Africa			
SWHS	Solar Water Heating System			
TS	Total Solid concentration in feedstock			
VFA	Volatile Fatty Acids			
VS	Volatile Solids in feedstock			
WAD	Wet Anaerobic Digestion			

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Chapter 1: Introduction

1.1. Research Theme, Context and Issues

1.1.1. Research Theme

This study deals with a comprehensive energy access strategy in developing countries. This theme is developed within the frame of strategies to improve access to modern energy services in rural areas of DC, with focus on Sub Sahara Africa (SSA).

The field of research of this thesis is in "Energy for sustainable development in DC" and specifically address the context of SSA and the issue of *access to energy* which requires a "*comprehensive energy access strategy*"

1.1.2. The Context of Sub Sharan Africa

In the past three decades, the African region, especially SSA witnessed the least improvement in both total primary energy supply (TPES) and total final energy consumption (FC) in terms of fuel share and per capita consumption with respect to the increase in the global energy system[1]. During the same period, the global energy system witnessed an increase, in terms of fuel shares, in the total primary energy supply (TPES) of about 120%, from 6106 to 13371 Mtoe. As illustrated in Figure 1, this increase was disproportionate amongst the different regions. While China and other Asian countries witnessed 200% and 100% increase respectively, the African region witnessed only 60% increase representing only 5.5% (13371 Mtoe in 2012) of the global TPES.



Figure 1: Evolution in Global TPES

The global energy situation, as described above, remains unchanged when global final energy consumption (FC) is considered. The global FC witnessed an increase, in terms of fuel shares, of 92% (from 4672 to 8979 Mtoe), as shown in Figure 2. Amongst the different regions, Africa, witnessed an increase of about 60% of FC, consuming only 6% of the global FC. This disparity in access to energy is further

depicted in the per capita energy consumption where the African region, especially SSA, with less than 1.5 toe per capita, has one of the lowest final energy consumption.[1,2].



Figure 2: Global evolution of TPEC

Currently, about 2.7 billion people rely on traditional use of solid biomass and are without access to clean cooking facilities. This is a huge challenge vis-à-vis the interlinked global energy targets of achieving universal access to modern energy services, improving energy efficiency by 40% and provision of 30% of the World's Energy needs from renewable sources by 2030 [3]. The Global population of those dependent on traditional use of solid biomass is unevenly distributed amongst the DC, (Table 1). The situation is more precarious in SSA where 80% of the population currently rely on traditional use of biomass. Most of these people, more than 75%, live in rural areas.

N ₋ Of	Channa af alahal
Source: [4]	
Table 1: Distribution of people relying on tradit	tional use of solid biomass

Region	No. Of people [xmillion]	Share of population [%]	Share of global population without access [%]
DC	2,679	49	100
Africa	728	67	27,2
Sub Sahara Africa	727	80	27,1
Asia	1,875	51	70
Latin America	68	15	2,5
Middle East	8	4	0,3
World	2,679	38	100

The African Region is projected to witness the most rapid population growth and to be amongst the fastest growing economies by 2040 [3]. These two factors will account for an increase in TPES of the region by 80%. Notwithstanding this increase in TPES, the per capita energy consumption will decline and the region will remain "energy poor" relative to other regions. Solid biomass will continue to dominate the FC with the greatest increase being in the residential sector and in rural areas. Sustainable energy carriers like biogas, biofuels and pellets will account for only 6% of the TPES. Thus, the economic prosperity of the region shall not translate into a shift towards more efficient and clean cooking fuels/ technologies as supposed by the energy ladder concept. Still, more than 650 million people, mostly in rural areas will continue to use traditional biomass for cooking with inefficient and hazardous technologies way into 2040 [3].

Improved biomass stoves are being promoted as a practical way forward to a more efficient use of solid fuels[4,5]. However, debates still persists as to the efficiencies of these cooking devices. A shift to alternative fuels away from traditional biomass was advocated [6]. Kerosene, LPG, Natural Gas are other alternatives which could be promoted but they may require, dedicated infrastructure, well-functioning institutions and regulations and a reliable supply chain in order to serve the rural population. These requirements are rare in DC, even where they may exist to an extent, they may not reach the rural areas where the largest population without access to energy live.

1.1.3. The Issue

The issue which this thesis addressed is the *problem of access to energy*. This issue, as already highlighted in the section 1.1.2, is a double-faced issue, namely: access to modern fuels and facilities for clean cooking and access to electricity. This thesis specifically focuses on access to modern fuels for clean cooking within the context of rural areas of SSA. Notwithstanding the huge efforts made by Governments, NGO and International development agencies, many people in DC still have inadequate access to energy. This situation is largely due to the lack of an energy access strategy. Without an adequate energy access strategy, no change may be envisaged in the number of persons without access to modern energy carriers, especially, clean energy carriers for cooking. This thesis copes with a *"comprehensive energy access strategy"*. Distributed renewables have been recognised as the primary tool for increasing energy access, particularly in rural areas of DC. Furthermore, improving energy access in rural areas of DC may entails innovative business delivery models, increased investment, local human capacity, policies, a comprehensive access strategy etc. According to REN21[7],to improve

access to energy in rural areas of DC a "comprehensive energy access strategy" is envisaged to intensify research, development and deployment of appropriate technologies. This thesis specifically tackles this issue by making substantial contributions towards the development of a "comprehensive energy access strategy" consisting of a sustainable rural energy planning, selection and optimization of appropriate small scale technology, such as biogas technology, to increase the energy carrier alternatives within the rural energy package to improve access to clean fuels for cooking.

1.2. Motivation

Energy has and continues to play a crucial role in human existence and evolution. Human population and prosperity is symbiotically linked to energy consumption. Increased access to energy allows for the support of larger human population and to increase human prosperity. Conversely human population growth and prosperity leads to greater energy consumption. This connection between energy and development has been demonstrated by the link between GDP and Energy Consumption per capita and also by the link between energy consumption per capita and the HDI of countries [8,9]. Between the necessities to increase energy consumption per capita, the constraints of limited resources and the need to protect the environment, emerge opportunities to develop new and sustainable energy systems and technologies that can enable greater access to energy consumption and achieving higher quality of life in a sustainable way. That is, sustainable energy for a sustainable development. As it was highlighted in previous paragraphs, the global energy system has evolved in the past three decades towards a greater supply and consumption of energy. However, disparities exist across different regions of the world, with some regions particularly affected by insufficient access to modern energy carriers. The sub-Sahara Africa (SSA) region hosts the highest number of persons without access to modern energy services and those heavily dependent on traditional use of solid biomass¹ for cooking. Notwithstanding the many actions taken to improve access to modern fuels in SSA, many people in the rural areas still lack access to modern energy services. Generation closer to the consumption point and the use of distributed renewable energy becomes a viable option to bring clean fuels for cooking to households in rural areas of DC[7].

Within the context analysed and issue highlighted in section 1.1, the situation cannot be resolved through fuel switching alone nor by the promotion of individual

¹ The use of solid biomass (firewood, agricultural residue, dry dung etc) together with inefficient technologies, especially the three stone open fire, for cooking

technologies. Therefore, the major question that arose when a response was attempted to address this energy situation was:

What is the best strategy to enable greater access to modern energy in DC, especially energy for cooking in households in rural areas of SSA?

An attempt to answer this question, which motivated the development of this thesis was: *a comprehensive energy access strategy*. This thesis contributes to the development of this "comprehensive energy access strategy" through three stages, namely:

- *Sustainable energization of rural areas:* This will require a rural energy planning methodology which takes into consideration the supply of sustainable energy carriers and the planning of integrated energy solutions. By "integrated energy solutions" it is intended that rural energy needs are matched to the locally available resources while considering other energy-related components of the rural areas, for example agricultural inputs like fertilizers and water should be considered and integrated in the energy delivery system.
- *Technology selection:* This will involve the identification, analysis, , and selection of an appropriate technology for a particular context
- *Optimization of the technology:* This will entail a procedure for the improvement of the performance of the selected technology within the local context.

These three stages defined the objectives of the thesis and presented in section 1.3.1

1.3. Research Objectives, Methodology and organization of research activities

1.3.1. Research Objectives

Within the above context, improving access to modern energy services, especially for cooking, in rural of DC, cannot be resolved through individual technology dissemination or fuel switching in isolated energy projects or programs as it is the current practice. A more comprehensive energy access strategy is required in order to intensify research, development and dissemination of appropriate technologies. Therefore, the set overall objective of this thesis was to contribute to the development of a comprehensive energy access strategy with focus on energy for clean cooking, in rural areas of SSA. The specific objectives of the thesis which are linked to the three stages in the development of the comprehensive energy access strategy were:

- 1. To propose a comprehensive procedure for sustainable energization of rural areas of DC.
- 2. To develop and apply a Decision Support Tool (DST) for the selection of an appropriate small scale technology to improve access to modern energy services in rural areas of DC with focus on SSA.
- 3. To elaborate a procedure for the optimization of the performance of the selected technology within its operational context.

1.3.2. Methodology

This study which is essentially applied research required competences in the fields of Energy Engineering and Fluid Dynamics, specifically Energy System Analysis, Rural Energy Planning and Computational Fluid Dynamics (CFD). The general methodology adopted to achieve these objectives included: theoretical review of the relevant literature in order to have a general understanding of issues discussed in the thesis. In the development of a sustainable rural energy planning procedure, desk study was the approach adopted. This was followed by field case study to test the validity of the developed procedure. A DST was selected, developed and applied in the selection of an appropriate digester design for mass dissemination in rural context of Cameroon. Field experimentation of a full scale version of the selected technology was carried out to investigate its performance within the application environment in order to identify parameters which led to the improvement of the technology. Laboratory investigations using numerical analysis was used to evaluate modified technology designs during the optimization process. In particular, CFD techniques and the OpenFoam software were adopted to investigate design structure modifications to improve mixing in the Nepali GGC2047 digester design. Qualitative and quantitative analysis were used to discriminate for an improved inlet configuration from eight candidates which modified the engineering structure of the digester design. Further field experimentation were carried out to validate the performance of the improved technology within the local context for subsequent dissemination. Furthermore, specific methods and tools were applied as appropriate at different stages of the study. Such methods and tools are discussed in the text where they were applied

1.3.3. Organization of research activities

In order to achieve the set objectives, the general approach to organize the study was divided into three main parts: *rural energy planning, technology selection process* and *technology optimization process*. The first part involved activities considered as essential to the development of an improved procedure for rural energy planning in DC. These activities included: the analysis of the access to energy situation in DC with focus on SSA, analysis of rural energy planning procedures, the concept of energization, formulation of the improved procedure for the sustainable energization of rural areas of DC, the application of the procedure, through a case study, in a rural area of Cameroon. The second part involved activities considered as building blocks of the technology selection process, with focus on technology for clean cooking in rural areas of SSA. These activities included: identification of relevant technology options, analysis of the options, and

selection of a decision support tool (DST), application of the DST for the selection of the appropriate technology. The third part involved context performance evaluation of the selected technology within the intended implementation context, optimization analysis of the design, testing of the optimized design, monitoring and evaluation of the optimized design within the implementation context.





Figure 3: Organization of the research activities

1.4. Position among the research themes of the Department of Energy

The thesis was a contribution to the activities of the UNESCO Chair. It also benefited from the gathered experience within the UNESCO Chair energy access group in DC, especially Africa. Thanks to the network of the UNESCO Chair with NGOs, international organizations, private sector and academia working in Africa and Italy, some collaborations were initiated during the thesis development. These collaborations provided some of the case studies and investigations considered in the thesis and permitted to deepen knowledge on some specific technologies considered to improve access to clean cooking fuels in rural areas of SSA.

Within the framework of collaboration between Politecnico di Milano and University of Milan, part of the second year activities of the PhD was devoted to investigating the performance of small scale digester based on the leaching bed dry anaerobic digestion concept for application in DC. Within the cooperation agreement between Politecnico di Milano and the Catholic University of Bamenda-Cameroon, part of the PhD activities within the second year were devoted to research activities to test the validity of the developed rural energy planning procedure and the last year activities were devoted to investigating the performance of a modified digester design within the context of Cameroon.

1.5. Structure of the Thesis

In order to capture and consolidate the results of the activities executed in the general approach adopted during the study, as shown in Figure 3, this thesis is organized into six chapters:

Chapter 1 presents an analysis of the research theme, context and issues addressed in the thesis. The chapter continues with a presentation of the motivation to the development of the thesis, research objectives, methodology and organization of the research activities. The chapter ends with a presentation of the research amongst the research themes of the department of energy.

Chapter 2 presents a summary of the review of relevant literature on the major topics discussed, namely: rural energy planning and small scale biogas systems in DC. The aim was to identify gaps in the literature on the topic of access to energy and rural energy planning and issues related to biogas technology with focus on the context of SSA.

Chapters 3 to 5 discuss the main findings of the study. In particular, chapter 3 presents the development of an improved procedure for the sustainable energization of rural areas of DC and testing of this procedure through its application in a case study within a rural context of Cameroon ; chapter 4 presents the application of a decision support system for the selection of an appropriate biogas digester for the context of Cameroon; chapter 5 presents a procedure for the optimization of the Nepali GGC2047 biogas digester design for application in the rural context of Cameroon.

Lastly, chapter 6 presents the conclusion of the study. The conclusion consolidates the study into a tool for the improvement of access to modern energy in rural areas of DC. This tool was titled "*Towards a comprehensive energy access strategy*".

Chapter 2: State of the art for Rural Energy Planning and Biogas Technology

In this chapter, the state of the art of rural energy planning procedures and biogas technology in DC is presented. The aim was to identify some gaps and highlight some issues on energy access in rural areas, and in particular access to modern energy for cooking by households in DC, which this thesis attempted to address. The chapter is organized into two main sections. The first section presents a summary of the issues related to rural energy planning and the second part is focused on biogas technology as an appropriate technology to improve access to modern energy carriers in households in rural areas of DC, in particular SSA.

2.1. Rural Energy Planning

Energy use in DC is rapidly increasing due to rapid economic growth, improving quality of life and to satisfy the needs and aspirations of the increasing population. This energy increase is occurring more in the urban areas and the industrial energy demand sector. The rural areas, on the other hand and household sector, may not be experiencing this rapid increase in types and amounts of energy consumed. The rural areas and households sector are often not fully considered in national energy policy, especially in most countries in SSA where these policies are often fragmented [10,11]. The situation of low access to energy in rural areas is evident by the high number of people migrating to urban areas in search of survival, jobs and better living conditions. The energy planning process has been identified as a enabler of environmentally and socially meaningful development kev [12]. Therefore, it becomes important to review Rural Energy Planning (REP) in order to understand the procedures and tools involved to enable access to energy in rural areas. Therefore, the goal of this section was to review the state-of-the-art of REP in order to be aware of the various approaches that have been employed and to identify gaps and issues related to the application of these planning approaches or procedures to improve access to modern energy services in DC, with focus on SSA. The chapter is divided into three sections. In the first section, rural energy needs are discussed as the logical starting point for a sustainable planning procedure. In the second section, the concept of energization is reviewed as foundation on which a more meaningful and sustainable approach to rural energy planning must be based. In the third section, highlights of the existing approaches to rural energization and the identification of gaps and issues which this thesis attempted to address are discussed.

2.1.1 Rural Energy Needs

The logical starting point for REP process is the identification of rural energy related needs. These energy needs may be considered as what is necessary to empower sustainable human socio-economic development. These needs have been identified namely[13–15]:

- *Energy for cooking:* This is the most basic of human energy need. Improved access to affordable, reliable and above all, sustainable energy carriers for cooking is required for a large majority of the global population still dependent on traditional use of solid biomass for cooking, especially the poor, who live mostly in rural areas of SSA.
- *Potable water pumping*: Energy is required to bring potable water from catchment areas, wells or boreholes for human consumption. About 89% of the global population were reported using improved water sources in 2010. However, huge disparities still existed. While in Latin American, Caribbean and North African regions, 90% of the population had access to improved water supply, in SSA region a relatively less proportion, 61%, of the population had access to improved water supply. These disparities were also observed within countries, between the rich and the poor and between urban and rural areas. Most of the people without improved drinking water sources lived in rural areas of SSA[16].
- *Energy for irrigation water supply*: Most economies of the DC, especially those of SSA, are based on agriculture. The agricultural practices are mostly rain-fed. However, with increasing global warming and water scarcity and the need to increase crop production for greater world food security, irrigation agriculture is becoming more significant. Energy plays a crucial role in irrigation-based agriculture[17,18].
- *Mechanical power:* This has a variety of valuable uses that are essential in rural areas, including: water pumping, irrigation, intensification of agriculture, food processing (crushing and grinding). Access to mechanical power can free give time for women and children. The free time could be used for other human development activities like education.
- *Electricity:* This is a versatile energy form required for diverse usages including: lighting, education, health, information and communication technology, and operation of appliances.
- *Transport:* Energy is required for the transportation of goods and people.
- *Fertilizers:* This is required for successful agriculture and are usually derived from fossil fuels sources.

The energy need profiles differ from one rural area to another within the same country and between rural areas of different countries depending on the socioeconomic level of development of both the rural areas and the country[14,19,20]. However, the end-uses of energy that satisfy these needs may be common. Therefore, categorizing these energy needs may be necessary, in order to facilitate the supply of sustainable energy carriers and the planning of integrated energy solutions based on the local energy resources. Based on the "quality of energy", these needs may be consolidated into four categories, namely:

- Low grade thermal energy (<100°C),
- Medium grade thermal energy $(100 300^{\circ}C)$,
- Electricity in both dc and ac forms,
- Rotating shaft power at fixed or mobile locations.

These different qualities of energy go to provide the fundamental energy services required in the rural areas. These energy services i.e. the final end-use of energy (useful energy demands) are [12,13,21]: *cooking, lighting, space heating, warm water, water pumping, refrigeration, powering of appliances ,communication, motive power for machinery and mobility.* These services provide health, social and livelihood benefits which are necessary for the well-being of the people. The space heating and warm water services may be satisfied via the provision of low grade thermal energy. Cooking services via the provision of medium grade thermal energy; the provision of lighting, communication, refrigeration and powering of appliances services may be met through electricity both in dc and ac forms. The need for rotating shaft power may be driven by a variety of services required in the artisan sector, especially in food processing.

2.1.2 The Theme of Energization

The issue of "access to energy" may be translated into the theme of *energization*. This theme has been in usage since the later 80s. Till date, its definition and usage has been varied depending on the context and purpose. Within the context of energy planning key features of the theme include [12]:

- Supply and planning of energy solutions taking into account energy efficiency and cost.
- Use of several energy forms of differing qualities and characteristics to provide a variety of energy and other needs.
- Matching of energy resources with energy needs and its optimization to form an energy package that provide for economic growth opportunities for long term viability. This need-resource matching may adopt ad-hoc solution strategies in order to cover energy demands in a better manner than the usual standardized approaches.
- Association of the concept of sustainable development in order to highlight the relevant features of accessibility, affordability, enhancing quality and quantity and variety of forms, in line with the sustainable development goals (SDG), especially SDG7.

Considering, the above features, the definition given by Nissing et al [12] becomes the most applicable within the context of global access to energy challenges. Their definition captured the concept of sustainable development and thus the theme was upgraded to *Sustainable Energization (SE)*.

The precursor to the theme of SE is the "energy ladder" myth. Improving access to modern energy carriers entails a transition from solid biomass, which is considered to be "dirty" and a less efficient fuel, to cleaner and more efficient fuels. This transition is often predicted using the "energy ladder" model. On this ladder, fuels are ordered according to certain household preferences based on some physical characteristic which include: cleanliness, ease of use, cooking speed and efficiency[19]. At the bottom of the ladder are less efficient fuels and at the top of the ladder are more efficient fuels, (Figure 4). According to this model, the transition from less efficient fuels to more efficient fuels follows a linear process through three main phases. The first phase is characterized by the household dependence on solid biomass which is considered inefficient, less costly, more polluting. The second phase is the transition phase characterized by the use of liquid fuels like kerosene, which have high commercial value, less polluting and of intermediate efficiency. The third phase is characterized by the use of non-liquid fuels (LPG, Natural Gas and electricity) which are less polluting and more efficient. Climbing the rungs of the energy ladder by the household, according to the model, is driven solely by household income and prosperity. The higher the households' prosperity (income), the more likely the household switches to the use of more efficient fuel up the energy ladder. However, studies have shown that income may not be the only determinant factor to the linear transition. These studies suggest that the relationship between household income and their transition to the use of more efficient fuels is not as strong as predicted by the energy ladder. Rather, as household prosperity increases, they tend to acquire a variety of appliances which provide specific energy services leading to more diversify energy demands. Furthermore, the transition through the different phases is not linear as predicted by the energy ladder, rather the households tend to consume a portfolio of energy options (consisting of a combination of fuels) at different phases of the energy ladder[19,22,23]. This process is called *fuel stacking* and the model that describe it is called the *multiple fuel model*, (Figure 5) [24].

Reasons advanced for fuel stacking include[22,23]:

- Livelihood strategies of the poor driven by irregular and variable income flows of the household which leads to specific budget strategies applied to maximize fuel security.
- Fuel supply is erratic and unreliable (fuel availability).
- Commercial fuel price fluctuations which makes the preferred fuel unavailable.
- Cultural and traditional cooking practices that prevent the use of modern fuels.


Figure 4: *Classical energy ladder* Source: [25]



Figure 5: *Multiple fuel model* Source: [19]

There are disparities in the fuel stacking phenomenon between the urban and the rural households. While it may be a transient phenomenon rather than a linear and continuous process in urban areas, in rural areas only partial switching along increasing income segment have been observed, with solid biomass remaining the predominant and important energy source irrespective of the income segment of the households both in the urban and rural areas.

Notwithstanding the predicted economic prosperity of the African region, forecast on the energy consumption profile of the residential sector in SSA by 2040 show very little transition towards the use of modern fuels in the urban areas with solid biomass still remaining the dominant fuels[3]. The rural households will continue to completely depend on the traditional use of solid biomass, especially firewood. Thus the predictions of the energy ladder and the multiple fuel models fail in this case, especially in the rural areas. This is due to the fact that both models focus on conventional forms of energy and do not consider sustainability in the ranking of the fuels[24]. A strategy to the supply and planning of energy solutions that is considered sustainable is, therefore, required to improve access to modern energy carriers in rural households of SSA.

2.1.3 Existing Approaches to Rural Energization

Existing approaches to enable access to the above mentioned energy services (section 2.1.1) in rural areas of DC include [26]:

- Electrification: This approach is aimed at providing the electricity needs of the rural areas. Various technologies e.g. grid extension, diesel generators, PV systems, Integrated Renewable Energy Systems are being deployed through this approach.
- Integrated Energy Centers: in this approach one-stop energy shop is established in the rural area where various energy carriers are supplied in bulk for further retail to the rural households. Most of these fuels are intended to meet the cooking and transport energy needs of the rural areas.
- Unplanned energy supply systems, e.g. local firewood markets being established, especially in peri-urban settlements. This strategy aims at meeting mostly energy for cooking needs of the households.
- Isolated energy carrier/technology programs e.g. biogas programs, improved cook stoves, LPG subsidy programs. Most of these programs have produced mitigated results, especially in SSA. For example, most national biogas programs in many countries in SSA have resulted in less than expected levels of digester adoption in rural areas as compared to the adoption of this technology in Asian countries (this will be demonstrated later in this chapter). Also, improved cook stove

programs in rural areas of SSA have produced similar results like biogas programs.

Notwithstanding the deployment of these strategies to improve access to energy in rural areas of SSA, it has been observed that rural areas still continue to depend heavily on solid biomass together with inefficient technologies, mainly the three stone open fire, to meet their energy needs, especially energy for cooking. However, much has been achieved in delivery of electricity in both dc and ac forms to rural areas. Greater efforts are required to deliver low and medium great thermal energy for cooking in particular. It could be argued that the non-transition to the use of more efficient and clean energy carrier by rural households as predicted by the energy ladder notwithstanding, the predicted increase prosperity and the deployment of the above mentioned several access strategies is because these strategies are often implemented in isolation. A comprehensive access to energy strategy is therefore required.. This is one of the key issues this thesis seeks to address.

The IEA, 2000,[27] developed the Advanced Local Energy Planning (ALEP) process on which most REP models are based. ALEP combines long-term strategic planning with the detailed planning of concrete subsystems. This process consists of six phases, namely:

- *Preparation*: this phase consist of analysis of the existing energy situation of the target community, stakeholder analysis and organization of a workshop for the initiation of the process.
- *Orientation*: during this phase a description of the existing situation of the energy system and related problems of the community are formulated, objectives of the planning process are set, system boundaries and socioeconomic framework in order to reduce the complexity of the technical energy system are defined; scenarios and strategies to be investigated are defined.
- *Main study*: it consist of a comprehensive analysis of the local energy system with the goal of a medium to long-term strategic planning. It is made up of five steps namely:
 - Definition of the structure of the comprehensive model (e.g. Reference Energy System)
 - Compilation of the model database
 - Design of scenarios and strategies
 - Integration of the subsystems analyses and
 - Sensitivity analysis.

During the design phase in the main study stage different approaches and tools have be used. These include: chronological simulations, Linear

programming using mathematical tools like MARKAL,TIMES and other commercially available computer tools like HOMER [28–30]

- *Evaluation and decision making*: in this phase the different energy system options obtained during the main study phase are assessed and prioritized by the stakeholders and a strategy for the implementation adopted.
- *Implementation*: the actions and priorities adopted in the evaluation and decision making phases are physically realized during this phase.
- *Supervision and monitoring*: it consist of regular collection of data on the energy system and reporting on successes of the implemented action plans. This phase last usually over several years.

The focus of rural energy system modelling within the ALEP process is on the Main Study phase.

As already mentioned in section 2.1.2, the issue of energy access could be translated into the theme of energization with the energy ladder as the precursor and within the present constraints to energy access and sustainable human development, the theme has been updated to sustainable energization and the definition proposed by [12] become currently more relevant.

Within the framework of SE, some shortcomings were observed in the few studies which analyzed rural energy systems with the aim of providing data for planning and modelling [14,21,29]. These shortcomings include:

- Studies are limited to energy accounting packages.
- The planning does not consider the sustainability of the energy system.
- There is lack of systematic database.
- The studies rarely quantify energy consumption to levels required for modelling.

Furthermore, within the context of sustainable energization, most models tend to marginalize the multidimensional issues of specific energy supply objectives. However, in most of these studies traditional fuels², mainly firewood, remain important energy carriers. These drawbacks were due to the non-integration of SE in the planning process. It was therefore important to integrate SE into the rural energy planning process. Nissing et al [29] proposed a six-step procedure in the main study phase of the ALEP process for the integration of SE in the rural energy planning process, as shown in Figure 6. These six-steps are:

- 1) Integration of the goals of SE in the decision making
- 2) Identification and prioritization of the energy services demanded according to energy drivers.

² These include: firewood, charcoal, agricultural residues, wood waste and other solid waste.

- 3) Local energy resource assessment with focus on renewable energy sources,
- 4) Design of an integrated renewable energy system
- 5) Set up of the energy services supply network system including the required level of depth regarding energy services demanded.
- 6) Control and adaptation of the energy services supply network.

The six-step procedure was a structured approach required to setup a comprehensive technical planning model which captures the multitude of aspects on which SE touches. The Nissing et al six-step procedure, addresses the shortcomings of hitherto rural energy planning procedures. That is the lack of systematic database and quantification of energy consumptions to levels required for rural energy system modelling and integration of the concept of sustainable energization. It has been translated into an economic model and demonstrated within an urban context[29]. However, it did not take into account the existing energy supply system and its translation into a technical model remained theoretical. Furthermore, in the step of setting up of the Energy Services Supply Network System (ESSN) it did not consider energy drivers. The non-consideration of energy drivers in the ESSN leaves room for the inefficient allocation of energy conversion technologies for the provision of the desired energy services leading to technology stacking, a situation where several technologies are used to provide the same energy service in different energy drivers. An approach which integrate the concept of SE and takes into account the current energy balance in the existing energy supply system with focus on need-resource matching is required. Also, the practical demonstration of the validity and/or relevance of such an approach is required. Furthermore, the integration of energy drivers in the ESSN will allow for a more efficient allocation of energy technologies.

Therefore, this thesis seeks to address these short-comings in the Nissing et al sixstep procedure, and thus addresses the weaknesses of existing approaches to improve access to energy in rural areas of DC. An improvement of rural energy planning procedure constitute the first stage in the development of a comprehensive energy access strategy.



Figure 6: The Nissing et al six-step planning procedure

Source: Adapted from [29].

2.2. Biogas Technology

Biogas technology could offer a more efficient, sustainable and long term solution to the use of biomass than the current use of three stone fire and improved cook stoves. It presents a logical shift from the use of liquid fuels to gaseous fuels. This technology is based on the anaerobic digestion of organic matter and has several applications and benefits. Moreover, the technology is simple and easy to operate and therefore is appropriate³ for DC, especially rural areas. The aim of this section is to highlight the fundamental principles of biogas technology and issues related to

³ Technology that is suitable to the social and economic conditions of the geographic area in which it is to be applied, is environmentally sound, and promotes self-sufficiency on the part of those using it, i.e small scale, decentralized, labor-intensive, energy-efficient, environmentally sound and locally controlled.

its dissemination as a means to improve access to modern fuels for clean cooking at the level of the households in rural areas in DC and SSA in particular. This section is divided into two subsections. The first subsection presents a review of the fundamentals of biogas technology. The intention of the review is to set the basis for a thorough understanding of the basic principles underlying the technology, parameters for characterizing its operation and performance; its benefits and applications. In the second sub section, issues related to the dissemination of small scale biogas technology as a means to improve access to modern fuels for clean cooking at the level of the households in rural areas of SSA are highlighted.

2.2.1 Fundamentals of Biogas Technology

This sub section reviewed the fundamentals of biogas technology, including: the anaerobic digestion process, properties and composition of biogas, feedstock for biogas production, process typology, environmental condition in the digester, operating parameters, performance parameters, technology typology and the section ends with some general applications and benefits of biogas as a fuel. These fundamentals are applicable to domestic, community and industrial scale biogas digesters.

Anaerobic Digestion Process

Anaerobic Digestion (AD) is the biochemical break down of organic matter in the absence of air (oxygen) to give a mixture of gases called biogas. The process consists of four sub-processes or stages, namely hydrolysis, acidogenesis (fermentation), acetogenesis or dehydrogenation and methanogenesis [31–34]. The process is coordinated by a consortium of bacteria with different bacteria communities coordinating each of the stages. The different stages of the process, input materials, coordinating bacterial community and output materials are illustrated in Table 2.

Stage	Input material(s)	microorganism community	Output material (s)
Hydrolysis	Complex organic substrate e.g. carbohydrates, proteins, lipids	Extracellular and/or acid forming bacterial	Simple organic substrate (amino acids, sugars, fatty acids)
Acidogenesis (Fermentation)	Simple organic substrate (amino acids, sugars, fatty acids)	Acidogenic/Fermentati on bacteria	Lower organic acids or Volatile organic acids (e.g. acetic, propionic and butyric acids), H ₂ , CO ₂
Acetogenesis /dehydrogenation	Lower organic acids or Volatile organic acids (e.g. acetic, propionic and butyric acids), H ₂ , CO ₂	Acetogenic bacteria or Acetates	Precursors for biogas formation i.e. Acetic acids, formic acids, H ₂ , CO ₂ .
Methanogenesis	Acetic acids, formic acids, H ₂ , CO ₂	Methagenic bacteria	Methane, CO ₂ , H ₂ S, Water vapor

Table 2: Stages of the anaerobic process

The eventual formation of biogas through AD can be achieved via two principal pathways, namely: acetoclastic and hydrogenotropic paths. Acetic acids are converted to biogas through the acetoclastic path and is coordinated by the acetoclastic methanogens. This path produces 70% of the methane content of the biogas. The hydrogenotropic path combines the hydrogen and carbon dioxide from the acetogenesis into biogas. This path is coordinated by hydrogentropic methanogens and produces 30% of the methane in the biogas[35]. The scheme of the pathways is shown in Figure 7.



Figure 7: Different pathways of the anaerobic process Source: [35]

Properties and composition of biogas

Biogas is a renewable and clean fuel. It has a calorific value which depends on the methane content (50 -75% vol/vol) and range between 21 - 37.5 MJ/m³. Biogas has a density of 1.1kg/Nm³ and its composition depends on the type of substrate used, digestion process and the technical design of the digester [5]. The composition of biogas is shown in Table 3.

Table 3:	Biogas	Comp	osition
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Constituent	Chemical formula	Percentage
Methane	CH ₄	25 - 75
Carbon dioxide	CO ₂	25 - 50
Hydrogen sulphide	H_2S	0,1-0,5
Water vapor	H ₂ O	1 - 2
Ammonia	NH ₃	0,1-0,5
Carbon monoxide	СО	0-0,5

Feedstock for biogas production

All bio-gradable materials may be used as feedstock for biogas production. Thus, organic materials ranging from food waste, organic waste from parks and gardens, industrial organic wastes and residues, sludge from wastewater treatment plants, agricultural residues, animal manure and organic fraction of municipal wastes may be used for biogas production. The choice of type of feedstock may depend on local availability and biogas yield potential. Table 4 shows the biogas yield potential for some common feedstocks.

Table 4: Biogas yield potential of common feedstocks

Feedstock	%DM	Biogas yield m ³ /kg DM	Biogas yield m ³ /animal/day
Pig manure	17	3,6-4,8	1,43
Cow manure	16	0,2-0,3	0,32
Chicken manure	25	0,35 - 0,8	0,01
Human excreta/sewage	20	0,35 - 0,5	0,04
Straw/grass	80	0,35 - 0,4	NA
Water hyacinth	7	0,17 - 0,25	NA
Maize	20	0,25 - 0,40	NA
Rice Straw	87	0,18	NA
Rice Husk	86	0,014 - 0,018	NA
Leaf Matter	-	0,6	NA

Source: adapted from [5]

Typology of Process

AD may be classified based on the operating range of temperatures and on the amount of solid concentration in the feedstock.

Operating temperature

The anaerobic process is due to a consortium of micro-organisms. Different groups of these organisms function under different temperature regimes. Three regimes

have been identified namely; *Psychrophilic* (0-20°C), *mesophilic* (20 -45°C) and *thermophilic* (40 -70°C). The active methanogenic bacteria in each of the regimes are referred to as psychrophiles, mesophiles and thermophiles. Figure 8, shows the growth rate of these methanogens with respect to temperatures.



Figure 8: *Growth rate of the different methanogens* Source: [34,36]

Solid content

The influent into a digester is characterized by the amount of *Solid Content*. This is usually defined in terms of percentage total solid (%TS). Depending on the %TS concentration of influent the process may either be characterized as Wet Anaerobic Digestion (WAD) or Dry Anaerobic Digestion (DAD). WAD is characterized by a %TS concentration of less than 10%; a retention time that varies between 40 to 100 days. WAD operating temperatures are usually within the mesophilic range. DAD is characterized by a %TS concentration of between 12 -45%; a retention time between 9 to 45 days. DAD operating temperatures are usually within the thermophilic range.

Environmental condition in the digester

The micro-organisms that are responsible for the biogas production process are very sensitives to the environmental conditions within the digester. These conditions include: presence of air (oxygen), temperature, acidity, nutrient supply (feedstock) and inhibitors [31,37]. These conditions are applicable to both WAD and DAD; industrial scale as well as small scale digesters commonly disseminated in DC.

Oxygen

Methanogenic archaea which are crucial in the final stage of biogas production are killed by small quantities of oxygen. However, some known as facultative anaerobic bacteria can co-exist with oxygen consuming bacteria. Therefore, the digester in which the process takes should be air tight.

Temperatures

The rate of biological decomposition and process increases partially with increased ambient temperatures. Thus, the activity of the different microorganisms involve in the biogas production process are affected differently by the ambient temperatures and therefore have different optimum temperatures. At temperatures below or above the optimum the relevant microorganisms may be inhibited or may suffer irreversible damage. Three temperature ranges have been identified corresponding to the different consortium of microorganisms, namely psychrophilic range (below 20° C), mesophilic ($20 - 40^{\circ}$ C) and thermophilic ($45 - 75^{\circ}$ C).

Acidity (pH value)

The consortium of microorganisms in the biogas production process are affected by the acidity of their medium. The microorganisms involved in the various stages require different acid concentration levels, i.e. pH value, for optimum growth. The hydrolytic and acidogenic bacteria require an acid medium with a pH range of 5.2 to 6.3 whereas the acetogenic and methanogenic bacteria require a neutral medium with a pH range of 6.5 to 8.0. The methanogenic bacteria are crucial for the biogas production. Therefore, in a single stage digester, where all the stages of the anaerobic process takes place, the neutral pH range must be maintained. The pH value is of limited use for digester control. However, because of its importance it should always be checked. The digesters commonly disseminated in DC are single stage digesters, therefore, environmental conditions within these digesters must be neutral for effectiveness of the biogas production process.

Nutrient supply (type of feedstock)

The microorganisms involved in the biogas production process have speciesspecific needs in terms of macronutrients, micronutrients and vitamins. The rate of growth and activity of various microorganisms' population is affected by nutrient supply. Thus, optimum nutrient supply must be ensured for optimal methane production. Methane production depends on the proportions of proteins, fats and carbohydrates in the feedstock. A balance of macronutrients and micronutrients is required for process stability. The macronutrients include carbon (C), nitrogen (N), phosphorus (P) and Sulphur (S). A high carbon concentration in the feedstock may lead to inadequate metabolism i.e. less of the carbon is converted into biogas. A high nitrogen concentration in the feedstock may lead to formation of ammonia (NH₃) which may inhibit the growth of the microorganisms or lead to the complete collapse of population of the microorganisms. Therefore, a balance between the carbon and nitrogen concentration i.e. C: N ratio of the feedstock is crucial. The optimal range is 10 -30:1. Since Phosphorus and Sulphur are also required the optimum C:N:P:S ratio that should be introduced into the digester is 600:15:5:3. The micronutrients required include: cobalt (Co), nickel (Ni), selenium (Se), molybdenum (Mo)- needed in co-factors for essential reactions, magnesium (Mg), Iron (Fe), manganese (Mn)- electron transport and functioning of some enzymes. Concentration of micronutrients in a digester is a crucial reference variable. Table 5, show the recommended micronutrients concentration in a digester.

	Concentration range [mg/liter]			
Trace element	Absolute Range Minimum		Recommended optimum	
Со	0,003 - 10	0,06	0,12	
Ni	0,005 -15	0,006	0,015	
Se	0,08 - 0,2	0,008	0,018	
Mo	0,005 - 0,2	0,05	0,15	
Mn	n.s.	0,005 - 50	n.s	
Fe	1-10	0,1- 10	n.s	

Table 5: Recommended micronutrients concentration in a digesterSource: Adapted from[35]

Inhibitors

These are substances which under certain concentrations may lower the anaerobic digestion process rate or bring the process to a complete stop. These substances may be introduced in digester through two pathways:

- i. during feeding of the digester: such substances include antibiotics, disinfectants, solvent, herbicides, salts, and heavy metals (e.g. Copper),
- ii. intermediate products from individual stage of the process: the substances include free ammonia , Hydrogen Sulphide (H₂S) Volatile Fatty Acids (VFA) and Oxygen (O₂)

Table 6 shows the inhibitory concentration of some of these substances.

Table 6: Inhibitory level of inhibitorsSource: [35]

Inhibitor	Inhibitory concentration	Comments	
Oxygen	> 0,1mg/l	Inhibition of obligate anaerobic methanogenic archaea	
Hydrogen sulphide	> 50mg/l	Inhibitory effect rises with falling pH value	
Vaolatile fatty acids	> 2000mg/l	Inhibitory effect rises with falling PH value. High adaptability of bacteria	
Ammoniacal nitrogen	> 3500mg/l	Inhibitory effect rises with falling pH value and rising temperature. High adaptability of bacteria	
Heavy meatls	$\begin{array}{l} Cu > 50 mg/l, \\ Zn > 150 mg/l, \\ Cr > 100 mg/l \end{array}$	Only dissolved metals have an inhibitory effect. Detoxification by sulphide precipitation	
DisinFCtants, antibiotics	n.s.	Product-specific inhibitory effect	

Digester operating parameters

Economic consideration are often the basis for the design, construction and operation of digesters. However, the focus is often on maximum gas yield or complete decomposition of organic matter (OM). The aim is usually to obtain optimum degradation performance at acceptable economic cost. In order to assess the performance of a digester the parameter important for its operation, in addition to feedstock and temperature as already discussed under the paragraph on

environmental conditions in the digester, include: organic loading rate, retention, digester volume and mixing [34,35].

Organic Loading Rate (OLR)

It is a measure of the fraction of the feedstock that can be converted into biogas, i.e. the quantity of volatile solid fed into the digester. It is quantified in terms of kilograms of volatile solid per unit digester volume per unit time (kg_{VS}/m^3 per day). It is evaluated using *Equation 1*.

$$OLR = \frac{C\dot{m}}{V}$$
 Equation 1

Where C is the concentration of the digestible organic matter (%VS), m is the quantity of feedstock fed into the digester per day and V is the active volume of the digester.

Retention Time (RT)

It refers to the time the feedstock spends in the digester for complete digestion before it is discharged from the digester. It is evaluated using *Equation 2*.

$$RT = \frac{v}{Q} \qquad Equation 2$$

Where V is the active digester volume and Q is the volume of feedstock added into the digester per day.

In some digester operation, water and the feedstock are mixed to give a slurry, wherein the water and the solid content spend the same time in the digester. This time is referred to as the Hydraulic Retention Time (HRT). In other digesters, the time the water spend in the digester, i.e. HRT, and the time the solid spend in the digester are different. The time the solid spends is called solid retention time (SRT). These parameters must be chosen so that the constant replacement of the digester content does not flush out the microorganisms than they can be replenished during that time. For example methanogenic archaea have a life span of 10days, so the retention time must be greater than 10days. Thus, retention time affects both the performance and size of the digester. Generally, RT depends on operating temperature of the digester, the loading rate and the type of feedstock. Figure 9 shows the relation between loading rate and RT



Figure 9: *Relation between retention time and OLR* Source: [35]

Mixing (agitation of digester content)

Due to differences in density of the various constituent of the feedstock fed into the digester, the digester content is often stratified. This leads to the bulk of bacteria mass collecting at the bottom layer of the digester while the feedstock is at the upper layer and floating solids form a scum on the uppermost layer. The performance of the digester is primarily affected by retention time of the digestible slurry in the digester and the degree of contact between incoming fresh influent and the viable microorganism population. The importance of mixing in AD has been highlighted in [38–40] to include: uniform distribution of the microorganisms throughout the digester volume, transfer of heat, reduction of particle size as digestion progresses and the removal of the biogas. Mixing of the digester content may be achieved principally through several mechanical systems (e.g. propellers and scrapers) and the configuration of the digester components. Digester commonly disseminated in DC are usually simple, without mechanical systems for mixing. Therefore, mixing in these digesters is achieved entirely through the configuration of the digester components.

The organic loading rate, retention time, mixing, together with the type of feedstock are important for the design and operation of the digester system.

Performance parameters

These are parameters which are used to characterize the efficiency of the AD process of a particular digester. They include, biogas production, biogas production rate, specific productivity, degree of degradation and pathogen reduction [31,41,42].

Biogas production measures the quantity of biogas produced per unit of time (usually a period of 12 or 24 hours). On the basis of biogas production and digester volume, the production rate and the specific productivity are evaluated using *Equation 3* and *Equation 4*.

$$production \ rate = \frac{biogas \ production}{V_d} \qquad Equation \ 3$$

$$productivity = \frac{biogas \ production}{VS} \qquad Equation \ 4$$

Where V_d = digester volume and VS = amount of volatile solids added per unit time

The biogas production rate and specific productivity denotes the efficiency of biogas production from loaded feedstock. As individual parameters they are of little informative value because they do not include the effective loading of the digester.

The degree of degradation provides information about the efficiency of the AD process. It may be determined in terms of the following parameters: total solid (TS), volatile solids (VS), chemical oxygen demand (COD) or biological oxygen demand (BOD). In terms of volatile solids the degree of degradation is evaluated using *Equation 5*.

$$\eta = \frac{(VSsub.min) - (VSef.mef)}{VSsub.min}.100$$
 Equation 5

Where η is the degradation efficiency, VS_{sub} is the volatile solid of the added fresh feedstock; m_{in} is the mass of the added feedstock; VS_{ef} is the volatile solid content of the digestate; m_{ef} is the mass of the digestate.

Typology of digesters

The principle of AD is the same in every type of digester, however, several methods could be used, depending on climate, soils, organic matter, and water availability. These methods leads to differentiation of biogas digester operation strategy and designs into categories based on some critical operating parameters which include: feeding mode, digester configuration and strategy of microorganism growth.

Feeding mode

The geometry of the digester has evolved from simply rectangular shaped digester through cylindrical and spherical/oval to tubular designs. The configuration of the digester together with other components has also evolved. The evolution has been motivated by the search for greater process efficiency, suitability of operation under different temperature regimes and simplicity of operation and maintenance. Hence, based on feeding mode, digesters may be grouped into three main feeding modes namely, batch, semi-continuous and continuous modes [31,34].

Batch fed digesters

The feeding mode of this category is characterized by periodic load and discharge of the feedstock. Once loaded, the feedstock is allowed to digest until little or no gas is produced. The feedstock used in such digesters ranges from fruits, vegetables, straw, animal dung, human excreta to municipal organic waste. Batch digesters may be operated within the thermophilic range of temperatures and at high total solid concentration of the influent (greater than 15%TS), thus are most suited for DAD principle[5]. The retention time for these types of digesters is usually high and the biogas production is also high. The configuration of the system could be such that the gasholder or storage is separated from the digester. The digester usually requires little space. The operation and maintenance of such digesters is laborious. Batch digesters could be very cheap and affordable to households; however, their size may limit the quantity of gas produced. They are not so popular amongst the models promoted at household level in rural areas of DC, however, they may be applicable in urban households where space is an issue.

Semi-continuous fed digesters

The feeding mode of this category is frequent (usually daily) loading of the digester through an inlet and automatic discharge of slurry through the outlet to the slurry (compensation) tank. Once loaded, the feedstock circulates in the digester for a period of time during which it is digested. Semi-continuous digesters are usually designed as mono-feedstock (pig, cattle or fowl) digesters; though in practice two or more other feedstock may be included. These digesters are designed to be operated within the mesophilic range of temperatures and at low total solid of influent (less than 10%TS), thus they are suited for WAD principle. The retention time for this type of digesters range from 10 -60 days. Biogas production from such digesters is usually lower than for batch digesters due to lower process efficiency. This design of digesters for household application are more expensive, less laborious in O & M, and usually require more space, than the batch type. The configuration of the system could be such that the gasholder or storage is separate from the digester. Most

digesters disseminated in DC, e.g. the family of fixed dome, floating drum and the plastic digesters, operates on this feeding mode,

Whenever the digester and the gasholder constitute single units, the latter may be of variable or fixed volume, this gives rise to two sub-types, namely floating drum and fixed dome digesters.

Floating drum design: this design was first developed by the Khadi & Village Commission (KVIC) in India and was standardized in 1962. It is characterized by a variable volume gasholder. The main advantage it has is that the gas pressure at the point of use is fixed thus enabling an effective functioning of the burner. It has a relatively high maintenance cost (associated with the renovation of the steel dome) and construction cost and requires relative skilled labour to realize the construction. The preferred feedstock is animal dung e.g. pig, cattle or cow. Several variations of the design for different geographical locations includes the KVIC, Pragati, Ganesh, Ferro-cement designs.

Fixed dome design: it is characterized by a fixed volume gasholder. Its main advantage is the relatively low maintenance and construction cost, and relative less skilled labour to realize the construction. The preferred feedstock is animal dung, e.g. pig, cattle or cow. Several variations of the design for different geographical locations includes the Indian fixed dome (e.g. Janata I & II, Deenbandhu), the Chinese fixed dome , the Nepali GGC2047 design, and the Vietnamese design [5,43–45]. It is worth to note that, while the installation cost for the fixed dome model is cheaper than for the floating drum type, the cost varies amongst the different fixed dome variety with the Indian Deenbandhu model claimed to be the cheapest.

Any of the above designs (floating drum or fixed dome) are applicable to both households and community (schools, hospitals, prisons etc.) levels. The discriminating factor being only the size. Usually, digester sizes of $4m^3$, $6m^3$, $8m^3$ and $10m^3$ are applicable at the household level while greater than $10m^3$ are applicable at the community level.

Continuous fed digesters

The feeding mode of this category of digesters is characterized by the continuous loading and discharge of the digester[46]. They are design to operate on one type of feedstock i.e. mono feedstock. They are also designed to be operated within the mesophilic range of temperatures and at low total solid of influent (less than 10%TS), thus are operated on the WAD principle. The retention time for this type of digesters could be lower than for the semi continuous feed digesters. Biogas production from such digesters could be lower than for batch digesters due to lower

process efficiency. The configuration of the system could be such that the gasholder or storage is separated from the digester. This design of digesters are useful mostly for industrial applications and therefore are not common in DC.

Configuration of digester design

In the operation of a digester, the fresh influent may either interact with the older content of the digester or may not. Based on this criteria there are two typologies of digesters namely: plug flow and complete mixed digesters[34].

Plug-flow or tubular digesters

In this type of digesters the incoming fresh influent does not mix with the older digester content. The only point of interaction is a surface area of contact. The digester is usually in a tubular form, from whence the nomenclature "tubular" is derived. The incoming fresh influent pushes out the older digester content, thus the feedstock along the length of the digester are at different stages of decomposition. The feedstock at the outlet is usually at a more advanced state of decomposition than the feedstock closer to the inlet. This strategy could allow for the separation of the different stages of the AD process wherein the methanogenic stage take place towards the outlet of the digester while the hydrolysis and acidogenic stages take place closer to the inlet. This designed could operate within both the mesophilic and thermophilic ranges of temperature and at slightly higher total solid of influent (up to 15%TS). Thus, operation of this digester configuration may be considers a transition between WAD and DAD principle. The retention time could range from 15 -45 days [41]. The feeding mode could be continuous or semi continuous. Its configuration is such that the tube can either be vertical or horizontal, with the latter most applicable in DC. The gasholder is usually detached from the digester. Application of this digester configuration is considered the cheapest amongst the models disseminated in DC in terms of construction (skills and materials), O&M, however it is very fragile due to the type of construction material often used (polyethene), hence, the nomenclature polythene or plastic digesters.

Well or complete mixed digesters

The incoming fresh feedstock and the older digester content are completely mixed in this type of digester configuration. This digester design could operate within both the mesophilic and thermophilic ranges of temperature and usually at total solid of influent less than 10%TS, thus are operated on the WAD principle. The retention time could range from a few days to about 45 days. Although complete mixing of fresh influent and older digester content may allow for contact between substrate and fully growth bacteria population, the fresh influent may be flushed outlet when it is not completely digested. The feeding mode in this digester design could be continuous or semi continuous. For domestic applications the feeding mode is usually semi continuous while in industrial applications the feeding mode is more towards continuous. The family of fixed dome digester and floating drum digesters, commonly disseminated in DC are based on this design configuration.

Leach bed digesters

These digesters operate on the leach bed anaerobic digestion principle, whereby the feedstock loaded in the digester as a bed of solid is hydrolyzed by soaking it with water. The rapid decay of the feedstock forms volatile fatty acids (VFA) which are extracted into the water phase in the form of a liquor called leachate. The leachate is often recirculated or pumped into another tank where methanogenesis takes place to produce biogas. These digesters could be single-staged or multiple-staged and the feeding mode could be batch or continuous and are operated at high solid content up to 60%TS, thus this design operate on DAD principle[47,48]. Some of advantages of this digester design include: no refine shredding of waste, no mixing, it can be operated at ambient conditions and can be operated in both mesophilic and thermophilic conditions. Originally designed to be a batch dual-stage process, the leach bed process has been modified to a batch single stage design and has been successfully applied in the biogasification of a variety of waste[49–51]. However, there is little or no development of this digester design for small scale applications in DC.

Microorganism growth strategy

Digester may also be categorized based on the growth strategy of the microorganisms, namely: suspended growth and fixed-film growth strategies.

Suspended growth strategy

In this growth strategy the microorganisms are embedded within the feedstock with no special accommodation for their growth. It is the simplest growth strategy. The microorganisms are flushed out of the digester if the feedstock is discharged from the digester. The population of the microorganism is variable and time is required for it to grow and reach the optimum. Most digesters, especially those common in DC operate on this growth strategy.

Fixed-film growth strategy

In this growth strategy, the microorganisms grow on specialized structures called biofilms[52]. The feedstock flows through the biofilms and are digested by the microorganisms. The advantage of the biofilm is, it maintain the microorganism population at an optimum, thus no time is required for the growth of the microorganism to reach optimum. Because of the optimum microorganism

population, the biogas production rate of these type of digesters is usually high. These configuration is common amongst digester used in the wastewater treatment industry, e.g. Upflow Sludge Anaerobic Digester (USAB).

Benefits and Applications of Biogas Technology

Benefits

Biogas technology have several environmental, economic and social benefits both at the level of the individual household, the community, national and global levels [5,53–57]. The environmental benefits included: reduction of Greenhouse gas emissions, elimination of odors, produces sanitized and nutrient-rich fertilizers and reduction of deforestation. The economic benefits include: improvement of household income through improved agricultural production and generation of CDM revenue. Within the context of DC, the social benefits could be more attributed to the households where there is high consumption of solid biomass in a traditional way leading to high indoor air pollution affecting mostly women and children. The social benefits of the technology therefore, include: improvement of health through the use of cleaner fuel for cooking and pathogen reduction in both human and animal waste, improvement of educational opportunities for the children.

Applications

The uses of biogas are wide and varied, for example, in industrial scale application for the production of Combine Heat and Power (CHP), injection into the Natural gas grid and as fuel in the transport sector[34,46]. In the context of DC, especially rural areas, biogas has been used to meet the following energy needs; low and medium grade heat, electricity and shaft power. The energy services met through the use of biogas include cooking, lighting, warm water and heating of households and the digestate is used as fertilizers[58–60].

2.2.2. Biogas Technology in DC

This sub section presents the review of the state-of-art of the dissemination of small scale or domestic size digesters in DC. The objective was to identify issues related to the deployment of the technology in DC, especially rural areas of SSA. The review is presented under the following topics: geographical distribution of small scale digesters in DC, the common design typology and the field performance of the technology in terms of functional state and specific technical parameters.

Geographical distribution and typology of designs of small scale digesters in DC Over 44 million small scale biogas digester have been disseminated in the DC mainly in China and India. Only 38.434 (about 1% of the global distribution of small scale digesters in DC) digesters have been disseminated in Africa. Table 7 shows the geographical distribution of small digesters in DC.

Several reasons have been advanced for the very low adoption of small scale biogas technology in Africa, especially SSA. These reasons included: variations in the digester design, insufficient feedstock, absence of well researched and standardized designs suitable for socio-economic and cultural context, lack of local technical know-how, cost of installation, and poor performance[61–63].

Table 7: Geographical distribution of small scale digesters in DC

Source:[5,32,64]

Country	Number of Digester	Population	Per capita adoption [unit/person] x e-03	No. Households [million]	Digester per Household [thousand]
China	38.500.000	1.393.783.836	27,62	232	165,74
India	5.000.000	1.267.401.849	3,95	211	23,67
Nepal	268.464	28.120.740	9,55	5	57,28
Vietnam	52.349	92.547.959	1,65	15	9,88
Bangladesh	26.311	158.512.570	0,17	26	1,00
Cambodia	19.173	15.408.270	1,24	3	7,47
Laos PDR	2.888	6.894.098	0,42	1	2,51
Pakistan	2.324	185.132.926	0,01	31	0,08
Indonesia	7.825	252.812.245	0,03	42	0,19
Bhutan	265	765.552	0,35	0	2,08
Rwanda	2619	12.100.049	0,22	2	1,30
Burkina Faso	4014	17.419.615	0,23	3	1,38
Ethiopia	8.161	96.506.031	0,08	16	0,51
Kenya	11.579	45.545.980	0,25	8	1,53
Senegal	334	14.548.171	0,02	2	0,14
Uganda	5.166	38.844.624	0,13	6	0,80
Tanzania	8.799	50.757.459	0,17	8	1,04
Cameroon	159	22.818.632	0,01	4	0,04
S. Africa	3.236	53.139.528	0,06	9	0,37
Total	44.023.666	3.753.060.134	11,73	626	70,38

The main types of digesters disseminated include; Chinese fixed dome, Nepali GGC2047 fixed dome, Vietnamese fixed dome (KT2), Indian fixed dome (Deenbandhu), Floating drum, the plastic (tubular) digester and Reinforces Fibre Prefabricated digesters. All of these digesters operate on the WAD principle. The plastic (tubular) digester is a plug flow digester while the others are complete mix digesters. They were all designed to operate within the mesophilic range and are fed on a semi continuously basis. These designs are shown in Figure 10



Figure 10: Digester designs disseminated in DC

Performance of small scale digesters in DC

The various designs of digesters common in DC have different performances. The performances were often evaluated in terms of functional state or technical performance in terms of biogas production, production rate and productivity.

Functional state

The functional state of digester simply refers to whether it is in use and producing biogas. It neither measures the efficiency of the biochemical process in the digester to convert biomass into products nor does it measure the quantity of biogas produced. On the average 50% of the over 44 million digesters disseminated in DC were reported in good functional state. Amongst the reasons advanced for the failure of the digester included: poor design, construction, lack of feed stock and labor to carry out the operational activities, as well as inadequate mixing of the digester content[38,65]. Lack of suitable logistics for market penetration and high investment capital required to build the digester could be added to the reasons that slow down the adoption of biogas technology in rural areas of SSA.

Technical performance

As already mentioned in section 2.2.1, based on the operating parameters of digester volume, feedstock, organic loading rate, temperature and retention time, the technical performance of a digester may be evaluated in terms of biogas production,

production rate, productivity, biodegradability in terms of total solid, volatile solid, biological oxygen demand or chemical oxygen demands and pathogen reduction. Systematic evaluation of the performance of these designs have been carried out in different regions as follows: Nepali GGC2047 in Nepal; the Chinese fixed dome and reinforce fiber prefabricate digester in China; the Indian Janata, Deendbandhu and Floating drum in India; the tubular plastic digester in the Andes –Peru. The technical performances of these designs is summarized in Table 8.

	Digester Designs							
Parameter	Chinese fixed dome	Nepali GGC2047	Vietnamese	Indian Deenbandhu	Floating Drum	Plastic	Prefabricate [composite]	Ref.
Biogas production [m3/day]	NA	2,12	2,8 - 3,7	1,1-1,23	2,79	0,17 - 1,76	1,96-2,24	
Production rate [m3/m3 digester]	0,12	0,212	0,35 - 0,52	0,23 - 0,4	0,279	0,03 – 0,5	0,28-0,32	[(()]
Productivity [m3/kgVS per day]	NA	2,9	NA	NA	0,18	0,03 - 0,36	NA	[66] [41] [67]
BOD [%reduction]	NA	NA	99, 36 - 99,65	NA	NA	51,05 – 97,01	99,41 – 99,73	[68]
COD [% reduction]	NA	98,6	99,10 - 99,71	NA	NA	92,02 – 99,50	99,10 – 99,65	
Pathogen (Coliform) [%reduction]	NA	NA	99,71 99,94	NA	NA	84,38 – 99,83	99,24 – 99,94	

 Table 8: Technical performance of digesters disseminated in DC

From the above analysis, different digester designs perform differently in different environment, operating conditions and different feedstock. There was no report of the systematic evaluation of the technical performance of the digesters within the context of SSA.

Conclusions

Small scale biogas technology produces a very versatile clean fuel that can be locally harnessed to improve options for clean cooking in rural areas of SSA. A variety of digester designs have been disseminated in DC. The adoption of the technology in SSA was still very low relative to other developing regions. The various designs disseminated in SSA were developed for specific socio-economic and cultural context different from those of SSA. Furthermore, there has been no systematic field evaluation of the technical performance of the designs commonly disseminated in SSA. Absence of well researched and standardized design appropriate for the socio-economic and cultural context of SSA was amongst the reasons advanced for the low adoption in SSA. Therefore the choice of design for mass dissemination in the context of SSA requires a careful choice. The selection of an appropriate digester design appropriate digester design from amongst the several designs commonly disseminated in DC, for the rural context of SSA is required. Furthermore, the optimization of the performance of the design within the desired context constitute and integral part of the development of the technology for deployment in DC to improve access to modern energy services.

The thesis seek to select and apply a decision support tool for the selection of an appropriate digester design for the context of SSA. Furthermore the thesis seek to develop a procedure for the optimization of the technology within the given context. The selection of an appropriate technology and its optimization within the context constitute the second and third stages in the development of a comprehensive energy access strategy in DC.

Chapter 3: Improved Rural Energy Planning, a Proposal

The first results of the research findings are presented in this chapter, namely: an improved rural energy planning procedure and its application in a rural context in DC. This chapter is divided into two main sections. The first section presents modifications that led to the extension and updating of the Nissing et al planning procedure into an improved rural energy planning procedure. The results of application of the improved procedure are presented in the second section.

3.1. An Improved Rural Energy Planning Procedure

From the review of literature, it was observed that the Nissing et al [29] six-steps rural energy planning procedure did not take into account the existing energy balance situation of the target rural community. Furthermore, the procedure did not consider energy drivers in the setting up of the ESSN and its application remained theoretical. In order to address these gaps, the six-step procedure was updated by further extending it to include an assessment of the existing energy balance situation of the target rural community and the integration of energy drivers in the ESSN. The modifications in the Nissing et al procedure resulted in a seven-step rural energy planning procedure which was named "Improved Rural Energy Planning Procedure (IREPP)". Figure 11 shows a flow chart of the IREPP. Furthermore, the validity and relevance of the IREPP was practically demonstrated through a case study in a rural area in Cameroon. The strength of the IREPP procedure is that it takes into account the energy balance in the existing rural energy system. The assessment of the existing energy balance situation of the target rural community allows for the creation of a systematic database and quantification of energy consumption to levels which permit a more realistic modelling of the energy system, thereby filling the gaps observed in existing studies which analyze rural energy systems with the aim of modelling. Also, focus on identification and integration of energy drivers at the stage of setting up of an ESSN model allowed for flexibility and a more cost-effective way to identify appropriate end-use devices to meet the energy services demanded. Thus, resolving the observed issue of "technology stacking"⁴ especially at the level of households. Furthermore, the practical application of the IREPP in a rural area in Cameroon demonstrated its validity and relevance in improving energy access in rural areas of DC. The IREPP constitute the first phase in the development of a "comprehensive energy access strategy"

⁴⁴ A phenomenon where several energy end-used devices are used to provide the same energy service.



Figure 11: The proposed IREPP and ESSN

3.2. Application of the Improved Rural Energy Planning Procedure

The general methodology adopted for the application of the IREPP; specific methods and tools used at each step of the procedure; the obtained results and conclusions are presented in this section. The general methodology, specific methods and tools are discussed in section 3.2.1; the results are discussed in section 3.2.2 and the conclusions are presented in section 3.2.3.

3.2.1 Methodology

The generally approach adopted for the practical demonstration of the validity and relevance of the IREPP procedure was a field case study of a rural area in Cameroon., Various methods and tools were used at each step of the procedure to gathered and analyzed the necessary data. These methods and tools are herein discussed. It is worth mentioning here that in the application of the IREPP, focus was on the first six steps of the procedure. These steps are the essentials in the planning procedure. Step seven is mostly on monitoring and control of the established ESSN. This step could not be applied to the established ESSN since the physical realization of the results were not carried out.

Study location

Cameroon Protestant College Bali was the case study area. It is located in the rural area of North West of Cameroon. It was made up of the following services and facilities: public administration, education, healthcare, craftsmanship, dormitories and households, a church. The population of this area was composed of 1187 inhabitants divided into 1008 students and 179 staff and their families. The spatial distribution of these services and facilities are shown in Photo 1. There is no universal definition for what is considered a "rural area", however, the characteristic features of a rural area include: isolation, low population density, low economic activities, insufficient infrastructure and lack of statistical data[69]. The spatial distribution of the services and facilities and population size and density of this community were typical of rural areas of DC, thus the study area was considered a *micro village*.



Photo 1: Case study area

Methods and Tools

Various methods and tools were used at each step of the procedure as deemed appropriate. In this paragraph the methods and tools used at each of the steps are discussed.

Step 1: Integration of Goals of SE into the decision making process

In order to integrate the concept of SE in the planning process, focused group discussions were conducted with key stakeholders, mainly the administrative authorities of the study area. The goal of the focused group discussions was to capture the development aspirations of the people and to link it to the delivery of an enhanced quantity, quality and variety of accessible and affordable energy carriers, in order to sustainably energize the socio-economic development of the area.

Step 2: Assessment of the existing energy balance situation of the target area

The goal of this step was to fill in the gaps observed in previous REP procedures, i.e. to consider the sustainability of the energy system; collect systematic energy-related data sets required for a more realistic modelling of the energy system and to quantify energy consumption to levels required for modelling.

In order to assess the existing energy balance situation of the study area, the local energy system was codified into a *reference energy system* through which the energy accounting activities were implemented. The approach used by Johnson et al [14] was adopted for the codification, wherein accounting for energy supply and consumption in a rural African village was analyzed by identifying the main energy drivers, the sources and energy end-uses. The adopted reference energy system is shown in Figure 12. Participants' observations were conducted in order to identify the main energy drivers. Survey questionnaires were administered through a face-to-face interview with the households and keys persons in order to realize the energy end-uses and devices census.



Figure 12: *Adopted Reference Energy System* Source: Adapted from [14].

According to Johnson et al, the energy drivers in a rural African village may include *domestic, public services, transport and artisan.* For the study area two main drivers could be identified: *public and domestic.* The public driver included the school,

dormitories, administrative buildings, church and library. The domestic driver was constituted by the households of the staff. Because of the geographical limitations of the study area, the Transport energy driver was considered negligible, therefore was not included in the analysis. Although some artisan activities, like baking of bread and petty trading, were practiced in the study area, their energy consumption were embedded in those of either the public or domestic driver. So in the accounting process the artisan driver was not analyzed. For each of the drivers, the energy needs and end-uses were identified as well as the corresponding conversion technologies to provide the energy services. Direct measurements were carried to determine the primary energy supply (PES) and the final energy consumed (FC) in each of the identified energy drivers. Adopting an initial energy accounting of the existing situation allows for a reasonable estimate of appliance penetration (energy consumption) as a starting point of the energy system design process; avoidance of overestimation of energy consumption and acquiring of hard data, e.g. load curves, for the energy system modelling.

The specific methods and tools used to determine the PES and FC for each of the drivers are discussed in the following paragraph.

Domestic Driver

The household energy consumption was assessed through a questionnaire administered in the form of a face-to-face interview. The respondents were mostly the head of the household since they were mainly responsible for the household expenses. The data collected via the questionnaire included: household socio-economic situation, primary energy supply and consumptions, household appliances and operation-time window. The electrical energy supplied and used was determined using the results of the devices census. For each device, the sum of the monthly consumption was calculated by the product of the rated power of the device (kW) and its operation-time window (h). The efficiencies of the device were not considered, hence the electrical energy consumption was considered equal to the supply. This approach was similar to that used by the IEA.

For other energy sources the PES were calculated using Equation 6

$$PES = m_{fuel}.EHV$$

Equation 6

Where PES is the primary energy supply, m_{fuel} is the mass of the fuel and EHV is the net calorific value of the fuels.

The properties of LPG used to determine its PES were: an EHV of 46.15MJ/kg and the efficiency of the LPG stove was assumed to be 63%. For kerosene, the LHV of 43.92MJ/kg and density of 802.6kg/m³ and the efficient of the stoves was assumed as 51%[70].

For the case of fuel wood, quantities consumed were determined in terms of kilograms (kg) supplied. Calculations were simplified by using an equivalent lower heating value (LHV) to convert the quantity supplied in kg to MJ. The LHV adopted was that of Eucalyptus Grandis (Rose Gum, Grand Eucalyptus) because it was the most used type of firewood in the study area. The energy properties of this wood that were assumed included: a moisture content of 40% and LHV of 18.43MJ/kg. These values were used to determine the net calorific value, EHV, using *Equation* 7.

$$EHV = LHV(1 - MCwet) - (MCwet. \Delta h_{H20})$$
 Equation 7

Where MCwet is the moisture content of the wood on wet basis, Δh_{H2O} the enthalpy of water.

In order to determine the FC, the efficiencies of the conversion technologies were required. Two technologies were predominantly used for burning of wood to meet thermal energy needs, namely: three stone fire and the sawdust pot. The efficiency of the three stone fire was assumed to be 15% for environment temperature condition of about $30^{\circ}C[71]$. The efficiency of sawdust pot was estimated experimentally using the Water Boiling Test (WBT) protocol. For the domestic driver, thermal energy needs were further differentiated into low grade thermal energy needs (less than $100^{\circ}C$) and medium grade thermal energy needs ($100 - 350^{\circ}C$). The final energy consumption to meet the low grade thermal energy needs (mainly for hot water needs at $60^{\circ}C$) was determined using *Equation 8*.

$$FC_{LGH} = m_{H20}c_{H20} \left(T_{ref} - T_{amb} \right)$$
 Equation 8

Where FC_{LGH} is the final energy consumed to meet low grade thermal energy needs, m_{H20} and C_{H20} are the mass of water boiled and specific heat capacity of water respectively, $T_{ref} = 60$, T_{amb} is the ambient temperature.

The corresponding PES for low grade thermal energy needs was determined using *Equation 9*.

$$PES_{LGH} = \frac{FC_{LGH}}{\eta_{3sf}} \qquad Equation 9$$

Where PES_{LGH} is the PES for low grade thermal energy needs and η_{3sf} is the thermal efficiency of the three stone fire.

The PES to meet the medium grade thermal energy needs was determined using Equation 10.

$$PES_{MGH} = PES_{wood} - PES_{LGH}$$
 Equation 10

Public Driver

The main energy needs in this driver included: electricity (mainly in ac form) and thermal energy needs (both low and medium grade heat). The methods and tools used to account for the PES and FC are discussed in the following paragraph.

The thermal energy needs of the public driver were located mainly in the school kitchen and the bakery. Observations and interviews were conducted with key persons in the kitchen and bakery to understand the activities and their weekly pattern. Once the pattern was established, after a one week observation, direct measurement of the daily use of firewood was carried out. The mass of the wood, already cut into logs, were determined using an industrial scale recalibrated for the purpose and grouped into hips of 400kg and 150kg for use in the kitchen and the bakery respectively, (Photo 2). At the end of each day, the unused quantities were measured and the used quantities were determined. This was done for a period of one week and a daily average was obtained. Equation 1 was then used to determine the PES. In other to determine the FC, the efficiency of the conversion technologies was required. The conversion technologies used were the oven and the wood stove. The methods used to determine their efficiencies are described in the following paragraphs.



Photo 2: Direct measurement of Firewood supply in the public driver.

In order to determine the efficiency of the oven used for baking, reference was made to the Energy Efficiency Index (EEI) for baking processes as defined by *Equation* 11[72]

$$EEI = \frac{energy \, used \, by \, the \, production}{energy \, consumped \, by \, the \, oven} \qquad Equation \, 11$$

The product of the baking process was bread. The energy used by the product is the enthalpy change of dough from the initial temperature to the final temperature plus the energy due to the moisture loss of the bread during baking. The specific energy demand for bread baking is 3.7MJ/ kg of dough [72]. About 37% of this is used to heat the dough and moisture loss. The daily quantity of bread baked was measured for a period of one week and the average obtained. This value together with the specific energy demand for bread baking were used to compute the FC for the baking of bread.

In order to estimate the efficiency of the stoves used in the kitchen, a reduced WBT was conducted. This test is a standard test to estimate the laboratory efficiency of an improved cook stove. It is implemented in three major phases, namely: cold, hot and simmering phases (Figure 13). The second and the third phases were not implemented for two reasons (i) it was not possible to disrupt the activities of the kitchen whose main purpose was to prepare food for the students; (ii) the pots used for cooking were very large and fixed to the wall of the stove so it was impossible to remove them during the WBT procedure. Thus, only the cold phase of the WBT was implemented.



Figure 13: Phases of the WBT

For electrical energy supply, a first estimate was done through a device census in the dormitories, classroom, laboratories, offices and the church. The procedure used to estimate PES and FC in the domestic driver was applied. Since the study area was connected to the local grid, the amount of energy taken from the grid was recorded by a central meter. In order to obtain the real load curve for the study area, data was gathered through daily observations of the central meter. A smart phone was used to take snapshots of the daily reading of the meter every 10seconds for a period of 5days (Photo 3). This procedure was repeated for two separate months (September and October 2015) in order to appreciate variations in power load and energy consumption when the study area was in full activity. Excel spreadsheet was then

used to generated the load curve. The load curve is a very essential data input for modelling in the design stage of the energy system.



Photo 3: Use of smartphone to determine load profile

Based on the results of the energy accounting process, Sankey diagrams were used to visualize energy flows in the reference energy system.

Step 3: Identification and prioritization of the energy services demanded within the Energy Drivers

The objective of this step was to identify and prioritize energy needs according to the energy drivers. The energy drivers were identified through participant observations and their corresponding energy needs were identified. Focused group discussions were used to prioritize these needs. Focusing on the energy needs rather than energy services, allowed for flexibility in the selection of end-user devices to meet the need in the most cost-effective way. And thus eliminated the issue of technology stacking observed in previous energy planning procedures.

Step 4: Local Energy Resource Assessment: Focus on RES

This step consisted of an assessment of the local energy resources of the target area. Within the framework of SE, renewable energy resources were the main focus of the local energy resource assessment. Biomass (agricultural residue, animal and human waste), hydropower, solar and wind resources were assessed using appropriate tools and techniques. The specific methods and tools are discussed herein below.

Biomass

Solid biomass i.e. forest resources were not assessed since it involved sophisticated approaches which could not be realized within the time constraints of the study. Biomass which could be converted into biogas was thus the focus when the local potential of biomass was assessed. Three biogas digesters had been installed in the study area. At the time of the studies, only one was operational. It consisted of two 20m³ digesters connected in series to give a total capacity of 40m³. The hourly and daily production was measured for a total of 43 days, using an industrial gas flow meter of type ECOMETROS R.E.M.I, Italy. The average biogas production was determined and used in subsequent steps of the planning procedure. The biogas potential feedstock which were considered included: corn, human and animal waste. The quantity of residues from corn production and manure from animals were assessed through the questionnaire administered at the level of the domestic driver. For human faeces and urine, the potential was assessed using the population of the area and the average daily per capita production of faeces and urine of 140g/day and 1500g/day respectively[73]. The biogas potential yield per ton of corn, animal manure and human faeces and urine (Table 9), the estimated monthly quantities produced together with the average LHV of biogas of 29.3MJ/m³ were used to estimate the biogas potential by applying *Equation 12*.

PES = mYh

Equation 12

Where *m* is the monthly quantities produced in tons, *Y* is the biogas yield of the feedstock and *h* is the lower heating value of biogas.

Feedstock	Nm ³ biogas /t DM
pigs	649
goats	120
cows	281
fowls	359
Human Faeces	450
Human Urine	340
Corn	530

Table 9: Biogas potential yield from local feedstockSource: [74,75]

Hydropower

The existence of a local river presented the opportunity for micro hydropower application. The hydropower potential was assessed by application of *Equation 13*.
$P = g\rho HQ$

Equation 13

Where g is the acceleration due to gravity, ρ is the density of water, H is the height difference between the point of capture of the river and the power house, Q is the flow rate of the river.

The parameters measured in order to estimate the hydropower potential were the Head (H) and the flow rate of the river (Q). The methods to determine these parameters are discussed herein below.

Flow rate (Q)

Several methods exists for the measurement of the flow rate of a river, these include: electromagnetic current meter, floating object, weir method and bucket method[76]. The method adopted was the floating object test method (Photo 4). By this method the flow rate was estimated by application of *Equation 14*

Q = cAv

Equation 14

Where c is a correction factor that converts the measured mean surface velocity into the effective mean velocity, A is the average cross sectional area of the stream and v is the measured mean surface velocity.

In order to measure the cross sectional area, A, of the river, a straight length of the river was selected. The average depth of the river was determined by taking the average of three measurements taken at equal intervals along the width of the river. This average depth of the river was multiplied with the width of the river to obtain the cross-sectional area, A. The mean surface velocity was estimated by measuring the time it took a floating plastic ball, partially submerged to traverse a 10m distance on the surface of the river. Ten measurements were made and the average of each of the obtained surface velocities was determined. The floating object test was conducted twice in October and November 2014. Assuming that the river was shallow and riverbed not flat, a correction factor of 0.45 was used [76] and together with the measured values of A and v, Equation 9 was then applied to have a first estimate of the flow rate (Q). For a more accurate estimation of the hydropower potential, it was necessary to have the annual flow regime of the river. Simple linear regression technique was used to obtain the annual flow regime of the river. The 2012 data for the nearby river Mewou were used as reference with the following assumptions made:

- The results of the floating object test represent the mean flow rates for the months of October and November.
- The catchment of river Mewou was sufficiently closed to the site and so have the same climatic conditions.

• The two river catchments are hydrogeologically similar.

Considering that a minimum flow rate has to be available in the river for ecological reasons, a compensation flow rate of 50% of the minimum flow rate of the river was defined[77].



Photo 4: *River Flow rate estimation. River depth measurements (Left) 10m length for velocity measurement Head (h) estimation*

A first sketch of the layout of the hydropower scheme was done using Google maps (Photo 5). The head (H) which is the height drop between the intake of the river (river catchment) and the power house (hydro turbine) was then determined. Several methods could be used to estimate the head[76], however, the altimeter method was deemed an appropriate method considering the long distance between the proposed intake and the powerhouse. The values obtained by use of the altimeter were checked with values obtained using Google Maps and very little discrepancy were observed. The penstock length and the electricity transportation line were also estimated using Google Maps.



Photo 5: Layout of the proposed hydropower scheme

Wind

Wind was one of the local renewable energy resource of interest. Making use of this resource entailed knowing the wind characteristics of the location. Estimates of the power potential of this resources was obtained by applying *Equation 15*. From this equation the parameter which required measurement was the average wind speed (v) usually over a period of at least one year.

$$p = 0.5\rho v^3$$
 Equation 15

Where ρ *is the density of air and v is the average wind speed.*

Amongst the several models used to study wind data[78], the Weibull model was considered adequate for this studies. This model characterizes wind speed of a location in terms of a probability density function given by *Equation 16*

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v-\mu}{c}\right)^{k-1} exp\left[-\left(\frac{v-\mu}{c}\right)^k\right]$$
 Equation 16

Where v is the wind speed, k is a shape parameter, μ is the location parameter and c is the scale parameter.

For this study, a simplified approach where the location parameter was assumed to be zero was adopted. Thus the Weibull model could then be characterized by only two parameters, i.e. the shape and scale parameters. These parameters were described in terms of the average wind speeds and its standard deviation .Two methods could be used to determine these parameters: the analytic and the empirical methods[78]. The empirical method was selected for this study wherein the shape and scale factor were determined using *Equation 17 and 18* respectively

$$k = \left(\frac{\sigma}{v_{mean}}\right)^{-1.086}$$
Equation 17
$$c = v_{mean} \left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}}$$
Equation 18

Where v_{mean} and σ are the average wind speed and standard deviation respectively, k is the shape factor, c is the scale factor.

In order to obtain the average wind speed and standard deviation, measurement of the local wind speed were recorded from May 2014 to January 2015, using a cup anemometer installed onsite at a height of 10m, (Photo 6). The period of data collection did not cover a full year for which characterization of wind regime was required. Simple linear regression technique was used to scale this data to cover a period of one year. The reference data was taken from the NASA databased for the city of Bamenda, which was located at about 15km for the study site. The captured data was analyzed using Excel Spreadsheet to obtain the average wind speed and the standard deviation. These values were then used to calculate the shape and scale parameters for the Weibull probability density function.



(Left) Data logger (Right) anemometer on Mast

Photo 6: Wind data collection.

Solar

The data used for the estimation of the solar resource of the study site were taken from the NASA database. The data for the city of Bamenda were assumed relevant for the study site. In the calculations, only monthly average values were considered. Solar maps were also used to compare the NASA data since the later was based on solar radiation.

Step 5: Design of an Integrated Renewable Energy System

In the design of the energy system, the approach based on matching the energy needs within each energy driver with the appropriate available RES was adopted. The energy needs demanded in both drivers were electrical and thermal. Two different approaches were adopted to match the electrical and thermal energy needs to the local RES, namely simulation of different technology combination scenarios and adhoc strategies respectively. Each of these approaches is describe in greater details in the next paragraphs.

Matching electrical needs with local RES

To match the electrical energy needs with the local RES, simulation of different technology combination scenarios were carried out. The objective function of the simulation was minimization of the Net Present Cost of system based on the Life cycle of the technology, given the constraints of availability of resources and meeting the load demand. The units cost of energy in each scenarios was also calculated. Two options were considered, namely:

- *Off-grid option*: wherein the electrical energy needs of study area were completely met by use of only indigenous local energy sources.
- *Grid –RES Hybrid option*: wherein part of the electrical energy needs were supplied from the grid which was already present.

In each of the scenarios, the HOMER software tool was used to analyze the different scenarios. The software, executed the analysis at three levels: simulation, optimization and sensitivity analysis.

The simulation phase involved specific technological configurations. The two configurations considered were the Off-grid configuration and the Grid-RES Hybrid. The inputs to the simulation phase included:

Load demand curve: this was provided by the load curve obtained in Step
 2 of the proposed procedure, described above. However, the measured
 load curves were further processed to cover a period of one year. The

average load input was 143kWh per day (lower than demand measured for the month of September and lower than the 152kWh measured in the month of October) with a peak power of 25kW which was slightly higher than field measured value of 16kW for the month of October. The simulated load was adjusted to annual load, the reason for the observe differences with measured values.

- (ii) Technology options, investment cost and O&M cost: focus was on the use of the local RES assessed in Step 4 of the procedure, i.e. hydropower, wind, solar and biogas and balance of the system unit (inverter and batteries).
 - a. *Hydropower:* the input for this technology included the turbine type and designed flow rate. The cross-flow turbine was selected for it simple design, good efficiency at a wide range of flow rates and the fact that it could be produced locally. The size considered ranged from 4,4kW to 37,8kW, with the electro-mechanical efficiency fixed at 75% and the penstock length of 1km with pipe head losses of 40%. The residual flow rate was set at 54l/s which was 50% of the minimum flow rate of the river obtained during field measurements described in Step 4 above. The local cost of the turbine was used ; O& M costs were assumed with references from the IRENA report [79].
 - b. Solar PV panels: maximum size to meet the entire demand at peak load was considered from possible standardized sizes of 3, 6,9,12,15,16,17 and 18kW. The cost of the PV was set through a compromise between local prices and the LAZARD report [80]. The scaling factor accounting for power losses due to different reasons (derating factor) was assumed as 90% with reference from a similar case study in neighboring Nigeria [81]. Additional conditions selected from options proposed by the databased of the software were: ground reflectance of 20%, slope installation of 5,8degrees, efficiency at standard condition of 17% and power temperature coefficient of 0.5% and nominal operating cell temperature of 47°C.
 - *c. Wind turbine:* the SEI-BNY1.5 of nominal power 1.5kW, height 36m option was selected from the database of the software and the size was determined to meet the entire load.
 - d. Diesel Generator: this was considered in order to exploit the biogas resource potential. The generator was considered to operate on a dual-fuel (diesel biogas) mode. The biogas resource results from Step 4 (described above) served as input. The investment cost of the generator was set to null since the generator was already onsite.

However, the cost to modify the generator to function in dual fuel mode was estimated from local experience, while O&M cost were obtained from records kept by the local operator of the generator. Characteristics of the generator were obtained from operation manual of the generator.

- *e. Converter:* two options were consider: 5kW, 24V and 10kW, 48V both with a lifetime of 15years were selected for the database of the software to match the maximum power flow between AC and DC from the PV panels, wind turbine and/or batteries to meet instantaneous load demand.
- *f. Battery:* the 6FM200D of capacity 12V200Ah battery type was selected from the database of the software and the cost was estimated with references from similar installation in neighboring Nigeria [81].

The optimization phase aimed at finding the optimal technological configuration in the Off-grid and Grid-RES option, at least Net Present Life Cycle Cost. The constraints were the available resource, already determined in step 4 and the load demand, also already determined in Step 2.

Finally, sensitivity analysis to verify the robustness of the optimal solution according to some input variable were investigated. Four sensitivity analysis were executed.

- (i) Changes in investment cost of Hydropower: The installation cost of micro hydropower plant could vary very much depending on the layout of the scheme and geographical location. In this study, the layout was consider an important variable given that the penstock and the electricity transportation line lengths could be greatly reduced and hence a reduction in their cost. Therefore, a cost reduction of 25%, 50% and 70% were investigated at a constant O&M cost.
- (ii) Investment cost of PV panels and Wind turbine: Considering the rapid fall in the market prices of these technologies it was interesting to check the investment cost at which these technologies could become competitive with the hydropower technology. Up to a 90% cost reduction was investigated.
- (iii) Price of Diesel: The World market prices of crude oil had witnessed fluctuations in the past decades. These fluctuations were also reflected in the local prices of petroleum based products. In the past decade, local diesel prices in Cameroon witnessed about a 20% increase. With recent drop of oil prices in the world market, a local drop in the price of diesel could be anticipated. Thus a sensitivity analysis of 20% increase and reduction in the local prices was investigated with the installed hydropower capacity remained unchanged. As a variable factor in the

O&M of the generator and considering fluctuations in local prices, a 20% cost increase and decrease were investigated.

(iv) Cost of power purchase from the grid: From the field survey, it was observed that the unit cost of grid electricity in the study area has been on the increase. Therefore, for the analysis of the effects of grid energy cost, price increase of 5%, 10% and 20% were investigated.

Thermal Energy Needs

In matching the thermal energy needs with the local RES, ad-hoc solution-focused approach was adopted for each thermal need. The approach consisted of first identifying the thermal energy needs of each energy driver and then investigating ad-hoc solutions to satisfy each need. This approach was adopted to take advantage of the data collected from the field. Both the public and domestic driver had specific thermal needs. These needs were:

- Public driver: medium grade heat for cooking and baking; low grade heat for warm water.
- Domestic driver: medium grade heat for cooking; low grade heat for water warm.

The solution strategies were designed to meet the thermal needs currently unmet or partially met.

 Medium grade thermal FC for domestic and public cooking as well as public baking were considered fully satisfied hence the needs were equal to the final consumption, since no shortage were observed during the field observations. However, energy losses were huge due to poor efficiencies of the conversion technologies in use; cooking conditions were also very poor. The ad-hoc solutions were aimed at energy efficiency and improvement of the local cooking environment without a change in the quantity of FC. The required PES was then estimated based on the efficiencies of the selected conversion technologies.

For both domestic and public cooking, improved cook stoves of higher efficiencies were proposed to substitute the current use of the three stone fire and locally made improved stove respectively, (Photo 7). In particular, the Envirofit G3300 model with a thermal efficiency of 30%⁵ was selected to substitute the three stone fire in the domestic driver and, the ASTRA model improved wood stove with a thermal efficiency of 40% [82] was selected to replace the locally made improved stove in the public driver.

⁵ <u>http://www.envirofit.org/products/?sub=cookstoves</u>, downloaded December 2014



Photo 7: The improved cook stove used in the public driver

For public baking, the substitution of the wood-oven, (Photo 8), with an electricity oven was investigated, since electricity could be produced locally from RES. The advantage of the electric oven over the wood oven was the guarantee of a better local environmental conditions for the workers. The electric oven selected for analysis was the E32D5 model manufactured by Moffat[83]. The choice was motivated by its suited dimensions and power rating and the fact that the specifics of the convection oven, such as energy input rate, preheating time, heavy-load cooking efficiency and production capacity had been tested with the ASTM Standard Test Method F1496-13 [83]. The flexibility with which the oven could be used presented an added advantage, since a known quantity of bread was produced 6 days per week to be supplied the day after. This allowed for a variable operation-time window for the electric oven. The HOMER software was used again to simulate the electrical energy solution with the an increase in the load equal to the power of the oven with the operation time of the oven fixed within the daytime period to lie between the morning and even peak loads. The simulations were done for both the off-grid and the grid-RES hybrid options.



Photo 8: The Locally made wood-power oven in operation

• Low grade heat required for water heating were consider partially unmet in the domestic driver and completely unmet in the public driver. The ad-hoc solutions adopted to meet these needs aimed at providing minimum standards for per capita warm water [84]. The solution approach consisted of first determining the quantity of energy needed and then determining the characteristics of the specific technological solution.

For the domestic driver, the quantity of low grade heat needed was determined using *Equation 19*.

$$FE_{DHW} = c_p \rho_{water} V_{water} (T_{hot} - T_{cold})$$
 Equation 19

Where c_p is the specific heat capacity of water, ρ_{water} is the density of water, V_{water} is the volume of water required, T_{hot} is the desired temperature of the warm water, and T_{cold} initial temperature of the water. T_{cold} and T_{hot} were set at 20°C and 45°C respectively [85].

In order to exploit the local solar energy potential, the technological solution investigated was the Solar Water Heating System (SWHS). SWHS consisted of a solar collected, a storage tank, water convey pipeline [86]. Based on the needs determined using *Equation 19*, the dimensions of the SWHS was calculated using *Equation 20*, adapted from [87].

$$SWHS_{capacity} = \frac{f_s}{\eta_c \eta_{syst}} \frac{FE_{DHW}}{G}$$
 Equation 20

Where $SWHS_{capacity}$ = capacity of the solar collector (Flat plate collector was considered), f_s =solar fraction (the hot water demand met by solar

irradiation), $\eta_c = efficiency$ if the collector, $\eta_{syst} = the$ system efficiency, $FE_{DHW} = the$ thermal energy need as determine in Equation 19, G = solar irradiation.

The following values were used: fs assumed to be 1, $\eta_c = 60\%$; $\eta_{syst} = 85\%$; G= 573MJ/m³ per month. The values of the collector efficiency and system efficiency were assumed from [87].

For the public driver, low grade thermal energy was needed to provide warm water to the 1008 students of the school. This need was considered a priority by the school administration in order to improve the living and hygienic conditions of the students. To determine the low grade thermal energy needs, the quantity of warm water required by each student, based on field investigations, was estimated to be 20litres per day. This was less than the quantity required in the domestic sector because laundry activities were not considered. *Equation 21* was used to determine the energy needed.

$$FE_{PHW} = Nc_p \rho_{water} V_{water} (T_{hot} - T_{cold})$$
 Equation 21

Where N= number of students, c_p is the specific heat capacity of water, ρ_{water} is the density of water, V_{water} is the volume of water required, T_{hot} is the desired temperature of the warm water, and T_{cold} initial temperature of the water. T_{cold} and T_{hot} were set at 20°C and 45°C respectively.

The solution investigated was to exploit the biogas resource using biogas powered boilers. Biogas boilers have a fairly wide range of efficiency[88], however, a thermal conversion efficiency of 80% was considered. This value together with an average LHV of biogas of 29.3MJ/m³ [5] was used to determine the quantity of biogas required.

Step 6: Set up of Energy Services Supply Network (ESSN) structure including the required level of depth regarding energy services demanded.

The ESSN is a conceptual model that captures the conversion of energy until it delivers a particular service. The ESSN provided a framework for the control and adaptation of energy conversion process. The "energy currencies" model wherein the intermediate energy forms after each step of the transformation are called "energy currencies" was used in this study. Previous models which captured the energy conversion process were made up of four principal stages, namely *source, conversion/distribution technologies*, end-*use devices* and the *demanded energy services* delivered, (Figure 6, page14). From the final energy form, the pathways to the delivery of the energy services is not unique. This had led to the use of several technologies to provide the same energy service. This phenomenon was referred to as "technology stacking". In setting up of the ESSN, the innovation was to integrate

energy drivers in the supply network system, thereby limiting the pathways through which an energy service was delivered. This approach allowed for a more costeffective way to allocate end-use devices to meet the energy end-use services. This approach eliminates technology stacking.

Step 7: Control and adaptation of the Energy Services Supply Network

The goal of this step is to improve on the energy conversion efficiency and a proper delivery of the energy services. In this study this step could not be implemented because the designed energy system was not physically realized.

3.2.2 Results

The results of the application of the IREPP in the case study area are presented in this paragraph. The results obtained shall be presented according to the various steps of the procedure.

Step 1: Integration of Goals of Sustainable Energization into the decision making process

The goal of delivering an enhanced quantity, quality and variety of accessible and affordable energy services; enabling the sustainable development of the study area and the optimization of the ESSN from a life cycle perspective was integrated in the planning procedure. Specifically, the PES and FC of the area were targeted for s improvement in terms of quantity, quality, variety of local RES, and affordability.

Step 2: Assessment of the existing energy balance situation of the study area

The existing energy sources in the study area were firewood, diesel, electricity, LPG and kerosene. These sources provided a TPES of 454.4 GJ/month, giving a per capita energy consumption of 0,761 koe. This was very low compared to the national average of 330 koe in 2013⁶. Two main energy drivers - domestic and public services were identified. A total of 245 GJ (53,9 %) was supplied to the public driver and 209,4 GJ (46,1%) was supplied to the domestic driver. The FC was 92,9 GJ/month, representing only 20 % of TPES. These FC were distributed as follows: 46,2 GJ (49,9 %) in the public driver and 46,7 GJ (50,3 %) in the domestic driver. Thus, there was an 80% loss of TPES⁷. The major energy losses were encountered in meeting the thermal energy needs in both drivers, i.e. 198,2GJ (43,6 %) in the public driver and 161,3 GJ (35,4 %) in the domestic driver. These losses were attributed to the

⁶<u>http://energyatlas.iea.org/?subject=-297203538</u>, accessed January 2016.

⁷ At the global level energy losses is about 49%, (<u>https://www.iea.org/Sankey/</u> accessed January 2016)

types of conversion technologies used to provide the energy services i.e. low efficient stoves and ovens in the public driver and the three stone fire in the domestic driver. The energy needs met were low grade heat for warm water services mainly in the domestic driver; medium grade heat for cooking and baking in both the public and domestic drivers; ac electricity for lighting and powering of electrical appliances. Two load curves for a typical week in the months of September and October, were obtained (Figure 14). These load curves were compared to those obtained through the appliance census. The estimated load curve from the results of the appliance census was 7 % higher than that obtained through direct measurement from the energy meter. The difference could be due to the tendency for people to overestimate the operation time window of the appliances they used.



Figure 14: Sample load curves

The peak power demanded was about 16 kW and this occurred in the evening hours between 19:00 and 23:00. The baseload demand was about 5 kW. The load curves helped to quantify energy consumptions to levels useful for a more realistic modelling in the design of the energy system as will be shown in step 5 of the procedure.

Energy flow charts are useful tools to depict how energy resources are used to meet various energy services, i.e. energy balance. Such charts are mostly applicable at national, regional and global levels. An innovation was introduced in this study to adapt the IEA energy flow chart approach to the level of a rural area. Thus the existing energy balance situation of the study area was summarized into an adapted energy flow chart using the Sankey software as shown in Figure 15. The nodes of the charts were primary energy sources, energy drivers and final used of energy.



Figure 15: *Energy flow in the study area*.

Step 3: Energy services demanded and priorities

Two main energy drivers were identified in the study area, namely the domestic and the public drivers. The energy services demanded in the domestic energy driver were low and medium grade thermal and electricity in both dc and ac forms. For the public driver the energy services demanded were low and medium grade thermal energy, electricity in both dc and ac forms and rotating shaft power at fixed locations. These energy services were of equal priority for the daily activities in both drivers and for the socio-economic development of the area.

Step 4: Local Energy Resources: Focused on Renewable Energy Resources

The local renewable energy resources assessed were biomass for biogas production, hydropower, wind and solar. The potentials of each of these resources are presented in the following paragraph.

Biomass for biogas production

Three sources accounted for the biomass resource for biogas production, namely: animal waste, human waste and corn residues.

From the questionnaires several animal species existed in the study area. The biogas potential from manure from the various animal species kept in the area are presented in Table 10.

Animal species	Dry Matter production [tons/month]	Biogas Yield [Nm ³ biogas/ ton DM]	Biogas Potential [Nm ³ biogas /month]
pigs	1,39	649	902
goats	0,56	120	67
cows	0,26	281	73
fowls	0,52	359	187
Total			1.229
DM = Dry Matte	er		

Table 10: Biogas potential from animal species

The human waste consisted of faeces and urine from both adults and children. The biogas potential from these waste is shown in Table 11.

Table 11: Biogas potential from Human waste

			Daily production [g/day	Biogas Yield [Nm ³ biogas/day	Biogas Potential [Nm ³ biogas
	Group	No.	head]	head]	/month]
	Adults	608	140	0,0189	48
Faeces	Children	544	70	0,0189	22
	Adults	608	1.500	0,0153	419
Urine	Children	544	750	0,0153	187
Total					676

From the interviews with the households and direct observations on the field, annual average harvest of corn residues was estimated at 20 ton/hectare. About 11,6 hectares of corn were cultivated annually and yielded an average corn residue of about 226 ton. Assuming an average biogas yield per ton of corn of 530Nm³, the annual biogas potential was estimated at 119780 m³, corresponding to a monthly average of 9981 m³.

Existing biogas production

As mentioned in section 3.2.1, a functional 40m³ biogas digester existed in the study area. This digester system was fed by faeces and urine from 543 male students. The daily biogas production for 43 days during which measurements were recorded is shown in Figure 16. During the 43 days period, 408 m³ of biogas was produced. This corresponded to a daily and monthly averages of 9,48 m³ and 284,4m³ respectively and energy equivalent of 8 GJ/month.



Figure 16: Existing biogas production

The total biogas resource from the three sources (animal manure, human waste and corn residues) and the existing production are summarized in Table 12.

Table 12: Total biogas resource

Source	Biogas Potential [Nm ³ biogas /month]	Energy Equivalent [GJ/month]
Animal manure	1.229	36
Human waste	676	20
Corn residue	9.981	292
Total		348
Current production	284	8

Hydropower

Two parameters were needed to assess the hydropower potential of the locally available river, namely the flow rate (Q) and the head drop (H).

Flow rate (Q)

As already mentioned in section 3.2.1, the "Floating Object Test" was used to measure the flow rate of the river. The results of two experiments conducted in the month of October and November 2014 and application of *Equation 14*, gave a first estimate of the flow rate of the river as shown in Table 13

Table 13: First estimate of river flow rate

Parameter	October 2014	November 2014
Average Cross- sectional Area [m ²]	0,81	0,74
Average velocity [m/s]	0,82	0,75
Correction coefficient	0,45	0,45
Estimated Average flow rate (Q _e)[m ³ /s]	0,30	0,25

In order to obtain the annual river flow regime, simple linear regression technique was used with the data for the nearby river Mewou as reference. The regression equation used was *Equation 22*.

$$Q = a + bQ_M$$

Equation 22

Where a and b are constants, Q is the flow rate of the local river and Q_M is the flow rate of the reference river.

Application of *Equation 22*, with the measured flow rate of the river in October and November 2014 as averages for these months yielded the values 0,0134 and 80,035 for the constants a and b respectively. Thus the regression equation used to obtain the annual flow rate of the river was *Equation 23*.

$$Q = 0,0134Q_m + 80,035$$
 Equation 23

The annual flow regime obtained after application of *Equation 23* and data of the reference river Mewou are shown in Table 14. A minimum residual flow rate of 50% was selected to safeguard aquatic life and other down dream usage of the river. With this minimum residual flow rate the design flow rate of 54,4 l/s was determined. This value was then used to determine the hydropower resource.

	Q _{Mewou} [l/s]	Q [l/s]	Residual flow rate [l/s]	Design flow rate [l/s]
Jan	3.727	130,0	65,0	54,4
Feb	2.373	111,8	55,9	54,4
Mar	2.151	108,9	54,4	54,4
Apr	5.372	152,0	76,0	54,4
May	5.513	153,9	77,0	54,4
Jun	9.037	201,1	100,6	54,4
Jul	11.630	235,9	117,9	54,4
Aug	12.786	251,4	125,7	54,4
Sept	13.831	265,4	132,7	54,4
Oct	16.326	298,8	149,4	54,4
Nov	12.598	248,8	124,4	54,4
Dec	7.543	181,1	90,6	54,4

Table 14: Annual, residual and design flow rates of the river

Head (H)

After locating the intake and power house positions, a head of 55 m was measured as described in section 3.2.1.

With the design flow rate, Q, and Head, H, determined, *Equation 13* was used to estimate the hydropower resource. The value obtained was $P_{gross} = 29,3$ kW. Assuming an overall system efficiency of 45 %, the net hydropower estimated was $P_{net} = 13,2$ kW. Further assuming a 70 % full annual operation of the system yielded an annual electricity production of 81 MWh/year, corresponding to 24,3 GJ/month.

In general, a crossflow turbine has efficiencies over 75 % when working between 60 % and 110 % of design flow rate. Thus, the hydropower resource could be further exploited by increasing the design flow to 90 l/s. With this design flow, the turbine can operate between 54,4 l/s and 99,8 l/s and thus follow better the flow regime of the river throughout the year, as shown in Table15.

At a design flow of 90 l/s and partial flow operation of the turbine, the average net power determined was 21 kW. Based on the same assumption of a 70 % full annual operation the system yielded an annual electricity of 128 MWh/year, corresponding to 38 GJ/month.

Month	Annual flow rate [l/s]	Residual flow rate [l/s]	Turbine flow rate [l/s	% of design flow rate
Jan	130,0	65,0	65,0	72,2
Feb	111,8	55,9	55,9	62,1
Mar	108,9	54,4	54,4	60,5
Apr	152,0	76,0	76,0	84,5
May	153,9	77,0	77,0	85,5
Jun	201,1	100,6	99,8	110,9
Jul	235,9	117,9	99,8	110,9
Aug	251,4	125,7	99,8	110,9
Sept	265,4	132,7	99,8	110,9
Oct	298,8	149,4	99,8	110,9
Nov	248,8	124,4	99,8	110,9
Dec	181,1	90,6	90,6	100,6

Table 15: Further exploitation of river through turbine partial operation

Wind

From the measured values of wind speeds the parameters that were necessary to define the Weibull probability density function and the wind power density were calculated. The average wind speed, v, was 3,3m/s and standard deviation was 1,9 m/s. Applying *Equations 17 and 18* yielded the shape factor, k = 1,85 and the scale factor, c = 3,7. Hence the Weibull probability density function was described by *Equation 24*.

$$f(v) = 0.5(\frac{v}{3.7})^{0.85} \exp\left(-\left(\frac{v}{3.7}\right)^{0.85}\right)$$
 Equation 24

The frequency distribution of the actual wind speed for a one minute time step for the period June to November 2014 and January 2015 is shown in Figure 17. From this frequency distribution the wind speeds spread from 0 to 10 m/s, with the most probable wind speed lying between 2 and 4 m/s.



Figure 17: Wind speed frequency distribution

Further information needed to assess the wind resource potential was the annual wind regime. Linear interpolation, by applying *Equation 25*, was used to obtained average values for the months during which data was not collected. Reference data for the interpolation were obtained from the NASA database. The results of application of *Equation 25* are shown in Figure 18.

 $v_{measured} = 1.6v_{NASA} + 0,289$

Equation 25

With the determined average annual wind speed, v = 3,3 m/s, Betz limit of 0, 59 and applying *Equation 15* yielded an average extractable power per unit area (wind power density) of 11,4 W/m². Assuming a small scale wind turbine class of 1,5 kW with a capacity factor of 7 % [89], the annual energy production was estimated at 920 kWh/m² which is equivalent to 77 kWh/m² per month (0,27 GJ/m² per month).



Figure 18: Annual wind speed regime of the study area

Solar

The solar insolation incident on a horizontal surface in the study area were obtained from the NASA database. The daily and monthly mean insolation are shown in Table 16.

		Monthly	
	Daily I _{mean}	I _{mean}	Monthly
Month	[kWh/m ²]	[kWh/m ²]	Imean [GJ/m ²]
Jan	6,14	190,3	0,69
Feb	6,19	179,5	0,65
Mar	5,5	170,5	0,61
Apr	5,01	150,3	0,54
May	4,83	149,7	0,54
Jun	4,42	132,6	0,48
Jul	4,01	124,3	0,45
Aug	3,92	121,5	0,44
Sept	4,21	126,3	0,45
Oct	4,38	135,8	0,49
Nov	5,21	156,3	0,56
Dec	5,79	179,5	0,65

Table 16: Solar insolation

Step 5: Design of the Energy Services Supply System

The goal of step 5 was to design an energy system that will enhance the sustainable development of the study area. The theme of SE had been integrated in step 1; assessment of the existing energy balance situation of the study area in step 2 enabled the acquisition of systematic data set and quantification of energy consumption to levels required for the design of the energy system. Thus filling the gaps observed in studies modelling rural energy systems. Energy needs were identified and prioritized in step 3 and in step 4 the potential of the local RES were assessed. From the results of step 3, two main categories of energy needs were identified, namely: electrical and thermal energy needs. Separate strategies were adopted in the design process to match these needs to the local RES. The first strategy focused on matching the electrical energy needs with the local RES. Each of these strategies are discussed in details in the following paragraphs.

Matching electrical energy needs with local RES

The HOMER software was the tool used for the modelling of the energy system. The objective function and input data were described in section 3.2.1. Only the results of the modelling process are presented in this paragraph. Figure 19 shows the architecture of the proposed electrical energy system.



Figure 19: Architecture of the electrical energy system

In the architecture of the energy system design, the hydropower plant, hybrid diesel generator and the grid were connected to the AC bus and the PV power plant and wind turbine and battery were connected to the DC bus. Both the AC and DC bus supplied the load through a converter. In the architecture of the energy system the simulated average load for the year was 143 kWh/day which was slightly lower that the 145 kWh/day measured for the month of September, and lower that the 152 kWh/day measured for the month of October. During vacations, most of the load was reduced, thus the load profile processed for the simulation purpose took into account this effect. Furthermore, the simulated maximum peak power was 25 kW higher than the 16 kW measured for the month of October. This was due to the random variability in the software and was considered a positive tolerance for future growth in electrical energy demands. In the design of the electrical energy system both Off-grid and grid-RES hybrid systems were considered.

Off-grid System

Based on the output of the HOMER software, ranking of alternative scenarios in terms of least Net Present Cost (NPC) of installation of the various technologies to meet the electrical energy needs, the system consisting of a 15 kW micro hydropower was the most techno-economically feasible solution, although, it did not meet the peak load of the electrical energy demands (Figure 20). In order to meet the excess load during the peak times, a hybrid diesel/biogas generator was

proposed. The hydropower system with a nominal power of 15 kW was to operate on a design flow of 40,8 l/s which was below the initial design flow rate of 54,4 l/s; the hybrid diesel generator was to operate at an average power of 24 kW, consuming 482 liters of diesel and 3tons of biogas per year. The Life Cycle Cost of energy from this option was 0,178 \$/kWh.

Double	uble click on a system below for simulation results.																	
<u>.</u> 7	水花	ð 🖻 🗹	PV (kW)	BN1.5	Hydro (kW)	Label (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Biomass (t)	Label (hrs)	
	ζĽ,	/ 🖻 🛛			15.0	24	20	10	\$ 86,750	4,360	\$ 163,088	0.178	0.98	0.00	482	3	459	
	本な」	ø 🖻 🗹		1	15.0	24	20	10	\$ 93,350	4,440	\$ 171,101	0.187	0.98	0.00	475	3	459	
🕊	Q,	ø 🖻 🖄	3		15.0	24	20	10	\$ 95,750	4,545	\$ 175,334	0.192	0.98	0.00	482	3	459	
🕊	本で	ø 🖻 🗹	3	1	15.0	24	20	10	\$ 102,350	4,626	\$ 183,348	0.201	0.98	0.00	475	3	459	
4	Q,	ø			15.0	24			\$ 80,250	9,208	\$ 241,491	0.264	0.81	0.00	5,590	4	1,739	
A	本で	Ø 🗹		1	15.0	24		5	\$ 87,780	9,432	\$ 252,944	0.277	0.82	0.00	5,537	4	1,738	
147	Q,	Ø 🗹	3		15.0	24		5	\$ 90,180	9,514	\$ 256,780	0.281	0.81	0.00	5,581	4	1,737	
47	本で	ø 🗹	3	1	15.0	24		5	\$ 96,780	9,618	\$ 265,195	0.290	0.82	0.00	5,533	4	1,737	
¶	本 」	ø 🖻 🗹	17	4		24	60	10	\$ 91,150	15,177	\$ 356,911	0.391	0.60	0.00	10,025	4	1,962	
🕊		ø 🖻 🗹	18			24	60	10	\$ 67,750	17,391	\$ 372,280	0.407	0.52	0.00	12,112	4	2,334	
	<u>k</u> 1	ø 🖻 🗹		6		24	40	10	\$ 49,850	26,993	\$ 522,505	0.572	0.26	0.00	20,552	4	4,425	
		ø 🖻 🗹				24	16	5	\$ 3,980	35,491	\$ 625,449	0.684	0.00	0.00	28,382	4	6,064	
47	<u>k</u> 1	Ø 🛛 🖉	18	6		24		10	\$ 96,850	33,250	\$ 679,069	0.743	0.09	0.00	25,977	4	5,683	
47		Ø 🛛 🖉 🖉	18			24		10	\$ 57,250	37,584	\$ 715,358	0.783	0.00	0.00	30,411	4	6,543	
4	東 」	Ø 🛛 🖉		6		24		10	\$ 42,850	44,654	\$ 824,765	0.902	0.00	0.00	36,229	4	8,032	
		ø				24			\$ 250	48,010	\$ 840,931	0.920	0.00	0.00	40,099	4	8,760	

Figure 20: Ranking of technology options to meet electrical load

This system configuration produced 83,4 MWh/year, thus meeting the entire 52,2 MWh/year demanded. A battery system consisting of 20units of type 6FM200D and a 10 kW converter was included in the configuration to store electricity when there was excess and deliver it during the peak hours, still there was an excess production of 27,6 MWh/year. This excess was mostly due to the software not minimizing excess energy production, since analysis were based on minimizing NPC.

An example of the behavior of the system on a typical day is show in Figure 21. During the day time, the power supplied from the hydropower (blue line) was far above the demand (green line). Since there were no constraints to excess electricity, the software did not recognize the difference between supply and demand as an option to limit the excess. To deal with such situation the following strategies were proposed:

- Reduction in the power output of the hydropower (this could be easily achieved with the capabilities of the selected turbine to run in partial flow conditions there by reducing output to about 5,4 kW).
- Supply of some loads in the specific time windows of the day e.g. use of electricity for baking.
- Extension of distribution grid to the neighboring population, or sales of electricity to the grid.
- Lastly, at the worst, dissipation through electrical resistances.



Figure 21: Example of load-supply matching in Off-grid option

Grid-RES Hybrid

In this scenario the best solution was the configuration consisting of a micro hydropower plant with a nominal power of 8,33 kW operating on a design flow rate of 22,64 l/s, although, it did not meet the peak load (Figure 22). Excess energy demanded during peak period was supplied by the hybrid diesel generator and electricity purchased from the grid. The grid replaced the battery in energy storage. The hybrid generator consumed 136 liters of diesel and 1 ton of biogas per year. The total energy produced in this configuration was 61,83 MWh/year, distributed as follows: 71 % from hydropower, 27 % from the grid and 2 % from the hybrid generator. This production met the entire 52,2 MWh/year demanded. Excess production was not considered since the software assumed the possibility to buy or sell electricity to or from the grid. In the case of sales of excess production to the grid, the energy sold amounted to 9,63 MWh/year. Alternatively this excess energy could be supplied to other loads during specific time windows of the day. The LCOE for this scenario was significantly reduced (by about 30 %) to 0,123 \$/kWh.

An example of the behavior of the system on a typical day is show in Figure 22. During the day time, the power supplied from the hydropower (blue line) was far above the demand (green line) in the early hours of the day, so energy was sold to the grid. At about the 6th hour, the hydropower supplied was less than demanded so energy was purchased from the grid. Between the 8th and 17th hour the hydropower supplied met the load for most of the time, very little power was purchased from the grid. Between the 18th and 22nd hour the demand was far more than the hydropower

supplied, so power was purchased from the grid and also supplied from the diesel/biogas hybrid.



Figure 22: Example of load-supply matching in Grid-RES hybrid

Sensitivity analysis

The objective of the sensitivity analysis was to test the robustness of the optimized configuration, given changes in some parameters. As mentioned in section 3.2.1, sensitivity analysis were investigated for the following changes (i) reduction in the investment cost of hydropower system by 25 %, 50% and 75 % (ii) a drop in PV and Wind turbine investment costs up to 90 % of the initial value in order to check the competitiveness of the hydropower plant (iii) 20 % change in the price of diesel and (iv) 5 %, 20 % and 20 % increase in unit price of grid electricity. The results are present below.

Reduction in investment cost of Hydropower

In the estimation of the components of the hydropower system, there was room for cost reduction, e.g. if the penstock length and size were reduced and/or the electrical energy distribution line shortened. The impact of the investment cost reduction on NPC and LCOE, while keeping O&M cost and the energy produced constant, were investigated and the results are shown in Table 17. A reduction in the investment cost resulted in a reduction in NPC and LCOE in both the off-grid and grid-RES hybrid systems. Thus, the viability of both options increased.

		NF	PC [\$]	LCO	OE [\$/kWh]
	Investment	Off-	Grid-RES	Off-	Grid-RES
	[\$/kWrated]	grid	hybrid	grid	hybrid
Base					
case	4.000	163.088	132.791	0,178	0,123
25%					
reduction	3.000	143.088	121.680	0,157	0,112
50%					
reduction	2.000	123.088	110.569	0,135	0,102
75%					
reduction	1.000	103.088	99.458	0,113	0,092

Table 17: Sensitivity on hydropower investment cost

Reduction in investment cost of PV and Wind turbines

The high investment cost per kW of PV and wind turbine made these technologies to be less competitive vis-à-vis hydropower technology. It was considered interesting to investigate the competitiveness of these technologies with respect to hydropower assuming a very high cost reduction of up to 90%. Four different permutations were considered in the Off-grid option, namely:

- PV-hydropower hybrid
- Wind-hydropower hybrid
- Maximum PV capacity
- Maximum wind capacity

The results in Table18 show that the Wind-hydropower came closed to being competitive with the optimized solution (hydropower only). This configuration had an NPC of \$ 163.994 and LCOE of 0,179 \$/kWh compared to \$ 132.791 and 0,123 \$/kWh for the optimized hydropower solution. In the situation were the hydropower resource were absent, the configuration with the maximum power from the PV was more competitive with respect to wind power, however with a relatively very high NPC of \$ 311.599. In fact, this configuration required an installation of 18 kW of PV panels, 90 batteries for storage. The annual electrical energy production from this system was 30 MWh which was lower compared to 80 MWh/year for a 15 kW hydropower plant. Hence the solar and wind technological option were still far from being competitive when compared to the hydropower solution, even under conditions of 90 % investment cost reduction.

	NPC [\$]	LCOE [\$/kWh]		
PV-Hydro	165.643	0,181		
PV _{max}	311.599	0,341		
Wind-Hydro	163.994	0,179		
Wind _{max}	394.021	0,431		
Hydro	163.088	0,178		

Table 18: Investment cost reduction of PV panels and Wind turbine

In the Grid-RES hybrid option, the PV and Wind configuration became appreciably competitive compared to the hydropower configuration. In fact the NPC for PV and Wind power configuration were \$ 134.314 and \$133.108 respectively and the LCOE were 0,142 \$/kWh and 0,140 \$/kWh respectively, compared to the hydropower configuration with NPC and LCOE of \$ 132.791 and 0,123 \$/kWh respectively.

Thus the competitiveness of PV and Wind both in hybrid and single configuration in the Off-grid and Grid-RES depended on huge reduction in investment cost of these technologies.

20% change in the price of diesel

The impact of this price change on NPC and LCOE in the Off-grid and Grid-RES option are shown in Table 19. A 20 % increase in the price of diesel resulted in an increase in the NPC in both the Off-grid (0,9 %) and Grid-RES hybrid (0,5 %) options. The LCOE in the Grid-RES option remained unchanged while there was a 1 % increase in the Off-grid option. A 20 % reduction in the price of diesel resulted in a drop in the NPC in both Off-grid (less than 0,9 %) and Grid-RES hybrid (about 2 %). There was also a drop in the LCOE, in both Off-grid (0,5 %) and Grid-RES (about 2 %) options. Thus, the optimized solution remained relatively competitive with changes of up to 20 % in the local prices of diesel.

	NP	C [\$]	LCOE [\$/kWh]			
	Off-grid	Grid-RES	Off-grid	Grid-RES		
base						
case	163.088	132.791	0,178	0,123		
20%	164.656	133.474	0,18	0,123		
-20%	161.519	129.694	0,177	0,12		

Table	19:	Impact	of	changes	in	price	of	^e diesel	on	the	solution	option
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Increase in unit price of grid electricity

It was expected that an increase in the price of grid electricity would encourage sales of electricity to the grid and purchase of less electricity from the grid. Unfortunately, this was not the case. The purchase and sales of electricity from and to the grid dropped as shown in Table 20. However, the NPC and LCOE both increased. Thus the effects of a 5 % and 10 % increase in grid energy prices did not encourage the sales or purchase of energy from the grid and led to an increase in NPC and LCOE. Thus the optimize solution remained the best option.

Increase in Price					
of Grid	Installed	Grid purchase	Grid sales		LCOE
electricity	capacity	[MWh/year]	[MWh/year]	NPC [\$]	[\$/kWh]
Base case	8,33	16,66	9,33	132.791	0,123
5%	8,33	15,23	9,33	134.639	0,124
10%	8,33	12,44	6,33	135.111	0,125

Table 20: Impact of increase in prices of grid electricity on the solution

Thermal Solutions

From section 3.2.1, the thermal energy needs identified in the two drivers were:

- Domestic driver: low grade heat for warm water (partially met) and medium grade heat for cooking (completely met).
- Public driver: medium grade heat for cooking and baking (completely met) and low grade heat for warm water (completely unmet).

The ad-hoc solutions adopted were based on matching these needs with the locally available RES; to reduce the consumption of firewood and the observed thermal losses in order to improve the existing energy system in terms of reliability and quality of fuel or cooking facilities.

Public cooking: The proposed solution was the substitution of the locally made improved stove whose efficiency was experimentally estimated at 24 % with the more efficient ASTRA stove with an efficient of 40 %. This led to a 40 % reduction in TPES mainly from firewood i.e. from 140 GJ/month to 84 GJ/month.

Public warm water: The need of 2,11 GJ/day for warm water was determined and was completely unmet. To match this need with the local RES, two possibilities existed i.e. use of biogas fired boilers or solar thermal collectors. Assuming the thermal efficiency of 80 % for a biogas boiler the TPES required was 2,64 GJ/day. Considering the average calorific value of biogas of 29,3 MJ/m³, the volume of

biogas required was about 90 m³/day. Biogas production from existing digesters was 9,8 m³/day. This represented only 11 % of the needs. The biogas potential from the entire student population was estimated at about 26 m³/day. With this consideration the gap to meet the warm water needs of the public driver was 71 %. Considering the existence of non-initiated digesters, these gap could be met via two ways, namely harnessing the 332 m³/day of biogas from corn or from 54 cows. The former solution presented a technical and logistic challenge to collect and transport the corn residue while the later entailed an investment in 54 cows by the community.

The second solution considered the use of flat plat solar collector. Assuming that 1000 students were to be provided with warm water, a flat plate collector of 60 % efficiency, the SWHS efficiency of 85 % and average annual irradiation of 19 $MJ/m^3/day$ a collector size of 216,6 m² was required. This was quite huge in terms of investment and technical O &M challenges in context of a DC.

Public Baking: The PES required by the bakery was 95,8 GJ/month and the FC was 4,8 GJ/month (fully met). The calculated efficiency index of the oven was about 5 %. The solution proposed was the replacement of the firewood powered oven by an electric oven. In this technological option, with the oven operated for 10hours per day, 5,2 GJ/month of energy was required. This energy could be supplied from the excess generated by the hydropower plant. Switching from the wood-powered oven to electricity-powered oven had consequences on the capacity of the power plant and load curve both in the Off-grid and Grid-RES hybrid. In both configurations, the nominal capacity of the hydropower plant resulted in LCOE of 0,15 \$/kWh and 0,09 \$/kWh for the Off-grid and Grid-RES configurations respectively. Thus with the conversion of the bakery wood oven to an electric oven the cost of energy in both Off-grid and Grid-RES configuration became cheaper. In addition to this advantage, the smoky working conditions in the bakery were greatly improved.

Domestic cooking: Since the objectives of SE was the use of clean and affordable energy services, LPG and kerosene were considered as options for cooking. In this scenario the TPES for cooking was 183,5 GJ/month i.e.173 GJ from firewood, 9,2 GJ and 1,3 GJ from LPG and kerosene respectively and a FC of 33,8 GJ/month i.e. 27,6 GJ, 5,8 GJ and 0,4 GJ from firewood, LPG and kerosene respectively. The domestic energy needed for cooking was considered fully met. The proposed solution of substituting the 3SF with ICS resulted in a 39 % reduction in the TPES from 183,5 GJ/month to 112,7 GJ/month. In addition to great reduction in TPES, the use of ICS improved the kitchen environment for the users.

Domestic Water Heating: The determined warm water needs per capita per day for the households was 3,14 MJ. Considering a flat plate collector with an efficiency of

60 %, and SWHS efficiency of 85 %, a collector of size 0,42 m^2 per capita was required. Thus, for a family of 4 persons and a storage tank of 120litres, a SWHS of size 1,64 m^2 was required to meet the daily warm water needs of the households. This size was considered technically feasible.

Step 6: Setting of the Energy Services Supply Network

The energy flows in the Off-grid and Grid-RES hybrid scenarios are shown in Figure 23 and Figure 24 respectively. For simplicity the conversion technologies and end-use devices were omitted in the Sankey energy flow diagrams.



Figure 23: Energy flow in Off-grid scenario



Figure 24: Energy flow Grid-RES scenario

From the two scenarios, there was a 25 % reduction in the TPES and an 85 % increase in the FC. The thermal losses were reduced to 161,6 GJ/month which represented a reduction of 55 % compared to the initial energy system. Also, there was less dependence on fossil fuels and grid electricity, this meant greater reliability and affordability of energy supply. In addition, some of the unmet energy needs were now satisfied.

To prioritize the options for implementation, two circumstances could be considered, namely: keeping the unit cost of energy during the life cycle of the project low and guaranteeing security of energy supply. The Grid-RES hybrid option was more attractive if the cost of the energy were to be kept low, since the LCOE was 0,123 \$/kWh against 0,178 \$/kWh for the Off-grid option. However, the Off-grid option offered greater security of energy supply, especially during peak hours, than the Grid-RES option which relied on the not too reliable grid supply during peak demand hours.

Step 7: Control and adaptation of the Energy Services Supply Network

The physical realization of the ESSN was beyond the scope of this study. Consequently, this step was not relevant to the study.

3.2.3 Conclusions

The applicability of the *IREPP* has been demonstrated within the context of a rural area in DC. The results showed that the matching of local energy resources to local energy needs, through the identified energy drivers led to an improved access to modern energy carriers with a great increase in the FC and a reduction in PES in accordance with the theme of SE, thus proving the validity and relevance of this procedure. Furthermore, the procedure led to the identification and integration of new local energy sources, e.g. Hydro, solar and organic biomass, thus enlarging the energy carrier package in the rural energy system. The new sources presented an opportunity for the identification of new technologies, e.g. hydro turbines, solar thermal collectors and biogas technology for improvement of modern energy for cooking in the rural areas. Amongst these technologies, biogas technology was identified for further research for its possible application at the level of rural households to improve access to clean fuel for cooking. The identification of this technology introduces the activities for the development of second phase of the "comprehensive rural energy planning strategy". This phase is titled "Technology improvement".

Chapter 4: Technology Selection Process

Often, there is a pool of technology options from which the selection of an appropriate options for a specific context could be made. The choice has to meet certain local social, cultural, environment, economic and technical criteria. Making such a choice was not obvious since there were often several criteria and options from which to make the selection. Thus the application of a decision support system (DST) was required. In this chapter, the selection process is demonstrated.

4.1 Appropriate Digester Design Selection Strategy

From the results of application of the IREPP procedure in chapter 3, biogas featured amongst the local renewable energy sources which could enrich the rural energy supply package within the theme of SE. Also from chapter 2, small scale biogas technology was widely disseminated in DC for application at the household level. However, amongst the technical reasons advanced for the low adoption of this technology in SSA, was the lack of appropriate well researched and standardized design for the context of rural areas in SSA.

The aim of this chapter was to apply a DST to select, from the several existing alternatives, an appropriate design for the context of SSA. The analysis and selection of an appropriate design required the coupling of technical feasibility and performance analysis with sustainability criteria. The context in which the qualifying criteria were situated was SSA, specifically rural areas of Cameroon. The selected design could serve as an initial option for further research and optimization for sustainable operation in the socio-economic, environmental and cultural context of rural SSA.

This chapter is divided into two main sections. In the first section the selection of a DST is discussed and in the second section the AHP, its application, results and conclusions are reported.

4.2. Choice of a Decision Support Tool

Most of the digester designs disseminated in DC were originally designed within the context of Asia and therefore, were characterized by specific social economic, environmental and cultural conditions which were, of course, different from those in SSA. Furthermore, each of these designs have different configuration and so require different levels of technical skills for construction with consequent socio-economic impacts. Operation within different geographical and cultural context resulted in different technical performances, as demonstrated in chapter 2. Therefore, the choice of a design for mass dissemination in a particular region was subject to several constraints.

The decision making process to select a particular design for mass dissemination is complex and will need to comply with some criteria. Such compliance will lead to the exclusion of some alternatives. Hence, the selected alternative must meet the specific needs of the target area as much as possible. These needs must take into consideration locally available resources, selected performance indicator as well as sustainability criteria. In the course of the decision making process there are bound to be trade-offs between alternatives. A systematic approach was required to evaluate alternatives based on agreed goals and criteria to come out with the most appropriate design. A decision support system provided such a systematic approach through which trade-offs could be weighed and valued judgment made in order to come out with a consensus amongst different and sometimes conflicting stakeholders' interest.

The objective of this section was to select a suitable decision support system which could be used for the selection of an appropriate digester design for SSA.

The choice of a decision method highly depends on the characteristics of the decision problem. There exist several decision making methods that could be used for the selection of the appropriate digester design for the context of SSA, specifically the context of rural areas in Cameroon [90,91]. The selection of a digester for the context of rural areas in Cameroon had several criteria that needed considerations. Thus the selection problem was a multi criteria problem which required a multi-criteria method for a solution. There are two big families of multi-criteria methods namely: multi-objective and multi-attribute methods [90-92]. The case of selection of a digester design for rural areas in Cameroon was characterized by several criteria (social, economic, environmental and technical), and finitely many digester design alternatives. Thus it was a multiple attribute problem with a finite number of alternatives which were explicitly defined. Thus a multi-attribute decision making tool was appropriate. Amongst the available multi-attribute tools, the Analytic Hierarchical Process (AHP) was considered the most suited for three reasons, amongst several strengths of the AHP[93]. Firstly, it is a linear additive model with procedures to derive weights and scores for alternatives in a straight forward manner. Secondly, its procedure is based on pairwise comparison between criteria and alternatives which reduces the complexity of evaluating several alternatives to the evaluation of only two alternatives at a time. Lastly, it uses the Saaty's scale, which allows for the use of qualitative indicators.

The AHP process is briefly described in section 4.2 and applied in the selection of an appropriate digester design for the context of rural areas in Cameroon.

4.3. The Analytic Hierarchy Process

The AHP requires the breakdown of the problem into smaller and simpler elements, i.e. *analytic*, at different levels of a *hierarchy*. The results of pairwise comparison at different levels of the hierarchy are aggregated from the bottom level to the top level, i.e. a *process*. AHP is realized in a series of six steps as follows:

- (1) Structuring the problem into a hierarchy of elements (analytic).
- (2) Successive rating of the alternatives based on pairwise comparison.
- (3) Synthesis of the priority and hierarchy building.
- (4) Consistency test.
- (5) Sensitivity Analysis.
- (6) Negotiation and evaluation of the consensus.

Steps 1 to 5 were applied in the case of selection of a digester design for the context rural areas in Cameroon. The last step on negotiation and evaluation of the consensus was not applied because, only a single stakeholder was involved.

The application of the process, results and conclusions are discussed in the following paragraphs.

4.3.1. Application of Analytic Hierarchical Process

Structuring the problem into a hierarchy

In the AHP, the chosen factors important for the decision making were arranged into a hierarchical structure with the goal at the topmost level of the hierarchy, descending to criteria, sub criteria and alternatives in a successive manner [33] as shown in Figure 25. The context of rural areas in Cameroon was characterized by high dependence on traditional biomass (firewood, charcoal, agricultural residue) together with inefficient technologies, mainly the three stone open fire, for cooking. In order to change this situation, the goal of the decision process was to select a digester design that was low cost and


Figure 25: AHP Hierarchy Scheme

appropriate for households, especially rural households. Appropriateness here meant the technology was suited to the social and economic realities of the place where it was to be used, locally controlled, environmentally friendly and sound and involves skills and materials that were easily available in the local area.

Cameroon is a lower middle income SSA country with an estimated population of 21,7 million and a GDP of UDS25, 32 billion. The poverty headcount ratio at national poverty line was 39.9 %. Its residential sector was characterized by very low energy intensity of 0,29 toe per capita. Furthermore, more than 80% of rural households and 60 % of urban households depended on traditional use of solid biomass and less than 5 % of rural households had access to electricity and modern fuels like kerosene and LPG. Biogas technology was relatively new in Cameroon. It is desired a transition from the use of traditional biomass to the use of modern fuels by rural households. Biogas technology presents and excellent opportunity for such a transition. Several alternative biogas digesters exist. Thus, the goal of the decision problem was to select a low cost appropriate digester design to improve access to modern energy fuels for clean cooking in rural households to enable their sustainable development. The AHP was set in order to select the most appropriate digester design from a list of alternative digester designs for rural areas of Cameroon to meet the above goal in accordance with the concept of sustainability. Thus, sustainability criteria were selected following the IEA approach [94] i.e. economic, social and environmental criteria. The corresponding relevant indicators for the sustainable development of the context were selected from the list of the IEA proposed indicators.

The context of Cameroon with a large number of users of traditional biomass coupled with inefficient technologies required more of such users to shift to more efficient, clean and safe fuels. Thus the *equity and safety &health* sub criteria were

considered more relevant under the social criteria. The associated indicators to measure these sub criteria were: *increase number of biogas users, number of local jobs create and the level of accidents resulting from the use of a chosen design.* Considering that 39.9% of Cameroonians were poor, with the level of poverty greater in the rural areas, the selected digester design must be affordable and reliable in its operation for the poor. Therefore, *use & production and security* were considered relevant economic sub criteria with the following associated indicators: *Net Present Value (NPV), Investment efficiency and improvement in the economic activities of the households and reliability/stability of biogas production.*

Most households in Cameroon, especially those in rural areas often faced water scarcity and many do not own much land. The construction and operation of a biogas digester has demands on water and some digester designs require more land space for their construction. The operation of digester designs commonly disseminated in DC require similar water demands for their operation, therefore, emphasis on water demands by alternative designs was on water required for the construction of the design. Hence water and land were selected as sub criteria under environmental criteria. The desired alternative should therefore have less demand for water and requires as small as possible land space for it construction. In addition to the above criteria and sub criteria, a technical feasibility criterion was considered. The selected design must be technical feasible in the context of rural areas in Cameroon. The technical feasibility was measured in terms of the *technical appropriateness* of the design. To measure the technical appropriateness, two sub criteria were considered relevant, namely: appropriateness for the household and appropriateness for mass *dissemination* to enable more households shift from the use of traditional biomass to the use of more efficient fuels. The indicators selected to measure these sub criteria were; daily person hours required for operation, repairs & maintenance, durability, excavation, construction time, special construction methods, local availability for *construction materials.* The design considered appropriate for the context should be one that was labor-intensive, fewer skills required for construction, simple and easy to operate and maintain and materials for construction were locally available. These four criteria (social, economic, environmental and technical) constituted the first level of hierarchy in the AHP. The sub criteria and related indicators constituted the second level of the AHP. The *bottom level* of the Hierarchy was constituted of the alternatives to be evaluated. These alternatives were digester design widely promoted in DC, namely; Nepali GGC2047 fixed dome, Indian Deenbandhu fixed dome, Vietnamese KT2 fixed dome, floating drum and plastic tubular digester, as discussed in chapter 2. To complete the hierarchy was the decision makers. The stakeholders' decision was represented by a mix of expert opinions which the author had gathered during over 5 years of field experience in the sector. Judgments at each stage of the process were therefore based on the Saaty's scale and also on the mix of the gathered expert opinions within the rural context under consideration.

Rating of alternatives based on pairwise comparison

This step begins with assigning of weights to each element in each level of the hierarchy. The weights represented the relative importance of an element of the hierarchy with respect to other elements. The weights were obtained through the construction of pairwise comparison matrices using pairwise comparison of the elements of that level relative to the higher level. Each entry of the matrix, a_{ij} was obtained by the expert judgment on the relative importance of element i compared to element j using the Saaty's fundamental scale. The priority vector of each matrix was evaluated using the geometric mean method. Three levels of weightings were obtained according to the decision hierarchy, namely;

- i. Weights of indicators relative to the sub criteria.
- ii. Weights of the sub criteria relative to the criteria.
- iii. Weights of the criteria relative to the goal.

There were three levels in the decision hierarchy. Therefore, three groups of matrices were constructed at each level of the hierarchy, namely:

- (i) Matrices that compared all the alternatives with respect to each other within the bottom-level criterion. The bottom-level criterion measured the performance of each alternative using one or more indicators. The indicators selected were all treated as qualitative, thus allowing for the direct use of the Saaty's fundamental scale. The alternatives were compared to each other relative to each of the selected indicators using pairwise comparison matrices. And their partial performance (Priority Vector) was obtained using the geometric mean method.
- (ii) The second group of matrices were constructed by comparing elements of the same level of the hierarchy with respect to the same element of the higher level of the hierarchy i.e. the second-level criterion. This process produced the weights of the sub criteria within the criteria. After the construction of a pairwise comparison matrix, the priority vector was evaluated using the geometric mean method.
- (iii) The third group of matrix consisted of only one matrix in which the relative importance of each first level criterion was obtained with respect to the goal. The priority vector of this matrix was evaluated using the geometric mean method.

Synthesis of the priorities and hierarchy building

This step was characterized by the calculation of the priority vector from each pairwise comparison matrix. Accordingly, the order given by a priority vector

reflected the cardinal preference indicated by the pairwise comparison. Starting for the bottom level, the priority vectors obtained from the pairwise comparison matrix of the alternatives relative to the indicators, which represented the performance of each alternative with respect to each indicator, were placed side-by-side to form the partial performance matrix of the alternatives at this level. The partial performance of the alternatives relative to the sub criteria were evaluated by multiplying the partial performance matrix by the weights of the indicators.

The priority vectors obtained at the level of the sub criteria were placed side-by-side to form the partial performance matrix at the level of the sub criteria. This partial performance matrix was multiplied by the weight of the sub criteria to obtain the partial performance of the alternatives at the level of the criteria. Likewise the partial performance matrix at the level of the criteria was multiplied by the weights of the criteria to obtain the global performance of the alternatives.

Consistency test

The usefulness of the AHP depends on the coherence and sensibility of the data used in the pairwise comparison matrices [95]. The coherence of the pairwise comparison matrices is measured using the consistency index (CI). The CI is then used to compute the consistency ratio (CR). A matrix and the related judgments are considered reliable if the CR is less than 10 %. For a CR > 10 % the results were not totally reliable for the AHP analysis. The CR for the matrices at each stage were evaluated according to [95] and the values ranged from 0 -10 % indicating that matrices were reliably and coherently filled.

Sensitivity analysis

The solution from an AHP analysis can only be useful if it was stable [95]. The weighting of the criteria were varied within 10 % and the same global priority vector was obtained demonstrating that the solution for the AHP was stable within this range.

Negotiation and evaluation of the consensus

The "expert" was the only typology of decision makers involved in the application of the AHP in this study. Therefore, a consensus was not necessary. However, in the case where several decision makers were involved it is important that a consensus be arrived at by the various decision makers through negotiations and evaluation of the results.

4.3.2 Results

Based on the expert weighting of criteria, sub criteria and indicators, the Nepali GGC2047 had the highest global ranking and so was the best alternative digester design for dissemination in Cameroon. This could be explained through the

attribution of the weights at the different level of the hierarchy. The weights of the sub criteria within the criteria were obtained as follows; social sub criteria equity and safety & health had 83 % and 17 % respectively; the economic sub criteria use & production and security had 85 % and 15 % respectively; the environmental sub criteria water and land had 10 % and 90% respectively; while for the technical sub criteria, appropriateness for small household and appropriateness for mass dissemination had 35 % and 65 % respectively.

At the level of the sub criteria, appropriate for mass dissemination and use & production, received the highest weights (65 % and 85 % respectively) within their respective criteria. This was considered relevant for the context of rural areas in Cameroon since the design must be appropriate and affordable in order to be accessible to a majority of the poor, especially those in the rural areas. The environmental sub criterion, land, had a higher weight because, most rural inhabitants in Cameroon do not own land, and therefore a digester design that takes up much space would be disfavored within this context.

These weightings were considered reasonable for the context of rural areas in Cameroon. Considering the very low energy intensity at the household level and the goal to shift more households from the traditional use of solid biomass with less efficient technologies to the use of the more efficient biogas and the need to curb poverty, it was logical that the sub criteria equity had a significant weight compared to safety &health issues related to domestic biogas systems which had received significant safety improvements over the years.

The national head count poverty level in Cameroon was 39 %. It was very important that the selected design be affordable and the investment profitable to the majority of the poor household who needed to shift from the use of less efficient fuels and technologies. Hence the more significant weight for the use & production over the security sub criteria.

All the designs consumed almost the same amount of water in their operation with differences in water consumption only arising in their construction techniques. The space taken up by the technology varied very much amongst the designs. A majority of the households in Cameroon do not own land, hence the significant weight of the land sub criterion over water was justified.

The alternative designs were adapted for households with very little variations in their operation and maintenance details; however, there were significant differences in their construction techniques, skills and materials required. Coupling this reason to the need for more households to shift to the use of more efficient technologies, the higher weight for the sub criteria *appropriateness for mass dissemination* compared to the sub criteria *appropriateness to households* is justified.

At the level of the criteria, the technical criteria scored the highest weight (66%), as shown in Figure 25. This was justifiable because, for a good number of the poor

people to acquire the design, it must be technically appropriate. This high score for the technical criteria coupled well with the economic criterion which had the second highest weight, guaranteed that the design was affordable and profitable to the poor households in rural areas of Cameroon, where cost of financing and well as interest rates for loans are very high.

The very high weight (66 %) (Table 21) of the technical criteria compared to the other criteria was due to the fact that in the pairwise comparison this criterion scores at least "strong importance" on the Saaty's scale when compared to the other criteria based on expert experience. This was justifiable since, within the context of rural areas in Cameroon, for more persons to adopt a digester it was very necessary that the digester was appropriate for small households and also be appropriate for mass dissemination.

Criteria	Technical	Economic	Social	Environmental
Weight	66	19	10	5

Table 21: Weights of the criteria relative to the goal

Without considering the weights of the criteria relative to the goal, the plastic digester was the most appropriate alternative largely due to its good performance with respect to the social criterion, (Figure 26). It performed far less than the Nepali GGC2047 with respect to the technical criteria, as shown in Figure 27. Also the Nepali GGC2047 performed better than the plastic digester in terms of the economic sub criterion-security, as shown in Figure 28. The combined dominance of the Nepali GGC2047 within the technical and economic criteria made it scored the overall best performance over the plastic digesters and the other alternatives, (Figure 29).



Figure 26: Ranking of the alternatives without weights of the criteria



Figure 27: Performance of the alternative w.r.t the technical criteria



Figure 28: Performance of the alternatives w.r.t the economic criterion



Figure 29: Global ranking of the alternatives

4.3.3 Conclusions

The selection of an appropriate digester design for the context of rural areas in Cameroon was a multi-criteria problem. The AHP was the suitable multi-criteria decision tool for the selection process. Applying the AHP with the selected social, economic, environmental and technical criteria, the Nepali GGC2047 design was the appropriate alternative for mass dissemination in Cameroon. The decision support system and tool used in the selection of the appropriated digester design for the context of Cameroon, provides a knowledge based framework relevant for a technology selection methodology which could be applied under different circumstances, and with different decision makers in the supply of a variety of energy carriers and technologies for the improvement of energy access in DC.

Chapter 5: The Technology Optimization Process

In chapter 4, the application of the AHP produced the Nepali GGC2047 digester design as the most appropriate digester design for mass dissemination in the context of rural areas in Cameroon. From the review of the state of the art of small scale biogas technology reported in chapter 2, no systematic evaluation of the performance of this digester design was reported within the context of SSA. However, the performance of small scale biogas technology in SSA was reported to be generally poor.

This chapter presents the development of a procedure for the optimization of the performance of the selected digester design within the context of rural Cameroon. The chapter is divided into five sub sections. The general optimization methodology is described in sub section 5.1. The field experimentation for the identification of crucial local performance parameters are discussed in sub section 5.2. In sub section 5.3, the laboratory investigations for the optimization of the engineering design of the digester based on the identified local performance parameters are discussed. In sub section 5.4, the field validation of the optimized design is reported. Lastly in sub section 5.5 an alternative digester design operated on DAD is discussed.

5.1. The Optimization Methodology

The general approach adopted towards the development of an optimization process of the selected digester design consisted of three main steps, namely: identification of the key local parameters which affect the performance of the design, laboratory investigations to optimize the performance of the digester design and lastly field investigations to verify the performance of the optimized design.

As discussed in section 2.2, several parameters affect the performance of biogas digesters. Naik L, et al,[37] highlighted the factors which affect the performance of small scale anaerobic digesters. However, these parameters may vary depending on the geographical context of operation of the digester. Furthermore, the off design operation of small scale biogas digesters may depend very much on the socio-economic, environmental and cultural context. Thus, the first step in optimization process is the identification of key parameters within the socio-economic, environmental and cultural context of rural areas in Cameroon which affect the performance of the selected digester design. Experimental approach was adopted wherein the off design field operation of the digester design was investigated. The application, appropriate methods and tools used in this step are described in section 5.2.

The second step in the optimization process was based on the identified key parameter(s) from step one. It consist of laboratory investigations carried out to optimize the engineering design of the digester in order to attain an improvement in the performance of the selected digester design. Numerical approach was adopted wherein the advantages of using Computational Fluid Dynamic techniques were exploited[96]. The application and details of the methods and tools used in this step are described in section 5.3.

The last step in the optimization process was the field experimentation to validate the results of the optimization of the engineering design of the digester. It is difficult and expensive to measure mixing of the content of an anaerobic digester. Thus, the results of the numerical investigations employed in the process could not be validated using the standard CFD procedures. Besides, no previous experimental study on mixing in small scale digesters was found in the literature. In order to validate the results of step two of the optimization process, an indirect approach whereby the improved mixing was measure through the biogas production performance of the modified digester design was used. The application and details of the methods and tools used in this step are described in section 5.4.

5.2. Identification of crucial local performance parameters

In chapter 2.2, it was highlighted that the adoption of biogas technology in SSA was very low compared to other developing regions. Amongst the reasons for the low adoption were: variations in the digester design, insufficient feedstock, absence of well researched and standardized design appropriate for socio-economic and cultural context, cost of installation, and poor technical performance, lack of suitable logistics for market penetration. In chapter 4, the AHP was applied to select an appropriate digester design for mass dissemination in the context of Cameroon. Based on the technical, economic, social and environmental criteria, the Nepali GGC2047 fixed dome was the most appropriate design for mass dissemination in Cameroon. The successful mass dissemination of this design will entail optimizing its technical performance within the local socio-economic and cultural context. Such optimization may lead to standardization of the design and reduction of the installation cost for the local context. The optimization process began with the identification of key local operational parameters which affect the technical performance of the design.

The technical and economic performance of the tubular polyethene, Indian fixed dome digester, floating drum and the Nepali GGC2047 fixed dome, based on operating conditions of digester volume, feedstock, temperature, OLR, HRT, within different specific contexts have been reported in section 2.2.2. The selected Nepali GGC2047 fixed dome design, for mass dissemination in Cameroon, was typically utilized on mono-feedstock (usually cow dung) and was operated on the WAD principle within the mesophilic temperature range. This operation principle could present challenges in the specific context. There was little in the literature on the field evaluation of the technical performance of this digester design based on the mentioned operating conditions within SSA, in particular within the context of

Cameroon. Furthermore, an evaluation of the operation and technical performance of this design within the context of Cameroon provided an opportunity to identify essential local operating parameters which affect the technical performance of the design. Such information was necessary for the optimization of the design. A full scale 10m³ Nepali GGC2047 digester design was installed and investigated within a rural context in Cameroon.

The objective of the study was to determine the operating conditions of a full scale Nepali GGC2047 fixed dome design and to identify the critical operating condition(s) that influence(s) the technical performance of the design within the rural context of Cameroon. In addition, important factors which affect the investment cost of the design were identified. An understanding of how these local operating conditions relate to the technical performance of the design led to clues for the optimization of the technical performance of the design.

5.2.1 Methods and Tools

The context

The rural context in which the digester was installed was Efah village located 10km South West of Batibo, headquarters of Batibo sub division of the North West Region of Cameroon. This village is located at Latitude 5.7° N, Longitude 9.8°E and at 2200m above sea level. It had about 2000 inhabitants living in about 300 households. The inhabitants were mostly subsistence farmers who also kept livestock like pigs, goats, fowls in a traditional way. The digester was installed in a family living in 3 households in what was locally known as a "compound" with an average of 6 persons per household. This family had 20 fowls, 4 pigs, a rabbit and 5 goats at the time of installation of the digester in August 2013. The fowls, pigs and rabbit were kept in a semi-modern way (Photo 9a) whereby the excreta could be gather easily. The goats were teetered during the day and brought home and put in a cage over the night. In October 2014, this family acquired one dairy cow, probably motivated by the presence of the biogas digester. Before the installation of the digester the household used entirely firewood to meet all their energy needs for cooking (Photo 9b).



(a) Semi-modern pigsty (b) household dependence of firewood

Photo 9: Life style of the rural households

The experimental digester was installed according to the specifications of the Nepali GGC2047 construction manual [97]. The digester walls and the outlet chamber were built with bricks and cement mortar. The bricks were made locally with cement and sand, the dome was made of concrete, sand and cement. Slabs made out of concrete, sand and reinforced with Ø 6 mm steel rods were used to cover the outlet chamber. The inlet was built with bricks and cement mortar and connected to the digester chamber through an inlet pipe of Ø10 cm PVC material. The inlet pipe was inclined at an angle of 45° to the vertical. A modern flexible plastic pipe with a copper lining was used to convey the biogas to three kitchens of the three households at an average distance of 15 m from the digester. Safety valves were installed in each kitchen and a main safety valve was installed above the dome. A breathing pipe, equipped with a valve, was installed at the lowest point of the pipeline to periodically flush out condensed water in the pipeline. A toilet was integrated into the digester, however, it was not used throughout the period of investigation. According to the construction manual the unit was designed to operate on 120 kg of slurry per day (i.e. 60 kg of fresh cow dung and 60 kg of water) and 60days hydraulic retention time[64]. Taking the average %TS of fresh cow to be about 23 % [41,98,99], the designed %TS of the slurry was about 10 %.

Experimental Procedure and Measurements

The operating conditions under which the performance of the digester was evaluated included; the digester volume, type of feedstock, organic loading rate, temperatures and hydraulic retention time.

Digester volume

The construction manual of the digester describes the digester as 10m³ size. This volume included the gas storage volume and the digestion chamber. The volume of the cylindrical digester and rectangular-manhole constituted the *actual* (operational) volume of the digester unit. The actual digester volume was determined by measuring the dimensions of the digestion chamber and the "manhole" using a builder's meter. The volume of the gas storage was also determined. The outline of the digester is shown in Figure 30.



Figure 30: Scheme of the installed digester

Inoculum and feedstock

The digester was inoculated with 7 tons of cow dung and 1 ton of pig manure mixed with about 6 m³ of water giving a %TS of about 10 %. The digester was subsequently fed with a variety of feedstock available to the household within the social, economic and environmental context of this rural village. The experimental period during which data was captured lasted from the 10th of August 2014 to 24th of January 2015 covering part of the rainy season and the dry season. The fresh mass of each type of feedstock used and the quantity of water used to dilute the fresh feedstock was measured using a standard scale with a 1kg resolution. The feedstock to water mixing ratio was then determined and the amount of total solid (TS) fed into the digester per day and %TS was determined using *Equation 26 and Equation 27* respectively.

Total solids $fed = \sum_{i=1}^{n} x_i m_i$	Equation 26
$\%TS = \frac{Total \ solid \ fed}{mass \ of \ slurry}$	Equation 27

Where x_i is the %TS⁸ of each type of feedstock; m_i is the mass of the fresh feedstock type; n is the number of types of feedstock used; the mass of the slurry was constituted of mass of fresh feedstock + mass of water used in the mixing.

Organic Loading Rate (OLR)

The OLR was determined by the quantity of volatile solids that was fed into the digester. The mass of volatile solids (VS) fed into the digester each day was determined using *Equation 28*. The OLR was then determined using *Equation 29*.

$$V_s = \sum_{i=1}^{n} y_i x_i m_i \qquad \qquad Equation \ 28$$

⁸ Values where obtained from the literature as shown in Table 22

Where y_i is the %VS of each type of feedstock, x_i and mi are same as in Equation 28.

Feed stock	%TS	%VS	BPP	References
Cow dung	22,5	85	0,2 - 0,3	
Pig dung	17	80	0,25 - 0,5	
Fowl dung	25	85	0,3	
Rabbit excreta	25	85	0,35	
Goat excreta	28	80	0,3 - 0,4	
Garden weed	18	82	0,7 - 0,8	[34,48,50,52,53,66,100]

Table 22: Characterization of feedstock

$$OLR = \frac{V_s}{V_d}$$
 Equation 29

Where V_s is total volatile solids fed per day, obtained from Equation 28, V_d is the volume of the digester.

Temperature

The ambient temperatures around the digester were measured using a simple mercury-in-glass thermometer with a 1°C resolution while the temperature inside the digester was measure using a thermocouple with a digital display. The sensor of the thermocouple, attached to a 2 m long cable, was introduced into the digester from the outlet chamber via the manhole. The daily highest and lowest temperature in Batibo sub division were obtained from the internet to serve as a check for the measure values.

Hydraulic Retention Time (HRT)

The goal of the study was to determine the actual local operating conditions of the digester, therefore, the digester was not constrained to operate on the designed input slurry volume. The input slurry volume was dependent on the availability of its constituents (i.e fresh feed stock and water) to the household. Within the context of operation, the amount of slurry volume fed into the digester on a daily basis was determined. Based on the daily slurry fed volume (Q), the corresponding HRT was calculated using *Equation 30*

$$HRT = \frac{V_{digester}}{Q} \qquad \qquad Equation \ 30$$

Where $V_{digester}$ the volume of the digester and Q is the daily volume of slurry fed into the digester.

Biogas production

To measure the quantity of biogas produced under the determined local operating conditions, an industrial gas flow meter of type ECOMETROS_R.E.M.I, Italy with a 1 liter resolution was installed along the biogas convey pipeline immediately after the safety valve above the dome. Records were taken at 24h interval during which time the digester was fed. In order for effective measurements of the biogas produced, before the records were taken, the breathing pipe was opened so that all the biogas in the storage (dome) completely flew out.

Biogas Production rate and Productivity of the digester

From the daily measurements of the biogas production and the determined actual volume of the digester, the production rate was determined using *Equation 31*

$$Biogas \ production \ rate = \frac{m^3 \ per \ day}{actual \ digester \ volume} \qquad Equation \ 31$$

From the measured biogas produced and the amount of volatile solids (kg_{VS}) per day fed into the digester, the productivity was determined using *Equation 32*

$$productivity = \frac{m^3 \, per \, day}{kg_{vs} \, per \, day} \qquad \qquad Equation \, 32$$

Energy recovery efficiency

The biogas production potential of the material fed into the digester was determined using *Equation 33*

The energy recovery efficiency of the digester was then estimated using *Equation* 34.

$$BPP = \sum_{i=1}^{n} TS_i bpp_i \qquad Equation 33$$

Where BPP = Biogas production potential; $TS_i = total$ Solid of each type of feedstock material, bppi = biogas production potential per kg for each type of feedstock

$$\varepsilon = \frac{Biogas \ produced}{BPP} \qquad Equation \ 34$$

Where ε *is the energy efficient of the digester.*

Economic Evaluation

One of the factors attributed to the very low adoption of biogas digesters in SSA was the high investment cost [61,101]. Therefore, the focus of the economic evaluation of the digester was on the capital cost. Details of the cost of materials and cost of construction of each component of the digesters were recorded during the installation of the system. Capital cost was analysed in terms of the cost of various components of the construction process in order to identify the cost intensive components and the capital cost in terms of the materials used. The following cost components were considered;

- Excavation works. This included the digging of the digester pit, the backfilling and dome mold formation, evacuation of the soil inside the digester after dome construction.
- Construction of digester floor and walls.
- Construction of the dome.
- Construction of the outlet chamber.
- Plastering and painting of the dome.
- Plumbing of the biogas convey pipeline.
- Skilled labour cost. This included payment of skilled masons and technical supervisor.

5.2.2 Results

Digester Volume

Table 23 shows the values obtained for the actual digester volume, biogas storage volume and total digester system volume. The effective digester volume was about 7.4 m³ and storage volume was 2.6 m³. The total digester volume (digestion chamber and gas storage) was about 10 m³, as indicated in the construction manual. The agreement between the values of the constructed digester and the manual was an indication of the good quality of the masonry works.

Table 23: Actual digester volume

Digester	Manhole	Actual	Gas storage	Total system
Chamber	chamber	Digester	volume	volume
[m ³]	[m ³]	volume	[m ³]	[m ³]
		[m ³]		
7,0	0,45	7,45	2,62	10,07

The determination of the actual digester volume and storage volume helped to clarify the issue of nomenclature of digesters often encountered in the literature. For, example in Nepal a 10 m³ digester referred to a digester size that included the actual digestion chamber volume and storage volume i.e. about 7 m³ digestion chamber volume and 3 m³ expected daily biogas production, while in Indian a $2m^3$ digester referred only to expected daily biogas production i.e. 2 m³ of biogas per day[15,35].

Types of Feedstock

The household operated the digester on six different types of feedstock, namely: pig, fowl, rabbit, goat and cow dung and garden weed, (Figure 31). However, predominantly pig and cow dung were used. Very little of goat dung was used probably because of the difficulty to collect the dung since the goats were teetered in the day far away from the households and brought back in the night. This practice could led to very little dung collection. Fowl dung sometimes was not available because either the dung was used to feed the pigs or the fowls were all sold away by the household for monetary income. This socio-cultural and economic practice highlighted the insufficient availability of feedstock in the context of rural areas for the operation of the biogas digesters. However, a variety of feedstock were available to the households. The digester functioned successfully on multiple feedstock. Therefore, co-digestion was possible in the Nepali GGC2047 fixed dome digester. Thus, co-digestion could be a strategy to valorize the use of the multiple locally available feedstock for biogas production. However, the use of multiple feedstock (co-digestion) and none strict respect of feedstock to water mixing ratio (1:1) in the operation of the digester resulted in an average %TS of 16±4% which was higher than the designed value of about 10% (Figure 32). With a high %TS, the digester was operated out of the WAD principle and towards the DAD principle [33,104]. The Nepali GGC2047 digester, like other types of fixed dome digester were design to operate in the complete-mix regime on a %TS concentration of less than 10 %. In this operation regime, mixing was achieved through the component configuration, especially inlet configuration [105]. The operation of the digester at a high %TS without improved mixing and/or increased temperature could lead to process instability and poor biogas production [38,39,104]. The average amount of influent into the digester was 57±20 kg which was smaller than the designed value of 120 kg per day. This lower than designed amount of influent into the digester was an indication of insufficient feedstock available for the proper operation of the digester size. [61,106,107].



Figure 31: Types of materials fed into the digester



Figure 32: Total Solid concentration in the influent

Digester temperature

The temperature inside the digester followed the variations in ambient temperatures (Figure 33). During the period from September to mid-December, the digester operated at a temperature that was always above ambient temperatures. The average operating temperature during this period was about 26 ± 5 °C. This operating condition was comparable to those reported for other high altitude regions [103,108]. As the ambient temperature fell (from mid-December),marking the transition to the dry season, the digester operating temperature also fell, however, still following the variations in ambient temperatures and stayed a little above ambient temperature. The dry season was characterized by very cold evenings and very hot daytime. During this period the digester operated at average temperature of 19 ± 1 °C. During the period of investigation, from 10th of August to about the 15th of December, the digester operated within mid-range of the mesophilic temperatures and from the 15th of December to the 24th of January 2015 the

operating temperature was within the psychrophilic range (0-20 °C). This behavior was also reported for digesters operated without any external source of heating in high altitude regions[103]. Throughout the data capture period, the digester operated at temperatures below the optimum for the mesophilic range (30 -35 °C). Operating under sub optimal temperature conditions could negatively influence the technical performance of the digester. An external source of heating, using appropriate technologies within rural context may be required to improve on the operating temperature and hence the biogas production of the digester.



Figure 33: Temperature conditions of the digester

Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT)

Figure 34 shows the variations in the OLR during the experimental period. It was observed that the operating OLR of the digester varied widely between the periods from 10^{th} of August to 20^{th} of November and became more or less stable from the 23^{rd} of November to the 24^{th} of January. The average OLR during the experimental period was 0.9 ± 0.3 kgVS/m³ per day, which was in the same order of magnitude as the design value of 1.5kgvs/m³ per day. OLR is one of the important factors that affects the stability and biogas production of a digester. Higher than normal OLR could lead to excess production of volatile fatty acids which could cause process instability and hence lower biogas production. A fluctuating OLR could also lead to anaerobic process instability[37]. For a more consistent digester operation and a stable anaerobic process, a uniform OLR is recommended. This could be achieved through continuous or daily feeding of the digester with fresh feedstock[109]. An OLR of 2-3 kgvs/m³ per day is common in domestic digesters, however, a maximum of up to 10,6 kgvs/m³ per day has been achieved in some digester designs[31,110].

The feeding rate was not regular during the period from 10th of August to the 20th of November, which was the reason for the highly fluctuating OLR. During the

period from the 20th of November to 25th of January the feeding was regular on a daily basis resulting in a less fluctuating OLR. The highly fluctuating OLR could lead to lower biogas production and hence poor technical performance of the digester. Thus a more regular feeding frequency was recommended to have a much higher and stable OLR.

The HRT also varied following the feeding pattern of the digester. Over the entire experimental period the average HRT was 147 ± 39 day. This value was higher than the design value of 60 days. The high HRT was due to the quantity of daily influent used, which was, in general, lower than the designed value. With a higher HRT, more biogas production was expected.

Biogas Production

The irregular feeding of the digester between the periods 10th of August to 20th of November was reflected in the irregular biogas production over the same period. This as unlike the regular feeding observed during the period from the 20th of November to the 24th of January (Figure 34). The average biogas production over the period of irregular feeding (10th of August to 20th of November) was 0,93±0,81 m^3 per day while during the period of regular feeding the average production was $1,3\pm0,80$ m³ per day, notwithstanding the fact that the average HRT were about the same, 147±50 days and 146±31 days respectively.. Between the 24th and the 29th of December the digester was fed solely on cow dung, and produced on the average 1,0±0,2 m³_{biogas} per day. Between the periods from the 14th to the 18th of January the digester was fed with a mixture of cow, pig, rabbit and fowl dung and produced on the average $1.2\pm0.81 \text{ m}^3_{\text{biogas}}$ per day. This showed that feeding the digester with a mixture of locally available feedstock (co-digestion) led to higher biogas production. Over the entire experimental period, the digester produced on the average was $1,2\pm0, 8 \text{ m}^3$ biogas per day. Notwithstanding the fact that the digester was operated at higher than designed %TS in the influent, the daily biogas production was less than the expected daily production of about 2 m^3 . The daily average production from the same digester design operated at a %TS concentration of influent of about 10 % was 2,0 m³_{biogas} per day [54,108]. Poor mixing could be attributed to this low biogas production. At greater than 8 % TS concentration in the influent, mixing of the digester content became a critical factor that affects biogas production [38,39].



Figure 34: Biogas production and OLR

Biogas Production rate and Productivity

The production rate and the productivity of the digester is shown in Figure 35. A pattern could be observed in the production rate and the productivity of the digester, namely from 10th August to 14th November; 15th November to 24th December and from 25th December to 24th January. The period from 10th August to 14th November was characterized by a low biogas production rate and productivity with average of 0,12 m³_{biogas}/m³_{digester} per day and 0,16 m³_{biogas}/kg_{VS} respectively. From the 15th November to the 24th December, the average biogas production rate and productivity were 0.20 m³_{biogas}/m³_{digester} and 0.21 m³_{biogas}/kgvs respectively. During the period from the 25th of December to 24th of January the average production rate and productivity were 0.16 m³_{biogas}/m³_{digester} and 0.16 m³_{biogas}/kg_{VS} respectively. These values were lower than those obtained in a similar digester operated under similar locations [108]. The fluctuations in the biogas production rate and productivity could be due to the feeding rates, %TS concentration of the influent and the operating temperatures. During the period from the 10th of August to 24th of December the operating temperatures were relatively higher than during the period from 24th of December to 24th of January. The feeding frequency during the period from the 10th of August to 14th of November was irregular with a low average OLR (0,8 kgVS/m³ per day). From the 15th November to 24th December the feeding frequency was regular with a higher average OLR (1,01 kgVS/m³ per day). As earlier mentioned, overall, during the experimental period, the average OLR was 0.9 ± 0.3 kgVS/m³ per day, which was the same order of magnitude as the designed value of 1,5 kgVS/m³. With a higher %TS concentration of the influent, a higher daily biogas production and hence biogas production rate and productivity were expected. From 10th August to 24th December the average operating temperature were 26±3 °C and during the period from 25th December to 24th January the

operating temperature dropped to an average of 19 ± 1 °C. The large drop in temperature may have resulted in a reduction in the activity of the biogas producing methanogenic bacteria [103,111] and hence lower biogas production rate and productivity. Over the experimental period the average biogas production rate and productivity were $0,16\pm0,11 \text{ m}^3_{\text{biogas}}/\text{m}^3_{\text{digester}}$ per day and $0,18\pm0,12 \text{ m}^3_{\text{biogas}}/\text{kgVS}$ respectively. This was lower than the biogas production rate and productivity of the same digester design operated under similar conditions[41]. The lower performance could be due to poor mixing of the digester content.



Figure 35: Productivity and Biogas production rate

Energy Recovery Efficiency of the digester

Figure 36, shows the biogas production potential fed into the digester and the biogas recovered by the digester during the experimental period. The total biogas production potential of the feedstock fed into the digester during the experimental period was 578,5 m³ and the total biogas recovered was 118,3 m³. Thus the energy recovery efficient of the digester was about 20,4 %. Although much solids matter (more energy) were fed into the digester the amount of energy recovered was low. The %TS in the influent was higher than the designed value. Mixing of digester content become significant with respect to biogas production when the TS concentration was higher than 8 %[39]. The high %TS in the influent required better mixing for an improved biogas production. Thus, the efficiency of the digester especially mixing and temperature inside the digester when the total solid input and OLR have been increased.



Figure 36: Biogas production potential and Biogas production

Economic Evaluation

Table 24 shows the capital cost profile in terms of components of the digester. The most costly aspect of the installation of the digester was the labour cost. This cost pattern was observed in other parts of SSA and high altitude regions [101,108]. Biogas technology was relatively new in Cameroon like in most SSA countries. The local technical know-how in the construction of biogas systems was still very limited [106]. Thus the cost of skilled labour cost by 50 % could reduce the capital cost of the system by closed to 25%. Therefore, human capacity building could lead to reduction in cost of the technology in Cameroon and other SSA countries. Excluding labour cost, the most expensive part of the digester system was the dome (biogas storage facility). The advantage of the dome was that it provided for safe storage of biogas and also enabled the biogas to be delivered at a constant pressure at the consumption point. Research for cheaper and safer biogas storage facilities could lead to reductions in installation cost.

The cost profile of the digester in terms of types of construction materials (Table 25), showed that, apart from the skilled labour cost, cement was the most expensive material used. Cement was not often available at the installation site, as it is common of rural areas of DC. The required cement was bought and transported from the nearest supply point, usually quite some kilometers from the rural villages. Most of the cement was used in making the bricks and in the concreting of the dome. Using locally made earth bricks could lead to the reduction in the cost of cement by 29 % and a reduction in the total installation cost by about 6 %.

Component	Cost	Domontogo	
Component	FCFA	€	Percentage
Excavation	85.000	130	10%
Digester floor	23.500	36	3%
Digester walls	73.425	112	9%
Dome	116.550	178	14%
Outlet Chamber	89.625	137	11%
Biogas Convey pipeline	22.750	35	3%
Skilled labour	400.000	610	49%
Total	810.850	1236	100%

Table 24: Capital cost profile of the digester system in Cameroon

Table 25: Digester cost profile in terms of materials

	Cost		Percentage
Material	FCFA	€	[%]
Cement	161.050	246	20
Gravel	28.000	43	3
Sand	95.250	145	12
Others	44.550	68	5
Unskilled labour	82.000	125	10
Skilled labour	400.000	610	49
Total	810.850	1.236	100

Table 26, shows a comparison of the cost per unit digester volume in some selected countries. The cost per unit digester volume was \in 123 within the rural context of Cameroon. The relatively high cost of the digesters in African countries compared to the Vietnam (and other Asian countries) was mainly due to cost of materials[101].

Table 26: Installation cost comparison for selected countries

	Cameroon	Kenya	Rwanda	South Africa	Vietnam
Cost per digester volume (€/m ³)	123	51	135	179	18

5.2.3 Conclusions

A 10m³ Nepali GGC2047 digester design has been technically and economically evaluated within the social, economic, cultural and environmental context of rural area of Cameroon. The digester successfully operated on multiple-locally-available feedstock (co-digestion) including garden weed, pig, fowl, rabbit, and goat and cow dung. The operation regime was towards the DAD principle. The quantity of daily influent was variable with an average of 57 kg fed per day. This feeding regime resulted in a variable HRT with an average of 147 days and a variable OLR with an average of 0.9 kgVS/m^3 per day. The digester operating range of temperature was between psychrophilic and mesophilic range. The average maximum temperature measured was 26 °C and the average minimum was 19 °C. Under these determined operating conditions of feedstock, HRT, OLR and operating temperature, the average biogas production was $1,2 \text{ m}^{3}_{\text{biogas}}$ per day, giving an average biogas production rate and productivity of 0,16 m³_{biogas}/m³_{digester} per day and 0,18 $m_{biogas}^{3}/kgVS$ respectively. The determined energy recovery efficiency of the digester was about 20 %. The total investment cost of the digester was FCFA 810.000 (€1.236) giving a cost per unit volume of FCFC $81.000/m^3$ (€ 123 /m³). The cost of biogas storage facility (dome) and local skilled labour constituted the greater share of the investment cost with Cement as the most costly material used.

Biogas production rate and productivity of the digester was lower than expected. This could be due to two main reasons. Firstly, operating the digester at a very high average %TS required supplementary mixing for a good biogas production. The only mechanisms for mixing in the experimental digester was its component configuration and the movement of the slurry inside the digester as a result of changes in pressure of the biogas storage. Secondly, the digester operated between higher psychrophilic and lower mesophilic temperature range, which was below the optimum mesophilic range for which it is design to function.

Therefore, key parameters for the optimization of the digester within the social, economic, cultural and environmental context of rural Cameroon and other SSA countries, could be:

- *Mixing of the digester content:* This could be achieved through the optimization of the engineering digester design configuration.
- *Operating temperature of the digester:* this could be achieved through the integration of appropriate decentralized renewable energy sources for heating of the digester contents.

Improvement of these essential technical operating parameters of the digester together with local capacity building in construction skills and use of local materials could lead to lowering of the required investment cost and hence mass dissemination of the technology in rural areas of Cameroon and SSA in general. This thesis focused on the improving mixing in the digester content.

5.3. Optimization of the Nepali GGC2047 Digester Design

The performance of the digester was primarily affected by retention time of the digestible slurry in the digester and the degree of contact between incoming substrate and the viable bacterial population. These parameters are functions of the hydraulic regime (mixing) in the digester. The importance of mixing in AD has been highlighted in [38–40,96,119]. The hydrodynamics in the digester is affected by the digester geometry and physical properties of the slurry, along with operating conditions. The effect of mixing on biogas production becomes important when total solid (TS) concentration is greater than 5 % [39]. From the experimental investigation of the performance of a pilot-scale Nepali GGC2047 digester within the context of rural Cameroon, it was found that the digester operated at a %TS greater than 5%. Poor mixing was identified as one of the parameters that contributed to the low performance of the digester. Therefore, improved mixing of the digester contents could increase the biogas production. In this digester design, the hydrodynamics is affected mainly by the geometry of the digester, in particular the configuration of the inlet[105].

The objective of the optimization of the Nepali GGC2047 design was to identify an inlet configuration of the digester geometry that provides an improved mixing of the digester content. To achieve this objective numerical approach was adopted to investigate mixing in the digester design with various inlet configuration.

5.3.1 Methods and Tools

Hydrodynamic Model

As mentioned in [105], the cause of flow within the digester is from three sources namely: (i) input of fresh material which makes the most of the contributions to the flow (ii) up flow of gas bubbles and warm material and (iii) back flow of slurry from the outlet tank and inlet pipe after the stored gas was consumed. Thus, mixing of the digester content was achieved entirely by the hydrodynamic forces of the digester design. Modification of the engineering design of the digester would avoid cost for additional stirring devices and extra handling time by the user. The dynamic behavior of the slurry inside the digester, determination of the flow patterns and the spreading of the fresh slurry from the inlet pipe into the digester belong to the field of Fluid Dynamics. Hence the slurry behavior was governed by the equations of *continuity, momentum* and *energy*. The forces that influence the flow of a volume element of slurry inside the digester are pressure gradient, viscous friction and gravity.

The following assumptions were made about the slurry in the digester:

- (i) Slurry was incompressible, that is, the density was constant.
- (ii) homogenous
- (iii)and isothermal

With these assumptions the relevant transport equations for the hydrodynamics inside the digester are *Equation 35* and *Equation 36*.

$$\nabla (\rho U) = 0$$
Equation 35
$$\frac{\partial (\rho U)}{\partial t} + \nabla (\rho U U) = -\nabla p + g$$
Equation 36

Further assumptions made included:

(iv) The Reynolds number for laminar- turbulent flow was given by

$$Re = \frac{vD}{\vartheta} \qquad \qquad Equation 37$$

- (v) The slurry exhibits non-Newtonian pseudo-plastic fluid behavior when TS \geq 2.5%. Thus the viscosity obeys the power law as in *Equation 38* and the density was a function of the TS content as in *Equation 39* [40].
- (vi)Digester temperature is constant $(25^{\circ}C)$

$\eta = k\gamma^{n-1}$	Equation 38
$\rho = 0.0367TS^3 - 2.38TS^2 + 14.6TS + 1000$	Equation 39

A two-step approach could be adopted to achieve the optimization of the design. The first step consist of identifying the digester inlet configuration that produces an improved mixing and the second step consist of optimizing the TS content for this configuration. A Newtonian fluid behavior was considered appropriate for the first step of the investigation and non-Newtonian fluid behavior was relevant for the second step. The first step was considered sufficient for this study.

A homogenous single-phase, non-reacting fluid model was selected to simulate the flow patterns of the slurry in the digester. Water was considered an appropriate modelling fluid since it constitute more than 90% of the slurry volume and also the movement of the solid particles relative to the bulk liquid was considered negligible.

Flow Regime

The mass flow rate of the slurry into the experimental digester was measured in the experimental digester to be 0.483 kg/s (see section 5.1). This mass flow rate corresponded to an in-flow velocity magnitude of 0.0474 m/s. Applying *Equation*

38 in both the inlet pipe and inside the digester, the Reynolds numbers were calculated as follows

<u>Inlet pipe</u>	<u>inside digester</u>
D = 3.0 m	D = 2.44 m
v = 0.047 m/s	v = 0.047 m/s
ϑ = 1.004 <i>e</i> -6 m ² /s	ϑ = 1.004e-6 m ² /s
<i>Re</i> = <i>141,446</i>	Re = 115,025

Hence the flow regime in both the inlet pipe and the digester tank was turbulence. Based on the investigation by [120], the standard k- ε turbulence model was selected to model the turbulence and *Equation 40* and *Equation 41* were applied for the turbulence kinetic energy and dissipation rate respectively.

$$\frac{\partial(\rho k)}{\partial t} + \nabla (\rho U k) = \nabla (\Gamma k \nabla k) + G k - Y k + S k \qquad Equation 40$$
$$\frac{\partial(\rho \epsilon)}{\partial t} + \nabla (\rho U \epsilon) = \nabla (\Gamma k \nabla \epsilon) + G \epsilon - Y \epsilon + S \epsilon \qquad Equation 41$$

Simulation conditions

The open source software OpenFoam2.3.0 platform and the pimpleFoam solver were used to solve the governing flow equations under different inlet geometric configurations. The pimpleFoam solver was modified to include a scalar transport equation for the tracer used in the simulation. Paraview 4.4 was used to post process the results the simulations.

Geometry and mesh

The simulations were done in a full-scale 6m³ digester whose dimensions were as described in the Nepali GGC2047 construction manual [97]. With the nomenclature in the manual, the size of the digester included the biogas storage volume. Since a non-reacting fluid was considered, the biogas storage volume was omitted and the digester volume used in the simulation was 4.7 m³. Eight different inlet opening into the digester constituted the different geometric configuration for investigation. The geometry of these configurations were generated and discretized into a 3D mesh made up of a combination of tetrahedral and hexahedral cells using Gambit 2.4.6. The 3D mesh was then exported to OpenFoam for simulations.

Boundary and Initial conditions

The following boundary conditions were applied

(i) Zero normal gradients for all variables at the liquid surface.

(ii) No velocity slip at solid walls and standard wall function were used near all wall treatment.

Four boundaries were created in the geometry, namely: *inlet boundary* (the open ends of the inlet pipe), outlet *boundary* (opening of the "manhole" of the digester), *Top boundary* (opening of digester into the gas storage) and *Wall boundary* (inlet pipe wall, digester wall and bottom and walls of the manhole). An initial velocity of magnitude 0.047m/s was imposed at the inlet and zero gradient for the pressure at the outlet. The initial k and ε values were calculated using *Equation 42* and *Equation 43*.

$$k = \frac{3}{2} (TU)^{2}$$
Equation 42
$$\varepsilon = \frac{C\mu^{\frac{3}{4}k^{\frac{3}{2}}}}{D}$$
Equation 43

With the initial velocity, U, inlet pipe diameter of 0.01m and turbulence intensity, T, of 3% the initial values of k and ε were 3.0251e-6 J and 8.645 e-9 m²/s³ respectively.

Discretization

The finite volume approach was used to discretize the governing equations. Euler approach was used to discretize the unsteady terms, linear Upwind was applied to the divergent terms, Guass linear and cellMDLimited LeastSquares were applied to the pressure and velocity convection terms respectively and the Gauss linear corrected technique as applied to the Laplacian terms. Linear interpolation of the velocity was adopted in the simulations.

RASmodel and Transport Model

The k- ϵ turbulence model was turned on. For the fluid transport properties the Newtonian transport model was selected with following input transport properties dynamic viscosity of water, $\mu = 10^{-6}$ s/m² at 25° C and 10⁻⁸ m²/s for the diffusivity of the tracer, assumed to be ink.

Solution control and numerical and physical convergence

Unsteady state simulations were executed. To control for smooth convergence of the solution relaxation factors were applied and set as follows: 0.55 for the pressure field, 0.3 for the velocity, turbulence kinetic energy and turbulence dissipation rate and 1 for their final values. The solution was considered numerically converged when the residuals for pressure field and tracer field reduced to 10^{-7} and 10^{-5} for the U/k/ ϵ fields. Two probes were placed inside the digester, one closed to the inlet pipe opening to the digester and the second at the bottom of the outlet. The simulations

were considered physical converged when the fluctuations in velocity were less than 0.1% per second which was well within the 5% acceptable limits.

Grid independence

To ascertain the accuracy of the solution, three meshes of element size 40mm, 35mm and 30mm representing coarse, medium and fine mesh respectively were generated and simulations executed with these meshes. At convergence, the Grid Convergence Index (GCI) was calculated. GCI of 0.09% was obtained for the fine mesh relative to the medium mesh. Notwithstanding, computational time increase with the fine grid size, the fine mesh was, however, adopted for the simulations of all eight geometric configurations.

5.3.2 Results

Both qualitative and quantitative methods were used to analyze the results of the simulations. Qualitative analysis were in terms of the spread of the tracer and the velocity field contours. The quantitative analysis were mainly in terms of the integral of the volume fraction of the tracer.

Qualitative analysis

The velocity field contours in a horizontal plane taken at half the height of the digester (Figure 37) for each of the candidate inlet configurations were obtained using Paraview 4.4 and compared. From Figure 42, in the geometries 1a and 3a it was observable two vortices indicating recirculation of the fluid in the digester, however, there was also a strong central jet of the fluid at a relatively higher velocity through the digester from the inlet to the outlet. This central jet fluid flow at higher velocity could lead to flushing out of slurry out of the digester and hence a short residence time.



Figure 37: Velocity contours in a horizontal plane through center of digester

In configuration 2a and 4a the jet fluid flow was also observable, although, the flow velocities were less compared to 1a and 3a. In configuration 1b and 3b, the flow was more spread around the walls of the digester compared to 1a and 3a. However, the spread was greater in 1b than 3b where the central jet was narrower. In 4b, the fluid flow spread appeared deeper into the digester away from the inlet whereas in 2b there was a greater spread from the inlet along the walls of the digester, similar to the spread of the flow in 1b, however, with a less stronger jet. Thus, the inlet configuration corresponding to 2b had a better flow pattern, than in the other configurations.

Quantitative results

The integral of the volume fraction of the spread of the tracer in each of the configuration was determined. The results are shown in Figure 43. The configuration corresponding to 2b had the largest value of the integral. This showed that the tracer spread more in this configuration than in the other configurations.



Figure 38: Volume integral of tracer

5.3.3 Conclusions

The qualitative results represented the flow pattern of the slurry in the digester while the quantitative results represented the spread of the slurry in the digester. Combining the qualitative and quantitative results, it could be deduced that the configuration corresponding to 2b provided a better spread of fluid flow in the digester and hence an improved mixing of the digester content compared to the other seven configurations.

5.4. Field Validation of the Modified Nepali GGC 2047 Digester Design

From section 5.2, the Nepali GGC2047 digester operated at % TS of more than 10% within the context of rural Cameroon. Also, from the numerical investigations in section 5.3, the inlet configuration corresponding to 2b, provided a better mixing of the digester content. It has been demonstrated that at a 10 % TS, improved mixing of digester content should result in more biogas production than unmixed digester content [39]. The objective of the field investigation was to assess the impact of the modified inlet on biogas production of the digester. The hypothesis verified was that "the modified digester performed better than the normal digesters". Hence the null an alternative hypothesis were:

- \circ H_0 : $\mu_m \leq \mu_c$ i.e. modified digester is not better than the control
- \circ H_1 : $\mu_m > \mu_c$ i.e. modified digester is better than the control

5.4.1. Methods and Tools (first experimental campaign)

In a first field experimental campaign, two digesters, one with the modified inlet configuration and the other with the "normal" inlet configuration; both of capacities 6 m³ were installed on the campus of Catholic University of Cameroon (CATUC) Bamenda in August 2015 (Figure 39). Both digesters were equipped with identical gas flow meters of type ECOMETROS_R.E.M.I, Italy, to measure daily biogas production. The digesters were both initially fed with equal amounts of cow dung mixed with water to bring the digester content to about 10 % TS concentration. After two days of operation the digesters started producing combustible biogas. Data collection was initiated on 13th of September 2015. Feeding of the digesters with fresh dung from the same source started on the 7th of October. The fresh dung was mixed with water to bring the %TS of the influent to about 10 %. The digesters were fed three times in a week with equal amounts of influent. Data was collected each time the digesters were fed. The quantity of influent was measured using a normal mass scale. The %TS of influent was determined using standard methods. Biogas production from each of the digester was measured using the installed gas flow meters. The pH inside both digester were measured using a portable pH meter. Temperatures inside the digester and ambient temperature were determined using a K-type thermocouple. These essential parameters, i.e. feedstock, operating temperatures, and pH were considered sufficient to assess the biogas production from both digesters.



Figure 39: Modified inlet and its installation

Results

Table 27, shows the average operating conditions in both digesters.

Table 27: Essential digesters operating conditions (first experimental campaign)

Essential Parameter	Control	Modified
Average Temperature inside digester (°C)	22,6	22,6
Average pH	7,9	7,8
Average fresh feedstock (kg/day)	20,9	20,8
Average water used in diluting feedstock (kg/day)	12,8	12,7
Average %TS	11,8	12,4

It could be deduced from these values that both digesters operated under identical essential conditions of digester content temperature, pH, feedstock and % TS concentration. Therefore the performance of the digesters may be validly compared.

The biogas production from the digesters is shown in Figure 40. The statistics of biogas produced in the modified and control digester were summarized in Table 28.



Figure 40: Biogas Production in the modified and normal digesters

It was observed that the daily biogas production from the control digester was most of the times higher than that from the modified digester. From September to 11th of November the average quantity of fresh feedstock fed into the digesters was 25,8 kg/day, while from 11th November 2015 to 24th of January 2016 the average quantity of fresh feed stock fed into the digesters was reduced to12,6 kg/day which was half of the quantity fed during the period from September to 11th November 2015. The reduced quantity of fresh feedstock used was reflected in the drop in the biogas produced per day during the same period. From the 2nd to the 13th of January 2016, although both digesters were fed with equal increased in the quantity of fresh feedstock, the production of the control digester rose suddenly while that of the modified digester remained very low. The rather low performance of the modified digester was unexpected. This unexpected performance was thought to be caused by the produced and installed modified inlet.

Parameter	Control	Modified
Mean (litre/day)	267,88	159,10
Standard error of mean (litre/day)	22,45	12,96
Standrad deviation (litre/day)	171,00	98,76
minimum (litre/day)	11,00	3,00
Maximum (litre/day)	742,00	401,00
95% confidence interval	(222,92 - 312,84)	(133,13 – 185,07)

Table 28: Statistics of biogas produced (first experimental campaign)

From the statistics of the two digesters, the standard error of the mean and standard deviation of biogas production from the modified digester were about half of those for the control digester. Thus, the recorded daily biogas production from the control were more spread out than for the modified.

A t-Test of the two samples assuming unequal variances produced a p (T \leq =t) one tail value of 3E-05. The H₀ statement was thus rejected.

On re-examination of the installed modified inlet, it was realized that it was not produced according to the results of the numerical studies. A correction of the modified inlet was done in March 2016 and a second experiment campaign was carried out from May to September 2016.

5.4.3. Methods and Tools (second experimental campaign)

In the second experimental campaign, the modified digester was emptied of its content, the inlet removed and corrected as shown in Photo 10. Three samples of cow dung used to feed the digesters were taken and analyzed for %TS. Both digesters were reloaded with about 1014 kg of cow dung mixed with 2358 kg of water to bring the %TS concentration to about 10%. The digesters were fed three times in a week with equal amounts of influent. Data was collected each time the digesters were fed. The quantity of influent was measured using a normal mass scale. The average %TS of fresh feedstock was determined by drying samples in an electric oven. The dry mass was determined from which the %TS was calculated using standard formulae. The calculated %TS was used to determine the %TS of the influent. Biogas production from each of the digester was measured using a portable pH meter which was also used to determine the temperatures inside the digester and ambient temperature.



Photo 10: Corrections made to the modified inlet

Results

Table 29, shows the average operating conditions in both digesters.

 Table 29: Essential operating parameters (second experimental campaign)

Essential Parameter	Control	Modified
Average Temperature inside digester (°C)	22,8	23,0
Average pH	8,2	8,1
Average fresh feedstock (kg/day)	11,8	11,77
Average water used in diluting feedstock (kg/day)	10,9	11,3
Average %TS	9,94	9,93

It could be deduced from these recorded values that both digesters operated under identical essential conditions of digester content temperature, pH, and feedstock and % TS concentration. Thus their performances may be validly compared.

Figure 42, show the biogas production from both digesters during the experimental period. It was observed that the daily biogas production from the control digester was most of the times higher than that from the modified digester. Between, the 25th of May and the 1st of June, the modified digester seemed to have exceptionally produced more biogas than the control digester. This was because the control valve of this digester was left open, so the time interval over which biogas production was measured was longer than in the normal digester.



Figure 41: Biogas production for both digester during second campaign

The statistics of the performance of the digesters were summarized in Table 30.

Parameter	Control	Modified
Mean (litre/day)	296,83	239,67
Standard error of mean (litre/day)	9,68	19,36
Standrad deviation (litre/day)	67,05	134,11
minimum (litre/day)	170	68
Maximum (litre/day)	296,83	883
95% confidence interval

(277,36 - 316,30) (200,72 - 278,61)

From the statistics, the standard error of the mean and standard deviation of biogas production from the modified digester were about double those for the control digester. Furthermore, the average daily biogas produced by the modified digester was 19% less than that produced by the control digester.

A t-Test of the two samples assuming unequal variances produced a p (T<=t) one tail value of 0,005. The H₀ statement was thus rejected. Thus the performance of the modified digester may not be less than the control digester. Although the actual average daily biogas production from the modified digester was lower than for the control digester, the statistical analysis showed that the control digester does not performed better than the modified. The large standard deviation of the modified could mean that it would perform better than the control. Therefore, the engineering modification of the inlet seemed to cause the digester to perform better than the normal digester.

5.4.4 Conclusions

The results from the field validation of the modified digester, the daily biogas production from the control digester was almost all the times higher than the production from the modified versions. The corrected modified digester produced 50% more biogas than the previous version. This demonstrated the need for local progressive improvement of small scale technologies to improve energy access in DC. Although, the mean biogas production from the control digester was higher than for the modified version, this had no statistical significance. This may imply that if the digester content was up to 10 %TS concentration, mixing would significantly improve on the biogas production of the digester.

The experience from the field validation of laboratory results demonstrate the challenges with implementation of improved small scale technologies within the context of DC where high-tech expertise is often lacking. Thus improving small scale technology within the context of DC would require coupling both laboratory analysis and capacity building in local manufacturing know-how.

5.5. The Leaching Bed Digester Design for DC

Increasing the adoption of biogas technology in SSA also entails a search for alternative digester designs which are low cost, compact and can operate on a wide range of organic materials. Ways to reduce the cost and widen the applicability of biogas technology include; improving biogas production per digester volume; widening the range of organic materials that can be treated; increasing the total amount of organic matter digested by the digester i.e. increasing the organic loading rate, simplifying the design of the digester and the materials used in digester construction [112,113].

Dry Anaerobic Digestion (DAD) principle could be a better option to make biogas technology more accessible to users in DC, especially rural areas of SSA, where

there is scarcity of animal dung but an abundance of a wide variety of biomass. DAD is rapidly gaining momentum because of its advantages which include higher biogas production, wide range of organic materials that could be used and compact digester volume. A number of researches have been carried out on DAD [33,104,110,114]. Amongst the various digester design options for DAD, Leaching Bed Digester Design (LBDD) is a promising technological option. The advantages of this anaerobic process and digester design include; no refine shredding of waste, no mixing, it can be operated at ambient conditions and can be operated in both mesophilic and thermophilic conditions. Originally designed to be a batch dual-stage process, the process has been modified to a batch single stage design and has been successfully applied in the biogasification of a variety of waste [115,116]. There is little development of LBDD for small scale application in DC.

An innovative concept of LBDD, was designed at the University of Milan, Italy. Evaluation of this concept was done through a collaborative research between the University of Milan and Politecnico di Milan. A full-scale prototype was built in Italy tested and evaluated to define its operational characteristics and potentials for digesting a variety of feedstock and its application in DC, especially rural areas. The evaluation was in terms of biogas production and productivity and stability of the AD process in the design operated on a mix of a wide range of organic matter without pre-treatment.

5.5.1 Methods and Tools

The experimental unit was an innovation in terms of digester design and anaerobic digestion process principle with respect to the principle common with digesters widely disseminated in DC. The experimental digester unit consisted of a 4,9m³ rectangular cylinder partitioned into three components, namely; a 0.31 m³ inlet chamber, 2.6 m³ digestion chamber and a 0.39 m³ outlet chamber. The digestion chamber was covered with a fixed metal lid which could easily be removed and replaced as required. The inner part of this metal lid was lined with a PVC sheet to prevent gas leakage. A mechanical mixer was installed in the digestion chamber for mixing of the feedstock. The digester was installed part below the ground and part above the ground. This construction approach was intended to achieve a certain control over the temperature inside the digester [115].The scheme of the set-up is shown in Figure 43.



Figure 42: Scheme of the experimental LBDD

The concept design was intended to be less complex, needing less mechanical maintenance and separating the solid retention time and the hydraulic retention time in order to achieve a higher formal over the later and operated on the leaching bed principle [116]. A spherical-roof Green House (GH) was integrated into the digester to capture solar energy to improve on the operating temperature of the digester.

Experimental procedures and measurements

The digester was operated as a hybrid between the continuous and batch feed mode. It was fed 2-3 times a week with a variety of organic matter collected from the farms and households around the digester in Melegnano-Milan. The variety of organic matter were fed into the digester in their original state without any pre-treatment. The type of feedstock used were selected to reflect those common in rural areas of DC. Waste water from a kitchen flowed via a pipe into the digestion chamber, leached through the organic matter inside the digestion chamber and exited into the outlet chamber from where it was discharged. Thus the hydraulic retention time and the solid retention time were separated. The content of the digestion chamber were mixed each time the digester was fed for 2-3 minutes.

The following parameters were monitored over the experimental period which lasted from May – October 2014, namely; the hydraulic and solid retention time, quantity and type of organic matter fed into the digester, temperature inside the digestion chamber, temperatures inside the Green House, the daily amount and the quality of biogas produced ; Volatile Fatty Acid (VFA), Total Alkalinity (TA), dissolve ammonia (N-NH₄+) accumulation and Acidity (pH) inside the digestion and in the outlet chambers.

The hydraulic retention time (HRT) was measure by determining the water flow rate, Q, into the digester. The flow rate was determined by timing how long it took to fill the digestion chamber, then standard formula was used to determine the HRT. The solid retention time (SRT) was calculated using standard formula. The mass of each category of organic matter fed into the digester was determined separately using an automatic dial scale. The temperature inside the digester were measured using a thermocouple with a digital display introduced into the digestion chamber via the inlet chamber each time measurements were taken. The temperature inside the GH were measured using an ordinary mercury-in-glass thermometer permanently kept in the GH. Temperature outside the GH were obtained from internet record of average temperatures in Milan. The quantity of biogas produced was measured using an ECOMETROS_R.E.M.I industrial gasflow meter installed at the biogas outlet of the digester. The quality of the biogas produced was determined by periodically taking samples to the laboratory for analysis using a Micro GC 3000, Agilent Technology gas chromatographer equipped with a Thermal Conductivity Detector. Samples of the contents inside the digestion and outlet chambers were taken periodically and analysed for VFA, TA, N-NH₄⁺, in the laboratory of the University of Milan-Paco Tecnologico, using the 8-point titration procedure [117,118]. The results of the titration were processed using a software on measurement of Volatile Fatty Acids and Carbonate Alkalinity in Anaerobic Reactors. The ratio of VFA and TA indicated chemical stability of the AD process. A ratio greater than 0.3 indicated that the system was tending to a high accumulation of acids in the digester thus inhibiting the growth of the methanogenic bacteria and hence low biogas production. The pH of the samples was determined using a EUTECH INSTRUMENTS PC 2700 pH meter.

5.5.2 Results

Hydraulic Retention and Solid Retention Time

The water flow rate into the digester, Q was determined to be 0,234 m³/day. Using the standard formula for HRT for a digester volume $V = 2,6 \text{ m}^3$, i.e. HRT = V (m³)/Q (m³/day) gives HRT of 11days. The calculated solid retention time was 139 days.

Feeding regime and organic loading rate

The types and quantity of feedstock fed into the unit is shown in Figure 44. On the average 25,5 kg/day of organic fresh matter were fed into the digester. The Organic Loading Rate (OLR) was stabilized at an average of 1,01 kgVS/m³ per day.



Figure 43: Types and Quantities of fresh organic matter fed into the unit

Temperature

The digester was installed part below the ground and part above the ground. With the integration of the Green House, it was possible to operate the digester at a stabilized temperature of 28 ± 3 °C which was closed to the optimum in the mesophilic range. This operating temperature was higher than the recoded average ambient temperature of 20 ± 3.5 °C. The daily record of the temperature inside the digester, the Green House and average ambient temperature are shown in Figure 45.



Figure 44: Daily Temperature records

Biogas production

Figure 46 shows the daily quantity and quality of biogas produced. Three distinct process phases were identified during the experimental period, namely; *start –up* (May – June 9), *stable* (Mid-June to October 8) and *saturation* (October 8 to end of experimental period). The start-up phase was characterised by slowly increasing biogas production, indicating the gradual growth of microorganisms involved in the biogas production process. The stable phase was characterised by stable biogas production indicating the full growth of the microorganisms. The saturation phase was characterised by declining biogas production. During this phase the digester was almost full and it was difficult to add additional fresh matter into the digester. This resulted in reduced OLR and hence decreased biogas production. During the stable phase, the average biogas production was 1,0 m³/day and the production rate was 0,36 m³_{biogas}/m³_{digester} per day. The quality of the biogas was between 62 and 65 % Volume/Volume.



Figure 45: Daily quantity and quality of biogas produced

Productivity

The daily productivity of the digester is as shown in Figure 47. The three distinct phases were also recognized in the productivity of the digester. Over the entire experimental period, the average productivity of the system was 1,52 m³/kgVS per day.



Figure 46: Productivity of the digester

VFA, TA, and pH in the digester

Table 27, shows the analysis of essential parameters determining the chemical stability of the AD process in the design.

Table 31: Analysis o	of VFA, TA and pH
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	Date	VFA [mg/l]	TA [mg/l]	VFA/TA	N-NH ₄ + [mgN/l]	рН
Inlet	19.06.2014	0,3	339,6	0,001	144,7	6,87
	30.06.2014	158,4	1.112,7	0,142	164,3	6,51
	07.07.2014	490,7	1.433,8	0,342	156,8	6,63
	24.09.2014	352,7	1.345,1	0,262	287,4	6,53
	24.10.2014	105,2	1.894	0,056	_	-
Outlet	19.06.2014	18,5	1.170,1	0,016	112	6,98
	30.06.2014	33,4	1.397,7	0,024	142,1	6,9
	07.07.2014	101,4	1.163,1	0,087	174,6	6,8
	24.09.2014	81,3	1.567,2	0,052	169,4	6,74
	24.10.2014	1	1.476	0,001		

The average VFA concentration recorded in the inlet and outlet were 221,5 mg/l and 58,65 mg/l respectively; the average TA was 1225,04 mgCaCO₃/l and 1354,82 mgCaCO₃/l respectively. The VFA/TA ratio in both the digestion and outlet chamber were less than 0,3 indicating very stable AD process in the design. The average N-NH₄⁺ in the inlet and outlet were 188,3 mgN/l and 149,53 mg/l respectively. The average pH in the inlet and outlet were 6,64 and 6,86 respectively. Overall, the pH in the digester was between 6,51 and 6,98 which was well within the required range for a stable anaerobic digestion process.

5.5.3 Conclusions

Under operating conditions of co-digestions and DAD principle, the experimental digester demonstrated that it could digest a mixture of a wide variety of feedstock. The design had three distinct operation phases- start-up, stable and saturated phases. The anaerobic digestion process inside the digestion was very stable with a pH range of 6,51 - 6,98. The integration of the GH in the digester system improved the operating temperature within the digester and led to a relatively good biogas production of 1,0 m^3 /day during the stable phase of the operation. The quality of the biogas produced was 60 -65 % Volume/Volume which was within the acceptable range for use of biogas as an energy source. The operational time of the digester was about one-person-hour which involved pushing the feedstock into the digester and mixing of the digester content. Thus this design could be a viable alternative digester for DC. However, some operational issues were observed with the system, these issues included; difficulties in pushing feedstock through the inlet chamber into the digestion chamber, floating back of the solid materials into the inlet chamber. Also floating scum was observed in the digestion chamber which could prevent the release of some of the biogas produced. Modification of the engineering structure of the digester to improve its operation requires further investigations, especially the design of the inlet chamber to eliminate the difficulties in feeding the digester and also the digestion chamber to reduce the formation of scum.

A major outcome of this experimental activity was the demonstration of the simple low cost technique to improve operating temperatures of digesters through the integration of a GH into digester systems. Thus a GH could be integrated in the Nepali GGC2047 digester system to improve on the operating temperature.

The activities realized in section 5, i.e. full scale field investigation of the appropriated technology, laboratory investigations to improve on the design of the technology and full scale field validation of the improved technology provides a framework for a procedure for the optimization of an appropriate technology for application in a specific context.

Chapter 6: Conclusions

The challenge to access to modern energy services in rural areas of DC could be better approached through the integration of the concept of sustainable energization (SE) within a more comprehensive and sustainable local energy planning process and the identification and optimization of appropriate technologies. This study successful fulfilled the set specific objectives. In particular:

- An improved rural energy planning procedure which integrates the theme of SE was developed and its validity and relevance was tested in a rural context through a case study. An innovation in the procedure was the integration of existing energy balance in the planning process and insertion of energy drivers in the ESSN model. The case study demonstrated that the innovations in the REP procedure led to a great improvement in the quantity, quality and variety of accessible, affordable and reliable energy services which are primordial for poverty alleviation and sustainable human development, as stated in SDG 7.
- A detailed analysis of the variety of small scale biogas systems currently disseminated in DC was realized and the AHP was applied in the selection of an appropriate design for the context of Cameroon. The Nepali GGC2047 design turned out to be the appropriate design for dissemination in the context of Cameroon.
- Mixing and digester operating temperatures were identified as local crucial operating parameters which affected the performance of the Nepali GGC2047 biogas digester design within the context of rural Cameroon.
- The engineering design of the Nepali GGC2047 digester was modified and investigated for an improved biogas production performance. The new design was proposed for integration in the energy supply chain to improve access to modern and clean cooking in rural areas of DC. Furthermore, an alternative digester design that digested a variety of biomass under DAD principle was investigated and its performance characterized for application in rural areas of DC.

In addition to the achievement of the specific objectives the study successfully developed a tool which could be used to improve access to energy in DC. This tool titled *"Towards a comprehensive energy access strategy in rural areas of DC"* This tool, consist of *three-stage namely:*

- An improved Rural Energy Planning Procedure (IREPP): This stage focuses on the integration of the theme sustainable energization in the planning process. It consist of seven steps, namely:
 - 1. Integration of goals of sustainable energization into the rural energy planning decision making
 - 2. Assessment of the existing energy balance situation of the target rural community.
 - 3. Identification and prioritization of the energy services demands according to the energy drivers

- 4. local renewable energy resource assessment with focus on renewable sources
- 5. Design of an integrated renewable energy system
- 6. Set up of the energy services supply network structure to include level of depth require regarding energy services demanded.
- 7. control and adaptation of the energy services supply network
- *Technology Selection Strategy:* The main steps in this stage include: Analysis of the applicable conversion technologies, identification of relevant alternatives and implementation of a Decision Support System for the selection of an appropriate option.
- *Technology Optimization Process:* this stage involves three main steps: identification of the performance parameters of the selected technology option within the relevant context, research to improve the performance of the technology, and Field validation of the improved technology.

These stages are executed in a sequential manner, beginning with the IREPP, then the technology selection process and the optimization process. Output of each of the stage serves as the input to the next stage.

The main steps are executed in a sequential manner, following the same logic as in the stages. In Figure 48, which shows a chart of the tool, the arrows indicted the flow in the execution of this strategy.



Figure 47: comprehensive approach to improve energy access in DC

This tool is an original contribution of this thesis to improve energy access in rural areas of DC.

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